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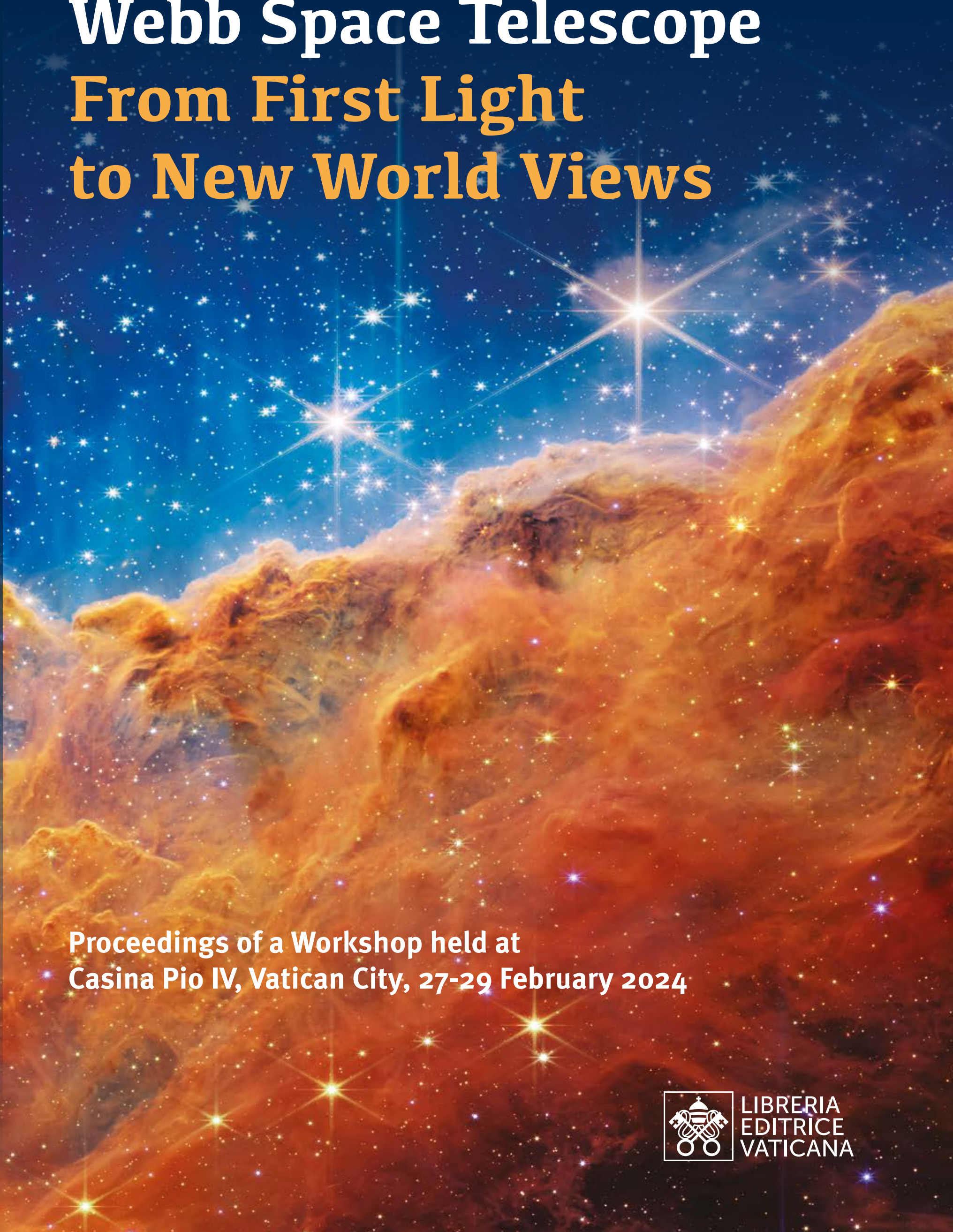
Edited by

Ewine F. van Dishoeck

Astrophysics: The James Webb Space Telescope
From First Light to New World Views



Proceedings of a Workshop held at
Casina Pio IV, Vatican City, 27-29 February 2024

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The Pontifical Academy of Sciences (PAS)
Casina Pio IV, 00120 Vatican City
Tel: +39 0669883195 • Fax: +39 0669885218
Email: pas@pas.va • Website: www.pas.va

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00120 Città del Vaticano
Tel. 06.698.45780
E-mail: commerciale.lev@spc.va
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We are amazed at the marvelous images sent from the new James Webb space telescope, and once the Vera Rubin Observatory becomes operative we expect to see how the universe continues to expand and change before our eyes. Above all, we are struck by the vastness of the universe, its enormous extent and the astonishing number of galaxies, stars and planets that have been identified…
My hope is that you will not remain content with the results of your research until you have also had the experience of being surprised. And even though you are looking at reality through the window of astronomy, be sure not to neglect the other windows that can show you other important realities, like compassion and love, realities that you are no doubt encountering also in the friendships that you are forming in these days. –Synodal Apostolic Exhortation

Message of His Holiness Pope Francis to Participants in the Summer School of Astrophysics of the Vatican Observatory, 15 June 2023

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Concept Note

The Pontifical Academy of Science of the Vatican (PAS) holds regular workshops to discuss issues at the frontiers of scientific knowledge and technological advances, including the ways in which such issues affect human life. An excellent contemporary example of such a theme is the James Webb Space Telescope (JWST) and the implications that its results have for the understanding of our place in the Universe.

This workshop took place at the seat of the Pontifical Academy of Sciences (Casina Pio IV) in the Vatican Gardens, on 27-29 February 2024.

The JWST data are revolutionizing many areas in astronomy, from the first galaxies to new worlds, thanks to its exquisite images and rich spectra that are orders of magnitude more sensitive and sharper than those of previous facilities. The aim of the workshop was to cover the exciting new results from JWST on topics including:

(i) earliest galaxies

(ii) galaxy evolution

(iii) lifecycle of stars and interstellar medium

(iv) exoplanets and protoplanetary disks

(v) our solar system

At the same time, the workshop also reflected on what this new knowledge means for science and society, and on what we can learn about the outreach and the public engagement efforts from JWST and other major astronomical facilities that would also be applicable to other disciplines.

The Scientific Organizing Committee consisted of E.F. van Dishoeck (chair), G. Consolmagno, K. Pontoppidan, M. Stiavelli, and G. Wright

Final Statement

Summary

- The James Webb Space Telescope (JWST) is revolutionizing many areas in astronomy, from first galaxies to new worlds, thanks to exquisite images and rich spectra that are orders of magnitude more sensitive and sharper than those of previous facilities. The workshop covered exciting new science from the high-redshift universe, to the spectroscopy of exoplanet atmospheres, to the study of bodies in our own solar system.
- The success of JWST provides lessons in how any such large international interdisciplinary program can succeed. For society to build and take full advantage of a telescope like JWST, a key element is recognizing that in every stage progress is dependent on multidisciplinary teams. This requires a necessary humility among the members.
- The societal impact of this telescope includes important economic benefits such as technology spin-offs and the training of bright, highly skilled young people who can take this experience to other fields and endeavours. The success of JWST shows how large and seemingly intractable technical problems can be broken down and solved.
- To bring the universe as observed by JWST down to Earth requires a global effort, including true partnerships to promote the growth of astronomy with society and local institutions. This includes access to the data for scientists in the developing world. Among the partners in this dialogue, one should not neglect the potential role that local churches can play in both disseminating the science and putting it into a human context.
- An important recent challenge is the preservation of dark and quiet skies vital to the ground-based observations that complement JWST. Moreover, the sight of dark starry skies has been inspirational to humankind since prehistoric times, notably for Indigenous peoples. A spirit of cooperation may be more likely to succeed in mitigating the problem of light pollution than relying simply on confrontation, with the ultimate goal to turn best practices into a regulatory framework to be endorsed internationally and adopted by appropriate national agencies.
- One of the remarkable successes of JWST has been its ability to excite and inspire the imagination of the public. This is a testament of the

excellent results of the observatory, but it also reflects years of careful study and work by the multidisciplinary team involved in creating the first color images and those who made themselves available to explain the science behind those beautiful images to the press and public.

– The astronomy represented by JWST provides an incentive to re-examine and re-appreciate our collective wisdom about the universe, from a dialogue with religion to a pondering of the possible existence of a multiverse. Staring into space with the huge communal eye of a telescope is a way of honoring the cosmos as a source of wonder and knowledge. In all of this, we encounter the other, the alien, not with fear but in an embrace, experiencing and responding to awe.

From first light to new world views

The James Webb Space Telescope (JWST) is revolutionizing many areas in astronomy, from the first galaxies to new worlds, thanks to its exquisite images and rich spectra that are orders of magnitude more sensitive and sharper than those of previous facilities. The workshop covered exciting new science from the high-redshift universe to planets in our own solar system.

Since its launch, JWST has produced outstanding data and one hopes it will continue to do so for many years – in fact, many more than we had originally anticipated. We note an important synergy of its work with that of other major facilities but also recognize that some of its instrumental capabilities are truly unique. There will not be another opportunity for more than 20 years or longer before a similar large facility will be in space.

At the same time, this workshop also has reflected on what this new knowledge means for science and society, deriving lessons learned from the JWST outreach and the public engagement program, which has reached billions of people around the world.

How JWST came to be

"Science's task is a patient yet passionate search for the truth about the cosmos, nature, and the constituents of the human being." (Pope Benedict XVI). The need for patience was certainly shown in the lengthy history that finally led to the launch of JWST. Likewise, the passion and the search for the truths it would reveal could be seen both in the commitment of the scientists and engineers toward this project, and the excitement elicited by its results.

JWST was thirty years in the making. Its original driver was to study the earliest galaxies ("first light"), but as it developed the discovery of exoplanets, i.e., planets around other stars than our Sun ("new worlds"), added to the impetus of its development. Advances in technology, such as the development of segmented large optics and new infrared arrays, were also crucial. But equally crucial was the ability to manage international teams with their mix of expertise to make this happen. Rather than being the vision of a single astronomer, JWST was the result of a large community where every person's abilities became crucial, both in designing, building, testing and launching the telescope and its instruments, as well as ensuring that the mission actually did happen in spite of numerous technical, political, and budgetary challenges.

Exoplanets

Before JWST, our knowledge of exoplanets was, with only a small number of exceptions, limited to a two-dimensional survey of their sizes (or masses) and their distances from their central stars. However, JWST now provides a new dimension to our survey of these new worlds by providing exquisite tools for detecting and measuring the compositions of their atmospheres.

Transits have already been a powerful tool for discovering exoplanets, with the depth of the transit dip giving a measure of the planet's size. Now with JWST, one can measure the depth of that dip as a function of infrared wavelength to much greater precision than previously possible. The absorption at a given wavelength by a constituent of the planet's atmosphere produces a slightly larger dip at the absorbing wavelength, and thus a plot of transit depth versus wavelength becomes a transmission spectrum of the atmosphere. JWST can also observe infrared emission from some exoplanets by taking spectra just before and after the planet passes behind its host star. Meanwhile, more distant planets can be directly imaged by JWST, and their thermally emitted spectra measured.

Three major science questions being addressed by JWST are the composition of giant planet atmospheres compared to their parent star, providing clues on their formation; whether terrestrial planets around very low-mass stars have atmospheres at all; and the nature of sub-Neptune exoplanets.

With the discovery of atmospheres especially in temperate (potentially habitable) zone planets comes a renewed study of the possibility of life on these bodies. A particularly interesting subset of planets are the sub-Neptune and super-Earth planets with radii and masses a few times those of Earth. They have rocky cores but their atmospheres may consist of a mix of primary and secondary (outgassing) material. "Hycean" worlds, with hydrogen rich atmospheres and oceans, are just one fascinating example of the new chemical environments in which the study of life's origin can be explored.

Protoplanetary disks

The spatial resolution of JWST in the infrared, again coupled with other space and ground-based telescopes, now allows spatially-resolved observations of the environments of planet formation around the nearest young stars. Furthermore, the higher spectral resolution free of interference from the terrestrial atmosphere offered by JWST allows us to infer the composition of the material that makes planets.

With the ability to study hundreds to thousands of such disks, around stars of all masses, one can outline the many different factors that result in the observed variety of known exoplanet systems. These include stellar mass and composition, radiation environments, age, and random variations that may have profound effects on how a planetary system develops. Indeed, JWST has already found a large diversity in the composition of the inner regions of disks, from water-rich disks to water-poor but hydrocarbon-rich disks.

One can, and must, take account of the variation of composition, pressure, and temperature not only as a function of distance from the young star but also as a function of depth within the disk, from the disk surface to the midplane. Gaps in disks, dust traps where material can accumulate, and the migration of ices across the "snow line", can now be directly observed, as well as the production of dust from the collisions of protoplanets in debris disks. Unlike the situation that held when the modeling of the solar nebula was first proposed, half a century ago, we now have a surfeit of data to model.

Life cycle of stars and the interstellar medium

Stars begin their lives in the tenuous clouds of gas and dust that are common throughout galaxies, and they return their material to interstellar space when they die. JWST probes all stages of this cycle out to large distances. The ability to study the formation of stars and stellar clusters in metal poor environments has implications not only for the nature of the stars and planets that might be found in earlier galaxies, but also the larger question of the evolution of galaxies in the earliest epochs of the universe.

The formation of young stars involves not only inflow of matter but outflows as well. Their supersonic jets light up at infrared wavelengths and produce beautiful images, showing what our Sun would have looked like when it was no more than a few ten thousands of years old and how it accreted most of its mass.

JWST, in conjunction with other observations, also allows us to identify and track the presence and roles of specific ingredients essential for life as we know it, such as water, various sulfur and nitrogen bearing species, ices, and complex carbon-bearing molecules produced in the earliest stages when the protostar is still deeply embedded in its natal cloud, or even before that cloud collapses to make a new star.

High redshift universe

First light is also earliest light. The results of discovering well-formed ("mature") and relatively metal rich galaxies with bright active galactic nuclei in the early universe, coupled with the confirmation of the dichotomy of the Hubble constant inferred from measurements of the Cosmic Microwave Background at the earliest times versus that directly measured (including by JWST) from galaxies at later cosmic epochs, highlights new challenges to the standard model of galaxy formation and cosmic expansion.

These new observations may suggest that important aspects in our understanding of the physics of the expansion of the universe and galaxy formation remain to be discovered and understood. Similarly, the high elemental abundances found in the early universe, if confirmed by future data, may challenge models for their formation and evolution.

Galaxy evolution

Galaxies are responsible for processing the baryons that make up the visible universe. JWST is opening an entirely new window on certain fundamental questions about galaxy evolution. How do galaxies get their shape and stellar mass? What drives galaxy evolution? What is the role of black holes? Why do galaxies stop forming stars? And how has this changed from "cosmic dawn", the first galaxies, to "cosmic noon", the peak of star formation?

JWST has already highlighted that the earliest galaxies are small and actively doubling their number of stars every few tens of millions of years. Supermassive black holes may play an essential role in the early evolution of galaxies: they can stimulate vigorous early star formation but quench it at a later evolutionary stage. Spectroscopy is essential to reveal the kinematic and dynamical properties of young galaxies as they are being assembled.

JWST is significantly altering the way we think about galaxy shapes, though we still have a long way to go to make full use of its capabilities. Its spectroscopy can reveal the distribution of low ionization emission lines in central regions of a galaxy, to more centrally concentrated high ionization atomic lines that trace accretion disks around black holes, to aromatic hydrocarbon features in the rest-frame mid infrared that trace dust and its interaction with other components in the interstellar medium. We can now detect oxygen lines that are direct tracers of the amount of metals in a galaxy out to large redshifts.

By the peak of star formation, cosmic noon, JWST imaging can resolve the distribution of stars in very dusty galaxies. For the first time we are able to see structures like spiral bars in such regions and measure the bar fraction in early galaxies, which can allow us to quantify their role in funneling gas into the centers of galaxies.

Solar system

The solar system provides a wide suite of potential observation candidates, from trans-Neptunian objects (TNOs) to ice giants, dwarf planets to planetary satellites, gas giants and their rings to comets and asteroids. Even Mars has already been observed with JWST, likely the brightest object that the telescope will ever observe. In fact, one of the challenges of planetary observations is that the objects in question are much brighter than typical JWST targets, requiring a careful choice of filters and short exposure times. Another is the ability to track targets that move in the field of view, which required a special effort of software development early in the project.

Primary science results are based on fundamental spectroscopy of volatiles, tracing their distribution in the surfaces and atmospheres of active main belt asteroids and water-rich satellites. The available spectroscopic detail has even allowed the measurement of the isotopic composition of volatiles, for example the deuterium and carbon-13 contents for the methane observed on the dwarf planet Eris. Among the achievements is the beginning of a spectral classification system for TNOs based on water and carbon dioxide spectral features. In many cases the data are outpacing what has been measured in the laboratory, sparking renewed efforts to identify organic compounds in JWST spectra.

Beyond the implications for the solar system, the study of the ancient composition of pristine bodies beyond the orbit of Mars provides the opportunity of comparative planetology with exoplanets and protoplanetary disks.

Outreach and public engagement

One of the remarkable successes of JWST has been its ability to excite and inspire the imagination of the public. This is a testament of the excellent results of the observatory, but it also reflects years of careful study and work by the multidisciplinary team involved in creating the first color images and those who made themselves available to explain the science behind those beautiful images to the press and public.

The importance of outreach ranges from the practical (letting the taxpayers see the result of their investment, and inspiring new generations of scientists) to the more profound understanding of why we (both society and ourselves) engage in the study of astronomy. Outreach should, by its nature, be maximally inclusive, and efforts have been undertaken to include underserved populations, such as ethnic minorities or the visually challenged.

Images have always had a remarkable power to change the way humanity sees itself and its place in the Universe. With this power comes a responsibility to understand what the public sees in the images, and how we can explain both the ways the images are made and the science behind the beauty. Outreach should emphasize not only that these images are beautiful, but that they are true.

Given that images from JWST are made electronically, matters of composition, resolution (number of pixels), dynamic range, and the removal of artefacts must be carefully attended to in order to produce an image that is impactful yet true. And given that the JWST images are made in infrared wavelengths, beyond the range accessible to the human eye, it is important to address the common question "Are the colors real?" and explain the mapping of the color palette from infrared to visible. Embracing the general public's curiosity triggered by the fascinating imagery can be beneficial to promote not only astrophysical knowledge but also key skills in modern society, such as data literacy and computational thinking.

In the face of ongoing concern of the proliferation of fake news and general mistrust of science and scientists by certain parts of society, one should engage the curiosity of the public with openness, not condescension. Questions and even skepticism from the public can be great ice breakers for a discussion. Trust comes from dialogue, two-way engagement with society, and it takes time, care, effort, and emotional energy to build that trust collectively.

Indeed, it is worth appreciating that science literacy and trust in science and scientists are increasing in many places. Furthermore, astronomers are well-liked and trusted by the general public (more so than many other kinds of scientists). We thus must see it as our responsibility, given this privileged platform, to have an open dialogue with the public about science and help promote their sense of awe, wonder, curiosity, and trust. A vivid example of such a dialogue was the public lecture held at Sapienza University of Rome as part of this workshop, attended by more than 200 students and members of the general public who were fully engaged with many questions about JWST and its science.

Societal impact of JWST and astronomy

The widespread interest in JWST reflects the advantage that astronomy has in providing the public with a better understanding of how science itself works – both of its promise and its limitations. One is much more likely to engage a stranger by saying "I am an astronomer" than by saying "I am a physicist"!

One of the lessons that the JWST experience can teach society at large is the importance of teamwork over a "superstar" model of approaching large problems. The ability of teams of scientists and engineers to work together, across international borders and oceans, to solve seemingly intractable problems has a special resonance in the less developed world, such as much of Africa, where the distance between rich and poor in society can seem especially daunting.

But the success of JWST itself provides lessons in how science in general, and indeed any such large international interdisciplinary program, can be achieved. What kind of society is needed to build and take full advantage of a telescope like JWST? A key element is the necessity of humility among the members; in every stage, progress is dependent on multidisciplinary teams.

For example, by making proposals for JWST time "dual-anonymous", where the reviewers do not know the identity of the proposers, and making all data publicly available after at most one year, a large number of younger and otherwise underrepresented communities have been able to be part of the scientific process. In the longer run, the JWST community will need to consider the balance between various observing programs (and types of programs) to ensure that major science questions are addressed, that the archive is homogeneously populated, and that JWST's unique capabilities are optimally used.

The societal impact of this telescope includes important economic benefits. These include, but go beyond, technology spin-offs. Particularly important is the training of bright, highly skilled young people who can experience how large and seemingly intractable technical problems can be broken down and solved.

This finally leads to the broader question of how to bring the universe, as observed by JWST, down to Earth. This requires a global effort, including true partnerships to promote the growth of astronomy *with* society and local institutions, including access to the data for scientists in the developing world. Among the partners in this dialogue, one should not neglect the potential role that local churches can play in both disseminating the science and putting it into a human context.

Preservation of dark and quiet skies

A seemingly daunting but important recent challenge is the preservation of dark and quiet skies which are important to obtain high quality ground-based observations that complement JWST. While providing important benefits for society, satellite constellations in Low Earth Orbit reflect sunlight to create streaks that degrade optical/infrared images; and they emit radio transmissions against which the highly sensitive systems at radio observatories can be unprotected.

Moreover, a dark and starry night sky is not only essential to advancing our understanding of the universe, but the sight of dark starry skies has been inspirational to humankind since prehistoric times. This holds most notably for Indigenous Peoples, for whom viewing the unpolluted night sky is an integral part of their cultures.

A spirit of cooperation and teamwork is more likely to succeed in mitigating the problem than relying simply on confrontation or attempting restrictive legislation. The International Astronomical Union's Centre for the Protection of the Dark & Quiet Sky against Satellite Constellation Interference (IAU CPS) and its partners are taking multiple approaches to mitigate negative impacts.

CPS-affiliated policy and space law experts have developed and are refining recommendations for ultimately turning best practices into a regulatory framework to be endorsed internationally and adopted by national agencies in licensing and oversight. Because of the IAU raising awareness, the UN Committee on the Peaceful Uses of Outer Space (COPUOS) is now adopting a five-year agenda item to consider the effects of satellite constellations on astronomy.

Philosophical perspectives, new world views

A telescope is often presented as something apolitical, a thing of objective science and facts. But it can be much more than that. In these times, searching for the furthest horizons is possibly an act of resistance to a society suspicious of the "other"; searching for life in alien form is a way of staying open for the otherness that some would try to make us fear.

The astronomy represented by JWST provides an incentive to re-examine and re-appreciate our collective wisdom about the universe and its very nature. This can range from a dialogue among those with deep religious convictions, to a pondering of the possible existence of a multiverse. In all of this, we encounter the other, the alien, not with fear but in an embrace, experiencing and responding to awe.

The James Webb Space Telescope can help remind us of the intrinsic value of the universe we inhabit, beyond a commodity from which private companies can profit. Staring into space with the huge communal eye of a telescope is a way of honoring the non-commercial values of the universe, honoring the cosmos as a source of wonder and knowledge. The search for habitable planets and possible alien presence makes us understand the stars as a force of life, as something to relate to. It is an antidote, aliens against alienation.

In one of her poems the Canadian astronomer Rebecca Elson formulated something called a *responsibility to awe*. In that phrase, she expresses the insight that we have a duty to honour the poetry of astronomy. Gathering data through a telescope is not about finding facts. It is about starting a conversation that keeps us connected with the universe we inhabit.

A Brief History of the James Webb Space Telescope

Marcia Rieke
Steward Observatory, University of Arizona, USA

Abstract

JWST's early history is described with a focus on how the mission and its capabilities were shaped.

Introduction

The James Webb Space Telescope (JWST) grew out of a confluence of technology, other NASA missions, and astronomical discoveries that made a large, infrared telescope an imperative. Three strands – astronomical discoveries, development of a mission architecture including optics for a large telescope, and infrared detector development – wove together to make JWST a required mission for the astronomical community and to make JWST feasible. Gardner et al. 2023 also present an overview of JWST's history while here we concentrate on the early history which shaped the mission and its capabilities. Wright et al. 2023 give more background on the genesis of MIRI. Doyon et al. 2023 provide more detail on the history of NIRISS. Jakobsen et al. 2022 present some of the background leading to the final design of NIRSpec.

The Astronomy Strand

On the astronomical discovery side of the story of JWST's development, much progress was made in discovering galaxies at redshifts above 0.5 in the 1980s (e.g. Spinrad et al. 1981, Gunn et al. 1986, Djorgovski et al. 1988, Koo and Kron 1992) although it was not known just how far in distance galaxies would be found. There was also a question about the angular extent of early galaxies with some predictions positing galaxies of order 10 arc seconds in size (Partridge and Peebles 1967). The first infrared observations of $z\sim0.5$ galaxies were executed using aperture photometers equipped with a single detector (Lebofsky 1981, Lilly and Longair 1982). These first infrared efforts demonstrated the feasibility and utility of observing redshifted galaxies in the infrared. The launch of HST in 1990 and the subsequent repair of the HST optics with the installation of COSTAR in 1993 provided the next opportunity to make a jump in the ability to find and characterize distant galaxies (e.g. Windhorst et al. 1994). The success of the post-repair observations led Bob Williams, then director of the Space Telescope Science Institute, to use some of his director's discretionary observing time to execute a deep imaging program of an "empty" field to see what could be found (Williams et al. 1996). This field was dubbed the Hubble Deep Field (HDF), and the imagery spawned many follow-up observations. Of particular significance was the development of the Lyman break technique by Steidel's group (Steidel et al. 1996) which afforded a method of selecting very high redshift galaxies from imaging alone. Figure 1 illustrates this absorption. Also important for the development of JWST was the realization from the HDF that galaxies exist at very great distances and appear to be compact in size, which enhances their detectability. Another element of the astronomy strand was the discovery of the relationship between nuclear black hole mass and the host galaxy's bulge mass (e.g., Ferrarese and Merritt 2000). This relationship, expressed as M• versus s (bulge velocity dispersion), strongly suggests that the evolution of nuclear black holes and their host galaxies are connected.

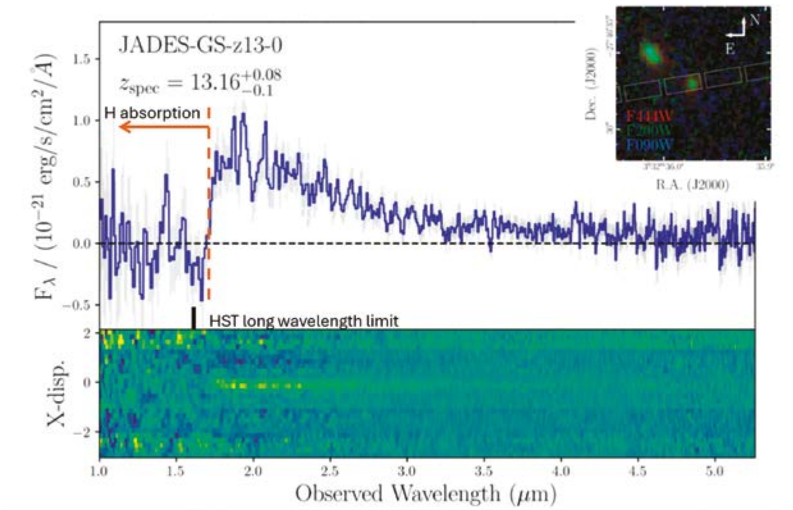

Figure 1. The near-infrared spectrum of a high redshift galaxy from the JWST Advanced Deep Extragalactic Survey (JADES) illustrating the effect of hydrogen absorption on the rest-frame ultraviolet spectrum (Curtis-Lake et al. 2023). Figure adapted from an illustration to appear in Hainline et al. 2024.

Combining the effect of the expansion of the Universe and the absorption of light below the Lyman limit led to the realization that HST images could not detect the most distant galaxies, nor would such images provide sufficiently large galaxy samples to study evolution much beyond a redshift of 7. A problem with extending HST's wavelength range is the simple fact that HST's primary mirror is heated to match the temperature of the lab where it was polished so the thermal background from the mirror would overwhelm the signal from faint galaxies at wavelengths beyond ~1.6 microns. The only way to make progress would be to observe deeper into the infrared. Infrared data would allow galaxy evolution and galaxy-black hole relations to be investigated. And once the decision is made to observe in the infrared, a cooled telescope with cold instruments becomes a necessity, and of course, this telescope would need to be large to provide both spatial resolution at these longer wavelengths and to detect distant and therefore very faint galaxies. The "HST and Beyond Report" (Dressler 1996) presented these and other arguments in favor of an infrared telescope. This report also pointed out that a large, infrared telescope would enable a broad range of topics to be studied.

The Large Optics and Mission Concept Strand

Even before the launch of the Hubble Space Telescope (HST) in 1990, Pierre Bely had begun thinking about larger space telescopes (Bely 1986), and pointed out that NASA missions take 10-15 years from inception to launch so it was not too early to start consideration of a 10-meter successor to HST. Bely's initial thinking focused largely on an ultraviolet to visible light telescope, but this line of thought was conditioned by the state of knowledge of the distant Universe and the lack of high-performance infrared detector arrays. Quasars out to z~4 were known in 1986 but not galaxies at that redshift. The significance of absorption by hydrogen gas was not yet fully appreciated. He also emphasized that new approaches would be needed to reduce costs. He suggested that the project should be international in character for cost-sharing and to take advantage of launch capabilities available in other countries. He considered various telescope architectures including a segmented primary whose disadvantage to him was the potential unreliability of a system with many actuators required for control of the mirror segments, so he preferred a monolithic mirror with the attendant cost of an expensive heavy-lift rocket.

The Space Studies Board of the U.S. National Research Council chartered a report entitled "Space Science in the 21st Century: Imperatives for the Decades 1995-2015" which included a volume on astronomy and astrophysics. This report, released in 1988, emphasized the need for a large area, high-throughput telescope. The report stated that some of the most fundamental questions in astronomy would require a telescope of 8-16-meters collecting area which would operate from the Lyman limit at 912Å to 30μm with radiative cooling to 100°K. The report also stated that the telescope should not just be a scaled-up version of HST because of the need for cooling and a large field of view to enable use of large detector mosaics and multi-object spectroscopy. However, this report was written before the launch of HST and well before the launch of Spitzer, and so detailed design work would have been premature.

The Space Studies Board Report was followed by a 1989 workshop entitled "The Next Generation Space Telescope" with a report that began to sharpen ideas for the HST successor (Bely et al. 1990), and which started the use of the name Next Generation Space Telescope (NGST) for the mission. This report examined the entire mission concept. The report weighed a lunar-based telescope against one in high earth-orbit while noting that low-earth orbit suffers from too many disturbances. The report concluded that the time was ripe to establish mission design teams. The lack of rockets

Figure 2. Designs proposed in 1998 for JWST. TRW later became part of Northrop Grumman. Figure from STScI.

with large nose cones suggested that segmented mirrors might be required for a large telescope.

HST was launched in 1990, and the discovery of its optical flaw led to the development of phase retrieval algorithms that are key to JWST's wavefront sensing procedures which are necessitated by the segmented primary mirror. As described later, the repair of HST led to an understanding that a large, infrared space telescope would be necessary for further progress. In late 1995, NASA chartered a study of the Next Generation Space Telescope at Goddard Space Flight Center with John Mather as a science leader. The telescope was assumed to be only 4-m in diameter based on the considerations in the HST and Beyond report (Dressler 1996), but was later increased to 8-meters. An orbit at the second Lagrange point (L2) was suggested on the basis of the need to be distant from the earth for radiative cooling but still close enough to downlink large volumes of data. Participation in studies by potential aerospace companies was initiated in 1996. The European Space Agency (ESA) chartered an NGST Task Force to consider science drivers and technologies. NASA opened discussions with ESA, the Canadian Space Agency (CSA), and the Japanese Space Agency (JAXA). The Space Telescope Science Institute was involved in these discussions and was designated as the NGST Operations Center. Figure 2 shows some of the concepts that grew out of this work.

Table 1: NGST Ad-hoc Science Working Group members

John Mather (co-chair)	James Graham	Avi Loeb	Mike Rich
Peter Stockman (co-chair)	Tom Greene	John MacKenty	Peter Schneider
Jill Bechtold	Matt Greenhouse	Michael Meyer	Gene Serabyn
Mike Fall	Don Hall	Harvey Moseley	Massimo Stiavelli
Harry Ferguson	Peter Jakobsen	Phil Nicholson	John Trauger
Robert Fosbury	Bob Kirshner	Takashi Onaka	Ewine van Dishoeck
Jonathan Gardner	Simon Lilly	Marcia Rieke	

Following the kick-off of industry work, NASA organized a group of astronomers to form the "Ad-Hoc Science Working Group" (ASWG) in 1997 whose charter was to refine the JWST's science goals and to prioritize instrument capabilities. Table 1 lists the ASWG membership. All of the interested space agencies had representatives on the AWSG. The ASWG sharpened the science goals for the mission and considered a variety of instrument concepts. The importance of extending the mission's observational capability beyond 5 microns was discussed at length by the ASWG. The ASWG's work and that of the industrial partners culminated in the NGST Science and Technology Exposition (Smith and Long 2000). The report from this meeting presented a concept very similar to the JWST that we have today, and also described the need for multi-object spectroscopy as realized in NIRSpec. What we now know as MIRI was also recommended (Mather 2000). By this time JAXA had decided that they could not participate in the project so the final collaboration of NASA, ESA, and CSA resulted.

During the period that the ASWG existed, work was progressing on infrared detector arrays and on technologies for multi-slit spectroscopy. The detector work is described below and resulted in 2048x2048 arrays being available for the near-infrared range. These detectors were presumed to be cooled radiatively to ~35K, and the feasibility of radiative cooling was confirmed with the launch of Spitzer whose outer shell cooled radiatively to this temperature. These detectors as well as the 1024x1024 detectors for MIRI were made by U.S. companies so all of JWST's instruments have some U.S.-based components. The ASWG concluded its work with a suite of recommendations for science priorities which can be summarized in four themes: "End of the Dark Ages: First Light and Reionization"; "Assembly of Galaxies"; "Birth of Stars and Protoplanetary Systems"; and "Planetary Systems and the Origins of Life". The ASWG also defined instrument capabilities which roughly match NIRCam, NIRSpec, and MIRI, but did not negotiate the division of instrument work among the participating space agencies.

The ASWG was disbanded in late 2000 and an Interim Science Working Group (ISWG), membership listed in Table 2, was formed. This change was necessitated to prevent a conflict of interest as NASA personnel began work on the Announcement of Opportunity (AO) that would select instrument teams and interdisciplinary scientists. A key recommendation from the ISWG was the need for JWST to incorporate non-sidereal tracking which would enable spectroscopy of outer solar system objects.

Table 2: NGST Interim Science Working Group

Marcia Rieke, Chair	Rob Kennicutt	Simon Lilly	Massimo Stiavelli	Mike Werner
Heidi Hammel	Bob Kirshner	Bruce Margon	Edwin Turner	
George Helou	Rolf-Peter Kudritzki	Mark McCaughrean	Ewine van Dishoeck	

The three space agencies finalized the distribution of instrument work with Canada slated to provide the Fine Guidance Sensor (FGS), NIRCam to be a joint contribution from NASA and CSA, NIRSpec to be developed largely by ESA but with detectors and a multi-slit mechanism from NASA, and MIRI to be developed by a consortium of European groups with detectors and cooling provided by NASA. The subdivision of work enabled finalizing the AO. The ISWG disbanded in anticipation of the release of the AO. During this same period the 2001 decadal survey ranked NGST as the top priority for space astronomy. The cost estimate in the decadal survey was unrealistically low which caused problems later when the true cost precipitated an overrun (Gardner et al. 2023). The size of the telescope primary mirror was descoped from 8 meters to 6.5 meters during the preparation of the AO.

The nearly final configuration of JWST (Fig. 3) was reached in 2002 with the selection of Northrop Grumman as the prime contractor with significant portions of the telescope work subcontracted to Ball Aerospace. The University of Arizona, teamed with Lockheed Martin's Advanced Technology Center, was selected to lead the development of NIRCam. A project science working group (SWG) was constituted from the instrument team leaders and interdisciplinary scientists chosen through the AO process. Other members represented major subsections of the project (see full list in Gardner et al. 2023). The project was renamed the James Webb Space Telescope after announcing the selection of Northrop as the prime contractor.

One of the first decisions made by the SWG was endorsing a change from a primary comprised of 36 segments to one comprised of 18 segments. This change reduced the collecting area slightly but enabled a more favorable production schedule. Larger segments were not selected initially as larger segments were deemed too risky. The production of the 85-cm Spitzer primary mirror demonstrated that larger segments were feasible. Another change endorsed by the SWG was splitting off the Canadian tunable filter contribution to NIRCam, and the tunable filter became a separate instrument sharing an optical bench with FGS.

The Infrared Array Strand

While Bely was considering a successor to HST, infrared arrays based on indium bump bonding were just beginning to be used in the ground-based astronomical community (Vural et al. 1983, Forrest et al. 1985). One array type used InSb which had been used extensively in single detector photometers and a second array type used HgCdTe which had been used originally in earth remote sensing applications. A key next step in the development of these arrays came with work aimed at InSb arrays for the IRAC instrument on Spitzer (then called Space Infrared Telescope Facility, SIRTF) (Lum et al. 1992, Forrest et al. 1993) and HgCdTe arrays for the Near-infrared Camera and Multi-object Spectrometer (NICMOS) for HST (Rieke et al. 1989). NASA funding expedited the development of these arrays. The 256x256 HgCdTe devices fabricated for NICMOS were operated at 58K with NICMOS installed onto HST in 1997. This was the first use of HgCdTe arrays on an astronomy space mission.

By 2000 NASA was funding competing near-infrared detector development with sizes as large as 2048x2048 becoming available (Hall et al. 2000, Hoffman et al. 2003). These devices were aimed at meeting the demanding performance requirements that had been outlined for JWST, and these arrays came very close to meeting the requirements if they were operated at an optimal temperature. The final choice of detector type was made in 2003 by the NIRCam Instrument Team who selected HgCdTe arrays based on two factors. First, HgCdTe arrays perform well as warm as 40K which alleviated cooling concerns, and second, HgCdTe can be produced with a variety of cut-off wavelengths which reduced the production risk for NIRCam which uses more short wavelength, 2.5-micron cut-off, arrays than long wavelength, 5-micron cut-off arrays. Short wavelength arrays are

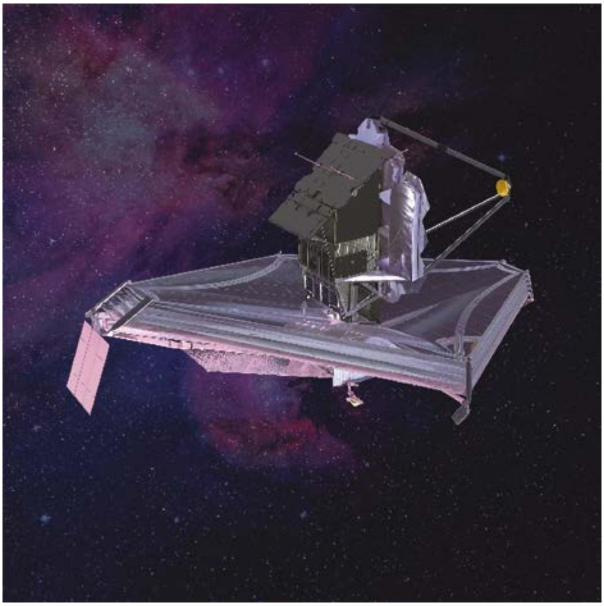

Figure 3. Artist's conception of JWST at L2. The box on the back side of the telescope is covered with radiators to cool the instruments inside the box. Figure from NASA.

somewhat easier to produce than the long wavelength arrays. NIRSpec, NIRISS, and FGS all use long wavelength HgCdTe arrays but only two for NIRSpec and only a total of three for FGS and NIRISS.

The array type used by MIRI, an Si:As IBC (impurity band conduction) detector, also benefitted from early work on arrays for IRAC (McMurray et al. 2000). Just as for the near-infrared detectors, further work was needed to achieve the desired 1024x1024 format and to achieve the level of performance needed (Ressler et al. 2008). A drawback to the Si:As IBC arrays is the need to cool them to ~6K. The initial cooling choice for JWST was a dewar using solid hydrogen. This arrangement was judged too heavy and was replaced by a pulse-tube cryocooler in 2005. The final MIRI design uses one of these arrays in an imager and two arrays in a medium resolution integral field spectrometer.

JWST in as We Know It

A few more decisions were made in the pre-2010 timeframe, including the choice of launcher which became the major ESA contribution to JWST. The Ariane V was selected since it is a very reliable rocket with the needed lift capability. The launcher selection was the last major project element to be chosen. A number of problems cropped up during the design and con-

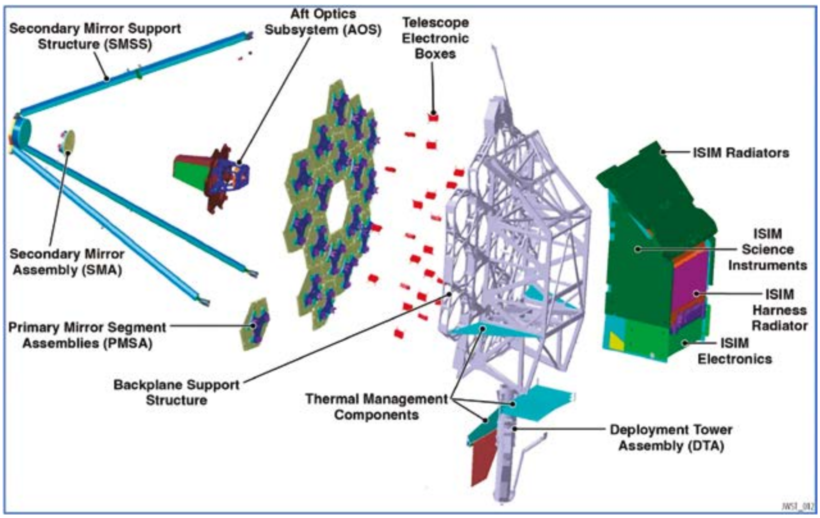

Figure 4. An exploded view of JWST. The four instruments are housed in the Integrated Science Instrument Module (ISIM). Figure reproduced from McElwain et al. 2023.

struction phase. The sun shield was redesigned several times to ensure that the five layers would deploy reliably. A major change to the instrument suite was the redesign of the Canadian contribution NIRISS to eliminate the tunable filter. NIRCam acquired grisms which were to be a backup for wavefront sensing in case the mirror segments were too far apart in focus after deployment to be phased using the dispersed Hartmann sensors. The replacement of degrading near-infrared detectors was another major hurdle, but did not result in any change to the mission design.

The JWST telescope and instruments (Fig. 4) were tested together in flight-like conditions in a large test chamber at Johnson Space Flight Center in 2016 (Acton et al. 2018). This test was very successful and demonstrated that all of the sensing and control required to align the 18 mirror segments worked properly. After this test, the telescope and instruments were mated to the spacecraft and sunshield at Northrop's facility in California followed by packing into a shipping container for the trip to French Guiana. A very successful launch on December 25, 2021, was followed by six months of commissioning (Rigby et al. 2023) which demonstrated a telescope working nearly twice as well as planned. The launch was so successful that the astronomical community will enjoy using JWST for as long as twenty-five years because so little rocket fuel was used during launch for insertion into the L2 orbit.

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SESSION 1: EXOPLANETS, NEW WORLDS

Characterizing Exoplanetary Atmospheres

Jonathan J. Fortney
Department of Astronomy and Astrophysics, University of California, USA

Abstract

I review the major open science questions in exoplanet atmospheres. These are mainly focused in the areas of understanding atmospheric physics, the atmosphere as a window into other realms of planetary physics, and the atmosphere is a window into understanding planet formation. For gas giant planets, high quality spectra have been delivered from *JWST* and from the ground, enabling the determination of atmospheric abundances. For the very common sub-Neptune planets, we are just beginning to obtain and interpret *JWST* spectra. For the terrestrial planets, which can be studied only around M stars, the field aims to determine if these planets even have long-lived atmospheres.

Introduction

The late 1990s saw a number of modeling efforts to begin to understand exoplanetary atmospheres [1–3], and in 2002 Charbonneau et al. [4] used *Hubble* to detect sodium atoms in the atmosphere of the transiting hot Jupiter exoplanet, HD 209458b, a 1500 K planet on a 3.5-day orbit. The field has dramatically expanded since that time, in terms of the range of modeling efforts, the number, quality, and wavelength range of spectra achieved, and the number of people working in the field. All of these areas continue to grow rapidly today, in many ways powered by *JWST*. Exoplanetary atmospheres have a truly tremendous amount of undiscovered country, with nearly all basic questions still to be uncovered. It can be a bit overwhelming. In order to set the scene, I think it is important to categorize the kinds of questions we are trying to answer, today, and how these kinds of questions differ depending on the type of planet.

How do planets work? What is the physics and chemistry operating within planetary atmospheres? How do atmospheric spectra tell us about the physics of the atmospheres as well as the physics of the time-evolving planetary interior far below the visible atmosphere? The abundances of some atoms and molecules may be representative of the local temperature and pressure conditions within the atmosphere. However, some molecules may instead be signposts of conditions far below the visible atmosphere, mixed vigorously upwards on timescales faster than chemical reaction timescales [5], or altered via incident stellar UV flux that drives photochemistry. Still other molecules, via their presence or absence, may be signposts of physical or chemical processes at play between a deep atmosphere and a solid or liquid surface. In much the same way that chemical abundances in Sunlike and evolved stars are used to constrain current and past interior processes, the same is true for planets.

How do planets form? Do atmospheric abundances hold clues to aspects of a planet's formation? Since a planet-forming disk, in bulk, has the same composition as that of the parent star, any deviations in planetary composition (more precisely giant planets, which accrete nebular H/He) may yield important insights into protoplanetary disks. Giant planets accrete both gas and solids [8], and the composition of both gas and solids change with orbital separation within the disk, in particular at condensation points, or "snow lines" where compounds change from vapor to solids. The relative abundance of important molecules like C, N, O, or other elements may

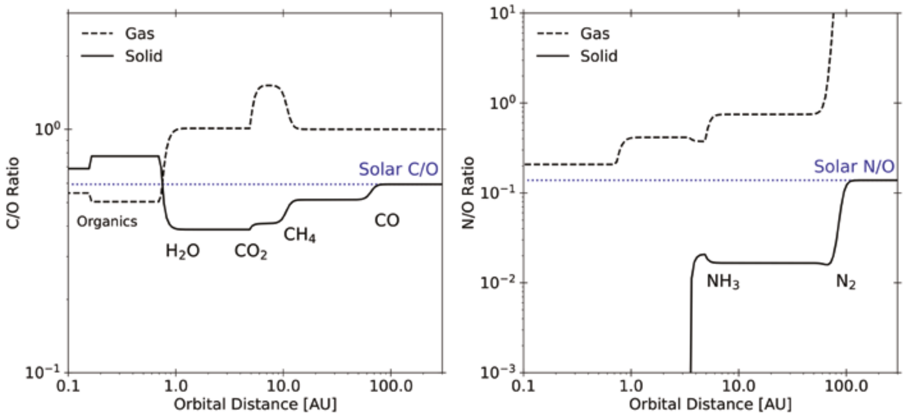

Figure 1. The C/O ratio (left) and N/O ratio (right) for nominal 1D protoplanetary disks. The solar ratios are in dotted blue. Condensation at a "snow line" of various volatile molecules (e.g., H_2O, CO_2) alters the C/N/O ratios of both the condensed solids and the leftover disk gas. Generally larger effects are seen for N/O than C/O. A giant planet will accrete both gas and solids to make up its metal-rich H/He dominated envelope and atmosphere. Figure courtesy Kazumasa Ohno, after [6], expanded from [7].

inform aspects of the formation location and relative accretion of gas and solids, as depicted in a simple disk model in Figure 1. For planets less than ~5 $M_\oplus$, particularly those on close-in orbits, an open question is whether some of these planets have atmospheres at all, given the high bolometric luminosity and XUV fluxes for their parent stars at young ages.

Methods of Observations

Photometry and spectroscopy of exoplanets, for transiting planets, and for directly imaged planets, both grew up quickly starting in the mid-2000s. For transits, *Spitzer* (in particular *Warm Spitzer*) and *Hubble* STIS and WFC3 provided photometry and limited-wavelength spectroscopy, respectively, for a few dozen planets. For imaged planets, the Gemini Planet Imager, SPHERE, VLT/GRAVITY, and Keck (among others) provided mostly JHK spectroscopy for around two dozen planets.

Transit Spectroscopy

Transiting planets are observed at a number of possible orbital phases. During the transit stellar photons pass through the day-night "terminator" transition region of the planetary atmosphere, imprinting planetary atmosphere absorption features on the spectrum. The size of these features is small – the area of the annulus of planetary atmosphere compared to the stellar cross-sectional area. For a given transit depth δ the extra transit depth $\Delta\delta$ due to atmospheric absorption is:

$$\delta = \frac{{R_\mathrm{p}}^2}{{R_\star}^2}, \quad \Delta\delta \approx 2N_H(\lambda)\delta\left(\frac{H}{R_p}\right) \propto \left(\frac{HR_p}{R_\star^2}\right) \tag{1}$$

where R_p and $R_\star$ are the planetary and stellar radii, respectively, N_H is the number of atmospheric scale heights probed (typically a few, and depends sensitively on the wavelength dependent opacity), and H is the atmosphere's scale height. A detailed study of the time-evolving ingress and egress light curves, at the start and end of the transit, may allow for the determination of differences in chemistry and temperatures of leading and trailing hemispheres of the planet. These properties constrain the hydrodynamics of atmospheres.

Transiting planets typically (but not always, if their orbits are eccentric) have a secondary eclipse, or occultation, when the planet passes directly behind the parent star. The disappearance of the planet's thermal emission, or potentially reflection, can be measured as well. For hot planets this signal can be larger than the atmosphere transmission signal, while also giving details on atmospheric thermal structure, but for cool planets the signal is challenging. For blackbody-temperature planetary (T_p) and stellar ($T_\star$) thermal emission, the size of the signal $\delta_{occ}(\lambda)$ is:

$$\delta_{\rm occ}(\lambda) = \delta \, \frac{B_\lambda(T_p)}{B_\lambda(T_\star)} \;\longrightarrow\; \delta \, \frac{T_p}{T_\star} \tag{2}$$

where the portion after the arrow indicates the further simplification of assuming the Rayleigh-Jeans limit. A detailed study of the time-evolving ingress and egress light curves, as the planet is gradually occulted, may allow for day-side thermal emission "eclipse maps," which provide a snapshot of the inhomogeneity of the planetary day side, including temperature or cloud-cover differences.

Transiting planet phase curves are also an important observational tool [9]. By measuring the thermal emission over an entire orbital period for the planet, the planet's day side emission, night side emission, and any hot and cool spot phase shifts in longitude can be measured. Via spectroscopy, these shifts can be measured as a function of wavelength, and hence, depth in the atmosphere, yielding a comprehensive 3D view of circulation in visible parts of the atmosphere.

Imaging Spectroscopy

For directly imagined planets, the difficulty in obtaining data is the twin problems of the necessary contrast, and the inner working angle of your telescope. The current state of the art is a contrast ratio of around 10−6 in flux. That being said, spectroscopy of these planets spans a broad range of spectral resolution (from $R \sim 100$ to $\geq 10{,}000$) and signal-to-noise ratio. Nearly all of these objects are young (tens of Myr or younger) and massive (more than a Jupiter mass) as older or smaller planets are just too faint. *JWST* may provide spectra for smaller and fainter planets on wide separations from M dwarfs or white dwarfs. A current area of interest is time series spectroscopy over an entire planetary rotation period (~ 5-15 hours). The time-variable emission can inform our understanding of cloud coverage (static or also itself time-varying) as a function of planetary longitude. This time-variable emission has been measured for many isolated brown dwarfs, in the absence of a bright parent star [10].

Main Physical Ideas

Planet Types

Gas giant planets like Jupiter (318 $M_\oplus$) have most of their mass in the massive H/He dominated envelope that they accrete from the protoplanetary nebula. The visible atmosphere is the top of this envelope. At lower masses, one transitions to "sub-Saturns" or "super-Neptunes", (~ 20 – 75 $M_\oplus$?) where the mass of H/He and the mass of total metals (in the central core and in the H/He envelope) are comparable. For Neptune and Uranus in particular (~ 15 $M_\oplus$), their H/He mass is only 10-20% of the total mass. For still smaller planets, the "sub-Neptunes" or "mini-Neptunes", the H/He envelope is ~ 0.1–5% of the planetary mass and these planets are typically 2-3 $R_\oplus$ and 5-10 $M_\oplus$. The *Kepler* mission showed that, at least inside of 100-day orbits, sub-Neptunes dominate over Neptune-mass and Jupiter-mass planets. A prediction from planet formation theory is that the metallicity of H/He-dominated atmospheres will be strongly anticorrelated with mass, which is seen in the solar system's 4 giant planets [11], where Jupiter has the lowest metallicity, of around 3× solar.

At some point in mass/temperature space (~ 5 $M_\oplus$???), planets transition from having accreted H-dominated atmospheres to those dominated by H_2O (perhaps with liquid water beneath: "water worlds"), CO_2 (like Venus and Mars), or N_2, like Earth, or perhaps other variations. These higher mean molecular weight "secondary atmospheres" are outgassed from the interior, rather than the H/He-dominated "primary atmospheres" accreted from the protoplanetary nebula. In the solar system there are clear distinctions between primary and secondary atmospheres, but that need not be the case, in particular for the sub-Neptunes. Similar-mass planets with secondary atmospheres, or perhaps no atmospheres at all, are usually termed "super-Earths".

Atmospheric Energy Balance

There are three important characteristic temperatures that come up often when discussing planetary atmospheres: effective temperature ($T_{\rm eff}$), which characterizes the total thermal output of the planet, equilibrium temperature ($T_{\rm eq}$), which characterizes the thermal output due only to absorbed and re-radiated stellar energy, and interior temperature ($T_{\rm int}$), which characterizes the thermal energy only from the cooling of the planet's interior. These temperatures are related by:

$$T_{\rm eff}^4 = T_{\rm eq}^4 + T_{\rm int}^4 \tag{3}$$

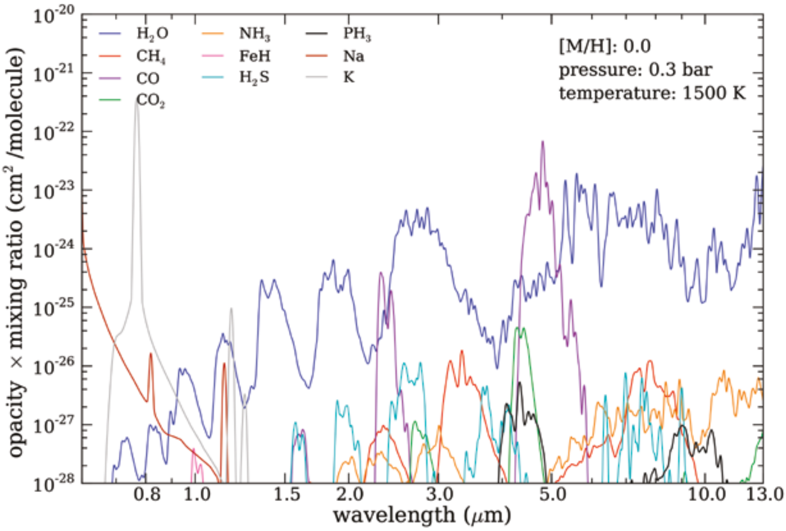

Figure 2. The expected dominant atmospheric opacity sources for hot giant atmospheres. The plot is at 1500 K and 0.3 bar, with spectral resolution *R*~ 100. It shows the absorption cross-section multiplied by the expected volume mixing ratio of each gas species at solar metallicity. *JWST* wavelengths capture the major absorption features of K, H_2O, CO, CH_4, CO_2, and NH_3. High metallicities and temperatures tend to favor CO and CO_2, and cooler temperatures favor CH_4 and NH_3, compared to this particular plot.

For a small old planet like Earth, T_{int} is negligible, and $T_{eff} \approx T_{eq}$. For a close-in hot Jupiter exoplanet, the incident stellar energy is extreme, driving $T_{eff} \approx T_{eq}$ as well, even if T_{int} is several hundred K. However, for a young gas giant planet on a wide separation orbit, T_{int} is large (typically 1000+ K for known imaged planets), so that $T_{eff} \approx T_{int}$.

Main Atmospheric Opacity Sources

The atmospheres of planets are typically dominated by the opacity of molecules, some atoms, and clouds. In giant planets, H_2O, CO, CO_2, CH_4, NH_3, SO_2, H_2S, Na, and K, are seen across a range of hot and warm planets from 700–2000 K with *JWST*, as shown in Figure 2. The very hottest planets have TiO, VO, and a host of atomic metals, like M dwarfs. All of these species have strongly wavelength dependent opacities, so that there is no "continuum", and consequently a wide range of atmospheric pressures are probed both in emission and transmission spectroscopy. The infrared spectroscopic capabilities of *JWST* are well-matched to the main absorption features of a host of important molecules.

For exoplanet atmospheres, clouds are like the "magnetic fields" of the rest of astrophysics – extremely important, difficult to model, and ignored only at your own risk. For the hot Jupiters at $T_{\text{eff}} \sim 1500\text{–}2000$ K, the dominant cloud species are expected to be silicate rock dust and iron droplets. We have ample evidence for the silicate clouds in brown dwarfs of similar temperatures. At cooler temperatures, $T_{\text{eff}} \sim 1000$ K, a host of other elements begin to condense, and Na_2S and KCl may form potentially optically thick clouds, especially as high metallicity. Eventually water clouds will form at $T_{\text{eff}} \sim 400$ K.

Another type of condensates, photochemical hazes, are certainly seen in most solar system atmospheres, and dominate the atmospheric opacity of Saturn's moon Titan. Our understanding of these aerosols is still in its infancy, as we cannot use the better studied (but isolated) brown dwarfs as any sort of guide for giant planet hazes. Our solar system's terrestrial planets likely cover only a modest phase space of possible hazes compared to exoplanets. It has been suggested that range of possible haze compositions in exoplanetary atmospheres is far larger than in the solar system, and there is a growing body of work demonstrating this in the laboratory.

The Major Science Questions

- How do giant planet atmospheres differ in composition compared to their parent stars? The solar system sample is limited by a tiny sample size and limited number of elements. What is the degree of metal-enrichment and non-stellar abundance ratios? (While many/most appear metal-rich to varying degrees, at least one giant planet atmosphere actually appears *metal-poor*! [12])
- Do terrestrial planets around M dwarfs have atmospheres? The prolonged high luminosity phase of pre-main sequence M dwarfs may drive the atmospheres off of planets that today would be able to sustain atmospheres. There is likely to be a major push in this area in *JWST* cycles 3-5, to find the "Cosmic Shoreline", as suggested in Figure 3. Whether these planets have atmospheres, or not, has major ramifications for ELT plans for exoplanet direct imaging, which seeks to study reflection and thermal emission of M-dwarf terrestrial planets.
- What is the nature (natures?) of sub-Neptune exoplanets? Their atmospheres will tell us if this population is dominated by those with thin H/

He envelopes or if some are water-worlds. Chemical abundances may hold clues to deep water or magma layers, below H/He- or steam-dominated atmospheres due to atmosphere/interior chemistry [13] affecting visible atmospheric abundances. What do combination primary/secondary atmospheres (unseen in the solar system) look like?

- For what kind of planets, and over what temperatures and compositions, do aerosols have a major impact on atmospheric opacity? This is important for a range of physics and chemistry issues, but also for the proposed Habitable World Observatory (HWO), where the reflected light signal is quite sensitive to clouds for terrestrial and giant planets.
- Can we understand the mechanisms that drive the atmospheric variability that is well-known in brown dwarfs, strongly suspected to occur in wide-separation imaged planets, and may also be detectable for transiting planets with strong day/night contrasts? The atmospheric dynamics of these objects span a wide range of physical regimes in rotation rate, surface gravity, and thermal forcing [14].
- How well can we extract information about inherently 3D atmospheric properties of exoplanets from their 1D disc- and terminator averaged

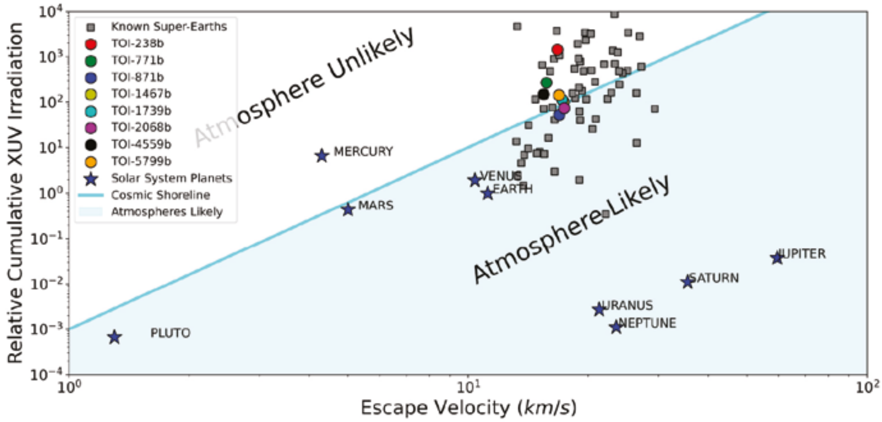

Figure 3. Cumulative XUV irradiation vs. planetary escape velocity for a range of rocky exoplanets (grey squares and colored circles) and solar system planets (blue stars). The cumulative lifetime XUV is thought to be the driving force behind planetary evaporation. Atmospheres can be found where gravity is high and solar irradiation is low. The light blue colored line represents the proposed "cosmic shoreline" which follows a power law, $I_{XUV} \propto v_{esc}^4$, following [15]. Rocky planets around M dwarfs can be studied with *JWST* to assess the validity of this shoreline. Plot adapted from [16].

observations? What are the limits on accuracy and precision for exoplanet spectroscopy, in emission, transmission and reflection, for planetary photospheres that can be strongly inhomogeneous?

Conclusions

The exoplanet atmospheres field is rapidly changing with the current flood of new *JWST* observations. For giant planets, a comprehensive theory of their atmospheres, that crosses from transiting planets, to imaged planets, to the solar system, and brown dwarfs, across a range of $T_{\rm eff}$, surface gravity, and formation conditions, seems like an attainable goal over the coming years. For the sub-Neptunes, which dominate the *Kepler* and *TESS* exoplanet populations, we await spectra across a range of planet masses, orbital separations, and incident flux levels. The complexity of these atmospheres is sure to be significant, given the role of the atmosphere/interior composition connection in altering molecular abundances. For rocky planets around M dwarfs, we are starting to build up a sample of planets that do or do not have atmospheres, via transiting planet transmission and emission spectroscopy. Understanding which of these planets have atmospheres, and the nature of these atmospheres, will be a significant undertaking over the next several years.

Acknowledgments

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The Hycean Paradigm in the Search for Life Elsewhere

Nikku Madhusudhan
Institute of Astronomy, University of Cambridge, UK

Abstract

The search for habitable conditions and signs of life on exoplanets is a major frontier in modern astronomy. Detecting atmospheric signatures of Earth-like exoplanets is challenging due to their small sizes and relatively thin atmospheres. Recently, a new class of habitable sub-Neptune exoplanets, called Hycean worlds, has been theorized. Hycean worlds are planets with H_2-rich atmospheres and planet-wide oceans with thermodynamic conditions similar to those in the Earth's oceans. Their large sizes and extended atmospheres, compared to rocky planets of similar mass, make Hycean worlds significantly more accessible to atmospheric observations. These planets open a new avenue in the search for planetary habitability and life elsewhere using spectroscopic observations with the James Webb Space Telescope (JWST). We observed the transmission spectrum of a candidate Hycean world, K2-18 b, recently with JWST in its first year of operations. The spectrum reveals multiple spectral features of carbon-bearing molecules in the planetary atmosphere, leading to the first detections of methane (CH_4) and carbon dioxide (CO_2) in a habitable-zone exoplanet. We discuss inferences of the atmospheric chemical composition and its implications for the atmospheric, interior and surface conditions on the planet, along with the possibility of a habitable ocean underneath the atmosphere. We discuss new observational and theoretical developments in this emerging frontier and their implications for exoplanetary habitability and search for life elsewhere.

1. Introduction

One of the central goals in exoplanetary science is the search for life beyond the solar system. Traditionally, the search for life on exoplanets has been primarily directed towards habitable planets similar to the Earth orbiting other stars. The concept of planetary habitability originated primarily with Earth-like planets in view. The terrestrial habitable zone around a star is defined as the range in orbital separation over which an Earth-like planet can host liquid water on its surface (e.g. Kasting et al. 1993). The habitable zone is closer-in for stars that are smaller and cooler than the sun and is farther out for stars that are larger and hotter, as shown in Figure 1. Extensive efforts are underway to detect Earth-like exoplanets orbiting nearby stars and to characterise their atmospheres using transit spectroscopy in search of chemical signatures of habitable conditions and/or biological processes. By Earth-like, it is customary to assume planets with sizes, densities and temperatures comparable to those of Earth.

The search for biosignatures on Earth-like planets is hindered by two key limitations. Firstly, there is currently no exact Earth-like planet known to orbit a sun-like star beyond the solar system. Nevertheless, efforts are underway to detect and characterise such planets around smaller stars, M dwarfs, which are more accessible to observations. Even then, there is a dearth of such planets known to be transiting nearby stars, with only about five planets that are conducive for detailed atmospheric observations with current facilities and several of which are in the same system – the TRAPPIST-1 system (Gillon et al. 2017). Secondly, even for the few such planets known atmospheric observations are challenging. Theoretical studies show that a substantial amount of JWST time may be required to robustly detect prominent biosignatures if present in such atmospheres (Barstow & Irwin 2016, Lustig-Yaeger et al. 2019).

Recently, the sub-Neptune regime has emerged as a new frontier in the study of exoplanetary habitability and search for life (e.g. Madhusudhan et al. 2021). The sub-Neptune class refers to planets with sizes between those of Earth and Neptune, which have no analogue in the solar system but dominate the exoplanet population (Fulton & Petigura 2018). These planets span a wide range in possible atmospheric and internal structures, from predominantly rocky interiors with heavy secondary atmospheres to volatile-rich interiors with light hydrogen-rich atmospheres (Rogers & Seager 2010, Valencia et al. 2013, Zeng et al. 2019, Madhusudhan et al. 2020). It is unknown which of these planets could host conditions that are conducive for life. Nevertheless, the large numbers of such planets known in the exoplanet population, including a significant number of temperate sub-Neptunes, raise important questions in the search for exoplanet habitability. Which currently known exoplanets in the sub-Neptune regime are potentially habitable? Which of them are conducive for atmospheric observations? What are the possible biosignatures that may be detectable?

In essence, the large population and diversity of the sub-Neptune regime motivate us to revisit the primary conditions of planetary habitability.

While a wide range of planetary properties contribute to planetary habitability (Meadows & Barnes 2018), the following question serves as an essential starting point. What are the limits on planet mass, radius and temperature for habitability in the sub-Neptune regime? A recent attempt to answer this question has opened the possibility that a wide range of planets with markedly different interiors and atmospheres to Earth may also be habitable, and observable with JWST (Madhusudhan et al. 2021). This Hycean paradigm, as discussed in this work, has the potential to significantly expand and accelerate the search for habitable conditions and life elsewhere and to place important constraints on the conditions for the origins of life.

2. The Hycean Paradigm

Hycean worlds are planets with habitable ocean-covered surfaces underlying hydrogen-rich atmospheres (Madhusudhan et al. 2021). The word Hycean is a portmanteau of "**Hy**drogen" and "O**cean**". The motivation for this new class of planets originated with the habitable-zone sub-Neptune K2-18 b (Montet et al. 2015). The planet has a mass of $8.63 \pm 1.35\ M_E$ and a radius of $2.61 \pm 0.09\ R_E$ (Cloutier et al. 2019, Benneke et al. 2019), and orbits an M3 dwarf star with an orbital period of 33 days. The planet receives a net stellar irradiation comparable to that received by the Earth from the Sun, giving it a zero-albedo equilibrium temperature of 297 K. However, the large mass and radius of the planet, with nearly half the density and 27% higher gravity compared to the Earth, are incompatible with a rocky Earth-like interior. The lower density requires the presence of a substantial volatile layer in the interior. Initial atmospheric observations of the planet with the Hubble Space Telescope (HST) revealed the presence of a H_2-rich atmosphere in the planet (Benneke et al. 2019, Tsiaras et al. 2019, Madhusudhan et al. 2020).

The combination of atmospheric observations and the bulk properties of the planet allowed for three possible scenarios for the interior composition (Madhusudhan et al. 2020): 1. a mini-Neptune with a rocky core, icy mantle and a thick H_2-rich atmosphere, 2. a gas dwarf with a rocky core and mantle and a thick H_2-rich atmosphere, and 3. a water world with a thin H_2-rich atmosphere. Based on coupled modelling of the atmosphere and interior, we were able to explore the range of possible conditions at the interface between the H_2-rich atmosphere and the interior (Madhusudhan et al. 2020). In particular, for the water world scenario we found that for most of the model solutions the water at the surface was in supercritical phase, too hot to be habitable. However, a small subset of solutions allowed for liquid water at pressures and temperatures comparable to those in the Earth's oceans. This later scenario implied the possibility of a habitable ocean-covered surface and a thin H_2-rich atmosphere in K2-18 b. The possibility of liquid water also depends on the right atmospheric conditions such as an adequate Bond albedo, atmospheric thickness and internal flux (Madhusudhan et al. 2020, Piette & Madhusudhan 2020, Leconte et al. 2024). For example, models without an adequate albedo due to clouds/hazes predict surface temperatures too high to allow liquid water (Schecher et al. 2020, Piette & Madhusudhan 2020, Innes et al. 2023).

Motivated by the above finding, we conducted a detailed exploration of the full range of possible planetary masses, radii, equilibrium temperatures and host stars which could allow habitable conditions similar to those possible on K2-18 b, i.e. with habitable ocean-covered surfaces underneath H_2-rich atmospheres, referred to as Hycean planets (Madhusudhan et al. 2021). We found that Hycean planets can occupy a wide region in the mass-radius plane, with radii up to 2.6 R_E for a 10 M_E planet. Similarly, such planets also significantly expand the habitable zone for all stellar types, as shown in Fig. 1. Besides the regular Hycean worlds with planet-wide habitability, we also identified dark Hycean worlds that are habitable only on the night side and cold Hycean worlds that receive little stellar irradiation but can still be habitable thanks to the strong greenhouse effect due to H_2. Overall, the wider habitable zone for Hycean planets significantly increase the number of potentially habitable planets in the search for life elsewhere. Their large radii and light (H_2-rich) atmospheres give rise to significantly larger spectral features compared to rocky planets of similar mass, making Hycean worlds significantly more accessible to atmospheric observations.

Based on these limits, we identified a dozen known temperate sub-Neptunes as candidate Hycean worlds which would be conducive for atmospheric spectroscopy with JWST. We also explored the feasibility of detecting biomarker molecules in such atmospheres. For Earth-like planets the prominent biomarker molecules are expected to be O_2, O_3 and/or CH_4 (e.g. Catling et al. 2018). However, the same molecules could either be underabundant or have abiotic sources in H_2-rich atmospheres of Hycean worlds. We therefore consider several secondary biomarkers (e.g. Domagal-Goldman et al. 2011, Seager et al. 2013, 2016) as more robust biomarkers on Hycean worlds. These include molecules such as dimethyl sulphide (DMS) and methyl chloride (CH_3Cl) which are expected to be present in small quantities

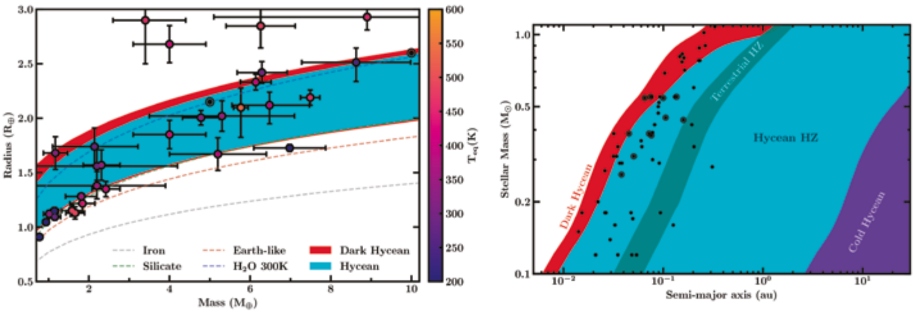

Figure 1. The Hycean mass-radius (M-R) plane and Habitable Zone (from Madhusudhan et al. 2021). The left panel shows the range of masses and radii possible for Hycean worlds. The dashed lines show M-R curves for planets with uniform compositions as noted in the legend. The circles with error bars denote several known exoplanets. The right panel shows the Hycean habitable zone. The Cyan, dark-red, and purple regions show the habitable zones for regular, Dark (nightside), and Cold (non-irradiated) Hycean planets, respectively. The terrestrial habitable zone is shown in teal (Kopparapu et al. 2013). Black circles denote several known sub-Neptune exoplanets. The planets with concentric circles indicate promising Hycean candidates.

but are not known to have significant abiotic sources and are detectable in the atmospheres of Hycean worlds. Based on simulated JWST observations, we demonstrated that these molecules can be detected robustly in several Hycean worlds with only a few tens of hours of JWST time per planet.

3. First JWST Spectrum of a Possible Hycean World

The advent of JWST is revolutionising the characterisation of sub-Neptune atmospheres, thanks to the generational leap in sensitivity and spectral coverage. We observed a transmission spectrum of K2-18 b as part of the JWST Cycle 1 GO program 2722, to characterise the chemical and physical conditions in the atmosphere and their implications for the interior. The program involves observations with three JWST instruments (NIRISS, NIRSpec G395H and MIRI) spanning a spectral range of ~1-10 μm, of which two observations have been conducted to date with NIRISS and NIRSpec in the ~1-5 μm range. A transmission spectrum is observed when the planet passes in front its host star as seen by the telescope. During the transit the planet blocks part of the stellar disk causing a reduction in the starlight observed. Some of the starlight passes through the atmosphere of the planet at the day-night boundary ('terminator') region before reaching the telescope. The reduction, or 'absorption', of the starlight observed varies with wavelength of light as the planetary atmosphere absorbs different amounts of light at different wavelengths depending on the atmospheric composition. This absorption as a function of wavelength is referred to as a transmission spectrum. The transmission spectrum of K2-18b observed with JWST is shown in Figure 2 (Madhusudhan et al. 2023).

The spectrum led to robust detections of multiple carbon-bearing molecules and unprecedented constraints on a range of atmospheric properties of K2-18 b, the first for a sub-Neptune. The spectrum revealed strong features of methane (CH_4) and carbon dioxide (CO_2), detected at 5σ and 3σ confidence, respectively. The atmospheric chemical abundances retrieved using the spectrum revealed substantial quantities of both molecules, at ~1% each, in a H_2-rich atmosphere. CH_4 is abundant in all giant planet atmospheres of the solar system, which are H_2-rich, and is similarly expected in temperate H_2-rich exoplanetary atmospheres but had not been detected in a temperate exoplanet before (Stevenson et al. 2010, Madhusudhan & Seager 2011). Therefore, the detection of CH_4 in K2-18 b addresses this long-standing 'missing methane' problem. On the other hand, the spectrum did not show significant evidence for other prominent molecules, including water vapour (H_2O), ammonia (NH_3), or carbon monoxide (CO) which are typically expected in H_2-rich atmospheres. Finally, the spectrum revealed tentative evi-

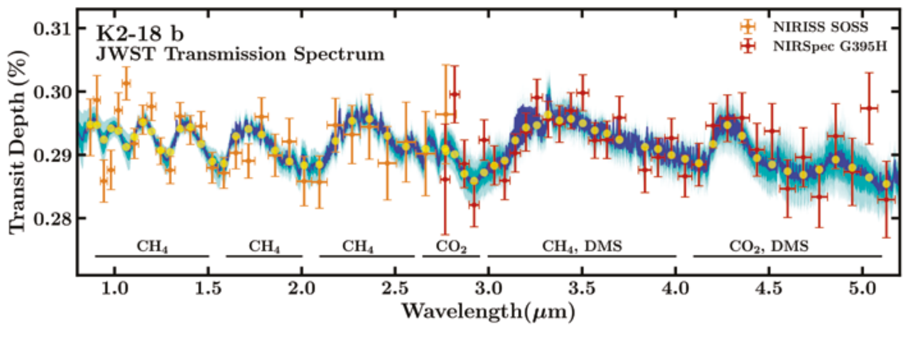

Figure 2. The transmission spectrum of the sub-Neptune K2-18 b, a candidate Hycean world (from Madhusudhan et al. 2023). The observed JWST spectrum is shown in the orange and red data obtained with the NIRISS and NIRSpec instruments on JWST as noted in the legend. The dark blue line denotes the median-fit model spectrum while medium and lighter blue regions denote the 1σ and 2σ contours, respectively. CH_4 and CO_2 are detected robustly at 5σ and 3σ confidence, respectively, as evident from their strong spectral features labelled in the figure. Only marginal evidence for DMS is found in regions of the spectrum overlapping with the strong CH_4 and CO_2 features as shown. The yellow circles show the median-fit model binned to the same resolution as the data.

dence (2σ or less) for dimethyl sulphide (DMS) which has been predicted to be a potential biomarker, both in Earth-like and Hycean atmospheres (Catling et al. 2018, Domagal-Goldman et al. 2011, Seager et al. 2013, Madhusudhan et al. 2021). The spectrum also provided 3σ evidence for the presence of clouds/hazes in the atmosphere at the day-night terminator.

The chemical detections provide important insights into possible atmospheric and surface conditions on the planet. The detections of CH_4 and CO_2 and the non-detections of NH_3 and CO are consistent with predictions for a thin H_2-rich atmosphere in contact with an ocean surface (Hu et al. 2021, Madhusudhan et al. 2023b). The lack of NH_3 in this scenario is explained by its high solubility in the underlying ocean. On the contrary, a deep H_2-rich atmosphere that would be required in the case of a mini-Neptune or rocky planet scenario is unable to explain the observed atmospheric composition as that would predict a higher NH_3 and CO compared to what is observed (Yu et al. 2021, Hu et al. 2021, Tsai et al. 2021, Madhusudhan et al. 2023b). The non-detection of H_2O is also consistent with expectations for a cold trap in the stratosphere whereby the temperature is low enough for H_2O to condense out of the observable atmosphere (Madhusudhan et al. 2023b). The observed constraint on the atmospheric temperature and the 3s evidence for clouds/hazes are also consistent with this picture. Finally, the marginal evidence for DMS is of significant interest given its promise as a potential biomarker. Given the low evidence, 2σ or less, more observations are required to robustly establish or rule out its presence in the atmosphere, which could have important implications for the possibility of biological activity on the planet.

A key question in the Hycean scenario is what atmospheric properties are required to sustain a liquid water ocean under the H_2-rich atmosphere of K2-18 b. As discussed above, some theoretical studies have shown that a significant albedo, up to ~0.5-0.6, due to clouds/hazes may be required to maintain a low temperature and a liquid water ocean in K2-18 b (Madhusudhan et al. 2020, Piette & Madhusudhan 2020, Madhusudhan et al. 2021, Leconte et al. 2024). On the other hand, a cloud/haze-free atmosphere could lead to a supercritical water layer that would not be conducive for habitability (Piette & Madhusudhan 2020, Scheucher et al. 2020, Innes et al. 2023). The evidence for clouds/hazes at the day-night terminator provided by the present data may contribute towards the required albedo. However, more observations are required to both improve upon the present constraints on the cloud/haze properties at the terminator as well as more directly measure the albedo on the dayside atmosphere using emission spectroscopy. Recent studies have also explored alternate mechanisms to explain the observed atmospheric composition of K2-18b (Wogan et al. 2024, Shorttle et al. 2024). However, none of those mechanisms are able to simultaneously explain the non-detections of NH_3 and CO and the high CO_2 and CH_4 abundances in the planetary atmosphere (e.g. Glein 2024). Therefore, currently, the Hycean explanation remains the most favoured by the data. More observations and theoretical work in the future could enable more stringent constraints on the different possible interpretations.

4. Summary and Emerging Directions

The JWST observations of K2-18 b represent a paradigm shift in the study of exoplanet habitability and search for life. Firstly, they have led to the first detections of carbon-bearing molecules in a potentially habitable exoplanet. Besides resolving the long-standing missing- methane problem, this is a major technical demonstration of the ability of JWST to characterise candidate Hycean worlds and temperate sub-Neptunes in general. This opens a new avenue to study a wide range of planetary processes in such planets, including atmospheric, surface and interior conditions as well as formation pathways. Secondly, and more specifically to K2-18 b, the detected atmospheric chemical composition is consistent with predictions for a Hycean world. Furthermore, the potential inference of DMS, if confirmed, raises the possibility of potential biological activity on the planet. Overall, these observations have opened a promising pathway to explore exoplanet habitability with JWST and to understand potential conditions for life in environments very different from Earth.

It is natural to wonder whether, theoretically, the conditions on Hycean worlds would be conducive for the origin and sustenance of life as we know it on Earth. The origin and evolution of life on a planet depends on a complex interplay of astrophysical, geological, geochemical and biological factors. As a first step in answering this broad question, we investigated whether Hycean worlds would allow the chemical conditions required for primordial life similar to that originated in Earth's oceans (Madhusudhan et al. 2023b). We find that the temperate H_2-rich atmospheres of Hycean worlds provide a rich source of organic prebiotic molecules in the early stages of the planets history that could be conductive for seeding life. The planet-wide oceans in Hycean worlds could also contain adequate bio-essential elements (CHNOPS) at concentrations comparable to those in the early Earth's oceans. This is particularly important considering that the oceans on such planets are expected to be up to hundreds of km deep with a sea floor of high-pressure ice which precludes direct interaction of the water with the mineral-rich rock (Nixon & Madhusudhan 2021, Rigby & Madhusudhan 2024). Overall, Hycean worlds provide promising prospects and a rich testbed for investigating the origin and evolution of life in planetary environments.

Is K2-18b unique? From an observational perspective, it is natural to ask whether K2-18 b is a unique, and perhaps fortuitous, case, or whether it belongs to a more general class of planets with similar characteristics. Most recently, JWST observed the transmission spectrum for a second candidate Hycean world TOI-270 d (Holmberg & Madhusudhan 2024, Benneke et al. 2024), as shown in Figure 3. The planet has a mass of 4.8 Earth masses and a radius of 2.1 Earth radii (Günther et al. 2019, van Eylen et al. 2021). Quite remarkably, the spectrum shows very similar spectral features as K2-18b of CH_4 and CO_2 in a H_2-rich atmosphere and no strong evidence for NH_3 or CO. In addition, the spectrum also revealed additional signatures of H_2O, confirming previous detection with HST (Mikal-Evans et al. 2023) and consistent with the equilibrium temperature of the planet being ~80 K hotter than K2-18b, and carbon disulphide (CS_2). The hotter temperature means that H_2O is unlikely to be condensed out over the whole atmosphere, and the surface temperature may also be significantly hotter compared to K2-18b. Therefore, while a Hycean scenario cannot be ruled out (Holmberg & Madhusudhan 2024) it is also possible that TOI-270 d may instead be too hot to be habitable (e.g. Benneke et al. 2024). More observations and theoretical work are needed to robustly constrain the atmospheric and interior properties and the possibility of habitable conditions on TOI-270 d.

Irrespective of their habitability, the remarkable similarity in the spectra between K2-18 b and TOI-270 d point to a new class of temperate sub-Neptunes with some commonality in the underlying physical and chemical conditions. Over the next few years, initial reconnaissance observations with JWST will be available for several more such candidate Hycean worlds. These developments provide impetus to a new era in exoplanetary science and astrobiology, with the potential for transformational insights into the sub-Neptune regime. It may be expected that these observations will provide unprecedented insights into three fundamental questions: How do planets form and evolve? How diverse are planetary processes? And, are we alone?

Overall, the phenomenal capability of JWST and other upcoming facilities promise a golden age in exoplanet science. The confluence of powerful observational facilities, diverse exoplanet population and transformational science questions provides the perfect storm for major scientific breakthroughs. In this backdrop, the Hycean paradigm provides an unprecedented opportunity in the search for habitable environments beyond the solar system. Theoretical and observational studies have already demonstrated the capability of JWST to detect potential biomarkers in Hycean worlds. The central question at present is not whether we would be able to detect presence of life on a Hycean world but whether we are prepared to identify a signature of life on a planet so unlike Earth. Are we prepared to find life as we don't know it?

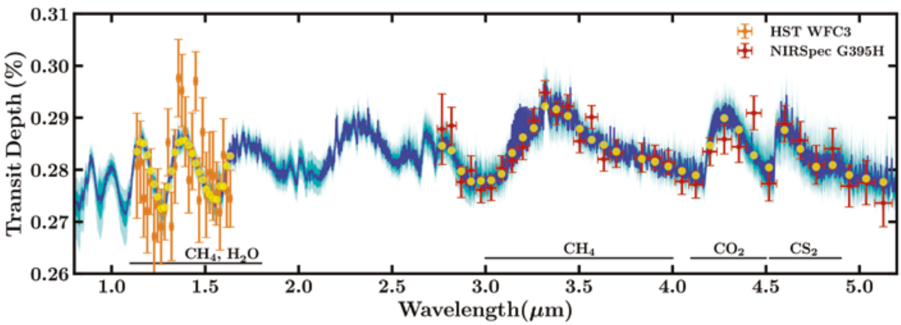

Figure 3. The transmission spectrum of the sub-Neptune TOI-270 d, a candidate Hycean world (from Holmberg & Madhusudhan 2024). The observed JWST spectrum is shown in the red data, along with a previously observed HST spectrum (Mikal-Evans et al. 2023) shown in orange, as noted in the legend. The dark blue line denotes the median-fit model spectrum while medium and lighter blue regions denote the 1σ and 2σ contours, respectively. The yellow circles show the median-fit model binned to the same resolution as the data.

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Deep Reconnaissance of Exoplanet Atmospheres Through Multi-Instrument Spectroscopy

Nikole K. Lewis
Cornell University, Ithaca, USA

Abstract

With JWST a new window into exoplanet atmospheres is now wide open. This paper focuses on initial results from JWST Cycle 1 programs that aimed to perform "deep" observations of specific transiting exoplanet hosting systems to explore the physics and chemistry at work in these planetary atmospheres. The JWST Telescope Scientist Team (JWST-TST) used 133 hours of Cycle 1 guaranteed observing time to perform Deep Reconnaissance of Exoplanet Atmospheres through Multi-instrument Spectroscopy (DREAMS) on three archetypical planets: a hot Jupiter (WASP-17b), a warm Neptune (HAT-P-26b), and a temperate Earth (TRAPPIST-1e). Through both transmission and emission observations spanning 0.6-12 microns, the DREAMS survey has uncovered new and unexpected chemistry at work in WASP-17b and HAT-P-26b's atmospheres and allowed us to explore their three-dimensional atmospheric structure. With DREAMS survey observations of the TRAPPIST-1 system, we have achieved precisions that will allow for detailed exploration of TRAPPIST-1e's transmission spectrum in search of planetary atmospheric signatures. The JWST observations presented here will hopefully prove to have a lasting legacy in our understanding of exoplanets and their atmospheres.

1. Introduction

Exoplanets that transit their host star as viewed from earth, which constitute the majority of the currently known exoplanet population, represent our best opportunity for atmospheric characterization studies with observational facilities like JWST. These transiting exoplanets allow their atmospheres and/or surfaces to be probed through high-precision (<1%) relative spectrophotometric observations obtained throughout the planet's orbit. Atmospheric transmission spectra obtained as the planet passes in front of the host star probe the chemical composition of the planet's atmosphere. The dayside thermal structure and emission spectrum of the planet are probed with secondary eclipse observations. Emission measurements as a function of orbital phase can be used to map the longitudinal thermal structure of the planet since most transiting exoplanets are on short period orbits within the tidal locking radius of their host star. Before the launch of JWST, space-based observatories such as *Spitzer* and *Hubble* provided the stability and precision required to probe the atmospheres of transiting exoplanets, but were limited in the wavelengths of light they could access and the achievable spectral resolution. JWST will go far beyond both *Spitzer* and *Hubble* to achieve unprecedented stability, precision, and wavelength coverage and resolution to usher in a golden age of exoplanet atmospheric characterization.

2. The JWST-TST DREAMS Strategy

The JWST Telescope Scientist Team[1] (JWST-TST) is using Guaranteed Time Observer (GTO) time awarded by NASA in 2003 (PI M. Mountain) for studies in three different subject areas: (a) Transiting Exoplanet Spectroscopy (lead: N. Lewis); (b) Exoplanet and Debris Disk Coronagraphic Imaging (lead: M. Perrin); and (c) Local Group Proper Motion Science (lead: R. van der Marel). A common theme of these investigations is the desire to pursue and demonstrate science for the astronomical community at the limits of what is made possible by the exquisite optics and stability of JWST. The transiting exoplanet spectroscopy subject area used 133 hours of JWST cycle 1 observing time to perform the Deep Reconnaissance of Exoplanet Atmospheres through Multi-instrument Spectroscopy (DREAMS) program on three archetypical planets: a hot Jupiter (WASP-17b, $M_p \sim M_{Jupiter,}$ T_{eq} > 1200 K), a warm Neptune (HAT-P-26b, $M_p \sim M_{Neptune}$, T_{eq} < 1200 K), and a temperate Earth (TRAPPIST-1e, $M_p \sim M_{Earth}$, $T_{eq} \sim 300$ K). The DREAMS survey takes advantage of JWST's spectral coverage, spectral resolution and achievable precision to characterize these three exoplanets in exquisite detail. Exoplanet scientists have long envied the observed spectra available for stars, brown dwarfs, and planets within our own solar system. Although spectral differences do exist among members of a given population of stars or planets, high-fidelity observed spectra of representative members are invaluable for understanding the bulk properties of the population and guiding observations of other population member. Additionally, by observing both

[1] https://www.stsci.edu/~marel/jwsttelsciteam.html

transmission and emission spectra for our hot Jupiter and warm Neptune targets, we have the opportunity to probe the three-dimensional atmospheric structure of these worlds and better understand their weather. The JWST-TST DREAMS observations will become 'Rosetta Stones' that will serve as benchmarks for further observations of planets within each representative population and a lasting legacy of the JWST mission.

3. New Windows into Hot Jupiter Atmospheric Chemistry, Clouds, and Weather

The hot Jupiter WASP-17b was among the best studied exoplanets in the era before JWST, but our knowledge of the physics and chemistry at work in its atmosphere was still limited by the wavelength coverage offered by *Hubble* and *Spitzer*. Figure 1 shows our transmission and emission spectra of WASP-17b before and after our 75 hours of JWST observations on this target. Before JWST, we knew that WASP-17b was likely to have an at-

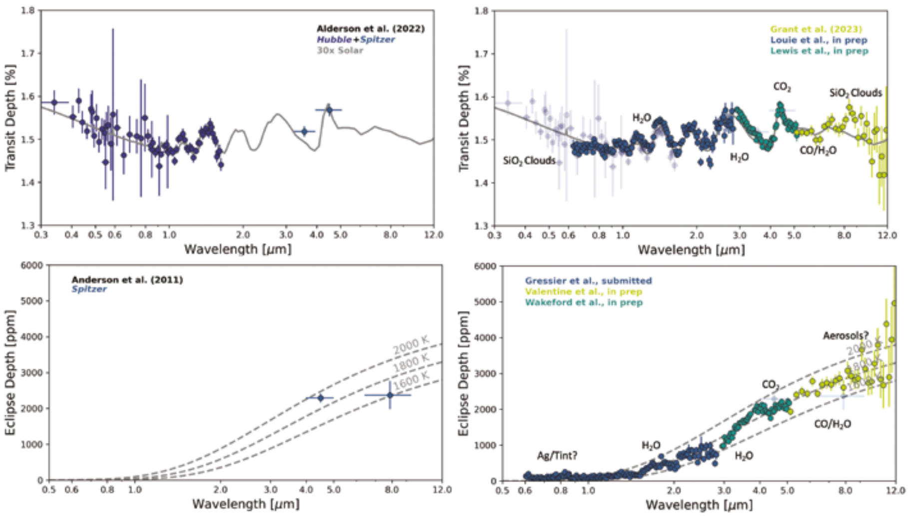

Figure 1. Transmission (top) and emission (bottom) observations of the hot Jupiter WASP-17b previously with *Hubble+Spitzer* (left) and now with JWST (right). The leap in spectral coverage (range of wavelengths) available with JWST has uncovered never before seen signatures of Quartz (SiO_2) clouds, carbon-bearing species (CO_2), and sulfur bearing species (SO_2). The JWST transmission spectrum of WASP-17b is consistent with an atmosphere significantly enhanced in elements and molecules heavier than hydrogen and helium, which is not expected for a planet of this size. The JWST emission spectrum of WASP-17b is consistent with a 1800 K average day-side temperature, indicative of some transport of heat from the dayside to the nightside of the planet via winds, and contains signatures indicative of highly reflective dayside aerosols.

mosphere rich in heavier elements (30x Solar Metallicity) and have aerosols present (Alderson et al. 2022). Our JWST transmission observations have confirmed the presence of Carbon Dioxide (CO_2) in WASP-17b's atmosphere, consistent with a metal-rich atmosphere, and revealed signatures of Quartz (SiO_2) clouds in its atmosphere, first reported in Grant et al. (2023). Before JWST, we had very little information on the temperature and dayside chemistry of WASP-17b's atmosphere. Our JWST emission observations have revealed a rich dayside spectrum from WASP-17b's atmosphere with features that add new dimensions to our understanding of the weather on this distant world, in particular strong winds that transport heat from the dayside to the nightside.

4. Trends Across Exoplanet Size and Temperature

The Warm Neptune HAT-P-26b had a strong detection of H_2O with *Hubbl*e (Wakeford et al. 2017) that gave us some insights into the atmospheric composition of this interesting member of the exoplanet population

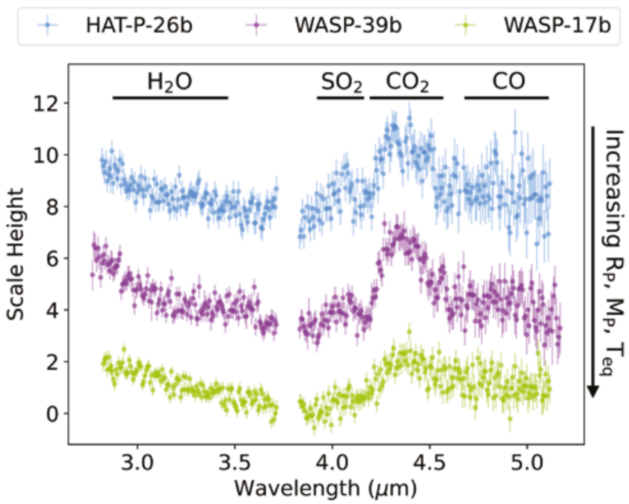

Figure 2. JWST Transmission spectra of the giant exoplanets HAT-P-26b (top), WASP-39b (middle), and WASP-17b (bottom) obtained with the NIRSpec G395H observing mode (with offsets applied in scale height/feature amplitude to facilitate comparison). Before the launch of JWST, there were no observational facilities that could provide spectroscopy of exoplanet atmopsheres across the full 3-5 micron wavelength range. Despite significant differences in planetary size and temperature, all show clear signatures of key molecular species that are important for understanding planet formation and atmospheric chemistry.

before the launch of JWST. HAT-P-26b is of particular interest because its mass (~22 M_{Earth}) is similar to that of Neptune in our own Solar System and its equilibrium temperature (~1000 K) places it at an interesting transition for the formation of atmospheric aerosols (Gao et al. 2021). With the JWST NIRSpec instrument, we were able to spectroscopically probe HAT-P-26b in the 3-5 micron wavelength region that for the first time revealed clear signatures of CO_2 and the photochemically produced SO_2 molecules in its atmosphere. In Figure 2, we compare the NIRSpec G395H transmission spectra of WASP-17b and HAT-P-26b from the DREAMS observations with similar observations of the warm Jupiter WASP-39b from the JWST ERS program (Alderson et al. 2023). Despite the fact that WASP-17b, HAT-P-26b and WASP-39b represent a broad range in planetary sizes and temperatures, their spectra show remarkable similarities, notably strong absorption features from H_2O, SO_2, CO_2, and CO (Figure 2). JWST has shown that photochemistry, in particular sulfur-based photochemistry, is a key process shaping a broad range of exoplanet atmospheres.

5. A First Detailed Look at Temperate Terrestrial Exoplanet Atmospheres

The high precision (<100 ppm) available with JWST observations of transiting exoplanets offers the opportunity to probe the potential atmospheres of earth-sized planets in the habitable zones of their stars. The TRAPPIST-1 system (Gillon et al. 2017) offers seven earth-sized planets orbiting a cool M-dwarf star, three of which reside in the system's habitable zone. As part of the JWST-TST DREAMS programs we focused our observations on capturing multiple transits of the habitable zone planet TRAPPIST-1e with JWST's NIRSpec Prism to obtain transmission spectra spanning 1 to 5 microns in wavelength. Before JWST, *Hubble* offered our only opportunity to spectroscopically probe the planets in the TRAPPIST-1 system (e.g. de Wit et al 2018). As shown in the top panel of Figure 3, *Hubble* provided limited coverage of each planetary transit in the TRAPPIST-1 system and with significant instrumental and observatory systematics that required careful correction due to its location in Low Earth Orbit (LEO). JWST, stationed 1 million miles from Earth at L2, has provided spectroscopic observations of the TRAPPIST-1 system that have continuous coverage of each transit event and minimal systematics (Figure 3, bottom panel). Our multiple JWST-TST DREAMS observations of TRAPPIST-1e's near-infrared transmission spectrum will allow us to push to even better precisions (<10 ppm) to search for signatures of its planetary

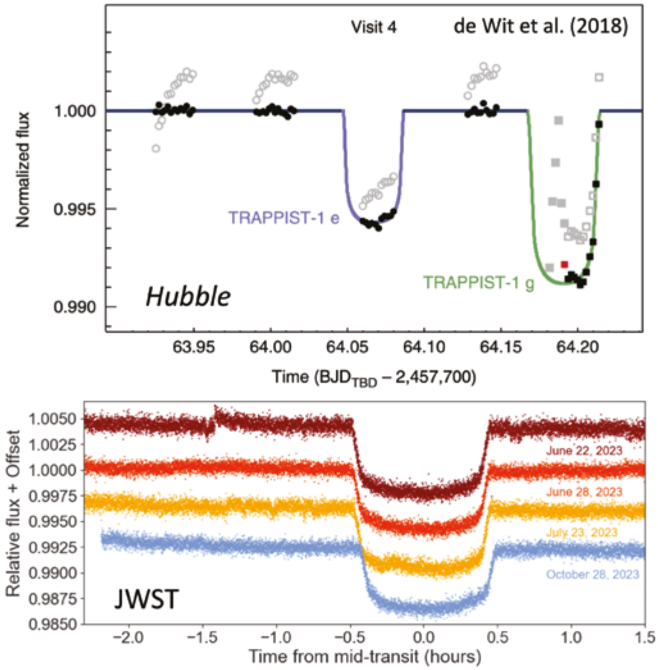

Figure 3. Transit lightcurves obtained as TRAPPIST-1e passed in front of its host star previously with *Hubble* (top) and now with JWST (bottom). The uncorrected *Hubble* observations are presented as light grey in the top panel and show significant systematic effects. With our four JWST transit/transmission observations of TRAPPIST-1e we will achieve better than 10 ppm precision that will allow us to search for spectroscopic signatures from the planet's atmosphere.

atmosphere, better understand the properties of its host star, and guide further JWST observations of this key target in the search for life beyond our solar system.

6. Conclusions

With JWST Cycle 1 observations now complete, our JWST-TST DREAMS team is working to carefully analyze and interpret our observations of WASP-17b, HAT-P-26b, and TRAPPIST-1e. This work includes performing multiple reductions of each observational data set to ensure consistent results between different approaches. We will also produce a suite of atmospheric models for each of these targets to compare with our transmission and emission spectra and perform atmospheric retrieval exercises that will place constraints on the abundance of key atmospheric species and the planet's thermal structure. Additionally, we will leverage our transmission and emission spectra to create multidimensional maps of WASP-17b and HAT-P-26b's atmosphere that will finally provide us with true "pictures" of these distant worlds (e.g. Challener & Rauscher 2022, MacDonald & Lewis 2022, and Grant & Wakeford 2023). With more than a dozen planned manuscripts, there will be a rich body of JWST-TST DREAMS literature that will fully explore the potential science that can be achieved with large amounts dedicated observational time on single exoplanetary targets.

Acknowledgements

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The Mid-IR View of Exoplanet Atmospheres

Michiel Min
SRON Netherlands Institute for Space Research, Leiden, the Netherlands

Introduction

The Mid-InfraRed Instrument (MIRI) is a joint US/EU project looking at the longest wavelength Universe accessible by the James Webb Space Telescope (JWST). With MIRI we can look at the thermal radiation from stars and planets. This unique wavelength range provides access to the spectroscopic fingerprint of many molecules and cloud particles not accessible by the other instruments on JWST. The European Guaranteed Time Observations (GTO) program has been used to demonstrate the unique capabilities of MIRI to characterise the atmospheres of exoplanets and constrain their formation and climate conditions. Here several examples will be discussed showcasing these capabilities.

Clouds and climate on a warm Neptune mass planet

In January 2023 the JWST was pointed towards the star WASP-107 to observe the transit of the Neptune mass planet WASP-107b. WASP-107b is a relatively warm planet with a mass similar to that of Neptune but with a much larger size (more similar to that of Jupiter). It is therefore heavily inflated and carries the nickname 'the cotton-candy planet'. The reason for its inflation is unknown, though there are speculations in the literature. This mystery makes it an ideal target for more in depth study of its atmosphere.

When the planet passes in front of its host star, the planet transit, some of the light from the central star filters through the upper layers of the planet atmosphere and imprints the spectroscopic signature of the molecules and cloud particles present in it. Figure 1 shows the resulting transit depth spectrum. Some interesting and unexpected results are seen in this spectrum.

First of all, very clearly there is the spectroscopic signature of sulfur dioxide. Under the conditions present in this atmosphere, this gas is only produced under the influence of significant ultraviolet radiation and even then it can only be formed if large amounts of sulfur and oxygen are available, more than would be expected for Galactic abundances of these elements.

Second, a very interesting result is the presence of a broad feature in the spectrum which can only be explained as coming from solid state silicate particles, more commonly known as grains of sand. These particles must float high in the atmosphere, creating a high-altitude sand cloud. The most likely explanation for the presence of these particles is that they were formed as condensation clouds. This system is similar to what we see in the Earth's atmosphere with water instead of sand. Here we have water evaporating from the surface and condensing in the cold regions high up in the atmosphere forming water clouds. In the atmosphere of WASP-107b it is significantly warmer, creating this same type of condensation clouds but now forming from 'silicate vapor' creating sand clouds. These types of clouds have been anticipated by theorists to form in these objects, but it is the unique wavelength coverage of the MIRI instrument that now for the first time reveals them and allows us to study their properties. The fact that we see these sand clouds in the atmosphere of WASP-107b must mean that efficient atmospheric mixing is at play to avoid the sand cloud particles to sink below the detectable atmosphere.

The third interesting result is actually the absence of a feature expected to be seen. This is the spectroscopic signature of methane, CH_4. At the ir-

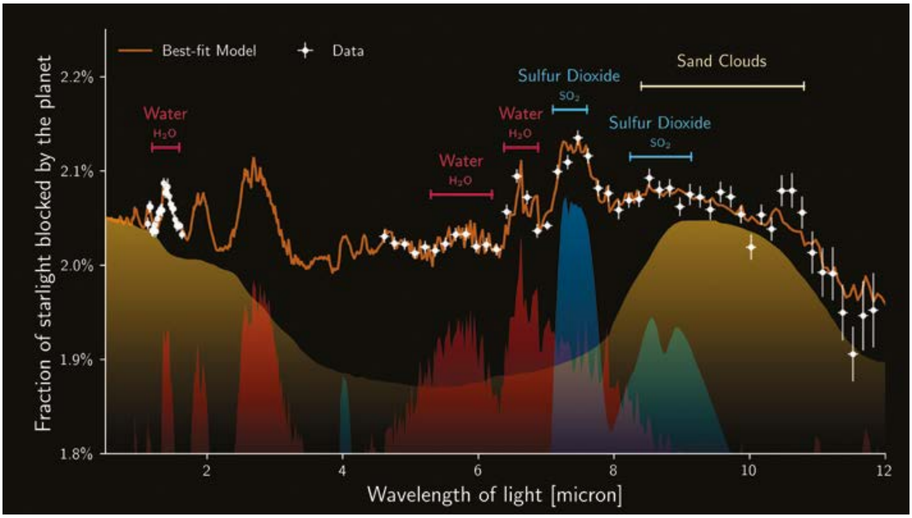

Figure 1. The transit spectrum of WASP-107b as observed by JWST/MIRI in white markers. The simulated model spectrum including the atmospheric gases sulfur dioxide and water along with sand cloud particles is shown in orange. The contribution of the gases and cloud particles is shown in the bottom of the figure.

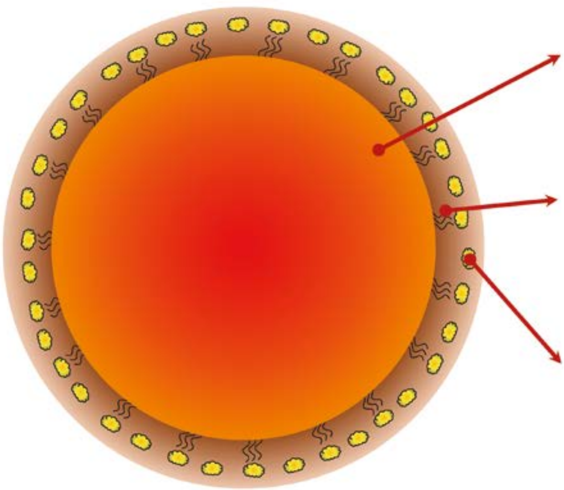

Figure 2. Schematic view of the emerging atmospheric picture for WASP-107b from the MIRI transit spectrum.

radiation temperature of WASP-107b methane is expected to be an important and detectable molecule. The fact that we do not see it in the spectrum can have two chemical explanations that need to work together to explain its absence. First, similar to the result from the sulfur dioxide, the absence of methane points towards an increased abundance of heavy elements (like carbon, oxygen, sulfur and other elements heavier than hydrogen and helium). For elemental mixtures with increased heavy element content, the methane abundance is reduced. However, this is not enough. In addition to this, we need the temperatures at which the chemistry is set to be significantly higher than the equilibrium temperature expected from its distance from the central star. This can be the case if there is a significant internal heat source. This internal heat source has been speculated on also to explain the inflation of the planet.

Overall, a picture unfolds of a turbulent atmosphere with a relatively high, and yet unexplained, internal heat source (see Fig. 2). Similar to other hot gas giant planets observed with JWST it seems that the heavy element content of the planets is increased compared to Galactic abundances. All these aspects provide crucial puzzle pieces to unravel the formation and evolution of these types of planets. For more detailed information see Dyrek et al. (2024).

The formation of substellar objects

Connecting to the formation of planets an interesting type of object are the Brown Dwarfs. These are objects with a mass in-between that of a star and a planet. Classically there are two formation scenarios proposed for giant planets: core accretion (similar to lower mass planets) and gravitational instability (similar to star formation). Roughly speaking in the gravitational instability scenario all mass available in the gravitational influence sphere of the forming planet is accreted in one go. Therefore, the composition directly reflects the composition of the formation environment. In the core accretion scenario, the slow accretion of material allows for several effects separating specific elements. More specific, in this scenario the significant accretion of planetesimals will create an enrichment of the planet atmosphere with icy material, similar to the material found in comets.

The cold brown dwarf named WISE J182831.08+265037.8 (hereafter WISE J1828) was observed with the MIRI instrument in very much detail (see Barrado et al. 2023). In the resulting spectrum we can find the presence of ammonia, water vapor and methane. Although this is the first ever observation of such an object in this detail, the model predictions of the spectrum very closely resemble the observed spectrum. The close match we can make with our model atmospheres allows us to look at very small deviations. One of these subtleties is the isotope ratio of nitrogen. Icy material typically is enriched in the heavier isotopes of nitrogen. Therefore, comparing the isotope ratio of various objects allows us to trace the amount of icy material that was incorporated in it. In the Sun there is around 400 times as much ^{14}N as there is ^{15}N. Comets are generally significantly enhanced in the isotope ^{15}N, dropping the ratio by roughly a factor of four. The value we observe in WISE J1828 is close to, or even higher than, the Solar value, indicating that no significant accretion of icy material has contributed to the formation of the atmosphere (see Fig. 2 in Barrado et al. 2023 for an overview of various objects). This is interpreted as being consistent with the picture that brown dwarf atmospheres form via gravitational instability, similar to stars. This detection shows the power of the MIRI instrument to detect these very low abundance molecules like the isotope of ammonia, to a level that they can serve as tools to unravel the formation mechanism of planetary bodies.

Imaging of a very young exoplanet system

The MIRI instrument has next to its spectroscopic capabilities also an imaging mode. In this mode the very large spatial resolution of JWST, thanks to its huge mirror size, can be used to separate the light of a planet from the overwhelming brightness of its central star. This is very challenging and works best for systems where the spatial separation between planet and star is large but the contrast in brightness between them is relatively small. The HR8799 system is such an ideal system for direct imaging of exoplanets. The system has four detected planets at large orbital separation. The planets are all more massive than Jupiter and even the closest in of these four planets is at a distance from its central star more than three times the distance of Jupiter to the Sun. The system is very young which causes the planets to be very bright at mid infrared wavelength as they are still radiating the leftover heat stored inside the planets by the planet formation process. The HR8799 system was imaged with MIRI at four different wavelengths (see Boccaletti et al. 2024). All four planets are clearly visible in the images. In addition, the dust disk is imaged. This disk is likely created from the debris left over from collisions of planetesimals in the system. By measuring the brightness of the planets at these long wavelengths, we can compute how efficient the cooling of these planets must have been since their formation which constrains the formation scenarios for this exotic system further.

What the future holds

With the JWST instruments we have opened up a window for exoplanet research far beyond the previous possibilities. The analysis of these observations is challenging and poses ever new questions challenging our understanding of how exoplanets form and evolve. The years before the launch of JWST have seen an explosion of theories of what we should be able to see. With these first data we scrape the surface of possibilities to constrain all these ideas with this revolutionary observatory. In the future our understanding will grow. Important questions that will be addressed when more observations will become available are: What types of weather and climate systems exist on hot, irradiated planets? What is the nature of the internal heat source in puffed up planets? What are the variations in planet formation and evolution mechanisms that create the observed planet diversity? What types of atmospheres can we see around low mass planets? And many, many more. For all these questions the JWST and its revolutionary MIRI instrument provide the right tools.

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Early Snapshots of Other Worlds with the James Webb Space Telescope

Sasha Hinkley
University of Exeter, Astrophysics Group, UK

Abstract

We discuss how some of the first JWST datasets from the Early Release Science (ERS) program have showcased the transformative power of JWST to characterize extrasolar planets in the mid- and thermal-infrared for the first time. The results from this program have verified that JWST has the imaging sensitivity, spectral coverage, and spectral resolution to revolutionize our study of extrasolar planets. Specifically, I will describe how the stability and very low thermal background inherent within the observatory means that JWST coronagraphy will be sensitive to an entirely new class of planet: analogs of Saturn and Neptune in our own solar system, but at much wider orbital separations. Only JWST is sensitive to this last remaining region of uncharted exoplanet parameter space. I will also discuss how this ERS program has provided spectroscopy of planetary mass companions at completely new wavelengths providing unambiguous evidence of phenomena such as disequilibrium chemistry and the presence of silicates in the atmosphere. Lastly, I will discuss how the results from this ERS program are already providing valuable "lessons learned" that will educate our efforts with the Roman Space Telescope, and ultimately the Habitable Worlds Observatory with the goal of obtaining images and spectroscopy of terrestrial exoplanets.

1. Introduction

In the relatively short span of a quarter century, astronomers have transitioned from speculating about the prevalence of exoplanetary systems to discovering thousands, and it is now clear that most stars host planetary systems (e.g., Cassan et al. 2012; Dressing & Charbonneau 2013). The vast majority of these, however, have been identified only indirectly via the transit and radial velocity detection methods, and lie at close orbital separations from their host stars.

As the indirect transit and radial velocity detection methods are inherently much less sensitive to wide-separation planets with long orbital periods, the direct imaging technique (e.g., Bowler 2016) will be the only approach to fully define the outermost architectures of planetary systems (~10 to hundreds of AU), and provide a more complete understanding of the true frequency of planetary mass companions to nearby stars (e.g., Nielsen et al. 2019; Vigan et al. 2021). In the last 15 years, imaging observations mostly at wavelengths of $\lesssim$2 µm have directly revealed ~10-20, young ($\lesssim$50 Myr), massive ($\gtrsim 1M_{Jup}$) planets (e.g., Marois et al. 2008; Lagrange et al. 2010; Rameau et al. 2013; Chauvin et al. 2017; Macintosh et al. 2015; Bohn et al. 2020; Janson et al. 2021). Direct Imaging is also the only technique that will be capable of characterising exoplanets at orbital radii $\gtrsim$0.5 AU, as transit transmission spectroscopy (e.g., Sing et al. 2016) requires multiple transits to achieve a strong signal for Earth-mass planets on Earth-like orbits around Sun-like stars (Morley et al. 2017) resulting in prohibitively long-time baselines. It is also the only technique projected to provide the in-depth characterization of such exo-Earths (e.g., The LUVOIR Team 2019; Quanz et al. 2021).

By spatially separating the light of the host star and the extremely faint planet, the direct imaging technique is also naturally suited to direct spectroscopy of planets themselves, allowing detailed characterization (e.g., Bowler et al. 2010; Macintosh et al. 2015; De Rosa et al. 2016; Chauvin et al. 2017; Currie et al. 2018). In addition to providing information on atmospheric properties and compositions (e.g., Hinkley et al. 2015; Kammerer et al. 2021), the direct imaging technique can provide powerful estimations of fundamental parameters, e.g. luminosity, effective temperature, and orbital properties (Gravity Collaboration et al. 2019). The characterization power of the direct imaging method becomes even more pronounced when combined with other exoplanet detection techniques, such as precise radial velocity monitoring or astrometry (e.g., Nowak et al. 2020; Lagrange et al. 2020; Wang et al. 2021a; Lacour et al. 2021; Hinkley et al. 2023), to more fully constrain parameters (e.g. planet mass) that are difficult to ascertain with one technique alone.

Going forward, direct imaging will ultimately provide direct, high-resolution (R~100,000) spectra of exoplanet atmospheres (e.g., Snellen et al. 2015; Mawet et al. 2018; Vigan et al. 2018; Otten et al. 2021; Wang et al. 2021b). Obtaining photons directly from the atmosphere of the exoplanet itself will allow us to apply to exoplanetary atmospheres all of the spectroscopic techniques that have been applied to stars and brown dwarfs over the last century. Indeed, all of the detailed information that can be retrieved using high-resolution spectroscopy of stars and brown dwarfs (e.g.

chemical abundances, compositions, thermodynamic conditions, Doppler tomography) will also be directly obtained for exoplanetary atmospheres, allowing much more precise interpretation of the spectra (Konopacky et al. 2013; Barman et al. 2015).

At the same time, the direct imaging technique has been especially prolific at imaging both very young primordial (protoplanetary) disks as well as dusty circumstellar debris disks. Direct images of these disk structures uniquely allow the study of the dynamical interactions between circumstellar disks, and the planets that are dynamically sculpting them (Choquet et al. 2016; Matthews et al. 2017; Avenhaus et al. 2018; Esposito et al. 2020). Upcoming space-based missions, the advent of the 30-40m telescopes, as well as updates to existing ground-based high contrast imaging platforms (e.g. MagAOX, GPI 2.0, SPHERE+, SCExAO; Males et al. 2018; Chilcote et al. 2020) will vastly improve exoplanet direct detection capabilities. Consequently, the development of the direct imaging technique will be a major priority for the broader exoplanet community going forward, and is a key mode for current and future space missions including JWST (Gardner et al. 2006).

1.1. JWST

With a combination of unprecedented sensitivity and wavelength coverage JWST has already demonstrated its potential for carrying out potentially transformative science related to the detection and characterization of exoplanetary systems (e.g. Hinkley et al. 2022; Carter et al. 2023). The

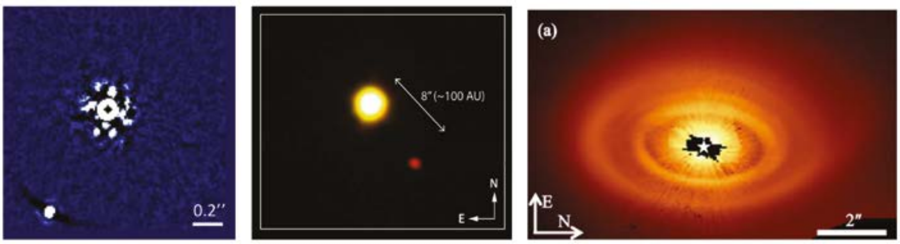

Figure 1. A montage of the three targets that were observed as part of ERS 1386 and as described in Hinkley et al. (2022). Left: HIP65426b (Chauvin et al. 2017) is a wide separation 6-9 M_{Jup} exoplanet that was a nearly perfect target for testing the performance of the JWST NIRCam and MIRI coronagraphs. Middle: the VHS1256b system (Gauza et al. 2015; Stone et al. 2016) is a planetary mass companion with an angular separation of eight arcseconds from its host star, making it ideal for obtaining clean NIRSpec and MIRI R~few thousand spectra that are relatively free from contaminating starlight. Right: The HD141569A circumstellar disk (Weinberger et al. 1999; Clampin et al. 2003) which is not discussed here.

exquisite wave front stability, as well as the capability to observe exoplanet atmospheres near the peak of their thermal emission at 3-5 μm and beyond, means that JWST has the extraordinary power for characterizing wide-separation exoplanets through direct imaging. The precise calibration of the observatory Point Spread Function (PSF) that is afforded by this spacecraft stability (e.g., Perrin et al. 2018), combined with sensitivity in the near- and mid-infrared that is in some cases hundreds of times greater than that for ground-based instruments means that JWST is already sensitive to an entirely new class of sub-Jupiter mass planets at wide orbital separations (e.g., Carter et al. 2021, 2023). This stability and wavelength coverage, combined with wide fields of view in JWST imagers, has allowed resolved imaging of circumstellar disks at wavelengths largely out-of-reach to ground-based observatories (Gáspár et al. 2023; Rebollido et al. 2024; Lawson et al. 2023). The broad wavelength coverage is also allowing the JWST spectrographs within NIRSpec and MIRI to cover multiple spectroscopic features of exo-

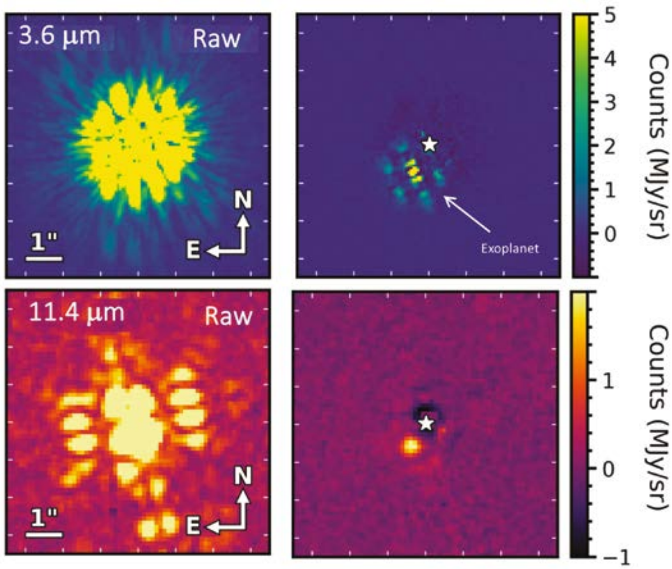

Figure 2. A montage of images adapted from Carter et al. (2023) showing the NIRCam (top row) and MIRI (bottom row) coronagraphy of the HIP65426b system. In the figure the left columns show the "raw" images of the star behind the coronagraph with the residual scattered starlight seen prominently. The rightmost column shows the system after the residual scattered starlight has been subtracted through post-processing. The star-shaped symbol indicates the position of the host star, and the arrow indicates the position of HIP65426b.

planet atmospheres, giving precise measurements of atmospheric compositions and atmospheric chemistries.

In 2017, the Space Telescope Science Institute (STScI) awarded roughly 500 hours of Director's Discretionary Time to 13 community-driven Early Release Science (ERS) programs with the goals of: 1) testing the observatory in the modes expected to be commonly used by that community; and 2) to make clear recommendations to the community on best-practices to be used in future cycles; and 3) to distribute a set of Science Enabling Products (SEPs). Our program "High-Contrast Imaging of Exoplanets and Exoplanetary Systems with JWST" (Hinkley et al. 2022), was ultimately awarded 75 hours of DDT time as program 1386 to utilize all four JWST instruments, and assess the performance of the observatory in these representative modes. In total, three targets were observed as part of this program: The primary target for coronagraphy, HIP65426b (Chauvin et al. 2017), is a wide (92 AU) separation 6-9 M_{Jup} exoplanet and is a nearly perfect target for testing the performance of the JWST NIRCam and MIRI coronagraphs given its angular separation from the host star of 0.8 arcsec. To test the spectroscopic capabilities of JWST, we observed VHS1256b (Gauza et al. 2015; Stone et al. 2016), a planetary mass companion with an angular separation of eight arcseconds from its host star making it ideal for obtaining clean NIRSpec and MIRI R~few thousand spectra that is relatively free from contaminating starlight. Our third target was HD141569A, a circumstellar disk (Weinberger et al. 1999; Clampin et al. 2003) with multiple, distinct rings which is not discussed here in this document. Figure 1 shows a montage of images of these targets from previous publications.

The first science products from this program have already been presented in two initial publications. Carter et al. (2023) showcase the first-ever direct images of an exoplanet with JWST, as well as the first images of an exoplanet at wavelengths longer than 5 μm. Miles et al. (2022) show the first direct spectrum of a planetary mass companion with JWST, and the first spectrum of such an object covering its full luminous range from 1 to ~20μm, clearly showing evidence for disequilibrium chemistry, and the first definitive detection of silicate clouds in an atmosphere of a planetary mass companion. In our ERS program, we also obtained images of a circumstellar disk, but we defer the discussion of this dataset as the data processing is still ongoing.

Here we utilize these results to highlight some of the capabilities of JWST that we have learned about in the last 18 months since the arrival of the first data. In §2.1 we highlight how JWST will help to complete our understand-

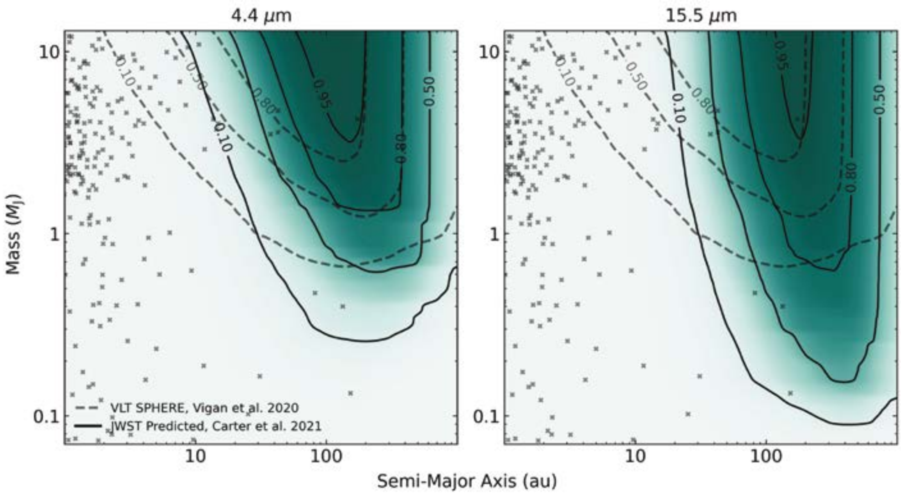

Figure 3. Maps showing the simulated probability of detection for JWST coronagraphy at 4.4μm (left) and 15.5μm (right) taken from (Carter et al. 2021), showing the dramatic improvement of JWST coronagraphy compared to the performance of the ground-based high-contrast imager SPHERE (Vigan et al. 2021). These simulations are for a set of several dozen stars in the nearby young Beta Pictoris Moving Group, as well as the TW Hya group. The performance of our coronagraphic observations of the HIP65426 system are largely in line with these estimates.

ing of the last remaining region of parameter space, and in §2.2 we highlight that JWST will help to provide precise chemical abundances in exoplanet atmospheres, which is the beginnings of our ability to connect precise abundances with a formation history; and in §2.3 we discuss how the lessons learned from current high performance space coronagraphy with JWST will be directly applicable to the Roman Space Telescope Mission in just a few years, as well as the Habitable Worlds Observatory (HWO) in the 2040s.

2. Three driving questions in exoplanetary science that jwst is helping to address

In this section, we will organize our discussion around three key themes of: 1) the architectures of planetary systems, 2) the atmospheres of planetary mass companions; and 3) the power of an image of an extrasolar planet. Specifically, we pose the following three questions:

– Architectures: What are the demographics of exoplanets at all orbital separations?

– Atmospheres: Can JWST help link our measurements of atmospheric composition with a formation history?
– Terrestrial Planets: How will JWST inform us about how to directly image terrestrial planets in the 2040s?

2.1. Architectures: What are the demographics of exoplanets at all orbital separations?

As part of this ERS program, HIP65426b was observed using both the NIRCam round mask and MIRI four-quadrant phase-mask coronagraphs in a variety of NIRCam filters from 2-5µm as well as the 11.4 and 15.5µm MIRI filters. Figure 2 highlights that the suppression of the host star light requires a combination of hardware via a physical coronagraph, as well as software, to suppress the host starlight. These images were the first-ever direct images of an extrasolar planet with JWST, but also showcased the first-ever direct observations of an exoplanet at wavelengths longer than 5 µm.

While these coronagraphic observations were a landmark moment for the field of exoplanet direct imaging and high contrast coronagraphy, another ancillary value of this dataset is that it verified that JWST will have the sensitivity to sub-Jovian planets at wide separation. These results largely verify the prediction shown in Figure 3 from Carter et al. (2021) that JWST would have sensitivity to an entirely new class of planet, reaching analogs

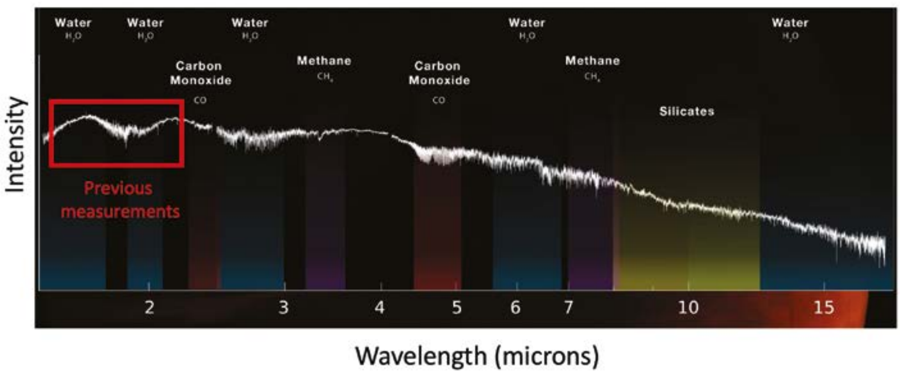

Figure 4. A plot adapted from Miles et al. (2022) showing the NIRCam and MIRI spectroscopy of the planetary mass companion VHS 1256b, shown in the middle panel of Figure 1. The "usual suspects" of CO, CO_2, CH_4 and H_2O are present, but also apparent is the silicate feature around ~9 µm. The red boxed region at left shows roughly the region over which this object had been characterized previously using ground-based imaging and spectroscopy in the JHK-bands.

of our Saturn or Neptune at wide separations. And while the photometry at wavelengths ≳5 μm can help to pin down basic quantities such as effective temperature and surface gravity, much more powerful characterization can come from direct spectroscopy as discussed next in § 2.2.

2.2. Atmospheres: Can we begin to link our measurements of atmospheric composition with a formation history?

VHS 1256b (Gauza et al. 2015; Miles et al. 2018) is a wide separation (~103 AU), substellar companion (19±5 M_{Jup}) to a young M7.5 binary star (Stone et al. 2016; Rich et al. 2016). While the VHS1256 system is not a member of any known kinematic young moving groups, Gauza et al. (2015) derive an age of 150-300 Myr, consistent with its low surface gravity. With a spectral type of L7, infrared parallax measurements (Dupuy et al. 2020) show that VHS 1256b shares a region in a colour-magnitude diagram with other planetary mass companions that are near the L/T transition, and close to the deuterium burning limit such as HR 8799b, HD 203030B, and 2MASS J22362452+4751425 b (Marois et al. 2008; Metchev & Hillenbrand 2006; Bowler et al. 2017).

Spectroscopy of point sources is highly efficient with JWST. Indeed, as pointed out in Hinkley et al. (2022), only 5.6 hours of observatory time were dedicated to spectroscopy of this object, with only 2.7 of these hours actually being dedicated to science observations. In Figure 4 we show the spectrum of VHS1256b as part of this ERS program, highlighting the very long wavelength coverage and multiple measurements of spectroscopic features due to various chemical species. The combination of a long wavelength range, which translates directly to measurement of multiple spectroscopic features, and good spectral resolutions of a few thousand, means that much more precise abundances can be measured for objects like this than ever before. Such abundance measurements are the beginnings of our ability to connect our measurements of the atmospheric composition of a substellar object with its formation location in a protoplanetary disk, but much more work is needed to understand the physics of chemical transport in a disk, as well as a more detailed understanding of the formation locations of circumstellar ice lines.

In addition to the multiple spectroscopic features shown in Figure 4, one of the most notable is the presence of a strong silicate feature at ~9 μm. Spectral fitting is under way to determine if any information about the cloud structure for this object can be inferred (Whiteford et al. in prep).

VHS1256b is a remarkable object because atmospheric measurements reveal that this object possesses three of the major phenomena that have been observed in several other substellar objects. Namely, VHS1256b clearly shows evidence for disequilibrium chemistry seen in other brown dwarfs and directly imaged planets (Skemer et al. 2012; Konopacky et al. 2013; Miles et al. 2020), a very high level of photometric variability (Bowler et al. 2020; Zhou et al. 2020), and the presence of silicates. All of these features point a young, turbulent, and dynamic atmosphere.

2.3. Terrestrial Planets: How can JWST inform us about directly imaging terrestrial planets in the coming decades

The observations gathered as part of ERS 1386 were really our beginnings of doing high-performance coronagraphy in space. The lessons learned on how to execute such observations in an optimal way from space will prove invaluable for the upcoming coronagraphic observations with the Roman Space Telescope. And while it is not expected that the Roman mission will directly detect an Earth-like planet, Roman will inform the community about the necessary protocols for carrying out high-performance coronagraphy in space with active wave front control, which is the necessary stepping stone for HWO. Thus, the lessons learned as part of ERS 1386 are really the beginning of a long-term, multi-decade, effort to directly characterize Earth-like planets in the habitable zones of their stars.

3. Final thoughts: the power of an image of a planet

The direct detection and characterization of terrestrial planets in their habitable zones, with the possible detection of biosignatures, may indeed occur in our lifetime. Such an effort to gather the first images and spectroscopy of an Earth-like planet, whether with HWO or another mission, will trigger an irreversible change in our worldview. As stated in the words of the 2020 United States Decadal Survey: "The scientific goals of this mission, when achieved, have the potential to change the way that we as humans view our place in the Universe."

However, it should be noted that we already have an image of an Earth-like planet with evidence for life: our own Earth. Indeed, with the goal of generating a "family portrait" of the members of our own solar system, on 14 February 1990 the voyager mission gathered on final snapshot of all the solar system planets as it was leaving our solar system. The power of this image inspired the writing of Carl Sagan in his book "Pale Blue Dot" (Sagan

1994), who wrote: "It has been said that astronomy is a humbling and character-building experience. There is perhaps no better demonstration of the folly of human conceits than this distant image of our tiny world. To me, it underscores our responsibility to deal more kindly with one another and to preserve and cherish the pale blue dot, the only home we've ever known."

Indeed, while we work for the next 20 years to gather images and spectroscopy of terrestrial exoplanets, we must not lose track of the fact that we currently face the greatest challenge of our lifetime: the climate crisis. Thus, while we search for other Earths, we should hold in equal importance the health of our own planet, the only home we've ever known.

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Do Temperate Rocky Planets Around M Dwarfs have an Atmosphere?

René Doyon

Université de Montréal, Département de Physique

Trottier Institute for research on Exoplanet and Observatoire du Mont Mégantic

Abstract

Detecting an atmosphere, as the first step in assessing the potential habitability of nearby temperate planets, is one of the most important scientific objectives of the Webb mission, an endeavour in practice limited to a handful of well-characterized planets: Trappist-1d, e, f, g, LHS1140b, and the mini-Neptune K2-18b. The first 18 months of atmospheric characterization with JWST have confirmed both its power and versatility to probe exoplanet atmospheres, and have highlighted the challenge that stellar activity could pose to studying those atmospheres through transmission spectroscopy. Assessing the prevalence of atmospheres in temperate planets with a minimal degree of confidence will require a multi-cycle program of order of a few 1000 hours involving both eclipse photometry and transmission spectroscopy, a program that would have to be executed over a significant fraction of JWST's lifetime. Implementing specialized fast readout modes tailored for time-series observations of relatively bright stars would greatly enhance the efficiency and productivity of JWST's exoplanet science programs. The forthcoming 500 hours of Cycle 3 Director Discretionary Time dedicated to exoplanet programs represent a unique opportunity to initiate a deep reconnaissance of habitability of the best keystone temperate planets.

1. Introduction

One of the most important scientific questions that the James Webb Space Telescope mission should answer is whether temperate rocky planets orbiting nearby low-mass M dwarfs possess an atmosphere and liquid water on their surface. On the one hand, M dwarfs present ideal targets for this exploration due to their smaller masses and radii, which simplifies the task of characterizing the mass, radius, and atmosphere of their planets compared to Earth-like analogs orbiting solar-type stars. This is known as the "M-dwarf opportunity". However, M dwarfs are also known for their intense stellar activity, including strong XUV radiation, an important source of atmospheric erosion. It remains very speculative whether the secondary atmosphere of small rocky planets can survive for billions of years within such a hostile radiation environment (Dong et al., 2020; Kite & Barnett 2020). Addressing this question holds significant implications for planning future flagship space missions and ground-based giant observatories aimed at detecting life beyond the solar system.

This paper highlights the main results and lessons learned from the past 18 months of atmospheric characterizations of small planets orbiting M dwarfs with JWST. We discuss the roadmap needed to assess, with a minimal degree of confidence, the habitability of nearby temperate planets orbiting M dwarfs. We contend that given JWST's limited lifetime, a comprehensive program of both eclipse and transmission spectroscopy of a key sample of temperate planets, that is initiated as soon as possible, is an essential way forward.

2. The best temperate transiting planets: the Golden-J sample

The most suitable temperate planets for atmospheric characterization are those with equilibrium temperatures (T_{eq}) low enough to avoid runaway greenhouse atmospheric conditions that could turn water into a supercritical fluid state (Aguichine et al., 2021; Turbet 2023). While this depends on several atmospheric parameters and spectral type of the host star, we conservatively adopt T_{eq} ~300 K as the maximum allowed value (assuming a Bond albedo A_B=0). These planets should also be required to have accurate mass and radius measurements to yield a planet bulk density (ρ) with an accuracy better than ~10%, which ultimately sets the precision on the mean molecular weight (μ) inferred from transmission spectroscopic observations since the transit depth variation due to the atmosphere scales as T_{eq} / $\mu\rho R_\star^2$. These criteria limit the selection to only a handful of rocky planets: Trappist-1d, e, f, g, and LHS1140b. We make an exception to include the temperate mini-Neptune K2-18b as a potential habitable world, despite its mass uncertainty of 18%. These planets, hereafter referred to the Golden-J sample,[1] represent the temperate subset of the overall population of Earths/super-Earths and mini-Neptunes, all characterized by a bimodal radius distribution with a radius valley near 1.6-8 $R_\oplus$ (Fulton et al., 2017), with the

[1] In reference to a JWST version of the Golden sample, the handful nearest southern habitable worlds amenable to biosignature search with ANDES on the Extremely Large Telescope (Palle et al., 2023).

Trappist-1 planets on the rocky side, LHS1140b in the middle of the valley, and K2-18b on the mini-Neptune side.

3. Highlights of the first atmospheric reconnaissance of small planets

Several important results and lessons learned have emerged from the first JWST observations both from emission and transmission spectroscopy program. Here we briefly highlight published results and ongoing analyses through private communications courtesy of several General Observations (GO) and Guaranteed Time Observations (GTO) teams.

3.1 The Trappist-1 planets

While the initial data suggests that TRAPPIST-1 b and c may be airless worlds (Greene et al., 2023; Zieba et al., 2023), the presence of atmospheres on these planets has not been definitively ruled out (Zieba et al., 2023; Ih et al., 2023; Lincowski et al., 2023). *These first results nonetheless highlight the power of eclipse photometry to put strong constraints on the presence of an atmosphere on small rocky planets*.

Reconnaissance transmission spectroscopy of several planets (b, c, d, e, f, and g) show, in general, strong evidence of stellar activity (Lim et al., 2023) in the form of flares and unocculted spots and faculae that significantly bias the transmission spectra via the transit light source (TLS) effect. TLS (Rackham et al., 2018) is the stellar contamination coming from the assumption that the light from the planet's transit chord is the same as the disk-integrated light of the star when the planet is out of transit. If the star has unocculted spots/faculae then the assumption is invalid and induces stellar spectral signatures on the transit spectra of the planets, thereby complicating the interpretation of the detected spectral features. This fundamental problem is not specific to Trappist-1 and has been shown to affect many other transmission spectroscopy programs focussed on hot Jupiters even those with mid-K host stars (e.g. Fournier-Tondreau et al., 2024) that are thought to have relatively low level of stellar activity.

The strong level of stellar activity of Trappist-1, in particular the TLS effect, poses a significant challenge to unveil relatively small (~50 ppm) atmospheric planetary signals. Several lessons learned from stellar activity have emerged, namely: 1) the need for short-wavelength observations to lift the degeneracy between atmospheric and stellar activity signal (Moran et al., 2023). 2) Repeated observations should be favored to better unveil the inherent variability nature of stellar activity (Lim et al., 2023). 3) A comprehensive campaign of stellar activity characterization through spectroscopic monitoring of the Trappist-1 star over one full rotation is called for, to characterize the spectroscopic properties of flares and better understand stellar heterogeneities (de Wit et al., 2023, Berardo et al., 2024). 4) Finally, more specific to Trappist-1, a double-transit observing strategy should be favored consisting of observing a given transit event paired with another one from b under the assumption that Trappist-1b is airless. The latter spectrum can then be used, to first order, as a TLS "beacon" to correct the transmission spectrum of the planet of interest (de Wit et al., 2023).

3.2 K2-18b

A hydrogen-dominated atmosphere was unequivocally detected on the temperate mini-Neptune K2-18b using HST/WFC3 observations, showing a strong absorption feature at 1.4 µm (Benneke et al., 2019; Tsiaras et al., 2019) interpreted as water vapor. Benneke et al. argued that water can potentially condense into clouds in the K2-18b atmosphere or even rain out. This discovery triggered the hypothesis that this planet could potentially be a Hycean world, a planet with a hydrogen atmosphere on top of a liquid water ocean (Madhusudan 2020, 2023a). Early JWST observations have provided a different picture showing a transmission spectrum dominated by methane (Madhusudhan et al., 2023), This is interpreted as evidence for the Hycean hypothesis but is challenged by other studies (e.g. Hamish et al., 2024; Wogan et al., 2024). While speculative, Hycean worlds may be a shortcut to biosignature detection with JWST, for instance through the dimethyl sulfide molecule featuring several molecular bands beyond ~3 µm. More work is needed to understand whether these planets are indeed habitable (Wogan et al., 2024) or if the DMS is more likely to be due to life or a planetary process. K2-18b serves as a reminder that the search for life in the universe should not be limited to only rocky planets that match the characteristics of Earth.

3.3 LHS1140b

This M4.5 dwarf is host of two small planets including LHS1140b which is the closest transiting temperate planet after those of the Trappist-1 system. The mass and radius of LHS1140b are now known with exquisite accuracy (a few %) similar to the Trappist-1 planets. LHS1140b's bulk density cannot be explained by an Earth-like composition (Cadieux et al., 2024). Detailed internal structure modelling, informed by stellar abundance measurements of refractory elements (Fe, Mg, Si), yields two likely scenarios for the nature of LHS1140b: a mini-Neptune with a small (~0.1%) H/He-rich envelope or a water-world with a water mass fraction of 14±5% (Cadieux et al., 2024). Recent transmission spectroscopy of LHS1140b (DD6543) with NIRISS SOSS of LHS1140b shows a rather flat spectrum with a clear TLS facula-dominated signal (Cadieux et al., in prep). The mini-Neptune scenario is excluded by these recent observations with high significance (See Figure 1).

Cadieux et al. (2024) presented detailed GCM models for the water world scenario suggesting that LHS1140b may be a snowball with a liquid patch at the sub-stellar point if it has an Earth-like level of CO_2 (400 ppm), or more, in its atmosphere. The transmission spectrum predicted by water world GCM models is heavily muted by H_2O/CO_2 clouds leaving only a small (~15-20 ppm) CO_2 features at 2.8 and 4.3 µm. LHS1140b is arguably the best temperate planet from which liquid surface condition may be inferred indirectly through the detection of an appropriate level of CO_2 in its atmosphere.

One important observational constraint of LHS1140b is its limited visibility. Only 8 visits (4 transits, 4 eclipses) are possible per year with JWST. As shown in Cadieux et al. (2024), it will likely take a dozen of visits (three years) to reach a minimal 3σ detection of CO_2 through transmission spectroscopy. Four visits (one year) with MIRI will be required to reach a 3σ detection of the secondary eclipse assuming the airless case with no heat redistribution (see Table 1).

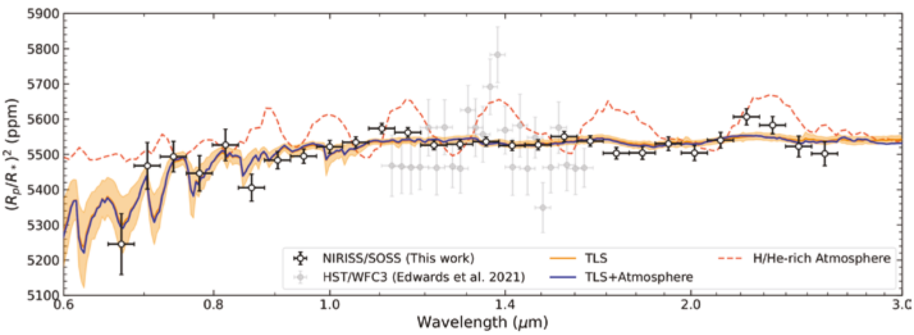

Figure 1. Combined transmission spectrum LHS1140b obtained with NIRISS SOSS on December 1st and 26th 2023 overlaid with HST observations (solid grey points; Edwards et al. 2021). The orange 2s-envelope is the best TLS model dominated by facula. The dashed line is the predicted GCM model of the mini-Neptune scenario of Cadieux et al. (2024); this specific model is excluded at more than 10 σ (Cadieux et al., in prep).

4. For a deep habitability reconnaissance of the Golden-J planets

Arguably, the single most important question that JWST should and *can* answer, under the scientific theme *Planetary Systems and the Origin of Life,* is the title of this paper: Do temperate rocky planets around M dwarfs have an atmosphere? As mentioned above, the best characterized planets to answer this key question is the Golden-J sample. How much observing time would be required to reach an unambiguous answer for this sample? Given the huge implication of the outcome, any results should be independently confirmed with *both* eclipse and transmission observations with some minimal (3σ) level of confidence from both modes. One should indeed take advantage of the full power of JWST to answer such a fundamental question with far reaching implications. A habitability reconnaissance of the Golden-J planets (see Table 1) should have the following two minimal components for the rocky planets:

1) 15 µm eclipse photometry with MIRI: goal to seek a 3σ detection of the airless planet scenario (no heat redistribution, A_B=0), i.e., the deepest possible eclipse depth.
2) Deep reconnaissance transmission spectroscopy: goal to seek a 3σ detection of the 4.3 µm CO_2 absorption feature.

Table 1 presents realistic estimates of the required observing time based on previous eclipse and transmission spectroscopy programs. This comprehensive reconnaissance effort would necessitate a minimum of ~700 hours, including approximately 200 hours dedicated to eclipse photometry. The latter could be conducted as early as Cycle 3 as part of the 500-hour Director Discretionary Time (DDT) program allocated to exoplanets. For the transmission spectroscopy component of the program, only Trappist-1e (128 hours) will be observed during the next two cycles (3 and 4) as part of GO programs. Given the current recommendation that the DDT program should solely focus on eclipse photometry, other equally important transmission spectroscopy programs on Trappist-1f, Trappist-1g, and LHS1140b would not commence until Cycle 4 through standard GO programs.[2] Imposing a higher detection threshold (4-5σ) for this reconnaissance program – as was published for the MIRI observations of Trappist-1b and c – would significantly increase the total observing time, potentially ranging from 1300 to 2000 hours, especially when considering the likelihood of

[2] LHS1140b will not be observed in cycle 3 as part of the normal GO program.

extensive follow-up programs triggered by potential tantalizing detections on any of the targeted planets.

This exercise is intended to demonstrate that thoroughly assessing the prevalence of atmospheres in the most promising rocky temperate planets, with a high degree of confidence, will likely necessitate of order a few thousands of hours of observation, spanning a significant portion of JWST's operational lifetime and most likely extending beyond its mission Level 1 requirement of 5 years. Initiating such an extensive habitability program at the earliest opportunity is paramount. The upcoming 500-hour DDT program presents a unique chance to kickstart an in-depth habitability reconnaissance of the Golden-J sample, potentially marking a pivotal moment for JWST in addressing one of its most important scientific questions.

The success of exoplanet science inevitably requires a substantial portion of JWST's observing time to be dedicated to observing relatively bright stars. In this regard, it is crucial for the JWST Project to promptly implement specialized fast readout modes to increase the dynamic range of both

Table 1. JWST Habitability Reconnaissance Program of the Golden-J Planets

15 µm Eclipse photometry (MIRI)					
Planet	T_{max} (K)[a]	F_p/F_* (ppm)	N_{visit}[b]	T_{exp} (hrs)[c]	Cycle
Trappist-1d	366	203	7	24	3
Trappist-1e	319	183	8	30	3
Trappist-1f	279	148	11	45	3
Trappist-1g	252	120	15	66	3
LHS1140b	288	77	4	30	3
			Sub-total	**195**	
Transmission spectroscopy					
Planet	**Instrument mode**		N_{visit}	T_{exp} (hrs)	**Cycle**
Trappist-1e[d]	NIRSpec prism		15	128	3,4
Trappist-1f[e]	NIRSpec prism		15	140	4,5
Trappist-1g[e]	NIRSpec prism		15	145	4,5
LHS1140b[f]	NIRISS SOSS+NIRSpec G395		12	77	4,5,6
			Sub-total	**490**	
			Grand total	**685**	

[a] Maximum temperature assuming no heat redistribution to the night side with A_B=0.
[b] Number of visits needed to achieve a 3σ detection of the eclipse depth for the airless case.
[c] Total exposure time assuming the same experimental design of Zieba et al (2023) equivalent to 1 hr + 3xt_{14} per visit where t_{14} is the transit duration.
[d] Already programmed for Cycle 3 and 4 (PID6456).
[e] Assumes the same double-transit experimental design for Trappist-1e.
[f] Assumes the CO_2-dominated spectrum of the water world scenario of Cadieux et al (2024). Details of the experimental design to be reviewed/optimized after 4 visits when stellar activity (TLS) is better characterized.

the NIRSpec prism and NIRISS SOSS modes. Implementing these new readout modes would significantly enhance the Observatory's efficiency to enable more and better exoplanet science.

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SESSION 2: HIGH-REDSHIFT UNIVERSE

Star-Formation in Cosmic-Dawn Galaxies

Sandro Tacchella
Kavli Institute for Cosmology, University of Cambridge, UK
Cavendish Laboratory, University of Cambridge, UK

Abstract

In the first two years of operation JWST has delivered key new insights into the formation and evolution of galaxies in the early Universe. By combining imaging with spectroscopy, we discovered and characterised the first generation of galaxies, probing the Universe at an age of 300 million years. While the current JWST observations confirm the overall cosmological framework and the paradigm of galaxy formation, there are also surprises, including large abundances of bright galaxies and accreting black holes in the early Universe. These observations, together with detailed measurements of the stellar populations and morphological structure, will help us to develop in the coming years a more refined understanding of the baryonic physics (including star formation and feedback processes) that leads to the formation of mature systems at later epochs, including our own Milky Way.

1. Cosmological structure formation

Cosmology builds on the fundamental assumption of the cosmological principle: on a large scale, the Universe is both homogeneous and isotropic. Together with general relativity as the theory for gravity, we can then relate the evolution of the Universe to its constituents and energy density. The standard cosmological model ("Hot Big Bang model") makes accurate and testable hypotheses in several areas, including (i) the expansion of the Universe (Hubble-Lemaître law); (ii) the origin of the cosmic microwave background (CMB) radiation; (iii) the nucleosynthesis of the light elements (including deuterium, helium, and lithium); and (iv) the formation of galaxies and large-scale structure. The standard cosmological model has three major components, including a cosmological constant denoted by Λ associated with dark energy, cold dark matter (CDM), and ordinary, baryonic matter. It is therefore referred to as the ΛCDM model.

While the nature of dark matter and dark energy is still a mystery, the ΛCDM model together with detailed measurements of the CMB radiation build the foundation for the initial conditions for galaxy formation and evolution. The CMB was emitted 380,000 years after the Big Bang (corresponding to a redshift of z≈1,100), containing an imprint of the density fluctuations in dark matter and the baryon-photon plasma. The baryonic fluctuations, suffering from acoustic oscillations and diffusion damping, were overall weaker than the dark matter fluctuations. These dark matter fluctuations grew with cosmic time throughout the dark ages (z≈1,100 ➜ 30), forming virialized dark matter haloes. Baryons, in particular hydrogen gas, fell into these dark matter haloes and were able to cool, thereby forming molecular hydrogen and the first stars.

The first stars – free of any metals (Pop III) – form around 100 million years after the Big Bang (redshift of z≈30), thereby ending the so-called cosmic dark ages. The high-energy photons emitted by these stars penetrate the atomic medium around them, generating Lyα photons that couple the 21-cm spin and kinetic temperatures. These Lyα spheres are visible in the 21-cm against the CMB. Therefore, global 21-cm experiments such as REACH (de Lera Acedo et al. 2022) or SARAS (Singh et al. 2018; in addition to future gravitational wave signals) are the most promising avenues to indirectly detect the formation of the first stars. While key questions regarding the timing and physics of the first stars remain open (Klessen & Glover 2023), massive Pop III stars of several 10^5 $M_\odot$ could form and give rise to the super-massive black holes observed in high-redshift quasars. Furthermore, it is clear that the feedback from massive Pop III stars plays a central role in regulating subsequent star formation (metal-enrich Pop II stars).

2. A simple model for star formation in dark matter haloes

The formation of galaxies is expected to be in full swing 180-270 million years after the Big Bang (z≈15-20). While the paradigm of galaxy formation is well established (formation of virialized dark matter haloes ➜ cooling of gas ➜ feedback to prevent over-cooling), star formation and the associated feedback processes from stars (such as radiation pressure, winds and supernovae explosions) and from super-massive black holes is not well understood. We can build a simple model of early galaxies (Tacchella et al. 2013, 2018, Mason et al. 2015) by assuming that the star-formation rate (SFR) of a galaxy is directly proportional to the supply of gas. Specifically, we assume the SFR of a dark matter halo of mass M_h at redshift z is

$$SFR(M_h, z) = \varepsilon(M_h)\, f_b \frac{dM_h}{dt} \ ,$$

where $\varepsilon(M_h)$ is the star-formation efficiency (SFE), f_b is the cosmic baryon fraction (f_b =0.17), and M_h/dt is the dark matter accretion rate, which depends on M_h and z. Here, we have assumed that the gas accretion rate is directly proportional to the dark matter accretion rate. Importantly, we further assume that the SFE $\varepsilon(M_h)$ only depends on halo mass, i.e., there is no dependency on cosmic time. Hence, this simple model can be referred to as the "constant-SFE" model.

The key physics about star formation in this model is encapsulated in the SFE $\varepsilon(M_h)$. While numerical simulations and semi-analytical models try to motivate $\varepsilon(M_h)$ (or a similar function) with a description for star formation and a range of feedback processes, empirical models such as this constant-SFE model calibrate $\varepsilon(M_h)$ via observations. Using the ultra-violet (UV) luminosity function at z=4, this model is then able to reproduce a wide range of observations across cosmic time, including the cosmic SFR density (left panel of Fig. 1), galaxy stellar mass function, star-forming main sequence, and mass-metallicity relation (Tacchella et al. 2018).

The strong increase in the cosmic SFR density can be explained by studying the evolution of the halo mass function. The right panel of Fig. 1 shows that the halo mass function evolves rapidly from z=10 to z=4, thereby increasing the number density of galaxies that are able to host efficient

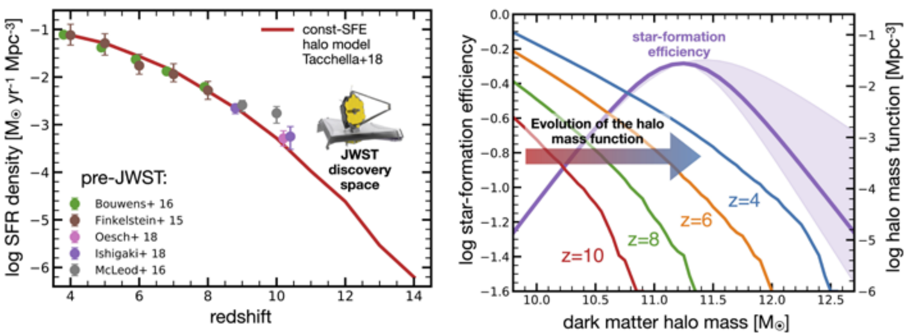

Figure 1. *Left:* the cosmic SFR density as a function of redshift, where redshift z=4 and z=14 correspond to 1.5 and 0.3 billion years after the Big Bang, respectively. The data points indicate the observational constraints pre-JWST, highlighting the large discovery space (z>10) of JWST. The solid red line shows the simple halo model, where the star-formation efficiency (SFE) is assumed to be constant (Tacchella et al. 2013, 2018). We find that such a model predicts a rapid increase of the cosmic SFR density from z=14 to z=4 (by 5 orders of magnitude over ≈1 Gyr in cosmic time). *Right:* the SFE and halo mass function as a function of dark matter halo mass. The reason for the strong increase of the cosmic SFR density is the rapid evolution of the halo mass function, where the number of haloes that host galaxies with a high SFE increases rapidly from z=10 and z=4.

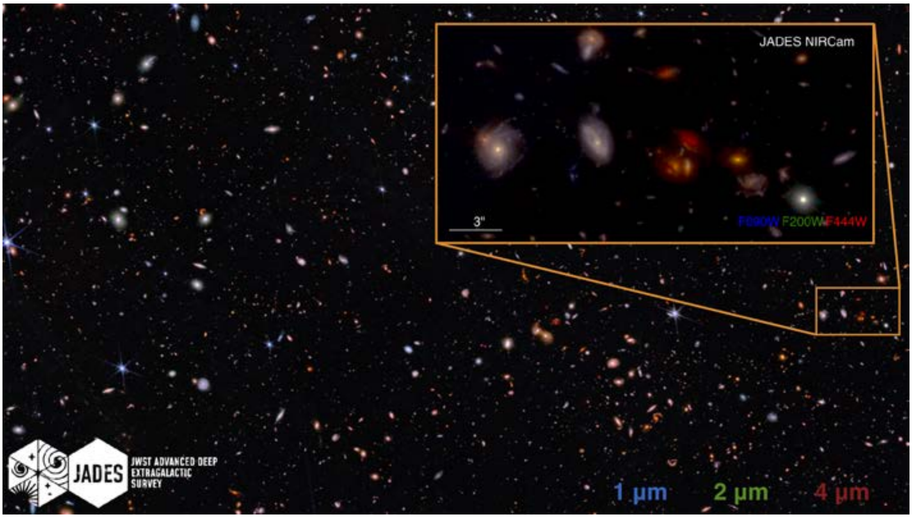

Figure 2. JADES NIRCam GOODS-S imaging (Eisenstein et al. 2023a), combining F090W, F200W, and F444W filters. This image shows the great diversity of galaxies revealed in JWST images, with a wide variety of colours and morphologies.

star formation (Tacchella et al. 2013). Furthermore, the halo mass accretion rates (at fixed halo mass) also increase with cosmic time. This highlights that the primary driver of galaxy evolution across cosmic time (and in particular at z=4-10) is the build-up of dark matter haloes, without the need to invoke a redshift-dependent efficiency in converting gas into stars.

Despite this strong link between dark matter haloes and galaxy formation, it is difficult to use observations of the high-redshift galaxy population to constrain different dark matter models. Specifically, within the framework of this model, changes in the dark matter model and their imprint onto the galaxy population can be mimicked by a change of the SFE (Khimey et al. 2021): for example, moving from a cold dark matter model to a warm dark model (which delays the formation of haloes) can be compensated by increasing the SFE in low-mass haloes. Basically, the dark matter model is degenerate with the baryonic physics. Therefore, understanding and constraining the baryonic physics of galaxy formation is crucial to also shed more light onto the nature of dark matter.

3. JWST: a new era of discoveries

Now, with the advent of JWST, we are able for the first time to directly detect the first generation of galaxies at z≈10-20 and characterise their descendants in detail during the Epoch of Reionization (EoR; z≈6-9). JWST, with its four science instruments (NIRCam, NIRSpec, MIRI and NIRISS), can take images and spectroscopy in the near-infrared (NIR) at wavelengths 0.6-28 μm. For performing detailed measurements of the stellar populations and morphology of early galaxies, NIRCam and NIRSpec – working at 0.6-5 μm – are the key instruments, probing the rest-frame UV and optical (out to z≈9) properties of galaxies. While NIRCam provides the deepest image ever taken of the cosmos and allows us to discover the faintest structures, NIRSpec's multi-object spectrograph provides us with the first NIR high-resolution (R>1000) spectra from space.

4. Finding and characterising the first galaxies

One of the key science goals of JWST is the finding and characterisation of the first generation of galaxies. While the Hubble and Spitzer Space Telescopes provided us with samples of z>9 galaxy candidates, the photometric redshifts were uncertain, and it was challenging to confirm their distances with spectroscopy. In the first two years of JWST operation, several extragalactic surveys have been developed and conducted with the aim to find new high-redshift galaxy candidates (Robertson 2022), including the *JWST Advanced Deep Extragalactic Survey* (JADES; PIs Rieke and Lützgen-

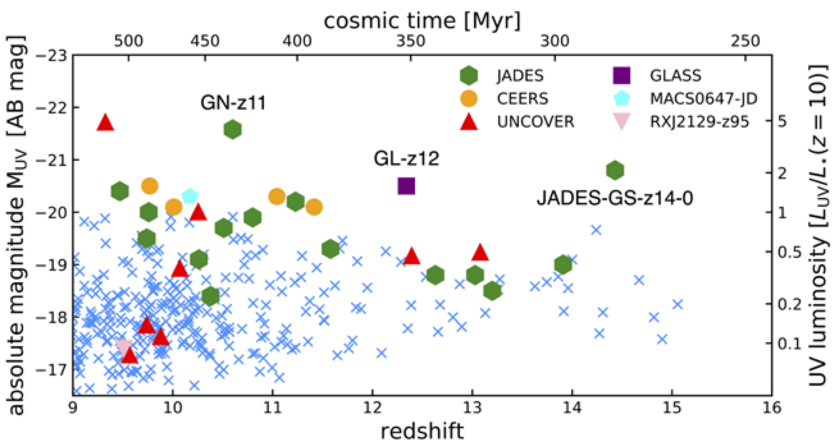

Figure 3. Absolute UV magnitude versus redshift. The blue crosses mark the high-redshift galaxy candidates with photometric redshifts from the JADES survey (Hainline et al. 2023), while the other symbols show spectroscopically confirmed galaxies from a range of surveys (Curtis-Lake et al. 2023, Arrabal Haro et al. 2023, Fujimoto et al. 2023, Hsiao et al. 2023, Williams et al. 2023, Carniani et al. in prep.).

dorf; Eisenstein et al. 2023a), the *JADES Origins Field* (JOF; PIs Eisenstein & Maiolino; Eisenstein et al. 2023b), the *JWST Extragalactic Medium-band Survey* (JEMS; PIs Williams, Tacchella & Maseda; Williams et al. 2023), the *Prime Extragalactic Areas for Reionization Science* (PEARLS; PIs Windhorst & Hammel; Windhorst et al. 2023), the *Grism Lens Amplified Survey from Space* (GLASS; PI Treu; Treu et al. 2023), the *Cosmic Evolution Early Release Science Survey* (CEERS; PI Finkelstein; Bagley et al. 2023), the *Next Generation Deep Extragalactic Exploratory Public Survey* (NGDEEP; PIs Finkelstein, Papovich & Pirzkal; Leung et al. 2023), COSMOS-Web (PIs Kartaltepe & Casey; Casey et al. 2023), and the *Ultradeep NIRSpec and NIRCam ObserVations before the Epoch of Reionization* (UNCOVER; PIs Bezanson & Labbé; Bezanson et al. 2022).

Within the first six months of JWST operation, the JADES team demonstrated the power and success of JWST (Fig. 3). Four galaxies at z>10 have been spectroscopically confirmed (Curtis-Lake et al. 2023), out of which two (with redshifts z_{spec}=13.2 and 12.63) have been newly discovered with NIRCam imaging (Robertson et al. 2023), while the other two (z_{spec}=11.58 and 10.38) have been high-redshift candidates based on Hubble Space Telescope observations (Ellis et al. 2013, Bouwens et al. 2022). These distant galaxies probe the Universe at an age of ≈300-400 million years after the Big Bang. This means that the light has travelled to us for nearly 13.5 billion years. Using stellar population modelling, we find the galaxies typically contain 100 million solar masses in stars, in stellar populations that are less than 100 million years old. The moderate SFRs and compact sizes of the order of 100 pc suggest elevated SFR densities ($\Sigma_{SFR} \approx 100\ M_{\odot}/yr/kpc^2$; Robertson et al. 2023).

With the aforementioned surveys, several groups (Naidu et al. 2022, Castellano et al. 2022, Finkelstein et al. 2023, Adams et al. 2023, Atek et al. 2023, Donnan et al. 2023, Hainline et al. 2023, Harikane et al. 2023) have unveiled a significant number of galaxies beyond redshift z≈10, but only a few have been spectroscopically confirmed (Curtis-Lake et al. 2023, Arrabal Haro et al. 2023, D'Eugenio et al. 2023, Fujimoto et al. 2023, Wang et al. 2023, Castellano et al. 2023). Still, the conservative lower limits on the bright end of UV luminosity function and the integrated UV luminosity density at z=9-12 suggest a milder redshift evolution than expected by many theoretical models (Harikane et al. 2023). Basically, there is very little evolution in the bright-end of the UV luminosity function from z=9 to z=12, challenging the aforementioned constant-SFE model and more complex numerical simulations.

Pushing the frontier beyond z≈13 is extremely challenging with the wide NIRCam filters, which have been mostly adopted in the Cycle 1 observations. This is because the broad-band spectral energy distributions (SEDs) of z≈15 galaxies cannot be differentiated from lower-redshift (in particular z≈5) galaxies (Naidu et al. 2022b, Zavala et al. 2023). This challenge is addressed by the JOF survey (Eisenstein et al. 2023b), which uses medium bands, including NIRCam F162M, to isolate the Lyα break at z≈12 and simultaneously control for contamination by lower-redshift line-emitting galaxies. JOF, building on-top of JADES, is the deepest imaging field observed with JWST, providing JWST images with 14 filters spanning 0.8-5 µm, including 7 medium-band filters, and reaching total exposure times of up to 46 hours per filter. By constructing the deepest imaging ever taken at these wavelengths (reaching as deep as ≈31.4 AB mag), we identify a sample of eight galaxy candidates at redshifts z=11.5-15 (Robertson et al. 2023b). These objects show compact half-light radii of $R_{1/2} \approx$ 50-200 pc, stellar masses of 10^7-10^8 $M_\odot$, and SFR of 0.1-1 $M_\odot$/yr. By carefully assessing the completeness, we constrain the UV luminosity function at z=12, which is consistent with prior results. Furthermore, we find that the UV luminosity density declines by a factor of ≈2.5 from z=12 to z=14, confirming the rather slow decline with redshift. The NIRSpec follow-up of JOF has been highly successful (Carniani et al. in prep.), with confirming two luminous galaxies at z_{spec} = 14.43 and z_{spec} = 13.91, being currently the highest-redshift systems known to us.

5. Understanding early UV-bright galaxies

In summary, the early studies mentioned above indicate that there is a higher abundance of bright galaxies at high redshifts than expected from theoretical models pre-JWST, including the constant-SFE model (Tacchella et al. 2013, 2018, Mason et al. 2015). Importantly, several of the brightest galaxies at z>10 have been spectroscopically confirmed (Fig. 3), including GN-z11 (Bunker et al. 2023, Tacchella et al. 2023) at z_{spec} = 10.60 with M_{UV} = -21.6, GHZ2/GLASS-z12 (Castellano et al. 2024, Zavala et al. 2024) at z_{spec} = 12.34 with M_{UV} = -20.5, and JADES-GS-z14-0 at z_{spec} = 14.43 with M_{UV} = -20.8. So why is there an over-abundance of UV-bright galaxies at z>10? Several studies have considered physics beyond the standard ΛCDM model, including a modified primordial power spectrum (Padmanabhan et al. 2023) or alternative dark matter models (Bird et al. 2023, Dayal et al. 2024). However, there is also a wide range of physical interpretations related to baryonic physics to explain the tension.

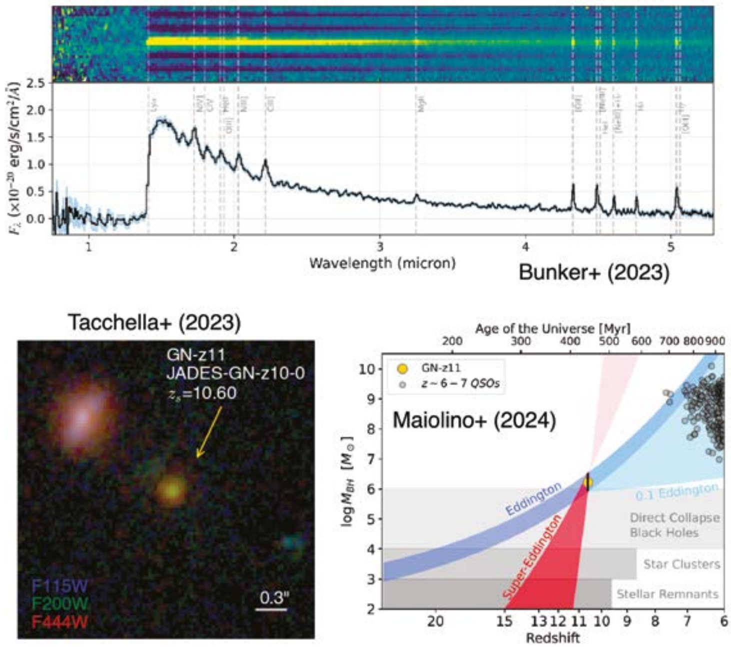

Figure 4. Observations of GN-z11, currently the highest-redshift known AGN (z_{spec} = 10.60). GN-z11 is very bright for its redshift (see Fig. 3). *Top:* prism spectrum of GN-z11, showing many emission lines and a clear Lyα drop (Bunker et al. 2023b). *Bottom left:* NIRCam imaging data of GN-z11 (Tacchella et al. 2023), showing that GN-z11 is compact and can be decomposed into a point source and extended component of size ≈200 pc. *Bottom right:* GN-z11 hosts a black hole mass of about a million solar masses, accreting at about 5 times the Eddington rate (Maiolino et al. 2023). GN-z11 lies above the local stellar-to-black hole relation, which is consistent with a scenario of either heavy seeds and/or super-Eddington accretion.

For example, we can extend the constant-SFE model by assuming that the SFE increases towards earlier cosmic times. There are models that predict a high SFE (feedback-free starbursts; Dekel et al. 2023, Li et al. 2023) at high gas densities and low metallicities – conditions that are more prevalent at higher redshifts. Connected, it is expected that the variability (or burstiness) of star-formation increases at high redshifts (Tacchella et al. 2020), because the characteristic galactic dynamical timescales become too short for supernova feedback to effectively respond to gravitational collapse (Faucher-Giguere 2018). Since the halo mass function is so steep, this star-formation variability scatters galaxies in low-mass haloes up to the bright-end of the luminosity function, thereby increasing the abundance of bright galaxies (Mason et al. 2023, Sun et al. 2023, Shen et al. 2023). Alternatively, one could modify the conversion between the SFR and the UV luminosity by (i) a redshift-dependent dust evolution with basically zero dust attenuation at high redshift (Ferrara et al. 2023, Mirocha et al. 2023); (ii) a more top-heavy stellar initial mass function (Inayoshi et al. 2022, Yung et al. 24); or (iii) contribution to the UV from non-stellar sources, including black holes (Tacchella et al. 2023).

The current observations cannot rule out any of those scenarios. On the contrary, we actually find support for all of them, so it is likely that all of these processes are at work. Galaxies are indeed very compact and metal-poor at $z \approx 10$, consistent with the feedback-free starburst picture. They seem to contain also very little dust. Furthermore, there are clear indications from stellar populations analyses that high-redshift galaxies have bursty star formation (Endsley et al. 2023, Looser et al. 2023b, Simmonds et al. 2024, Tacchella et al. 2023). While most of those systems are observed during a burst (observational bias), low-mass quiescent galaxies have also been discovered (Looser et al. 2023a,b), which are probably only temporally quiescent ("mini-quenching"; Dome et al. 2024).

Most interestingly, we can also find clear indication for black hole growth. A prime example of this is the galaxy GN-z11, which has been a high-redshift galaxy candidate with a grism redshift of z_{grism} = 11.09 from the Hubble Space Telescope (Oesch et al. 2016) for many years (Bouwens et al. 2010). The intriguing aspect of GN-z11 is that it is extremely bright (M_{UV} = -21.6 AB mag) for its redshift ($z>10$; see Fig. 4). The JADES team has confirmed the redshift of GN-z11 to be z_{spec} =10.60 using NIRSpec (Bunker et al. 2023). The NIRCam imaging (Tacchella et al. 2023) of GN-z11 shows that this galaxy contains a nuclear point source, which outshines the underlying rest-frame UV emission of the galaxy by factor of 3. The underlying galaxy has a size of ≈200 pc and contains a stellar mass of $10^{8.9}$ $M_{\odot}$. We interpret the point source to be an accreting black hole (Maiolino et al. 2023), because the NIRSpec spectrum is consistent with the one of a Broad Line Region of Active Galactic Nuclei (AGN). Assuming local virial scaling relations, we derive a black hole mass of about a million solar masses, accreting at about 5 times the Eddington rate. Similar AGNs have been found in the EoR (Maiolino et al. 2023b, Greene et al. 2023, Matthee et al. 2023, Harikane et al. 2023b, Juodzbalis et al. 2024), typically lying a factor of 10-100 times above the local stellar-to-black hole mass relation, which is consistent with a scenario of either heavy seeds and/or super-Eddington accretion.

6. Future characterisation of early galaxies

JWST works! After nearly two years of operation, we have over 14 spectroscopically confirmed galaxies at z_{spec} >10 and over ≈400 z>10 galaxy candidates. These galaxies contain roughly a 100 million solar masses in stars and are actively forming stars, doubling their stellar mass every few tens of millions of years. The compact sizes (≈100 pc) imply high SFR surface densities. In the future, it will be important to connect this first generation of galaxies with their descendants in the EoR, for which we can access the powerful rest-frame optical diagnostics. This will allow us to probe the stellar population and morphological structure in detail. For example, spatially resolved studies (Baker et al. 2023, Baggen et al. 2023) indicate that EoR galaxies have a compact core and are growing inside-out. Overall, it seems that the central regions of galaxies assemble very early (within the first billion years after the Big Bang), given the compact sizes of galaxies at z>10 (Robertson et al. 2023a, Robertson et al. 2023b) and the overly massive black holes during EoR (Maiolino et al. 2023a,b, Harikane et al. 2023).

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Emergence of Early Large-Scale Structures of Galaxies Revealed by JWST

Takahiro Morishita
IPAC, California Institute of Technology

Abstract

Recent observations with JWST have revealed that some galaxies have evolved already in the first billion years, exhibiting similar properties as have been observed at later times. We present the discovery and spectroscopic confirmation of a galaxy overdensity at z=7.88, consisting of 7 galaxies within a very close proximity. Some of those galaxies exhibit an enhancement of dust attenuation and more evolved stellar populations compared to the field counterparts at similar redshifts, indicating the evolution in that specific region may proceed even further. We introduce our ongoing JWST NIRCam pure-parallel imaging survey, BEACON, that envisions to sample many random sightlines of the universe and to construct a large galaxy sample of z~2 to z>10. Identification of luminous candidates, with spectroscopic followup, will enable statistical studies of early galaxy populations.

Introduction

Hierarchical structure formation is one of the fundamental features of our standard cosmological model. The first overdensities to collapse and form stars and galaxies play a particularly important role in the evolution of the universe and cosmic reionization (Tegmark et al. 1997). Identifying and studying the sources associated with these first overdensities thus provides critical insights into the evolution of galaxies, the intergalactic medium, and the underlying dark matter scaffolding (e.g., Mo & White 1996).

The clustering of sources around a luminous galaxy or quasar includes an expected excess of fainter companions, under a broad assumption that galaxy luminosity is correlated with the mass of the dark-matter host halo. Such early overdensities are thought to be the seeds of today's galaxy clusters, and sites where galaxy formation and the evolution of the surrounding gas is progressing more rapidly compared to the mean of the universe. As such, the identification of galaxy over-densities at high redshift (z>6) has been of particular interest in the literature (e.g., Trenti et al. 2012, Castellano et al. 2016,2018,2022, Harikane et al. 2019, Tilvi et al. 2020, Hu et al. 2021, Endsley & Stark 2022, Larson et al. 2022). Furthermore, galaxy overdensities serve as ideal laboratories for studying the ionization of neutral hydrogen around galaxy systems; the presence of a large ionizing bubble may boost the fraction of escaping Lyman-alpha photons, which otherwise are scattered and absorbed by surrounding neutral hydrogen (Miralda-Escude 1998, Dijkstra 2014, Mason & Gronke 2020; see also Trapp et al. 2022).

JWST has opened up a path for us to directly observe those building blocks in the first billion years. With the unprecedented sensitivity in near-infrared wavelengths, it enables us to see the rest-frame optical features of early galaxies, i.e. those seen and studied in the SDSS for galaxies today. Early studies have been watershed with a number of discoveries, including luminous galaxies, record-breaking redshift, and evolved stellar populations. The equipped sensitive spectroscopy is capable of determining the detailed chemical composition and enrichment history in earlier times.

Here, we first present our discovery of a galaxy overdensity at z=7.88, merely ~650 million years after the big bang, consisting of 7 member galaxies in a small sky area. We then present our effort of investigating oxygen abundances in galaxies and their redshift evolution from our Cycle 1 GTO program. Lastly, we present our latest observing program, BEACON, that exploits the pure-parallel capability of JWST to identify early galaxies from many sightlines.

JWST's confirmation of an early galaxy overdensity

As part of the JWST ERS program GLASS-ERS (PID1324), we observed the sightline of a cluster of galaxies, Abell 2744. Our observations were gained from the strong lensing magnification, amplified by this foreground cluster, making faint galaxy light detectable at high significance. In our spectroscopic observations, we assigned the spectroscopic slits on 7, previously known, galaxy candidates at z~8. These galaxies were previously identified in near-infrared observations by the Hubble Space Telescope but remained as "photometric" candidates i.e. sources that have no spectroscopic information.

Surprisingly, our spectroscopic observations not only confirmed the redshift of all 7 galaxies, but found that they are at the same redshift, z=7.88 (Morishita et al. 2023). The spatial distribution of the 7 galaxies is also tight, within an area of ~300 kpc in radius (Figure 1). Hereafter, we refer to this overdensity system as A2744-z7p9OD.

Their very tight proximity indicates that these galaxies formed and evolved in the excess area of matter density in the early universe. Such an overdensity is expected to grow to one of the most massive systems in the universe today. By looking into simulations, we identify a similar overdensity in the EAGLE simulation — the simulation predicts that an overdensity system like A2744-z7p9OD would have grown to a massive cluster of galaxies, with the total halo mass of $\sim 10^{15}$ Msun, comparable to the Coma cluster.

However, the prediction made from our comparison to simulations may suffer from a few uncertainties. One of such is the uncertainty in the halo mass estimate at the observed redshift. While an overdensity of 7 galaxies in such a small area could be a signature of a large-scale structure, it may well be part of a proto-group system; leading to a much smaller halo mass. To

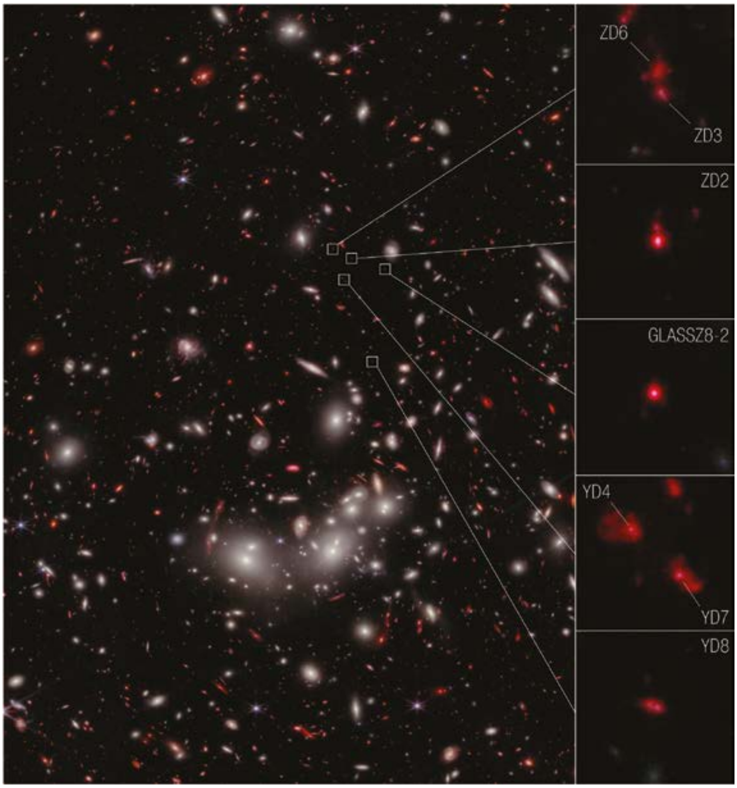

Figure 1. The seven galaxies highlighted in this James Webb Space Telescope image have been confirmed to be at a distance that astronomers refer to as redshift 7.9, which correlates to 650 million years after the big bang. This makes them the earliest galaxies yet to be spectroscopically confirmed as part of a developing cluster.
Credits: NASA, ESA, CSA, T. Morishita (IPAC). Image processing: A. Pagan (STScI).

be definitive about the halo mass, and therefore the future evolution of the system, one solution is to characterize the system. This includes the search of other member galaxies to a larger extent (Morishita 2024, in prep.).

Besides the characterization of A2744-z7p9OD as part of a large-scale structure, the high-sensitivity imaging and spectra allow us to investigate the physical properties of the individual member galaxies. Remarkably, two pairs of the member galaxies (ZD3 & ZD6 and YD4 & YD7) show evidence of interaction in their morphologies, indicating potential enhancement of dust and ISM metallicity. Indeed, the spectra of these galaxies exhibit a red rest-frame UV slope, i.e. attenuation by dust (also see recent study by Hashimoto et al. 2023). While direct confirmation of such dust will require resolving sub-mm observations from, e.g., ALMA, this further characterizes this early overdensity as a place where galaxy evolution might be advanced, compared to field galaxies.

Toward better understanding of galaxy evolution in the early universe

We note that this finding is from a merely single pointing of JWST. Similarly, other remarkable findings of early luminous galaxies reported from the Cycle1 observations are from a very small portion of sky. The universe is characterized by fluctuation of matter density, which causes biases in pencil beam observations, known as *cosmic variance*. To mitigate such biases, we will have to sample the universe for a larger area and correct our statistics built upon a limited number of observations. To better understand the census of galaxies, we have initiated a large imaging program in Cycle2, BEACON. The BEACON project takes advantage of the pure-parallel opportunities available by the observatory, where a secondary instrument can be utilized while the primary instrument is observing their target. Since our goal is to construct an unbiased sample of early galaxies, the pure-parallel mode is ideal.

We note that there exist previous efforts of such using HST's pure-parallel mode. However, it is worth highlighting that HST has wavelength coverage only up to 1.6μm. Without sufficient red sensitivity, the contamination fraction in the selected high-z candidates was known to be large. JWST's NIRCam pure-parallel imaging, on the other hand, affords much higher purity and robust characterizations of the candidates' properties (see below).

Similar to existing extragalactic observations, our observations are configured with multi-band filters of the NIRCam instrument, with 4-8 filters depending on the availability. Those filters span a wide range of wavelength, 0.8-5.0 micron, allowing us not only to identify high-z galaxies but also lower redshift galaxies and enhance legacy values. With the allocated ~ 600 hrs, we will be able to explore ~0.4deg^2 of sky, or ~200 pointings. Figure 2 shows the predicted numbers of high-z galaxy candidates from our program.

Figure 3 shows the mosaic image of one of the fields observed recently. Despite the exposure time in this field being relatively short (~1.2 ksec each), the depth is considerably good (27-28.2mag, 5 sigma). We show an example galaxy identified in one of the initial fields (Fig. 4).

Summary

In this paper, we reported the discovery of an early galaxy overdensity, A2744-z7p9OD, the physical properties of the member galaxies enabled by JWST, and future prospects for improving our further understanding of the universe. The BEACON program is such an ideal path for us to robustly investigate the census of early luminous galaxies and their clustering properties, which could have a critical impact on a wide range of research.

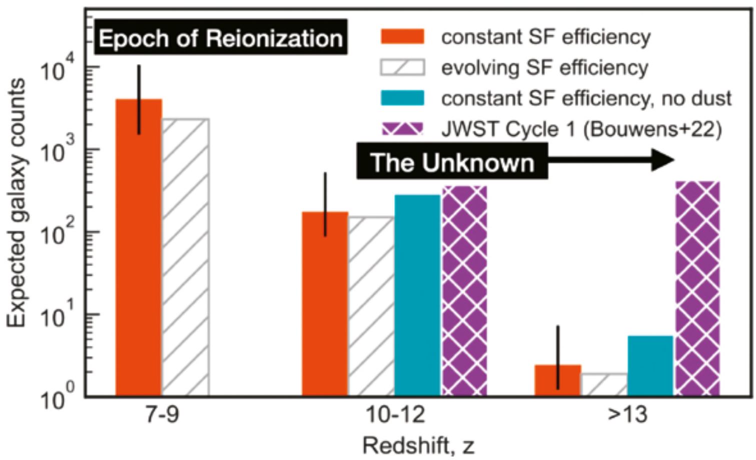

Figure 2. Expected numbers of galaxy candidates from the BEACON program (Morishita, in prep.). Predictions from different models (from Mason et al. 2023) and extrapolation from Bouwens et al. (2022) are shown.

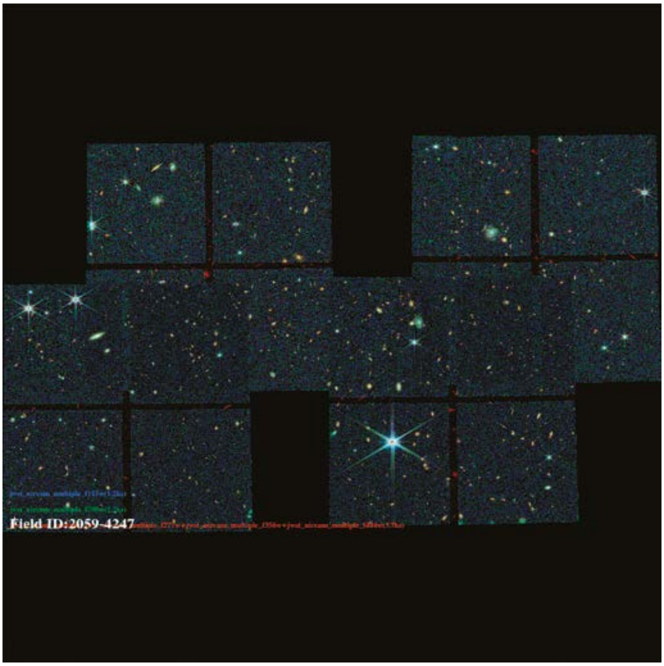

Figure 3. RGB color image of the BEACON_2059-4247 field (Morishita, in prep.). Note that this field has two separate visits, and the final imaging coverage is ~1.5x NIRCam footprint size.

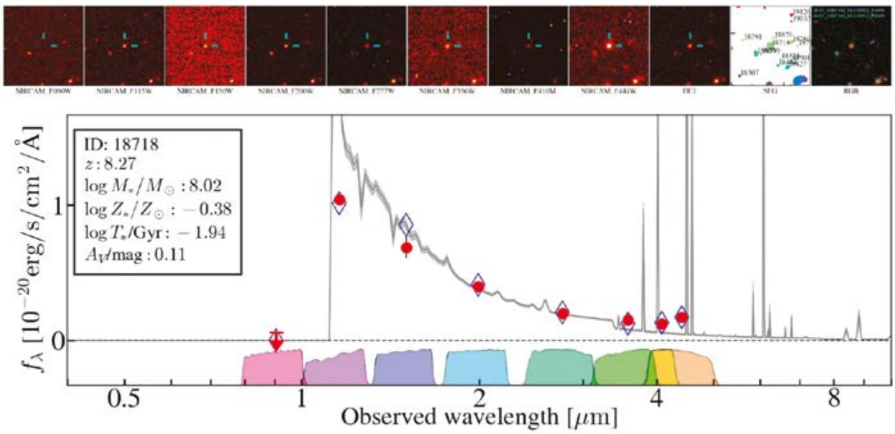

Figure 4. An example high-z galaxy candidate (z~8.3), identified in a recent BEACON field. (Top) Stamp images of the candidate in NIRCam filters. (Bottom) The result of our SED fitting analysis on the candidate (Morishita, in prep.).

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The Physics of First Galaxies: Fresh Results from JWST

Adriano Fontana

INAF, Osservatorio Astronomico di Roma

Abstract

A brief summary of JWST observations of the earliest galaxies is presented, in particular the evolution of the luminosity function at high redshift up to z=11 as compared to a variety of models. Surprising results on elemental abundances (e.g., high N/O) and ionization parameters are also found.

1. Introduction

The search for and characterization of the very first galaxies has been one of the main drivers for the development of the James Webb Space Telescope (JWST). Before I summarize the status of this field – that is evolving literally every day – and present few fresh results, it is wort re-assessing why this search is important.

Undeniably, part of its fascination arises from the exploratory nature of this search. By detecting galaxies at higher and higher redshift we are literally exploring backward in time, tracing the formation and evolution of galaxies as we approach the post-Big Bang epoch.

Beside this aspect, though, there are solid physical reasons to study these objects. The very early Universe, indeed, is remarkably different from the local Universe, as also were the physical processes at play. The early Universe is indeed much denser, leading to dynamical times that were certainly much smaller than nowadays. Average metallicity was certainly lower, and islands with (nearly) zero metal pollution were also present. Due to a largely neutral Inter Galactic Medium, the large-scale UV background was extremely suppressed, while the CMB radiation was 10x warmer than nowadays. There is a general expectation that newly born stars were distributed along a top-heavy IMF, which combined with a low metallicity, determined the conditions for a high ionization parameter and a hard UV ionizing flux within the interstellar medium of early galaxies. These conditions led to a formation of stars and first structures through paths that are not well understood and very poorly characterised and tested now.

In addition, the early Universe is an ideal lab to test the existence of ‘new physics’ – i.e. deviations from the current cosmological scenario. Among the various options, it is intriguing to speculate the existence of black holes of intermediate and large mass, originated not by the standard mechanism (supernovae) but formed through different channels either in the very first seconds after the Big Bang and/or in the direct collapse of massive gaseous halos at z~100-20. If these objects existed, they triggered additional star formation and acted as the seeds of Super Massive Black Holes in galaxies. An example of the effect of a population of primordial black holes is reported (Figure 1 left), from Cappelluti et al. 2022, where it is shown that they may significantly increase the average star-formation rate *only at z>10,* when their effect is still significant with respect to the accretion on normal dark matter (DM) haloes.

At high redshift it is also possible to identify deviations from the predictions of the standard cosmological model. For instance, the so-called Early Dark Energy (EDE) models predict more dark matter haloes at z~8 and beyond than the standard Λ-CDM model, resulting in *larger* numbers of galaxies at the same redshift. An example is shown in Figure 1, right, from Liu et al. 2024, where the distribution of DM haloes is shown at different redshifts in the standard and in the EDE model – the latter being significantly higher at z>7. Conversely, Warm Dark Matter models predict a significant deficit

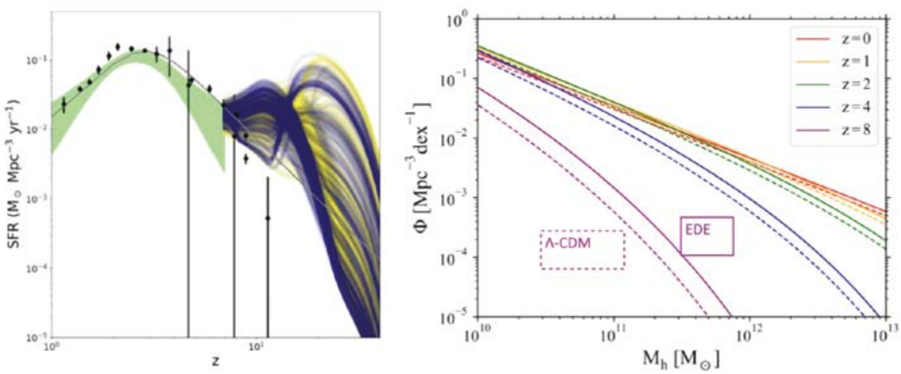

Figure 1. Left: Evolution of the Cosmic Star Formation Density as a function of redshift, from Cappelluti et al. 2022. Dots and green area represent the observed data with relative uncertainty. Blue and yellow curve represent models with different types of primordial black holes. Right: Halo mass functions for the standard cosmological model Λ-CDM and for Extended Dark Energy models (EDE), at different redshifts, from Liu et al. 2024.

of small mass haloes, resulting in a *lower* number of small-mass galaxies (e.g. Menci et al. 2022). These effects are noticeable, and therefore can be directly tested directly by observation, only at high redshift.

2. The JWST surveys: context and early results

2.1. Photometric surveys

Previous surveys executed with HST and groundbased telescopes have been able to gather extensive statistics of galaxies up to z~8, and sparser samples at galaxies up to z~10. For most of the galaxies beyond z~7, the available information was mostly limited to HST photometry covering the UV range of the spectrum, together with a few spectroscopic redshifts obtained on the rare Lyman α emitters, and detections at very low S/N up to 5.6μm obtained from the warm Spitzer mission. Overall, these data sets were certainly able to reveal the existence of these galaxies and establish their number evolution, showing a progressive decline of the Luminosity Function from z~4 to z~9, assuming that the photometric selection is reasonably complete and free from major contamination.

Based on extrapolations from these data, a steady decline of the number density beyond z~10 was expected, which is not surprising as we approach the Big Bang. While the statistics were reasonably well assessed, the physical characterization of these objects remained elusive. Reliable measures of stellar masses and star-formation rates were hampered by the lack of proper sampling of the rest-frame optical bands, and metallicity and ionization status were very uncertain or impossible to measure given the lack of spectroscopic follow-up.

This situation has been completely and immediately revolutionised by the advent of JWST. Thanks to its thousand-fold increase in sensitivity with respect to Spitzer, and spatial resolution 3x HST, it has been immediately possible to search for galaxies well beyond z~10 and characterize the entire sample at z>7 with large spectroscopic follow up.

In only 18 months, a spectacular data set has indeed been collected by a wealth of large deep surveys, which released images and spectra over at least 12 different public fields, each with a coverage of at least 7-8 bands NIRCAM data, some of which with MIRI counterparts, and hundredths of redshifts at z>7 (Roberts-Borsani et al. 2024). As of today, more than 210arcmin^2 have been observed in imaging at typical 5σ magnitude limits between 28 and 30.

These earliest results based on these data have not been short of surprises. As demonstrated by a number of different surveys, (e.g. Finkelstein et

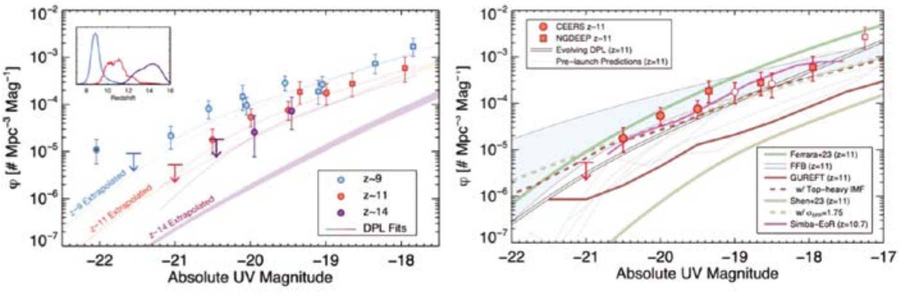

Figure 2. Left: Luminosity Function at z=9, 11 and 14 as observed by the JWST survey CEERS (dots) compared with the predicted LF computed by extrapolation of lower-z LF. Right: the z=11 LF compared with a suite of theoretical models. Both panels from Finkelstein et al. 2024.

al. 2022, Finkelstein et al. 2023, Harikane et al. 2023, Bouwens et al. 2023, Pérez González et al. 2023, McLeod et al. 2024), the density of galaxies (and in particular of the brightest ones) at z>9 is significantly larger than previously estimated by extrapolation of lower redshift observations as well as by theoretical models.

This is clearly shown in Figure 2, where the computation is reported of the Luminosity Function (LF) at z~9, 11 and 14, respectively (Finkelstein et al. 2024). These LFs are compared with the extrapolations based on the LF computed on HST survey (left) and the expectations of theoretical models (right). Both extrapolations of lower-z LF and theoretical pre-JWST models were predicting a significant evolution in the LF that is not observed. These results lead to a scenario where the formation of early galaxies is accelerated after the Big Bang, and to the expectation that the epoch of very first assembly is shifted to z>14-15.

Several scenarios have been proposed to explain these findings, ranging from a higher star-formation efficiency, the effect of stochastic star-formation histories, a lower dust extinction, an increased luminosity owing to the contribution of active galactic nuclei (AGNs) or of low-metallicity stars, or even nonstandard cosmological models (e.g. Ferrara et al. 2023, Mason et al. 2023, Melia et al. 2023, Padmanabhan et al. 2023, Trinca et al. 2024).

2.2. Spectroscopic surveys

Follow-up spectroscopy of the newly discovered high-redshift candidates is fundamental both to confirm the measured excess compared to theoretical predictions and to understand its physical origin. Early spectroscopic campaigns carried out with JWST NIRSpec have already provided support to the robustness of photometric selections and enabled the exploration of the physical conditions of galaxies at unprecedented redshifts (e.g. Curtis-Lake et al. 2023, Arrabal-Haro et al. 2023b, Boyett et al. 2023, Roberts-Borsani et al. 2023, Wang et al. 2023).

Early results have found a trend of decreasing metallicity and increasing excitation and ionization efficiency with increasing redshift (Trump et al. 2023, Tang et al. 2023, Nakajima et al. 2023, Curti et al. 2023), although most of the sources show physical conditions comparable to those of low-redshift analogues (Schaerer et al. 2022). A relatively small number of objects have shown features that are not usually found in low-redshift counterparts, and which may be due to physical properties unique to the first phases of star formation and galaxy assembly. A tantalizing example is the bright galaxy GNz11 at z=10.6 (first discovered by Oesch et al. 2016), whose NIRSpec spectrum shows evidence of a nitrogen abundance which is higher than expected for its metallicity (Bunker et al. 2023, Cameron et al. 2023). The discovery of other objects with a comparable nitrogen enrichment (Topping et al. 2024) has suggested that we may be witnessing the formation of globular-cluster progenitors (D'Antona et al. 2023, Watanabe et al. 2024). Instead, a high C/O ratio in galaxy GSz12 at z~12.5 has been interpreted as the imprint of ejecta from a previous generation of Population III stars (D'Eugenio et al. 2023).

A surprisingly large incidence of AGNs has also been suggested by NIRSpec follow-up observations of high-redshift objects (Larson et al. 2023, Maiolino et al. 2023b), with candidates reaching z~10 and beyond including GNz11 itself (Maiolino et al. 2023).

While these early results are tantalising, the emerging picture is far from being accessed. It is fundamental to push spectroscopic investigations to larger samples and higher redshifts to achieve a deeper understanding of the physical conditions of early star-forming regions and to assess the potential contribution of AGN accretion to the ultraviolet (UV) emission of distant galaxies.

3. GHZ2

The galaxy dubbed GHZ2 provided the first example of an unexpected population of high-redshift bright galaxies being discovered in the very first JWST data released on July 14, 2022. Two discovery papers appeared on arXiv the same day, and named the galaxy GHZ2 (Castellano et al. 2022b) and GLASS-z12 (Naidu et al. 2022) (we refer to it only as GHZ2 for conciseness). Initially discovered as a robust z~12.0-12.5 candidate, GHZ2 was

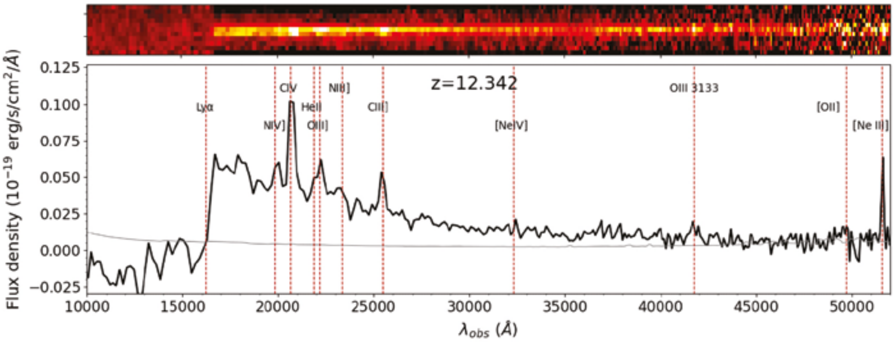

Figure 3. Observed 2D (top) and 1D (bottom) NIRSpec PRISM spectra of GHZ2. In the bottom panel the gray line shows the RMS noise, and red dashed lines highlight the wavelength of the UV features discussed in the present paper. From Castellano et al. 2024.

targeted with JWST NIRSpec multi-object spectroscopy through Program GO-3073 (PI M. Castellano), which is aimed at extensive follow-up observations of the z≥ 10 candidates selected in the GLASS-JWST region. A full discussion of the results is given in Castellano et al. 2024.

The NIRSpec spectrum of GHZ2 (Figure 3) shows a sharp Lyman break and list of very prominent emission features, with a full suite of high ionization lines (CIII, CIV etc) all consistent with z~12.3. From a weighted average of the measurements of the best resolved, high-SNR lines (NIV, CIV, CIII, and NeIII), we obtain an accurate redshift z=12.342 ±0.009, which we adopt hereafter.

The spectroscopic redshift is in remarkable agreement with the estimates obtained from NIRCam photometry, lending support to the accuracy of JWST-based photometric selections of high-redshift galaxies, at least as far as bright objects are concerned. Together with similar results obtained from NIRSpec follow-up spectroscopy (e.g. Arrabal-Haro et al. 2023b), this provides a crucial confirmation that the relatively large density of bright galaxies at z>9 is real and deserves detailed investigation in order to understand the earliest phases of galaxy and structure formation.

The spectrum of GHZ2 shows strong NIV, CIV, HeII, OIII, CIII, OII, and NeIII emission lines. The prominent CIV line puts GHZ2 in the category of strong CIV emitters (Izotov et al. 2024). In fact, GHZ2 is the most distant, brightest, and most massive member of this recently discovered class of objects. Assessing the main source of ionizing photons from

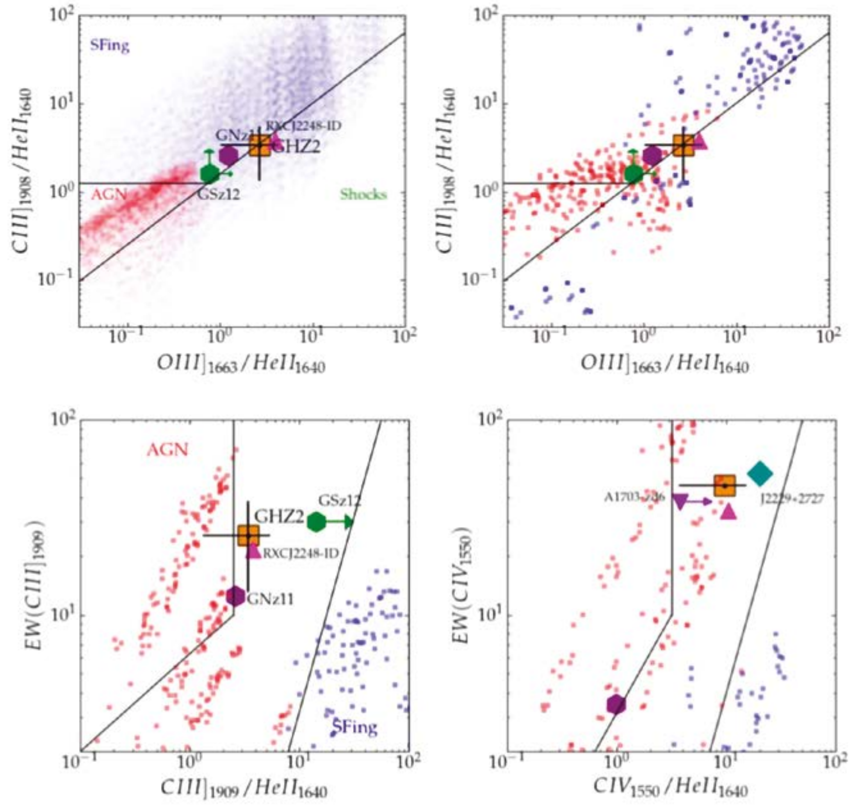

Figure 4. Upper panels: line ratio for GHZ2 (orange square) and other high z objects, compared to star-forming (blue dots) and AGN-driven models (red dots). Lower panels. EW of high exhitation line for GHZ2 (orange square) and other high z objects, compared to star-forming (blue dots) and AGN-driven models (red dots).

UV spectroscopy is known to be challenging, in particular for high-redshift objects likely dominated by young, low-metallicity stellar populations.

Unfortunately, the diagnostics more often used to discriminate between star-forming and AGN-dominated objects yield inconclusive results when applied to the observed lines in GHZ2.

This is shown in Figure 4, where we plot indexes obtained from line ratios (the two upper panels) and from line equivalent widths. The former are essentially inconclusive with GHZ2 being at the boundary between the two classes and eventually compatible with both.The latter seem to indicate the preference for AGN-driven values, but the AGN solution is at the same time disfavoured by the lack of high ionization lines with ionization potential > 60eV, such as NeIV and NeV. Clearly, high resolution spectra are needed to ascertain or not the presence of an AGN in this object.

Regardless of the nature of the dominant ionizing flux, we found that GHZ2 has a very low metallicity (below 10% solar) and a high ionization parameter (logU > -2). The N/O abundance is found to be 4-5 times the solar value, while the C/O is subsolar, similar to a number of recently discovered high-redshift objects (Topping et al. 2024). Given its small effective radius ($R_e \sim 100$pc), GHZ2 has a high Σ_{SFR} and a high stellar mass density similar to gravitationally bound stellar clusters; it is intriguing to speculate that GHZ2 is undergoing a phase of intense star formation in a dense configuration that may evolve into the nitrogen-enhanced stellar populations of globular clusters and other dense environments that are observed at low redshifts.

The origin of the copious amounts of ionizing photons in objects such as GHZ2 is currently unknown, but scenarios of dense star formation at very low metallicity including supermassive stars and high-mass X-ray binaries have the potential to also explain the atypical abundance patterns and the high-ionization spectra. A detailed investigation of the rare detection of the OIII-Bowen fluorescence line in GHZ2 can provide further insight into its sources of ionizing photons and their local environment. The high CIV/CIII ratio and the abundance patterns of GHZ2 are also suggestive of a high escape fraction of ionizing photons. A comprehensive search for sources in this evolutionary stage can reveal if they play a significant role in the reionization of the inter-galactic medium.

We caution, however, that in-depth studies will be needed to consolidate the proposed scenario. The N/O ratio needs to be assessed based on a robust detection of the NIII line in a higher-resolution spectrum considering the strong dependence of our measurement on the extrapolated continuum level at its position. Similarly, a high-resolution spectrum is needed to estimate the density and temperature of the ionized gas, to ascertain the presence of broad components due to AGNs or stellar winds, and to separate nebular and stellar contributions to the CIV emission.

The remarkable brightness of GHZ2 makes it accessible to a wealth of follow-up strategies, as showcased by the results described in this paper and by the MIRI detection discussed in a companion paper (Zavala et al., 2024). As such, GHZ2 has the potential to become a reference object for understanding galaxy formation at only 360~Myr after the Big Bang.

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The Earliest Galaxies – A MIRI Perspective

Steve Gillman
Cosmic Dawn Center and DTU-Space, Technical University of Denmark Lyngby, Denmark

Abstract

A brief overview of early results of JWST-MIRI deep imaging and spectroscopy observations of very high redshift galaxies taken as part of the Guaranteed Time program is presented.

1. Introduction

Understanding how galaxies form and evolve is one of the key, open questions in the field of modern-day astrophysics and has been a constant theme in NASA decadal surveys (e.g. National Academies of Sciences and Medicine 2021). In particular, identifying the epoch in which the first galaxies formed, deciphering how they formed and what their fundamental properties are is a major goal of today's observational surveys and tomorrow's state-of-the-art instrumentation projects (e.g. Block et al. 2003; Gilmozzi and Spyromilio 2007; Laureijs et al. 2011).

With the recent developments in instrumentation, in the form of the James Webb Space Telescope (JWST; Gardner et al. 2023) it is now possible to observe the rest-frame infrared Universe beyond our local neighbourhood at unprecedented resolution. In particular, the Near Infrared Camera (NIRCam; Beichman et al. 2012) and the Mid-Infrared Instrument (MIRI; Rieke et al. 2015) instruments on *JWST* now enable observations from 0.9

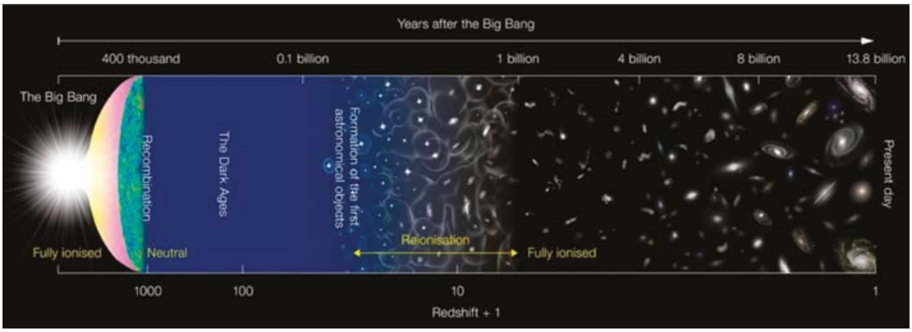

Figure 1. A cartoon of our current understanding of the Universe.

to 25μm. Consequently in its first few years of operation, *JWST* has started to shed light on the rest-frame near-infrared Universe beyond cosmic noon ($z > 2$, ≥10 Gyr ago), probing into the earliest origins of our Universe, as depicted in Figure 1.

These technological advances have been exploited in the first few years of operation of JWST by the astronomy community, with deep multi-band, multi-instrument and wide-area surveys of the cosmos (e.g. Bagley, Finkelstein, et al. 2023; Bagley, Pirzkal, et al. 2023; Casey et al. 2023; Eisenstein et al. 2023). Combining these surveys with targeted near-infrared spectroscopic observations has been an effective tool in unlocking the secrets of the early Universe (e.g. Naidu et al. 2022). This is the approach adopted by the the European MIRI Consortium's (GTO) High-Redshift Working Group, with the goal of studying the distant Universe with state-of-the-art MIRI observations. In particular, we utilise both the imaging component of MIRI (MIRIM; Bouchet et al. 2015) to produce one of the deepest images of the Universe in the near-infrared at 5.6μm as part of the MIRI Deep Imaging Survey (MIDIS; Östlin et al. in prep.) as well as spectroscopy. In addition to targeted observations with the medium resolution spectrograph (MRS; Wells et al. 2015) which constrains the spectral properties of a multitude of galaxies across cosmic time from high-redshift line emitters, quasars and sub-millimetre galaxies (SMGs) are observed. In total the MIRI GTO High-Redshift observing time equates to 125 hours, with 60 hours on the MIRI Deep Imaging Survey and 65 hours of MRS spectroscopy, in addition to 125 hours of coordinated parallels and simultaneous observations with NIRCam and MIRI.

2. MIRI Deep Imaging Survey (MIDIS)

The MIRI Deep Imaging survey consists of 60 hours of MIRI imaging centred on the HUDF, with 50 hours dedicated to the 5.6μm filter and the remaining 10 hours in the 10μm filter. Alongside these primary observations, deep (5σ point-source depth ~29mag) multi-band parallel observations in the HUDF-P2 region with NIRCam (e.g. Pérez-González et al. 2023; Caputi et al. 2023) and HUDF-P3 with NIRISS (Melinder in prep.) were obtained.

Amongst the ongoing projects being undertaken with one of the deepest images ever taken in the near-infrared (see Figure 2), including the analysis of the cosmic evolution of stellar morphology (Gillman et al. in prep.), 5.6μm-only (NIRCam-dark) sources (Jermann et al. in prep.), ALMA

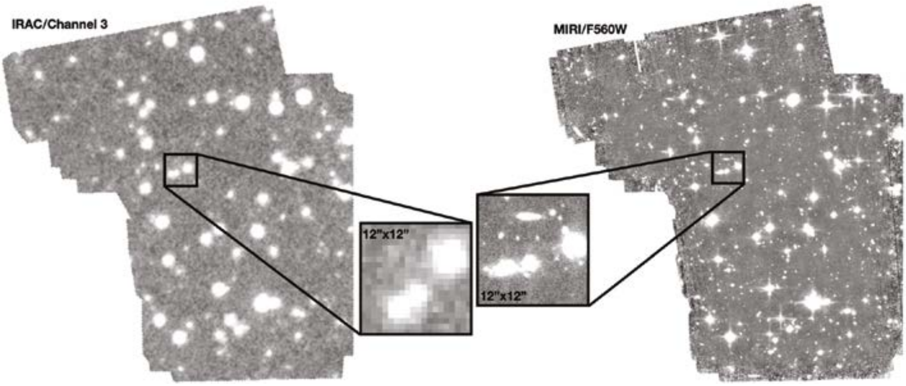

Figure 2. A comparison of the MIRI Deep Field at 5.6µm to previous IRAC Channel 3 (5.8µm) imaging from Spitzer. The incredible improvement in resolution and sensitivity is very apparent from the direct comparison.

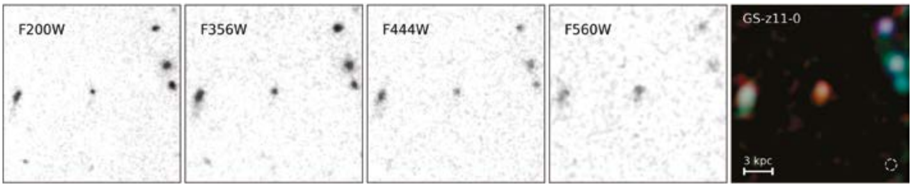

Figure 3. NIRCam F200W, F236W, F444W and MIRI F560W observations of JADES-GS-z11-0 with a F356W/F444W/F560W false-colour image convolved to 0.3".

sources in the HUDF (e.g. Boogaard et al. 2023), and the stellar populations of Lyman-Break galaxies (e.g. Iani et al. 2023) (see Karina Caputi's talk), we are also analysing the F560W emission of one of the highest redshift, spectroscopically confirmed, galaxies JADES-GS-z11-0, at a redshift of $z \sim 11.58$ as first identified by the JADES team (e.g. Robertson et al. 2023).

In Figure 3, we show the multi-wavelength observations of JADES-GS-z11-0, including the MIRI/F560W emission, with indications of an extended morphology at rest-frame UV-optical (0.43µm) wavelengths (Östlin et al. in prep.). As identified by the JADES team (e.g. Robertson et al. 2023), through spectral energy distribution fitting, this galaxy has a stellar mass of $\log_{10}(M*[M_\odot]) = 8.9$ with a star-formation rate of $\log_{10}(SFR[M_\odot\ yr^{-1}]) = 0.3$. The moderate star-formation rates and compact sizes indicate elevated star-formation efficiencies, providing insights into the formation of one the earliest known galaxies.

3. MACS1149-JD1

One of the targets of the MRS observing program was MACS1149-JD1, a lensed galaxy at redshift z = 9.1 when the Universe was 530 Myr years old. In these observations we spatially resolve, for the first time the Hα emission, identifying two clumps, one in the north (N) and one in the south (S) of the galaxy, as shown in Figure 4 from Álvarez-Márquez et al. (2023). In total the galaxy has a star-formation rate of ~5 $M_\odot$ yr^{-1} with a velocity map that reflects a rotating disk.

The extended overall structure of Hα follows the [OIII] 88μm emission of the galaxy imaged with ALMA, whilst the clumps show very different kinematics, with a factor ~2 difference between the velocity dispersions, potentially associated with the UV clump identified in the north and a potential outflowing component.

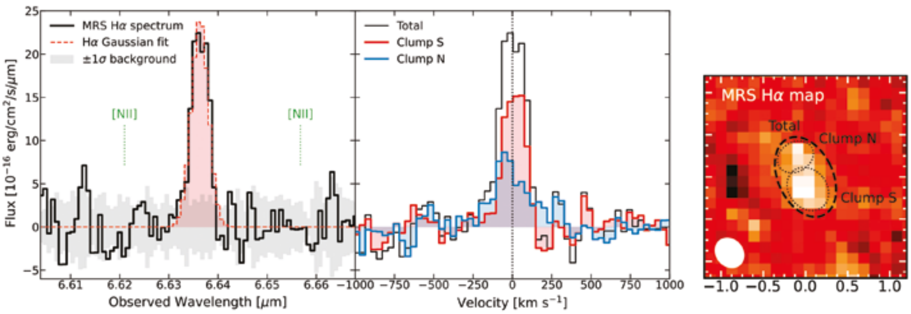

Figure 4. Left: The integrated MRS spectrum of MACS1149-JD1 (black line) centred on the Hα line. The Hα spectra for the two spatially separated N and S clumps, as identified in the emission line map, are also shown (right).

4. J1120+0641

In addition to lensed galaxies, our GTO MRS observations also comprise of the first infrared spectrum of a z > 7 quasar, J1120+0641 at z=7.0848, during the epoch of re-ionisation. For the first time, we detect a hot dust torus at this epoch, defined by a upturn in continuum emission at $\lambda_{rest} \simeq 1.3\mu m$, as shown in Figure 5 from Bosman et al. (2023), leading to a black-body temperature of $T_{dust} = 1413.5_{-7.4}^{+5.7}$ K. Compared to similarly-luminous quasars at 0 < z < 6, the hot dust in J1120+0641 is somewhat elevated in temperature (top 1%). The temperature is more typical among 6 < z < 6.5 quasars (top

25%), leading us to postulate a weak evolution in the hot dust temperature at z > 6 (2σ significance).

We measure the black hole mass of J1120+0641 based on the Hα Balmer line, $M_{BH} = 1.52 \pm 0.17 \cdot 10^9 M_\odot$, which is consistent with previous measurements using the rest-UV Mg II line and measurements utilising the Pas-

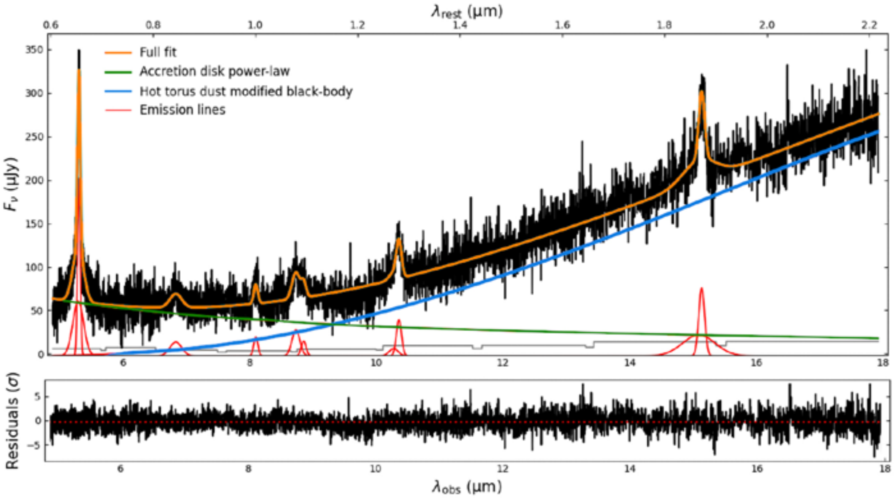

Figure 5. Full fit to the MIRI-MRS spectrum of J1120+0641 (orange). The coloured lines show the emission coming from the accretion disk (power law, blue), the hot torus dust (black-body radiation, green) and the broad quasar emission lines (red). The residuals show no signs of deviation from the continuum model, nor additional broad emission lines.

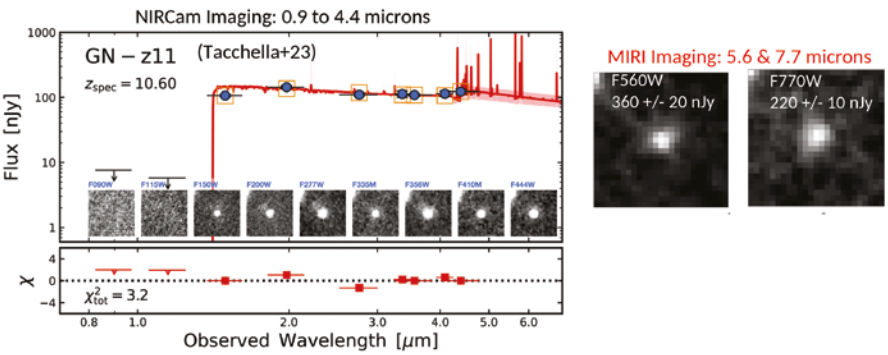

Figure 6. Left: The SED as published in Tacchella et al. 2023 showing clear NIRCam detections with the MIRI F560W and F770W imaging of GN-z11 shown on the right.

chen-series lines indicating that no significant extinction is biasing the M_{BH} measurement obtained from the rest-frame UV. By comparing the ratios of the Hα, Pa-α and Pa-b emission lines to predictions from models, we find that the hydrogen broad lines are consistent with originating in a common broad-line region. Overall, we find that both J1120+0641's hot dust torus and hydrogen broad-line region properties show no significant peculiarity when compared to luminous quasars down to z = 0. The quasar accretion structures must have therefore assembled very quickly, as they appear fully 'mature' less than 760 million years after the Big Bang.

5. GNz11

Finally, we obtained targeted MIRI Imaging observations of the highest redshift galaxy pre-*JWST* at z ~ 11 (Oesch et al. 2016). The galaxy has clear detections in the NIRCam observations from the JADES survey with a spectroscopic redshift of z = 10.60, stellar mass of $\log_{10}(M_* [M_\odot]) = 9$ and star-formation rate of $(SFR[M_\odot\ yr^{-1}]) = 21$, with a physical extent of 64 pc (Tacchella et al. 2023; Bunker et al. 2023). We have two high signal to noise detections in the MIRI filters F770W and F560W, as shown in Figure 6, with very red colours, with a flux ratio of F560W/F444W = 2.7 and F770W/F444W = 1.6, indicating either a extreme line emitter ([OIII], Hα) or active galactic nuclei (AGN) origin of this intriguing source, however the MRS spectroscopy upcoming in March will reveal the true nature of GNz11.

6. Summary

MIRI is the only instrument capable of exploring the (rest-frame) near-infrared spectral range in high redshift galaxies with both deep spectroscopy and imaging. The unique instrument allows the first characterization of the old stellar populations, in addition to mapping the obscured star-formation in galaxies and its connection with molecular interstellar medium. Furthermore, the state-of-the-art spectral capabilities of the MIRI enable the derivation of the physical properties of the black hole, torus and broad line regions in high-redshift quasars, in addition to quantifying the ionized interstellar medium properties and stellar populations in epoch of re-ionisation sources at z > 9. No other instrument or observatory will be active in this spectral range with similar capabilities as planned for the foreseeable future (the next 20 years). We have a unique opportunity to exploit the legacy value of JWST/MIRI now.

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SESSION 3: OUTREACH AND PUBLIC ENGAGEMENT WITH JWST

Creating the James Webb Space Telescope's First Color Images

Klaus Pontoppidan
Jet Propulsion Laboratory, California Institute of Technology

Abstract

The first color images from the James Webb Space Telescope (JWST, Gardner et al. 2023) were designed with the understanding that a NASA/ESA/CSA flagship must explain its purpose and science to the tax- paying public, and that to earn the opportunity to explain and educate, we must first inspire. The feeling that many people have when seeing a well-composed color image of a deep space scene for the first time is visceral. It connects to a deeper part of the psyche than that of pure reason, like the effect of music or other visual arts. It is in eliciting this emotion that we have an opportunity to draw people in and educate; inevitably questions follow: What do I see? What do the colors and shapes mean? How large, distant, or old is this? And how does it relate to us, the Earth, the Sun, and my environment? It is in answering these questions we can educate, encourage children to take up careers in STEM, and hopefully convince the public that science is a fundamental human endeavor.

JWST Early Release Observations

Early Release Observations (or EROs, not to be confused with the Early Release Science – ERS – programs) are a common activity at the end of commissioning an astronomical observatory. EROs are intended to provide a first, dramatic, look at science-like data from an observatory, but with the public as the primary audience. Clearly, we owe the existence of JWST to the decades-long efforts of thousands of dedicated engineers and scientists at immense personal and monetary cost. Given an observatory that outperformed expectations (Rigby et al. 2023), the ERO team was keenly aware of their responsibility in the eyes of the public, lawmakers, scientists, and the JWST project. They should clearly demonstrate that the observatory works technically well, but should also meet a spectacular standard, capable of inspiration and awe.

For JWST, the EROs were the culmination of a years-long process by a small advisory committee, coupled with an implementation team at the

Space Telescope Science Institute. Targets were kept strictly confidential, to not set expectations for any specifics. Indeed, the final EROs were not known until close to the end of JWST commissioning, as the exact timing of the observations determined which targets would be visible to the observatory. The process for selecting ERO targets is described in detail in Pontoppidan et al. (2022), including the implementation team. During the final 6 weeks of JWST commissioning, a team of more than 30 experts at STScI observed, processed, and delivered the JWST EROs (Figure 1). Despite the very short amount of time, the team knew that nothing would be good enough and worked non-stop, through weekends, through the night at times, to meet this standard. Ultimately, the first ERO product (a deep NIRCam image of the SMACS 0723 galaxy cluster) was presented by US President Biden on July 11, 2022. The JWST EROs resulted in 200 billion impressions worldwide (meaning that every person on earth had many opportunities to view them).

Figure 1. Scenes from the creation of the JWST EROs. Top left: Viewing the first data for the first time. Top right: Discussing the final composition of an image (still image from PBS production). Bottom: At the end of the ERO effort, just before delivery.

Requirements of cosmic art

There is something special about the imagery produced by Hubble. The most famous Hubble images seem more *real* than most astronomical images. They pioneered many techniques in modern astrophotography (Levay 2021). You get the feeling that, if you were there in person, the image would be what you might see with your eyes. There is a *photorealistic* quality to them. Of course, this is not the case. The collecting areas of our human eyes – the pupils – are even in the darkest places only 1 cm^2 or 250,000 smaller than that of JWST. Under these circumstances, a person would only be able to see a ghostly, grey scene, if anything at all. But this does not matter – outreach images provide us with a superhuman capability to view the invisible.

First, some of the unique quality of a Hubble or JWST images comes from high signal-to-noise (S/N) in every pixel. For JWST public imaging, we required S/N>20 per pixel per filter, and set exposure times well beyond what is typically used to support science investigations of the same scene (typically 30 minutes per filter). The deep field on SMACS0723 remains one of the deepest images obtained with JWST with several hours per filter. The NIRCam outreach images use a custom dither pattern to ensure as uniform depth as possible, with a minimum of 5 dithers per pix-

Figure 2. Example of use of a leading line in the golden ratio in the "Cosmic Cliffs" ERO image (Credit: NASA/ESA/CSA/STScI/PID2731 – Pontoppidan).

el, implemented as a mosaic pattern with a 71.5% overlap (Pontoppidan et al. 2022).

Second, the images appear extraordinarily sharp, with great detail and structure, and the ability to support exploration. One may think of a "Find Waldo" or "Busytown" image – you can zoom in and find something special happening in the image on multiple scales. It turns out that scales of least 1:1e3-1:1e4 are needed. That is, the overall motif is >1000 times larger than the smallest resolved structure. Conversely, viewers of images with much larger scale range than this (better than 1:1e5) are not able to appreciate the smallest scales, and individual stars become invisible. An important point is that this requirement is not directly related to the absolute angular resolution of the telescope. Rather, it sets a requirement of the total angular size of the image, given a spatial resolution. Thus, there is no reason that a smaller telescope cannot produce spectacular outreach images, only that there must be at least 1000 meaningful resolution elements across the image. That said, a large telescope with a high angular resolution has more opportunities for excellent photographic compositions in the sky.

Photographic composition

A central requirement for composition of outreach images is a well-defined object or motif. Examples include an entire galaxy/protostellar outflow, compact HII region, all of which would include a well-defined, mostly empty, outer boundary. Examples of these include Stephan's Quintet or the Oph core (Figure 3). Alternative motifs can be designed via a strong leading line, such as the Cosmic Cliffs (Figure 2). We avoided a section of a cloud without a dark boundary, or leading line, or empty deep fields, which are mutually indistinguishable to the non-expert.

We used best practices from photographic art to design compositions for outreach images. These include the use of leading lines, rule-of-three (collections of three items is more aesthetically pleasing than two or four), brightness/color contrast, golden ratio, as well as the S/N and scale requirements discussed above. For instance, the famous Cosmic Cliffs in Carina uses an obvious leading line across the "mountainous" crest, placed at the golden ratio (the ratio satisfying the relation (a+b)/a=a/b). This composition (Figure 2) also uses NIRCam filters designed to create a strong color contrast between the cloud (PAH emission) and the photodissociation flow (Paschen Alpha). Finally, outreach images are nearly always designed to be rectangular, also when composed of multiple mosaic tiles.

Figure 3. The Ophiuchus Core image created for the 1st anniversary of JWST uses both the golden ratio and the rule of three, as indicated. The prominence of the VLA 1623 outflow was a (fortuitous) surprise, and not an intended part of this composition (Credit: NASA/ESA/CSA/STScI/PID 2739 – Pontoppidan).

Optical versus infrared outreach images

Some use the term “False Color” to apply to infrared color images, or indeed color images from any part of the electromagnetic spectrum. This is an unfortunate misnomer that should be avoided (Hurt 2013). Granted, JWST operates in the infrared and is therefore sensitive to photons that are not visible to the human eye. However, this does not make the colors “false”, as opposed to real. Color is defined as a ratio in the energy received from photons of one wavelength relative to another. If most energy is represented by photons with wavelengths near 550 nanometers, our eyes generally interpret that as a green color. There is no difference in representing differences in energy received in different infrared wavelengths as color. In fact, there are many more colors available in the infrared than in the visible;

the light available to JWST is over 20 times more colorful than what can be perceived by humans! To call this false color would be a great injustice to Nature, as if we had just painted the images arbitrarily. Rather, we have translated the infrared spectrum into a visible one, like one might translate from one human language to another. To aid in this translation, rules are applied, the most important of which is *chromatic ordering*. In chromatic ordering, increasing infrared wavelengths are assigned increasing colors representing increasing visible wavelengths.

Another less strictly applied principle, but also important, is to limit the total spectral range from the bluest to the reddest filter. There are several reasons for this: One is that, since the spatial resolution of a space telescope generally scales inversely with wavelength, the reddest band will appear blurrier than the bluest band. If the range is more than 2-3 times in wavelength, this will affect the sense of "photorealism" seen in the best Hubble and JWST color images and can result in red halos around stars and sharp features. Further, a wider wavelength separation of bands also generally means that the bluest bands see very different physical processes than red bands. In this case, the spatial structure seen in each band may not match, leading to clumps of primary color (red, green, blue), rather than smooth color blends. This also degrades photorealism.

Motif	Context	Press release
SMACS J0723.3-7327 Deep Field	ERO / PID 2736	July 11, 2022
Stephan's Quintet Galaxy Group	ERO / PID 2732	July 12, 2022
Cosmic Cliffs (NGC 3324)	ERO / PID 2731	July 12, 2022
Southern Ring Planetary Nebula	ERO / PID 2730	July 12, 2022
Cartwheel Galaxy	ERO / PID 2727	August 2, 2022
30 Doradus Star-Forming Region	ERO / PID 2729	September 6, 2022
Neptune	Cy 1 outreach / PID 2739	September 21, 2022
Pillars of Creation Star-Forming Region	Cy 1 outreach / PID 2739	October 19, 2022 October 28, 2022
L1527 protostellar outflow	Cy 1 outreach / PID 2739	November 16, 2022
Wolf-Rayet Star 124	ERO / PID 2730	March 14, 2023
Arp 220 Interacting Galaxy	Cy 1 outreach / PID 2739	April 17, 2023
Ophiuchus Core Star-Forming Region	Cy 1 outreach / PID 2739	July 12, 2023
HH 46 Protostellar Jet	Cy 1 outreach / PID 2739	July 26, 2023
Uranus	Cy 1 outreach / PID 2739	April 6, 2023 December 18, 2023

Table 1. JWST observations obtained for outreach imaging during the first year of science operations.

Defining the first year of JWST outreach imagery

JWST ERO imagery were designed and obtained with the purpose of creating spectacular color images. These are clearly separate from competed science programs, which are designed to accomplish science goals in the minimum amount of observing time, with essentially no consideration for aesthetics. That is, the outreach quality of color images from science programs is incidental, and rarely, if ever, optimal for this purpose. Consequently, the STScI Director allocated additional observing time during Cycle 1 to obtain additional outreach images, following the same style as that used for the EROs. This resulted in a new set of observations, including the L1527 pro-

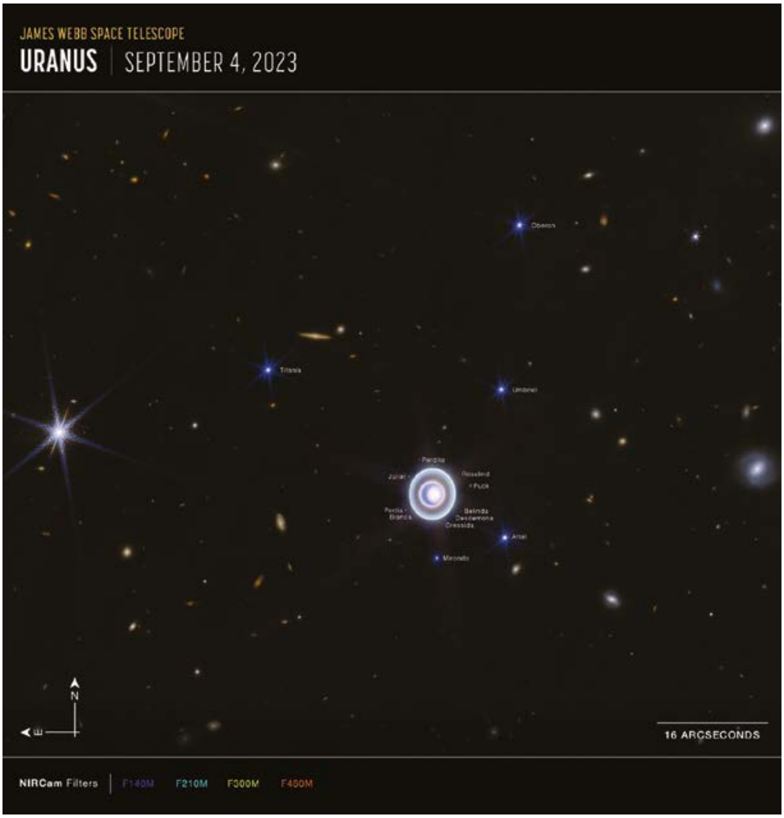

Figure 4. JWST allows us for the first time to view our solar system in the context of the distant cosmos from which it came. Outreach NIRCam image of Uranus, its rings and moons, seen against a distant universe of a multitude of galaxies (Credit: NASA/ESA/CSA/STScI/PID2739 – Pontoppidan).

tostellar outflow, the JWST version of the famous Pillars of Creation, the first anniversary image of the nearest young star-forming region in Ophiuchus, and not least the ice giants, Uranus and Neptune (see Table 1). These last set of images were designed to do something new: to image a planet in the solar system on a background of the deep Universe, creating a composition of our own back yard reaching out to the beginning of time. This is a challenge as there is a vast difference between the brightness of the ice giants and distant galaxies, and because the planets and its moons move relative to the sidereal sky, as well as relative to each other. With JWST, it is possible to see the planets rotate and the moons to move in minutes. To solve these issues, the ice giant observations were designed to include multiple images with different exposure times. A short exposure to capture the bright planetary disk, and a much deeper exposure to image rings and the background galaxy field. By registering each component separately, it was possible to create the composite image seen in Figure 4, striking in its contrast between the blue, icy moons and the ancient red universe beyond.

JWST has now transitioned into the routine of normal science operations, but there are surely many more spectacular images in the future.

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Session 3: Outreach and Public Engagement with JWST

Pedro Russo
Leiden Observatory, Leiden University, the Netherlands

Panel discussion members

- Antonella Nota, *International Space Science Institute, Bern, Switzerland*
- Nathalie Nguyen-Quoc Ouellette, *University of Montreal, Canada*
- Marcia Rieke, *University of Arizona, Tucson, USA*
- Jeyhan Kartaltepe, *Rochester Institute of Technology, USA* (Remote)
- Ewine F. van Dishoeck, *Leiden Observatory, Leiden University, the Netherlands*

Introduction and summary

This session presents a timely opportunity to explore the multifaceted role of the James Webb Space Telescope (JWST) within the broader context of scientific progress and societal engagement. The sessions focused on valuable insights from historical precedents, such as the role of the Catholic Church, particularly the Jesuits, in the dissemination of scientific knowledge during the early modern period. While the case of Galileo Galilei highlights the potential limitations to scientific freedom, it also underscores the importance of public support and public engagement efforts. As Galileo himself recognized, effective communication with the public, including policymakers like the House of Medici, is crucial for the advancement of scientific inquiry.

The transformative potential of the JWST for our understanding of the Universe is undeniable. However, as the discussions during the other sessions clearly demonstrated, it is equally important to ensure that this impact extends beyond the confines of our scientific community and reaches the broader public. The sessions delved into the power of captivating imagery, the importance of international collaboration to reach global audiences, and innovative approaches to connect with diverse populations, including the intriguing intersection of art and science.

The JWST project has demonstrated remarkable success in fostering public interest in astronomy by drawing on the positive experiences gleaned from public engagement with the Hubble Space Telescope. From the momentous launch event to the awe-inspiring release of the first images, JWST has captured the imagination of various sectors of our society. This session serves as an opportunity to build upon this momentum and further refine our strategies for fostering public understanding and appreciation of the JWST's groundbreaking scientific contributions.

Klaus Pontoppidan from JPL gave us a behind-the-scenes perspective on the production of the first JWST images. Klaus highlighted the motivation and choices with an emphasis of the importance of planning for such a mission as JWST. The short presentations put together a myriad of specific examples from the JWST community. Some of the key points:

Antonella Nota highlighted the importance of international collaboration and availability of resources from the Space Agencies, NASA, ESA and CSA – and some luck – for a global reach.

Nathalie Nguyen-Quoc explained the importance of providing personal stories about the Canadian researchers involved in the JWST mission and allowing youth to take on the role of scientists themselves by imagining what they would observe with the JWST. Given Canada's small amount of resources for JWST outreach, it is also important to leverage the astronomers themselves and provide them with support and training in science communication. Nathalie also stressed the need to provide materials in different languages.

Marcia Rieke showed how to use real JWST data to engage with pre-University students and teachers: https://jades-survey.github.io/public/for-teachers.html

Jeyhan Kartaltepe, discussed the recent experiences of using JWST data in citizen science projects, like Galaxy Zoo. These initiatives are good examples of the importance of public participation in scientific research.

Ewine van Dishoeck provided a comprehensive overview of the JWST outreach activities in the Netherlands, with some examples ranging from political engagement, working with planetariums, the importance of physical scale models of JWST as eye-catchers and partnering with professionals, for example, for the development of the JWST Universe exhibition.

During the discussion, some relevant remarks and suggestions were discussed, namely:

- Working with libraries: Libraries could act as multipliers, they have strong links with the communities and are always looking for new content and activities.
- Reach underserved and under-reached communities, for example, by engaging with the IAU Offices for Astronomy Outreach and for Educa-

tion; they have national coordinators across countries that are members of these communities and understand their needs, constraints, and realities better than we do; it is important that we listen to them.

- JWST's budget crisis in 2020/2011 is a good reminder of the importance of policy engagement, which is long-term, time-consuming, but potentially highly impactful.
- Taking into consideration the upcoming PAS workshop on *Indigenous Peoples' Knowledge and the Sciences*, more work needs to be done to work closely with Indigenous Peoples, which can be an insightful and enriching experience for both communities.
- The right balance between institutional support for outreach and the support of researchers to conduct outreach activities and programs.
- Public Outreach needs resources (and budgets), and the number of 3% of the mission's budget from STScI is a good indicator.

The Planning for the First JWST Images: Lessons Learned and an Outlook to the Future

Antonella Nota
International Space Science Institute, Bern, Switzerland

In 2021, as we approached launch, JWST was poised to revolutionize humanity's understanding of the cosmos. Designed to answer fundamental questions related to formation and evolution of the Universe, stellar systems, exoplanets and planets, JWST was 100 times more powerful than Hubble. The expectations for outstanding performance were high.

Approximately two years before launch, an interagency (NASA/ESA/CSA) committee had been created to design a list of recommended astronomical targets for the very first JWST images. These were to be taken immediately after the commissioning phase, and to be released to the world to announce that JWST was fully operational, and its performance, as expected, was superb.

Looking back at the success of the first images and the choice of the targets that were eventually used, some lessons can be learned that hopefully can be used for future missions. First, it was necessary to agree on a clear definition of the criteria these targets/first observations had to satisfy:

- Showcase JWST uniqueness, while avoiding a direct comparison with the Hubble Space Telescope, at least at the beginning;
- Showcase the power of the entire observatory, highlight the capabilities of all instruments, celebrate the international nature of the partnership;
- "wow" the public with the beauty and the colors of the Universe, as seen by JWST.

Because of the uncertainty on the launch date, targets had to be prepared for any time of the year, so that the appropriate subset could be ready when the final launch date was announced.

The second lesson learned was that preparedness was key to success. These observations were to be the apex of the "crescendo" that had started with the spectacular launch, followed by the deployment and commissioning phase, which lasted approximately six months. One recurrent question at the time was: how to maintain public interest when there is nothing to see for six months? This is where the space agencies' powerful communication machines went into action, led by NASA colleagues, to continue telling the story of this beautiful scientific observatory coming to life: the journey to its final destination, the deployment of all its precious subsystems, the telescope being aligned, the instruments being awaken. And while it had been decided not to show any colorful images along the way, communications effectively conveyed (via a very effective NASA blog) that the telescope was performing well, and the first engineering data was already showing that the observatory's performance was exceeding the already ambitious expectations. Because of this well-crafted and coordinated communication strategy, we could see that, along the way, a very faithful crowd had accrued that was already following JWST at every step. Their patience was rewarded when the first stunning images were released to the world in a coordinated set of simultaneous worldwide events which were seen by millions of people.

The rest is history, and as we marvel at each single spectacular image or superb spectrum produced by the JWST observatory, we are holding our breaths waiting for that revolutionary discovery that will change the way we see the Universe. That "big science" will make the investment of resources, funding, and thousands of people's careers absolutely worthwhile.

Engaging with Diverse Audiences through the Wonders of JWST in Canada and Beyond

Nathalie Nguyen-Quoc Ouellette
University of Montreal, Canada

Introduction

Canadian astronomers, thanks to the contribution of the FGS/NIRISS instrument through the Canadian Space Agency and several government, university, and industry partners, benefit from approximately 5% of JWST observing time. The reaction from both the Canadian astronomical community and the Canadian public to our nation's involvement in such a revolutionary mission has been fantastic. However, conducting outreach for the mission in Canada has presented some challenges, including catering to a public in two official languages, English and French, trying to make the most out of limited resources and people power, and getting the Canadian public acquainted with the local and homegrown scientists who are participating in JWST. These challenges have been tackled using a number of targeted initiatives.

Connecting the Canadian public with the people of Webb

One key emphasis in Canada's outreach strategy for JWST has been to highlight the Canadian scientists that contributed to the development of the mission and observatory through features such as the Canadian Space Agency's "People of Webb". With an avalanche of scientific results now coming in, many press releases have been created to showcase discoveries made by or with strong contributions from researchers at Canadian institutions. These are crafted to showcase the scientists behind the science, in particular when students or early-career researchers are involved. One fan favorite discovery has been the study of The Sparkler Galaxy, which was performed by the CANUCS Science Team and led by two postdoctoral research fellows, Lamiya Mowla and Kartheik Iyer, at the University of Toronto. Showcasing our researchers has been especially crucial for Canada, as JWST is by far the largest space astronomy mission the nation has ever been involved in. It is an ongoing exercise to make sure that Canadians know that we are valued partners in the mission. It is one of our goals to show Canadian youth that one does not necessarily need to live in the United States or work directly for NASA to be involved in such breakthrough projects.

Finally, all researchers at Canadian institutions working on JWST data have access to a small, but dedicated, "Outreach Help Desk" which provides them with personalized presentation and media training and advice, help for press releases, visuals and slide decks, and ways to connect with local audiences such as science centers, youth groups, and amateur astronomy clubs. Given the limited resources of the JWST Outreach Team in Canada, it is imperative that we train as many of our astronomers in science communication as possible and leverage their enthusiasm to increase the reach of Webb across the country.

Putting Webb in the hands and minds of our youth

Many activities have been created and deployed across Canadian classrooms and youth centers to get children and students excited about JWST. In particular, we are working hard to allow children to imagine themselves as scientists at the helm of the telescope, leading their own inspiring observing programs. For younger children, the Université de Montréal and partners have hosted many drawing contests encouraging them to decide what they would like the telescope to observe next and to draw their idea in a hexagonal shape, representing a segment of JWST's mirror. Through events such as the Montreal Planetarium's AstroFest and the Eurêka! Festival, the province of Québec's largest science festival, tens of thousands of families have partaken in this activity while interacting with and gaining inspiration from professional astronomers who have worked on and used the JWST. Thanks to a collaboration with educational platform "Exploring by the Seat of your Pants", two virtual editions of this contest were also launched across Canada and beyond, amassing nearly 1,000 individual submissions from several Canadian provinces, the United States, India, Ukraine, and Ghana.

Older students are instead invited to write mock telescope time proposals in teams to observe a chosen exoplanet target. This activity was created as part of a larger suite of educational resources called "Exoplanets in the Classroom"[1] by the Trottier Institute for Research on Exoplanets and Discover the Universe. Students put themselves in the shoes of professional

[1] https://www.decouvertedelunivers.ca/exoplanetes

astronomers: select a target, provide a scientific justification for their proposed program, and determine when and where to point the telescope by using astronomy software such as *Stellarium*. They then present their proposals to the other groups and discuss the merits of each proposal, ranking them as a Time Allocation Committee would. The goal here is to demystify the work of astronomers and help students learn about real research while getting better acquainted with JWST and exoplanets.

Webb across languages

Educational and outreach initiatives in Canada have the added challenge of ideally being created in both of the country's official languages: French and English. While there is an abundance of astronomy and Webb-specific educational resources in English thanks to the incredible efforts of NASA, STScI, ESA, and others, there is a notable dearth of them in French, especially for French Canadian audiences. Many of our efforts have thus focused on creating activities and resources in French showcasing researchers from the province of Québec. These include the aforementioned "Exoplanets in the Classroom" project, which was originally devised as a French suite of resources called "Des exoplanètes à l'école" and is currently being fully translated into English for use in the rest of Canada and beyond. As part of a series of short videos explaining different astronomy and exoplanet concepts in French called, "Les ExoBouchées",[2] or "ExoBites", a video on modern telescopes heavily featuring JWST was also created. Finally, moving beyond just French and English, we are collaborating with the International Astronomical Union's Office of Astronomy Outreach and the STScI to translate many of STScI's visuals and infographics into a plethora of other languages, including Arabic, Spanish, Mandarin, and more.

[2] https://youtu.be/0sar5pND8P4

Outreach by a Large, International Collaboration

Marcia Rieke
University of Arizona, Tucson, USA

The JWST Advanced Deep Extragalactic Survey (JADES) collaboration has members at several sites in North America as well as in the U.K. and many European countries. The collaboration has no funding for outreach, but collaboration members realized that a tool developed to assist in the collaboration's work, "FITSMap" (https://jades.idies.jhu.edu), could afford the public a way to look at the team's high redshift imagery. Having the audience snap a QR code presented in a talk which then lets them examine galaxies on their phones has been quite popular (although care is needed to ensure that the presentation venue has adequate internet access). The JADES web page at https://jades-survey.github.io/ also has a link to a video explaining in more detail how to use the viewer. An important outcome of this type of outreach is that the public can begin to see that science is not cut and dried or yes or no with a real data set presenting a large variety of behaviors to be understood.

The notion of using real research imagery has been expanded to include activities for K-12 students. The activities use data from JADES to explore several concepts such as distance and spectroscopy. Each activity includes a teacher's guide which outlines the goals of the exercise, and which provides the teacher with further discussion topics. The goals of the activities include developing critical thinking, pattern recognition, working in groups, and writing for exercises aimed at younger students with older students challenged to develop analytical and research skills. The guides include a section on how the activities relate to science education goals in both the U.S. and the U.K.

The collaboration has also begun creating videos available at https://www.youtube.com/@jades-survey to highlight some of the team, and to illustrate the more personal side of research. We hope to expand this set of videos with more recordings in the future.

Outreach and Public Engagement with JWST: Extragalactic Examples

Jeyhan Kartaltepe
Rochester Institute of Technology (RIT), USA

Our teams (e.g., CEERS, COSMOS-Web, NGDEEP) and research group have been involved in a number of JWST-related outreach activities. These include organizing campus exhibits and demos (for example, the annual ImagineRIT event held on the RIT campus), delivering public talks to a range of audiences (e.g., K-12, community events, affinity groups), participating in press releases and interviews related to new science results, and media interviews such as the two-part NOVA special. More specialized activities include citizen science activities, where members of the general public not only learn about astronomy, research, and datasets, but actually contribute to scientific measurements. Two such examples are Galaxy Zoo-JWST and Redshift Wrangler.

Galaxy Zoo – JWST

The Galaxy Zoo project has been ongoing for many years, first using Sloan Digital Sky Survey observations, then Hubble, and now JWST images. Citizen Scientists visually classify the morphologies of large numbers of galaxies and these measurements have made discoveries and been included in a number of publications. This work has now been extended to JWST NIRCam images, first using images from the CEERS Early Release Science field. The classifications have been completed and the first set of papers are in progress. Images from the other public fields will soon be incorporated into the project.

Redshift Wrangler

The "Redshift Wrangler" citizen science project to analyze extragalactic spectroscopic measurements was launched last summer with great success with ground-based spectroscopic observations in the COSMOS field. Astronomy is faced with ever-increasing dataset sizes. Currently, distant galaxy surveys contain spectra of tens to hundreds of thousands of galaxies, but these numbers will soon grow into the hundreds of millions as new instruments come online. Automated methods of analyzing spectra are in their early stages, prone to inaccuracies, and still require visual inspection of individual objects. Citizen science can help bridge the gap between the current method of individual PIs inspecting every spectrum and the eventual improvements to automated algorithms. In fact, citizen scientists may be the key to providing ample training sets needed for these improvements. The large spectroscopic datasets being obtained by JWST, particularly several large wide-field slit-less spectroscopy programs, will soon be incorporated into Redshift Wrangler. Volunteers undertake two main tasks: 1) to mark the positions of emission and absorption features in the spectra, which are then used to calculate the redshifts of the galaxies, and 2) to quality check the automated fitting of the emission lines that is used to measure emission line flux.

Examples of JWST Outreach in the Netherlands

Ewine F. van Dishoeck
Leiden University, the Netherlands

This short contribution highlights four points that helped outreach in the Netherlands, namely the importance of (i) being involved in the building of some part of JWST as a small country; (ii) having a big centerpiece for outreach; (iii) using planetarium shows to create new experiences; and (iv) reaching more diverse and younger audiences through special exhibitions and projects.

Being part of JWST for 25 years

The Netherlands has been involved in JWST for more than 25 years as part of the European Consortium of ten countries that built the Mid-InfraRed Instrument (MIRI) together with the US. Specifically, the Netherlands, under leadership of the Netherlands Research School for Astronomy (NOVA), was responsible for the design, construction and testing of the medium-resolution spectrometer main optics. Being a relatively small country, an important part of the outreach was showing to the Dutch general public that, yes, one can still have a significant role in such a flagship mission even as a minor partner. The NOVA outreach office, led by Marieke Baan, was crucial in alerting the press at key dates and linking them up with MIRI astronomers and builders. As a result, the public and press, from newspapers to radio and tv, clearly became fascinated by the story and followed the journey of "our" part of the MIRI hardware from the Netherlands to the UK, and then to the USA and finally to launch, over more than two decades. Triggered by the NASA messaging strategy (see contribution by Antonella Nota), the main Dutch radio channel (close to 1 million listeners) asked for brief updates every few weeks in the months between launch and first images. The first MIRI image in April 2022, when MIRI was finally cold, was a particularly emotional moment for the MIRI team.

Having an eye catcher: the JWST 1:10 model

The impact of the in-person and tv outreach events was helped by acquiring a unique 1:10 JWST scale model. This beautiful and highly accurate model, only a few of which exist in the world, does the unfolding of JWST exactly as it happened in space, from its "origami" position in the nose of the Ariane V rocket to the fully functional telescope, in the same sequence. It was displayed at various locations in Leiden from late 2020 onward in numerous events, with PhD and MSc students presenting and demonstrating the model and the JWST science. In particular, Leiden was the 2022 European City of Science, with the big conference happening (by chance) exactly in the week of July of the first images release. Most events also had a children's corner in which small JWST telescopes were built from Lego. A smaller 1:20 model was built by NOVA to bring to schools for outreach and education events.

The power of planetarium shows

The software and astronomical data for planetarium shows has undergone huge improvements in recent years, with beautiful images of the sky and all kinds of phenomena in it now available open source. NOVA partnered with the Omniversum planetarium in The Hague to develop a JWST-specific show, consisting of a mix of a more traditional outreach talk by an astronomer with planetarium journeys into space to visit JWST and specific objects, from nearby exoplanets to star-forming regions to beautiful galaxies and ultimately the deep universe. It was surprisingly easy to develop and simple to update (when new JWST images are released) and has also been used in, for example, Amsterdam, Groningen and Copenhagen planetaria. These shows generally attract younger and more diverse audiences than traditional outreach talks.

Diverse audiences: astronomy & art and exhibitions

One of my personal hobbies is astronomy and art. In 2019-2020, an exhibition was hosted in the Boerhaave science museum in Leiden (2019 European Museum of the Year) on *Cosmos: Art and Knowledge*, visited by 60000 people; it also looked forward to JWST and ended just as corona hit in 2020. One of the 1:10 JWST models is now part of the permanent exhibition at the Boerhaave museum since 2021 in its Big Questions room.

Inspired by the Boerhaave success, a smaller exhibition *On the Road to the Beginning* was hosted in September 2022 in the Leiden University hospital gallery in collaboration with astronomer-artist Vincent Icke. It was a mix of the first Webb images next to Icke's astronomy-inspired paintings, with again a children's corner with Lego models. The hospital location was chosen to attract a different cross section of society and to inspire those that are going through difficult times – from young to old - with the wonders of the universe.

The development of exhibitions benefits hugely from partnering with professionals. Good relations with small companies that specialize in their design and deployment are highly worthwhile the time and effort it takes to initiate them. One example is the JWST Universe exhibition, which ran in the Leiden Old Observatory through 2023-early 2024, see https://www.jwst-universe.net/. Such exhibitions also provide an opportunity to include videos that tell personal stories and show new science results, especially from the younger generation.

SESSION 4: LIFE CYCLE OF STARS AND ISM

Star Formation at Low Metallicity: James Webb Space Telescope Results from Imaging and Spectroscopy

Margaret Meixner
Jet Propulsion Laboratory, California Institute of Technology

Olivia Jones UKTC, ROE
Alec Hirschauer STScI
Omnarayani Nayak NASA/GSFC
Laura Lenkić JPL/Caltech
Conor Nally Univ. of Edinburgh
Nolan Habel JPL/Caltech
and the N79, NGC 346, NGC 6822 and I Zw 18 GTO teams

Abstract

JWST has opened the field of infrared stellar populations in nearby galaxies with its exquisite image quality and sensitivity in the near and mid-infrared. These wavelengths are ideal to identify young stellar objects and thereby enable studies of star formation in the Large and Small Magellanic Clouds, I Zw 18 and NGC 6822 where the metallicities are subsolar. In N79, an embedded super star cluster candidate region in the Large Magellanic Cloud (0.5 $Z_{\odot}$), we have obtained spectroscopy of the forming stars identifying ice and dust features as well as atomic and molecular lines in these sources. In our imaging and spectroscopy study of NGC 346, a massive star formation region in the Small Magellanic Cloud (0.2 $Z_{\odot}$), we have identified the young stellar objects with masses less than 5 solar masses. In NGC 6822 (0.2 $Z_{\odot}$), we have a census of the young stellar objects of Spitzer I, the massive star formation region at the center of the galaxy. In I Zw 18 (0.03 $Z_{\odot}$), we identify the star formation regions and report on an early census of the dusty inhabitants that also include evolved stars.

Introduction

Most of the detailed physics of star formation derives from detailed, infrared studies of star formation regions near our Sun; e.g. Orion, Taurus, Chameleon, and Ophiuchus. However, the highest production of stars within galaxies in the Universe occurred during the peak epoch of star formation (at redshift of z=2) in conditions very different from local star formation. The metal and dust content (a.k.a. metallicity), which is critical to cooling and coalescing gas, was much lower at that point, approximately 20% of the Sun's metallicity. The star formation intensity was significantly higher, likely producing stars in super star clusters, the remnants of which may be current-day globular clusters.

With its exquisite image quality and sensitivity in the near- and mid-infrared, the James Webb Space Telescope (JWST) enables detailed studies of star formation regions at low metallicity and high intensity in the Large Magellanic Cloud (50% solar metallicity) and Small Magellanic Cloud (20% solar

Figure 1. N79 is the most luminous infrared region of the Large Magellanic Cloud. This multi band color image uses Mid-infrared instrument data from shortest to longest wavelengths of MIRI at 7.7 and 21 microns (770W and 2100W filters) (Nayak et al. 2024; Image credit: ESA/Webb, NASA & CSA, O. Nayak, M. Meixner).

metallicity) that rival Milky Way studies of star formation. In more distant, low metallicity dwarf galaxies such as NGC 6822 (30% solar metallicity) and I Zw 18 (3% solar metallicity), the studies are focused on dusty stellar populations containing both evolved stars (red supergiant and asymptotic giant branch stars) as well as young stellar objects. The JWST MIRI and NIRCam data reach up to 7 magnitudes deeper than prior surveys of these targets revealing entirely new populations. Will we find great differences that explain the cause for the peak epoch of star formation? Does the lower metal content change the initial mass function of stars produced? Is the composition of the dust and ices surrounding embedded young stellar objects different than in the Milky Way? Is the density and temperature of the gas in these star formation regions different from those found in the Milky Way?

N79: the birth of a super star cluster

In the Large Magellanic Cloud, the N79 region hosts an embedded super star cluster candidate H72.97-69.39 (Ochsendorf et al. 2017) which was discovered as the most luminous infrared source from the Spitzer SAGE and Herschel HERITAGE surveys (Meixner et al. 2006; 2013). The multi-color Mid-InfraRed Instrument (MIRI) image shows a spectacular red star emanating radiation from its embedded central region (Figure 1). Based on photometry of extracted sources from the MIRI images, we found 106 young stellar objects with masses ranging from 0.7-40 $M_{\odot}$ with the most massive objects concentrated at the location of H72.97 (Nayak et al. in prep). These most massive objects saturated the MIRI image creating the brilliant star like image and the MIRI MRS spectroscopy of Nayak et al. 2024 was used to derive synthetic photometry of this most luminous region. Moreover, the Nayak et al. 2024 paper created a comprehensive catalog of identified emission and absorption line detections from young stellar objects in the region that will be used to determine the density, temperature and excitation of the gas, and the composition of the dust and ice features. This composition is important and interesting to understand the potential for planetary system formation at low metallicity.

NGC 346: discovery of low mass young stellar objects

In the Small Magellanic Cloud, the most luminous massive star formation region is NGC 346. Its young stellar populations have been well studied with HST (e.g., Sabbi et al. 2007) which found an optically visible pre-main sequence population. Spitzer SAGE survey results identified the massive young stellar objects (>8 $M_{\odot}$) in the region (Sewilo et al. 2013).

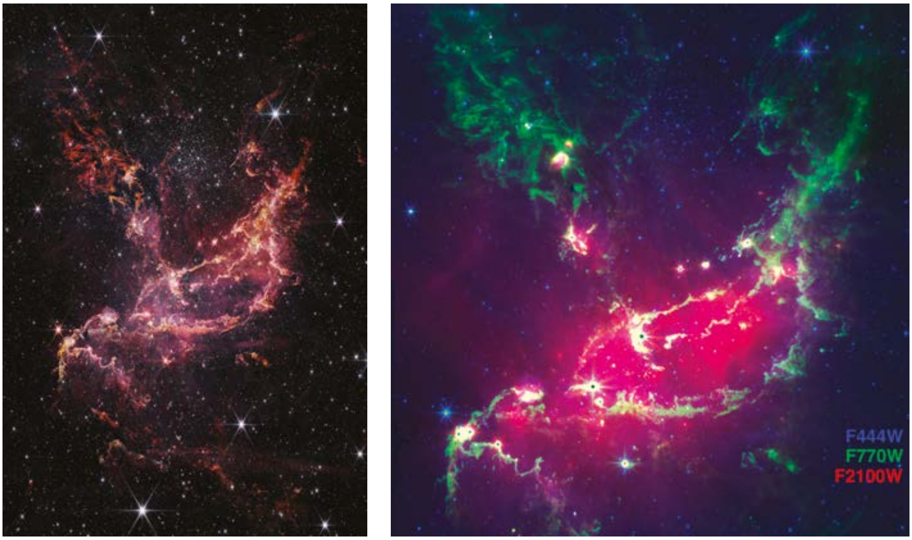

Figure 2. NGC 346 is the most luminous massive star formation region in the Small Magellanic Cloud. Left: a multi-band NIRCam image (Image credit: NASA, ESA, CSA, Olivia C. Jones (UK ATC), Guido De Marchi (ESTEC), Margaret Meixner (USRA); Alyssa Pagan (STScI), Nolan Habel (USRA), Laura Lenkić (USRA), Laurie E.U. Chu (NASA Ames)) Right: a NIRCam and MIRI 3 band image that traces the stars (F444W), the small carbonaceous dust grains – polycyclic aromatic hydrocarbons (PAHs, F770W), and warm dust surrounding massive star formation (F2100W) (Habel et al. 2024).

With JWST NIRCam images and photometry (Figure 2), Jones et al. (2023) discovered thousands of low mass young stellar object candidates, probably down to ~0.1 $M_\odot$. Candidate populations are identified with color-color and color magnitude diagrams that cleanly separate the young stellar objects and pre-main sequence populations from the old red giant branch stars and main sequence stars. Jones et al. highlighted the F200W-F444W vs. F115W-F187N color-color diagram which not only separates out the reddened young stellar objects, but also cleanly identifies the pre-main sequence stars as having Paschen-α (1.87 micron F187N filter) excess due to accretion. In the young stellar objects, the apparent Paschen-a excess is due not only to accretion but also to extinction/IR excess. The NIRCam photometry catalog has over 200,000 sources with the thousands of young stellar object candidates being redder and fainter than the other populations. Moving to the longer wavelengths of MIRI (Figure 2), the young stellar object population is prominent, perhaps even the dominant popula-

Figure 3. NGC 6822 images of the central stellar bar region. Top: NIRCam multi-wavelength images dominated by the stars Bottom: MIRI multi-wavelength image reveals the active star formation region, Spitzer I at the center of the stellar bar (Nally et al. 2023; Lenkic et al. 2023; Image credit: ESA/Webb, NASA & CSA, M. Meixner).

tion. Habel et al. (submitted) added the MIRI photometry and identified 833 young stellar object candidates. The discovery of the low mass young stellar objects with dusty disks and envelopes indicates that the building blocks for planets (dust) are present in systems with metallicities as low as 20% solar. The photometry from both NIRCam and MIRI provide an excellent definition of these young stellar objects using the Robitaille (2017) models. The model fits define luminosity, mass and evolutionary stage and are used to identify sources for MIRI medium resolution spectroscopy and NIRSpec multi-shutter array spectroscopy. This follow-up spectroscopy will reveal the composition of the dust, ice and gas in the circumstellar environment of these young stellar objects.

NGC 6822: Spitzer I Massive Star formation region

NGC 6822 is a nearby (490 kpc), isolated, low metallicity dwarf irregular galaxy with many active, optically bright star formation regions (e.g., Hubble I, III, IV, V and X). Studies with Spitzer by Jones et al. (2019) and Hirschauer et al. (2020) reveal the infrared selected young stellar objects in these star formation regions and also found a new region with 90 young stellar objects, dubbed Spitzer I. These studies hypothesized it to be a super star cluster in formation similar to the N79 region in the Large Magellanic Cloud. Our JWST observations targeted the central bar region that contains Spitzer I in addition to the bulk of stars in this galaxy (Figure 3). The larger purpose of this data was is to study dust evolution by taking an inventory of all the dusty stellar populations (dying stars and young stellar objects) in this galaxy with the same fidelity as the SAGE project accomplished for the Magellanic Clouds. Nally et al. (2023) have analyzed the NIRCam and MIRI photometry to identify ~900,000 sources and to study the dusty stellar populations with a particular focus on the evolved star population. Lenkić et al. (2023) have focused their analysis on the Spitzer I in which there were >82,000 individual sources, mostly from the NIRCam data. Using MIRI data in combination with NIRCam data, they identified 130 young stellar object candidates in the Spitzer I region from color magnitude diagrams. Using Robitaille (2017) models to estimate masses and luminosities, they find masses and luminosities of individually identified young stellar objects lower than those identified by Jones et al. (2019) and Hirschauer et al. (2020). JWST's superior angular resolution has resolved some of the Spitzer sources into multiple young stellar objects and in some cases found that they were background galaxies. Further analysis will be required to determine if the star formation activity is unusually high and warrants a super star cluster status.

I Zw 18: First census of dusty stellar populations

I Zw 18 is an extremely metal poor ($0.03Z_\odot$) dwarf galaxy, with active star formation 0.17-1 $M_\odot$ yr^{-1}. Located 18.2 Mpc away, I Zw 18 resides in the local volume of galaxies. Spitzer observations barely resolve I Zw 18 into a galaxy. JWST NIRCam and MIRI images of I Zw 18 have sufficient angular resolution to separate the stars from the dust and gas (Figure 4). Hence for the first time, we can study its dusty stellar populations. As can be discerned from the images, the shortest NIRCam wavelengths, F115W and F200W, have numerous sources and the numbers drop off with wavelength. We use the color magnitude diagram of F200W vs F115W-F200W to capture the source identifications. The longer wavelength NIRCam color-magnitude diagrams are used to inform which of the sources have significant infrared excess. Two populations are identified: 1. a young population with upper main sequence stars and candidate red supergiant stars and 2. a redder and older population of asymptotic giant branch, likely mostly carbon rich, stars. Younger sources tend toward the NW star-forming lobe, while older sources tend toward the SE star-forming lobe, suggesting staggered epochs of peak star formation. Mixed in with the second population are probably candidate young stellar objects. A cleaner understanding of the young stellar object population awaits a finalized MIRI catalog.

Figure 4. I Zw 18 is an extreme metal poor, blue compact dwarf galaxy. Top: NIRCam image combing F115W, F356W, and F444W. Bottom: MIRI image combining F1000W, F1500W and F1800W (Hirschauer et al. 2024).

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Illuminating Planet Formation: The Role of Ultraviolet Radiation from Massive Stars in the Physics and Chemistry of Planet Forming Disks

Olivier Berné

Institut de recherche en astrophysique et planétologie,
CNRS, CNES, Université de Toulouse, France

Abstract

The formation and evolution of (exo-)planets is one of the central questions in astronomy, and in the context of the JWST mission. The earliest stages of these processes take place in protoplanetary disks of gas and dust around young stars. It has become clear that most of these disks are born in the midst of a cluster of stars and are thus submitted to strong ultraviolet (UV) radiation. Despite its relevance to planet formation theories (our proto-Solar System disk formed in a cluster) very little is known about the role of this external UV radiation in the formation, evolution, and chemical composition of embryonic planetary systems. The unprecedented capabilities of JWST combined to ground based facilities now enables us to characterize protoplanetary disks irradiated by UV from the cluster.

1. Introduction

One of the most fundamental questions of astronomy concerns the origin of our planet: how it formed and how life emerged. In this context, special interest is directed toward the earliest stages of this emergence, specifically the point at which an interstellar cloud succumbs to gravity, giving rise to a young star encircled by an accretion disk of gas and dust. It is within these disks that planets take shape. These initial phases of evolution occur over a relatively brief period, just a few million years, in contrast to the potential longevity of a planetary system, which can persist for up to ten billion years. Nevertheless, these early stages hold paramount importance as they establish the initial conditions governing the physical properties (such as planetary size), chemical compositions (as the molecular content of planetary atmospheres and cores), and the potential for the emergence of life in the developing planetary system.

To study this early stage, astrophysicists observe the evolution of proto-planetary disks (PPDs) in star-forming clouds within our Galaxy. This field of research is one of the most active in astrophysics, as it addresses many fundamental questions: how does the gas and dust of PPDs lead to planet formation? Which fractions of the disk mass are accreted on the central star, transformed into planets, or blown away back to the interstellar medium by winds/jets? And, last but not least, what is the chemical composition of nascent planets and how is it acquired?

New generation telescopes, in particular the ALMA and NOEMA radio interferometers, and the JWST [1] are revolutionizing our understanding of the architecture, physical properties, and chemical composition of PPDs, enabling the direct observation of planet formation "in action". The vast majority of studies dedicated to PPDs are targeting nearby low-mass star-forming regions (Taurus, Ophiucus, and Lupus, at distances of less than 150 pc). This is, however, a significant observational bias, as the majority of low-mass stars form within stellar clusters that contain one or more massive stars [2]. These massive (OB-type) stars, being on a faster track formation path than solar-type stars, light up first and emit strong ultraviolet (UV) radiation: ionizing extreme ultraviolet (EUV; $E > 13.6$ eV) and dissociating far ultraviolet (FUV; ~ 6 eV $< E <$ 13.6 eV) photons. Hence, in environments where most low-mass stars and planets form, EUV and FUV photons are expected to be ubiquitous and thus to have a major impact on the physics and chemistry in these environments [3]. Such an impact is also applicable to the Solar System, which is known to have formed near massive stars [4, 5]. Despite the importance that UV may have during planet formation, there have been very limited studies focusing on its role in the chemical inventory at the moment when planets form. This is nonetheless of paramount importance, since the chemistry occurring during the early steps of planet formation determines the composition of planetary atmospheres, in the Solar System and in exoplanets.

FUV photons also heat the gas such that the thermal velocity of the particles exceeds the liberation velocity, creating winds which remove material from the disk [6]. This process, called "photoevaporation", can be fundamental in PPD evolution. The evaporation of disk material can modify the mass of gas available to form giant planets and blow away the small grains reducing the capability of the disk to form rocky bodies. The evaporation rate can be large enough to suppress planet formation [7].

The importance of UV-triggered evaporation in PPDs was first driven home by the discovery of almost two hundred irradiated disks, aka

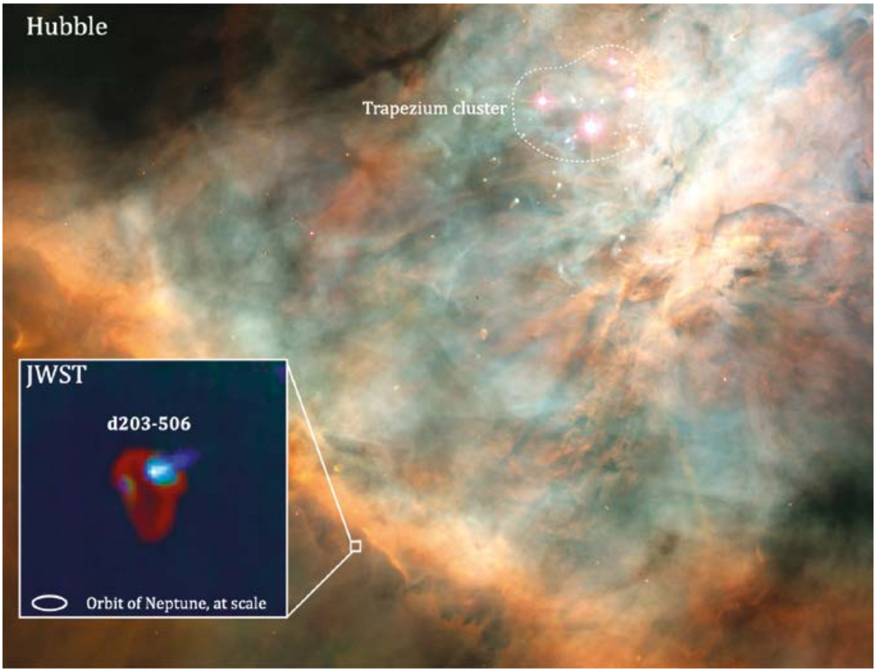

Figure 1. Hubble space telescope optical image of the Orion Nebula. In blue is [OIII] at 0.502 μm, green Hα at 0.656 μm and red [NII] at 0.658 μm. Zoom-in on the d203-506 disk. Red is the emission in the JWST-NIRCam 2.12 μm filter, tracing molecular hydrogen, blue is the 1.64 μm filter tracing the emission of [FeII], and green is the emission in the 1.40 μm broad-band filter that traces scattered light. Credits: HST Image: NASA/STScI/Rice Univ./C. O'Dell, JWST image: I. Schroetter/O. Berné et al. 2024.

"proplyds", in the Hubble Space Telescope images of the Orion Nebula cluster [8, 9]. Images of these systems have been improved using VLT instruments [10, 11]. These visible-light images are mostly sensitive to the hot uppermost atomic and ionized disk gas layers affected by EUV but prevent any detailed analysis of the bulk disk chemical composition and its dynamics. A major limitation stems from the large distances to the planet-forming disk present in large clusters containing massive stars, such as Orion, which is at 390 pc (according to the latest GAIA measurements [12]), that is about three times farther than Taurus or Ophiucus. This has made it more difficult to obtain spectroscopic observations of the various disk constituents (molecular gas, dust grains, and ice) in cluster environments and thus to characterize their disk physical properties and chemical composition.

2. JWST observations of protoplanetary disks within stellar clusters

Recent JWST observations conducted in the context of the PDRs4All[1] Early Release Science program [13] of Orion have uncovered a "Rosetta stone" of irradiated disks: the d203-506 system (Fig. 1, [14]). This is an example of a PPD (of ~ 10 Jupiter masses) around a low-mass star externally irradiated solely by FUV from nearby massive stars. The FUV photon flux is about 10^4 times higher than the radiation field around the profusely studied isolated disks in Taurus-like clouds, thus d203-506 is more representative of the irradiation conditions of the proto-Solar System disk [5]. Analysis of the H_2 line emission detected with JWST in d203-506 using

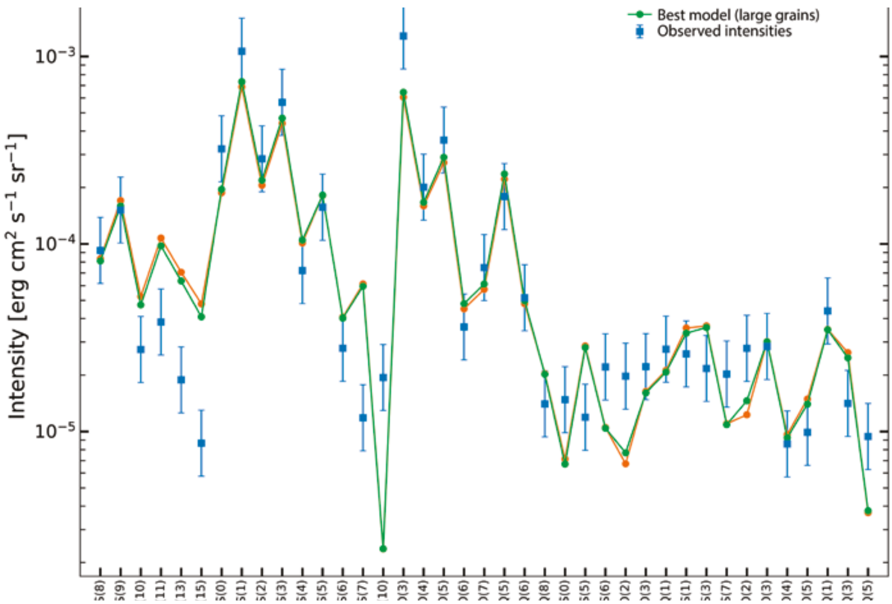

Figure 2. Comparison of the observed and modeled H_2 line intensities for d203-506. Observed intensities are the blue squares, the associated error bars represent a total uncertainty of 50%, as considered in the estimate of the χ^2 [14]. The instrumental uncertainties are smaller than the markers, and given in table S2. Modelled intensities for the best models obtained using the MEUDON PDR code are shown with the orange (for a model using small dust grains) and green circles, for models using small and large dust grains, respectively. Figure reproduced from [14] with permission.

[1] pdrs4all.org

the MEUDON PDR code (Fig. 2, [15]) allowed the first direct determination of the mass-loss rate associated with external FUV photoevaporation, about 10^{-7} solar masses per year [14]. This high rate has the ability to inhibit giant planet formation and illustrates the crucial role that external FUV can play in the context of planet formation. So far, however, this kind of detailed analysis has been conducted only towards this object, and additional studies are required to obtain a more general picture regarding the effect of FUV photons on planet formation.

The JWST (*NIRSpec+MIRI*) spectrum of d203-506 also reveals a rich photochemistry (Fig. 3). CH^+, a key intermediate in gas-phase UV-driven organic chemistry, which has been searched for many years, was detected for the first time in this object [16]. This discovery expands the possible routes available to build complexity in the early stages of planet formation. The detection of CH^+ relied on the unique quality of the JWST spectrum combined with major efforts from scientists in the field of quantum chemistry and laboratory spectroscopy. This synergy has led to a spectacular match between the JWST spectrum and predictions for CH^+, providing new constraints on the molecular physics of this species [17]. OH arising from the photodissociation of a hidden reservoir of water vapor has also been detected in this source (Fig. 3, [18]), highlighting how FUV photons truly govern the chemistry in the upper layers of this externally illuminated disk. The chemical signatures observed in d203-506, dominated by molecular ions and radicals, differ radically from what is so far observed with JWST in isolated disks (Fig. 3) where neutral species (H_2O, C_2H_2, etc.) dominate the emission [19, 20, 21].

It is however difficult to truly rationalize things in terms of types of environments. For instance, recent JWST results show that tracers of UV chemistry such as CH^+ can be observed in isolated disk (at least one, i.e., TW Hya, see contribution by I. Kamp in this volume). This may indicate an active photochemistry in this disk, perhaps driven by FUV photons from the central source. Conversely, a PPD in the NGC 6357 massive star cluster has been found to show emission compatible with the inner disk chemistry of isolated disks [22]. Therefore, while the results of PDRs4All on d203-506 do point to a change of paradigm with respect to the origin of chemical complexity in planet-forming systems (organic molecules can form in situ, triggered by the presence of FUV radiation, and not only be inherited as part of the ice grain-mantles formed in previous evolutive pre-stellar cloud stages) a lot remains to be done to disentangle the role of several chemi-

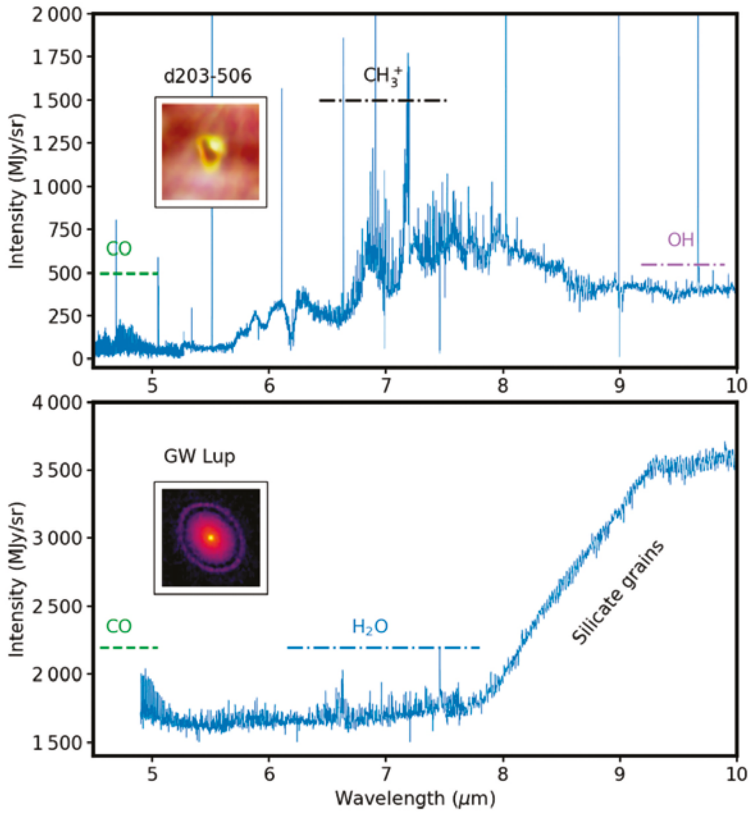

Figure 3. Upper panel: the rich mid-IR spectrum of the externally irradiated disk d203-506 in Orion taken by JWST/MIRI, and showing signatures of ongoing photochemistry [16]. The bright emission lines refer to H_2 and HI recombination lines. Lower panel: spectrum of the nearby and isolated disk GW Lupus [19]. Figure courtesy of I. Schroetter.

cal and physical processes involved in the formation planetary systems near massive stars within stellar cluster, and elsewhere.

Several irradiated disks are bright in the NIRCam images of the Orion Nebula [23, 24], hence future spectroscopy with JWST should clearly help unravel their physical and chemical properties. This may also help uncover an additional blind spot regarding the question of the presence and composition of ices in these targets. So far, even with the sensitivity of JWST, we have not been able to detect their absorption clearly in d203-506 or other UV irradiated disks. Specific observations with JWST should probably be designed, following what has been successfully achieved by the Ice Age ERS program [25] to detect these ices and determine their composition.

Another intriguing topic concerns the presence/absence of polycyclic aromatic hydrocarbons (PAHs) inside those disks or their winds. While PAHs are ubiquitous in the Orion Nebula [26, 27], they have only been detected clearly in one externally illuminated disk [28]. There are some hints of their emission at 3.3 μm in d203-506 (Fig. 3), however this will require a careful extraction including background subtraction, or dedicated observations with NIRSpec. In the context of the study of externally illuminated disks, radio interferometers such as ALMA are also critical tools: they provide the complementary data to probe the disk kinematics and colder phase chemistry [29, 30], and may also be used to search for the products of the FUV-driven chemistry revealed by the JWST. Ground based observations in the visible, using adaptive optics, also provide spectacular images allowing to probe the hot neutral and ionized layers of those disks [11].

Of course, the interpretation of these data will require models. Precursor models of irradiated disks, focusing on the dynamics, have been based at first on analytical expressions [4], and still continue to rely on semi-analytical approximations for some key processes (see e.g., [31]). Other disk models consider the impact of external FUV illumination on the disk chemical structure [32], but without including the photoevaporation dynamics and adopting a simplified radiative transfer and thermo-chemistry. While these studies have been key in starting to chart this new domain, their lack of detailed modeling of the interaction of external FUV photons with the disk material makes them inappropriate to directly interpret the JWST observations of numerous molecular and atomic lines. Conversely, 1d models such as the Meudon pdr code include details of the molecular physics necessary to successfully interpret the observations (Fig. 2) and provide the assessment of gas density and temperature, but do not relate at all to the local dynamics. Therefore, self-consistent models including dynamics, chemistry, and radiative transfer combined (in more than one dimension) will be required in the future.

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1 was made by O. Berné et Ilane Schroetter. Fig. 2 was made by E. Bron and published in [14]. Authorization of reuse license 5756960878235 provided by AAAS. Fig. 3 was made by I. Schroetter. I thank J. Goicoechea, E. Bron, and F. Le Petit for their help writing parts of this text.

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Early Formation of Planetary Building Blocks in Icy Molecular Clouds

Melissa K. McClure

The Ice Age ERS team, and MIDAS GO team Leiden Observatory, Leiden, the Netherlands

Abstract

How universal is life? Were special conditions required for the formation of pre-biotic molecules in our Solar System, or are they a natural outcome of star-formation? These are fundamental questions at the intersection of astrophysics, chemistry, and Solar System studies that can be addressed through analysis of astrophysical ices using laboratory and chemical models. I present initial results from two JWST programs that reveal how the chemical environment and physical structure of cloud ices influences their inheritance by protoplanetary disks. These results provide additional complications in the community's efforts to connect exoplanets' atmospheric compositions with their formation histories.

1. Introduction

Volatile elements, like Carbon, Hydrogen, Oxygen, Nitrogen, and Sulfur, are critical to the detectability of planetary atmospheres and the origins of life as we know it. These elements are mostly confined to a thin layer on the surface of Earth, where they were likely delivered by icy planetesimals, like Comet 67P. These comets brought much of these elements in as ices, particularly simple ices like water, carbon monoxide, carbon dioxide, methane, and ammonia, but also as larger molecules, including complex organic molecules like methanol and ethanol, as well as higher temperature, refractory materials like PAHs. Cometary ices most likely originated in the Sun's natal molecular cloud. However, the total amount and variety of ices inherited by planetary systems in this way is an open question.

In order to understand how common life could be in the universe, we need to quantify how much ice extrasolar comets and planets receive. These bodies are the final outcome of the star and planet formation process, which takes place over millions of years. Ices form at the beginning of this sequence in cold, dense molecular clouds, and they can be destroyed and refrozen multiple times as the icy grains infall from clouds towards disks around protostars, depending on the physical and chemical environments in the ices.

Therefore, we must understand the chemical and physical evolution of ices at each stage of the star formation process in order to understand the distribution of these elements in other planetary systems. We can break this problem down into three questions:

a) What are the chemical and physical properties of ice that forms in cold, dense molecular clouds?
b) How are ices chemically altered during the protostellar phase?
c) Which cloud ices are inherited by comet-forming regions of disks?

I summarize my teams' new results on ice properties in clouds and disks, while protostars are covered in other papers within these proceedings (Y.-L. Yang and L. Tychoniec).

2. Overview of JWST observing programs

Ices are detectable through features seen in mid-infrared spectroscopy in ground-based laboratory experiments. Motions between constituent atoms within the icy matrix produce broad spectral features at frequencies characteristic of each different solid material, e.g. the O-H stretch water ice feature seen at 3 microns. Full spectral coverage between 3 and 15 microns is valuable, as many ices have weak and strong features over this wavelength region, enabling a chemical fingerprint of the ices with sufficient instrument spectral resolution [1]. These wavelengths are only partially visible from the ground, due to absorption by Earth's atmosphere. Therefore, the new James Webb Space Telescope (JWST) is uniquely suited to capture such ice observations.

To answer the above questions, we designed two JWST observing programs in Cycle 1: the Early Release Science (ERS) program "Ice Age" and the GO program "Midplane Inclined Disk Astrochemistry Survey" (MIDAS). Ice Age maps ice evolution across each stage of star formation in a compact field within a single molecular cloud, Chameleon I. It uses a combination of NIRCam Wide Field Slitless Spectrograph to map the ices in the cloud in absorption against background star continuum spectra, with two targeted NIRSpec Fixed Slit and MIRI LRS spectra, respectively, to cover the full set of ice features for the two most extincted background stars in the cloud, near a young Class 0 protostar. Then we mapped an older Class

I protostar and Class II edge-on disk using the highest spectral resolution IFU modes of NIRSpec and MIRI.

3. Comprehensive volatile budget for molecular clouds

Our first results paper was published in January 2023 on the two full NIRCam/NIRSpec/MIRI background star spectra [2]. In the NIRCam imaging (see Figure 1), we see a large number of background stars, a jet from the hidden Class 0 protostar, the spectacular outflows from the older Class I protostar, and dozens of interloping galaxies. The targeted background stars are in a part of the cloud that is extremely cold, below 15 K, and the faint stars behind the cloud could not be detected previously without JWST's high sensitivity.

In the NIRCam/NIRSpec/MIRI spectra, we can clearly see all the major ice features of water, CO_2 and CO ice on the cold surfaces of the silicate dust grains within the molecular cloud. JWST's high sensitivity and spectral resolution allows us to detect sulfur bearing ice species like carbonyl sufide and sulfur dioxide for the first time in pre-stellar clouds, at only 2% of the total sulfur budget: much less than we expected. Performing both global

Figure 1. NIRCam mosaicked image of the central region of the Chameleon I molecular cloud. The Class I protostar, Ced 110 IRS 4 is seen in the upper left with a spectacular outflow. A jet from the hidden Class 0 protostar, Cha MMS1, is seen in orange near the center of the image. Stars located behind the molecular cloud are seen through the wispy, blue cloud material. Many faint galaxies are seen around the cloud edges. Image credit: JWST NIRCam, NASA, ESA, CSA, M. Zamani (ESA/Webb), Fengwu Sun (Steward Observatory), Zak Smith (The Open University).

fits to the whole spectrum using the ENIIGMA fitting tool [3] and local fits to individual features, we determined column densities for the major and minor ice species. While there is more ice at higher extinctions, the ice looks remarkably similar between the two sources. After accounting for the remaining gas phase CO, we can calculate the fraction of each elemental budget that is locked up in ices (see Figure 2). For all four key elements, ices make up less than half of the elemental budget that we see. For carbon and oxygen, some of the remaining budget may be in CO gas that has yet to freeze out. Similarly, nitrogen could be carried by N_2, which freezes out at colder temperatures than CO and has spectral features overlapping the strong CO_2 band at 4.3 microns. However, the remaining fractions of each budget may be carried by refractory solid species, e.g. FeS, silicates, or soot that are difficult to observe. We confirm that the refractory carbon cannot be distributed into frozen PAHs, as we do not see their spectral signatures between 3.4-3.5 microns.

4. Chemical environments of cloud ice formation

The formation sequence of ices may determine their chemical properties, through the layering of different species. Fortunately, the ice keeps a record of its history through the profile of each ice feature, and with JWST's high spectral resolution, we can resolve these profile variations to study how the ices formed.

Traditionally, ice has been thought to form in a sequence in which water forms first on grains, with other ices (CO_2, NH_3, and CH_4) forming in small amounts within the water matrix. Then CO gas catastrophically freezes out, allowing more complex species like methanol and ethanol to form by hydrogenation of CO. However, interestingly when we look at methanol, we see evidence for both a CO-rich component and water-rich component [2]. The former can be explained by traditional hydrogenation of CO,

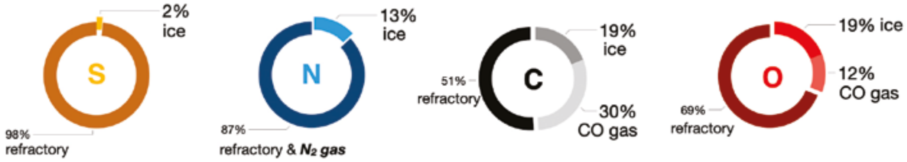

Figure 2. Fraction of elemental budgets for sulfur, nitrogen, carbon, and oxygen that are carried by the ices observed by JWST in this region of the Chameleon I molecular cloud.

but the water-rich component suggests that methanol and methane may be formed early by the H-abstraction processes investigated in recent works [4,5]. Ice Age also detected more complex species, including ethanol, for the first time in molecular cloud ices. They were best-fit by laboratory ice spectra mixed with water ice, suggesting that they, too, formed early before CO froze out. Such early formation is predicted by laboratory experiments and chemical models [6,7]. Similar complex species have been identified at later protostellar Class 0/I stages of evolution by JWST studies [8].

5. Physical cloud ice environment

JWST's superior sensitivity and spectral resolution also provide insight into the physical structure of the icy grains. Weak dangling OH features are detected towards eight lines of sight in the NIRCam WFSS data at 2.7 microns for the first time [2,9]. These features indicate either that the ices are porous or result from substantial mixing of other ices into the water ice matrix. Since the latter is indicated by the main ice feature profiles, both processes could occur simultaneously. In addition to these potential modifications of the ice matrix structure, distortions in the H_2O, CO_2, and CO ice profiles suggest that the ice grains have grown in these dense clouds, relative to their sizes in more diffuse clouds. Detailed radiative transfer fitting suggests the maximum grain size is nearly four times that of the ISM [10]. This is consistent with the growth predictions of dynamical models at timescales of 1 Myr and densities consistent with this part of the cloud. Larger grains have less bulk surface for chemical reactions and absorb less radiation. The combination of large, mixed ice grains may preserve more volatile ice species intact during the hot protostellar infall phase, leading to more cloud inheritance by protoplanetary disks.

6. Protoplanetary disk CHONS inventories

The first spectra of edge-on protoplanetary disks, from both the Ice Age and MIDAS programs, show absorption signatures of the major ice species, H_2O, CO_2, and CO, in addition to spatially resolved PAH emission signatures [11,12,13]. Since these disks are around low-mass T Tauri stars, with minimal external UV radiation that could excite the PAHs, this suggests that the UV produced by the stellar accretion shocks is sufficient to excite a thin layer of PAHs in the upper layers of the disk [12]. There is also spatially resolved jet emission seen via atomic lines in the IFU data; the same data is able to provide spatially resolved ice absorption spectra as well [11]. The vertical distribution of ices in particular shows a surprisingly large amount of CO ice at higher elevations in the disk than it would be expected to exist in the solid state. This could suggest that CO ice is trapped within either a H_2O or CO_2 ice matrix. Such trapping has been observed in laboratory studies [14]. Whether this CO is inherited from the cloud or produced in the disk is still an open question.

Comparing the depth of the ice features with those in the molecular cloud, at first these ice absorptions appear weaker, suggesting that ice has been lost to sublimation. However, the ice is locally saturated by scattered dust continuum emission. This prevents a straightforward conversion from optical depth into true column densities; using CO_2 isotopologues, the true column of CO_2 is a factor of 10 larger than the naive optical depths would suggest [11]. This result indicates that radiative transfer models are necessary in order to retrieve abundances [15].

The effects of ice mixing and scattering can be seen by combining radiative transfer models with updated optical constants for mixed ices. Grain surface models for mixed and layered ices can be used with these optical constants to produce new opacities for radiative transfer models. These models reveal that the ice feature profiles are strongly impacted by the degree of ice species mixing versus layering. Our team shows that it is not possible to have layers containing pure CO ice; rather CO must be trapped with CO_2 and H_2O [16]. Additionally, these disks appear to have enhanced ice abundances relative to the ISM, which could explain the pattern of enhanced ice giant atmospheric carbon abundances seen in our Solar System.

7. Conclusions

We have demonstrated JWST's capabilities for measuring the elemental budgets and chemical and physical environment of ices in molecular clouds and protoplanetary disks. The mixing of ices emerges as a key result, both in clouds and disks. In clouds, it allows greater chemical complexity at earlier stages, using up a larger fraction of the CHONS volatile elemental budget, and possibly aids in the survival of the most volatile ices as they heat up when entering the disk. Additionally, the potentially large refractory solids fraction of the CHONS budget in clouds could increase CHONS solids survival during infall. Within the disk, taken to the extreme, the trapping of CO in mixed ice matrices could allow carbon-rich ices to survive closer to the star, potentially erasing the presence of a CO snowline. Ultimately this should impact the compositions of planets forming in these disks.

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Protostellar Chemistry in Ice and Gas

Yao-Lun Yang
Star and Planet Formation Laboratory, RIKEN, Japan

Abstract

JWST observations of the formation and evolution of ices at the earliest stages of the formation of new stars are presented and comparisons with our own young solar system are made. The detection of complex organic molecules in ices is highlighted and their relation to complex molecules in the gas discussed.

Background

Protostellar chemistry, while it may appear distant from that on Earth, has substantial implications for planet formation as well as the chemical environment in the early stages of the Solar system. Comets, which are thought to be a major reservoir of Earth's oceans, likely inherit heavy water (deuterated water) from the formation stage of our Sun because of their similar abundance to that in young protostars, classified as Class 0 and I protostars (Cleeves et al. 2014; Tobin et al. 2023; Nomura et al. 2023). For more complex molecules, recent observations start to routinely detect gaseous organic molecules in protostars, some of which also have similar compositions as that in comet 67P/Churyumov-Gerasimenko, which is the most well-studied comet (Drozdovskaya et al. 2019), further emphasizing the need of understanding protostellar chemistry to realize the formation and evolution of our solar system.

Protostellar environments are cold (~10-20 K; ~250°C below zero) and low-density (10^6-10^8 cm^{-3} compared to ~10^{19} cm^{-3} in Earth's atmosphere at surface), making them uniquely different from terrestrial chemistry. In such environments, a substantial amount of gas freezes out onto dust grains, forming ice mantles where molecules have greater opportunities to react. Thus, the reactions that take place on the ice mantles and between gas and ice drive the chemical evolution at the protostellar stage. In the last decade, interferometric observations at sub-millimeter wavelengths enable a leap of discovery in the gas-phase protostellar chemistry, detecting rare isotopologues and complex organic molecules (so-called COMs; Jørgensen et al. 2020 and the references therein). Using these gas-phase measurements, we can infer the chemical reactions on ice mantles if the gas simply sublimates from ice at high temperature without any additional gas-phase reactions. However, this assumption greatly simplifies the reality and must be tested by direct observations of ice.

Measuring the absorption spectral features at infrared wavelengths is the most accessible way to characterize the ice compositions. Radiation coming from the central protostar penetrates the icy molecules in the cold dense gas around the protostar (the so-called envelope). In this process, parts of radiation could be absorbed due to the vibration of the icy molecules, leaving distinct absorption patterns on the observed IR spectra, which allow us to identify the species as well as quantify their abundances. Detecting ice absorption requires high-sensitivity IR observations, especially toward young protostars where the dusty envelope heavily attenuates the emission. Prior to the arrival of JWST, ice measurements relied on the Infrared Space Observatory (ISO), the AKARI Space Telescope, and the Spitzer Space Telescope combined with ground-based data (e.g., Whittet et al. 2001; Öberg et al. 2011; Kim et al. 2022). Because of the limited sensitivity, these observations detect mostly simple ice species, including H_2O, CO, CO_2, CH_4, and CH_3OH, toward the sources with sufficiently bright continuum. Thus, while we obtained a general picture of ice compositions and their evolution in protostars, further studies on ice mixtures in various environments and the search for rare isotopologues and complex organic ice species were on hold until JWST.

Protostellar Ice Chemistry in the Era of JWST

Since the start of JWST's science operation, it has revolutionized our understanding of ice chemistry in protostars with its sensitivity, which is about two orders of magnitudes better than that of Spitzer, enabling ice measurements with exquisite details of the absorption features toward fainter sources. The first spectrum of an extremely young protostar, IRAS 15398-3359, showed exactly what we anticipated (Yang et al. 2022; Figure 1). Absorption features are clearly detected by the MIRI instrument (Rieke et al. 2015; Wright et al. 2015) with their shape unambiguously traced with high fidelity. We identified the commonly known ice features, including the H_2O bending and libration modes, CH_3OH, CH_4, and NH_3. Furthermore, we detected absorption features likely due to COMs at 7-8 μm, which were only hinted at in Spitzer observations of this source (Boogert et al. 2008). In Cycle 1 of JWST's science operation, several other spectra of protostars with similar quality are also taken (Beuther et al. 2023; Federman et al. 2023), which will play a critical role in the first stage of reshaping our understanding of ice chemistry in protostars.

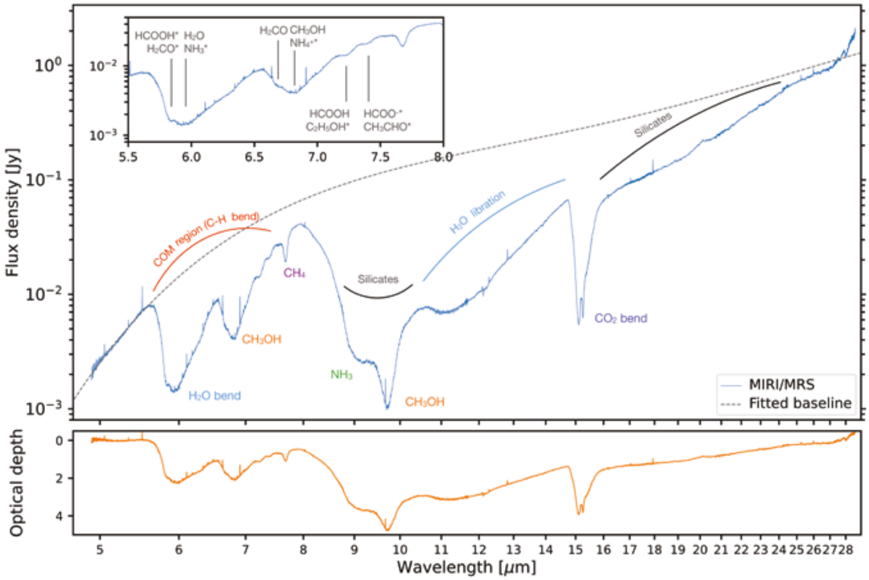

Figure 1. JWST MIRI/MRS spectrum of IRAS 15398-3359 with ice features labelled (top panel; Fig. 1 in Yang et al. 2022). The inset figure shows a zoom-in view of the 5.5-8.0 μm range. The bottom panel shows the optical depth spectrum derived with the estimated continuum in the dashed line.

The shape of ice absorption features is sensitive to the ice mixture as well as its structure (amorphous or crystalline). Changes from amorphous to crystalline and the mixing ratios often suggest ice processing in the past. Thus, constraining the ice morphology and their mixing ratio unveils the history of ice evolution. The pure CO_2 ice feature is commonly considered as a signature of thermal processing (i.e., experiencing high temperature in the past), which can be easily identified by its narrow absorption feature. In a sample of five protostars, Brunken et al. (2024) decomposed the $^{13}CO_2$ ice feature detected by JWST NIRSpec observations, detecting pure $^{13}CO_2$ in the two most luminous protostars, which is consistent with the scenario of thermal processing. Previous studies of pure CO_2 ice mostly rely on the 15 μm bending mode because the 4.27 μm stretching mode is usually saturated. But the bending mode is mixed with silicate and H_2O ice features, introducing uncertainties to the analysis. Thus, the decomposition of $^{13}CO_2$ demonstrated in Brunken et al. (2024) presents a new avenue to characterize the thermal history of protostars, which is only possible with JWST's sensitivity.

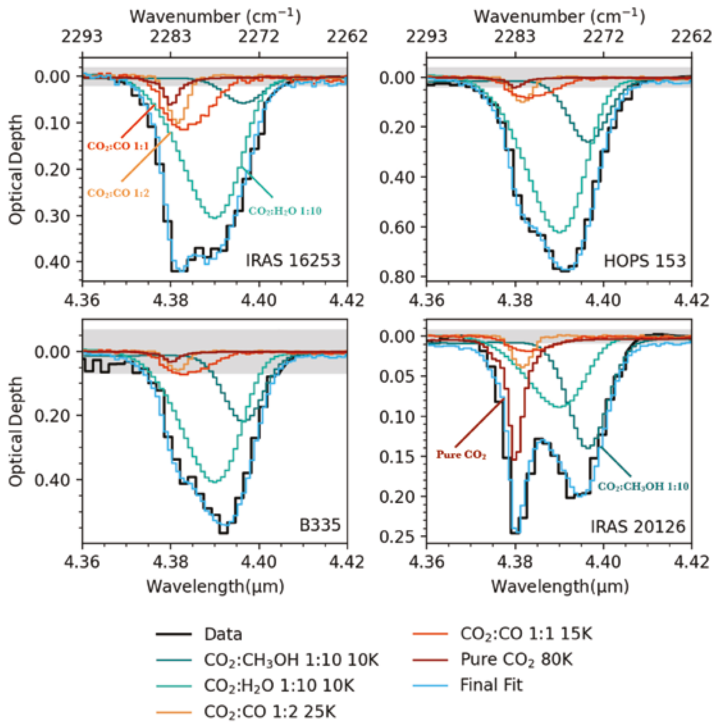

Figure 2. A subset of $^{13}CO_2$ ice features shown in Fig. 3 from Brunken et al. (2024) with the best-fitting ice mixtures indicated.

Icy Complex Organic Molecules

In recent years, detection of gas-phase COMs has become common in embedded protostars. However, while some protostars have abundant gas-phase COMs (so-called COM-rich), many protostars show no sign of COM emission (so-called COM-poor). The contrast of their gas-phase chemical signatures begs the questions: Do these protostars go through distinctively different chemical evolution? And what processes govern the chemical evolution in the early phase of star formation? Gas-grain reactions on icy grains are the major pathways to form COMs; thus, it is imperative to directly probe the ice, searching for signatures of icy COMs. In the CORINOS program (PI: Y.-L. Yang), we targeted four protostars with and without abundant gas-phase COMs to determine whether the diversity in gaseous COMs originates from ice or is simply due to the efficiency of ice sublimation. As shown in Figure 1, detailed ice features are detected along with

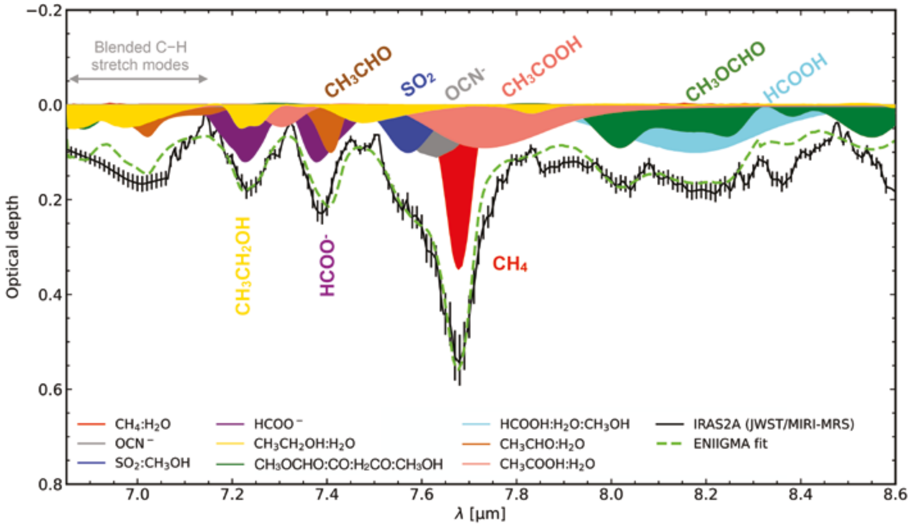

Figure 3. The ~7-9 µm spectrum of NGC 1333 IRAS 2A along with the best-fitting ice compositions taken from Fig. 6 Rocha et al. (2023).

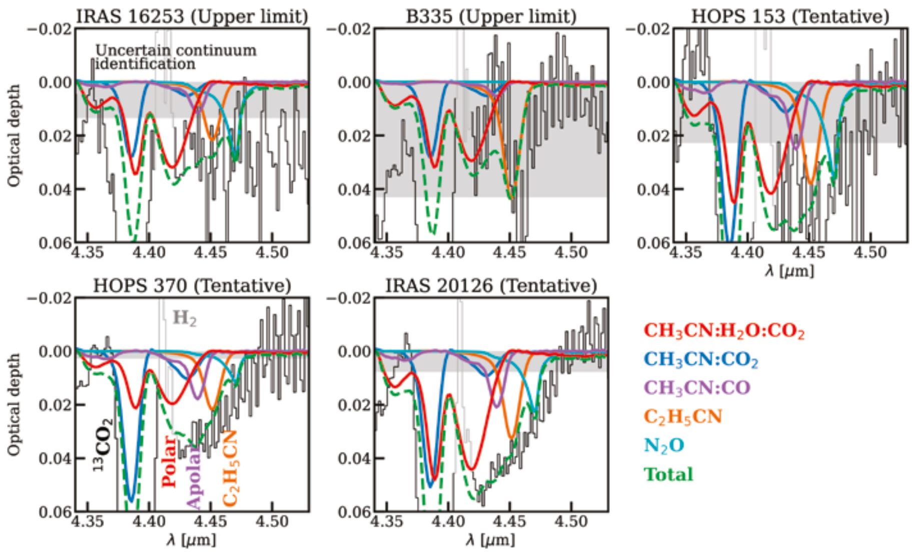

Figure 4. Tentative detection of CH_3CN in Fig. 3 of Nazari et al. (2024).

tentative detection of icy COMs. We also detect likely signatures of icy COMs in all four sources regardless of the presence of gaseous COMs. If these signatures represent icy COMs, our preliminary analysis suggests a similar abundance in ice- and gas-phase, hinting a direct connection between two phases (Kim et al. in prep.; Yang et al. in prep.).

Absorption features of icy COMs are also detected by other programs. In the JOYS+ program, which combines two Guaranteed Time Programs led by E.F. van Dishoeck and M. Ressler, Rocha et al. (2023) present icy COM signatures toward a high-mass and a low-mass protostar, supported by modeling of their ~7-9 µm spectra (Figure 3). Several COMs are detected and all of them are O-bearing COMs. The abundances of several COMs in ices are consistent with those in the gas-phase as well as the abundances of Comet 67P, suggesting an inheritance. Their analysis also highlights systematic uncertainties due to the challenge of determining a continuum without absorption features, which could substantially affect broad ice features, such as CH_3OCHO.

N-bearing COMs are also searched using JWST spectroscopic data. Before JWST, there is no detection of N-bearing COMs. Using the same dataset of Brunken et al. (2024), Nazari et al. (2024) found tentative detection of CH_3CN ice in three protostars and derived upper limits in another two protostars. Despite being heavily blended with the C-N stretching mode of other N-bearing COMs, CH_3CN ice feature is likely to present in HOPS 153, HOPS 370, and IRAS 20126+4104, the three more luminous protostars in the five-sources sample. They also found tentative evidence of enhanced icy N-COM abundances in warmer ice. These studies of icy COMs portray a promising picture of identifying unique absorption features of COMs and connecting the ice chemistry to what we have learned from gas-phase measurements.

Concluding Remarks

We are only in the second year of JWST's science operation. The selected JWST's Cycle 1 results already show the scientific questions that we can address only because of JWST. These observations highlight the need for sensitivity; they also demonstrate the complexity in constructing a robust ice inventory, contributed by various mixing ratios and the limitations inherited from laboratory measurements. We are now standing at a vantage point where we can characterize the changes of mixing ratios of simple ice species and their processing. We also start to detect COMs in ice and quantify their abundances. These first results are the first step in revamping our understanding of ice chemistry and their evolution in the protostellar stage.

Acknowledgement

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Formation of Sun-Like Stars in the JWST Era: Protostellar Outflows, Jets, and Disks

Łukasz Tychoniec
Leiden Observatory, Leiden University, the Netherlands

Abstract

Protostellar outflows and jets are one of the first signposts of a new star being born. We discuss here the revolution brought by the James Webb Space Telescope (JWST) to the studies of these phenomena with an emphasis on the synergies with other state-of-the-art observatories. Atomic and ionized content can be revealed with JWST NIRSpec and MIRI instruments at unprecedented detail. In concert with submillimeter observations, the complete chemical content of the jets can be studied. Young disks are also objects of active research, as the nascent location for planets. JWST reveals warm molecular gas in the warm inner disks elucidating the contents of gas that feeds the young planetary systems.

1. Introduction

The formation of stars is a complex interplay of different physical processes. Infalling gas and dust fuel the formation of the protoplanetary disk. At the same time, supersonic jets and wide-angle winds are ejected from the system. Those processes are most pronounced in the earliest stages of star formation, in the protostellar stage (up to 500,000 years since the beginning of the star-formation process). Their accretion is the most vigorous, and outflow activity is at its peak. However, this stage is also very well hidden in the dense molecular cloud from which the protostars gain material. Near- and mid-infrared (IR) wavelength range unlocked with the James Webb Space Telescope (JWST) is therefore essential, as it probes hot gas while at the same time offering to peer through the layers of dust, blocking light at shorter wavelengths. Since the beginning of JWST science observations, several works on protostellar sources have been published. Here, we present studies of emission lines from the outflows and jets coming from the compact regions close to the protostar and hot molecular gas from the young, freshly formed disk. They shed light on physical conditions and processes relevant at the onset of planet formation in the first stages of the star formation process.

1. Jets and outflows from the youngest protostars

Apart from being one of the first signposts of ongoing star formation, protostellar jets, and outflows are also important in extracting the angular momentum from the system, allowing the accretion to continue. Jet activity is also variable in nature, showing periodic knots (or bullets), which are explained by the variable nature of the accretion process. Therefore, they carry a fossil record of the accretion history of the system (Vorobyov et al., 2018). Finally, jets and winds are being launched from the inner regions of the protostellar system, in the inner few au. Therefore, they potentially carry information on conditions and composition of the inner disk, which are otherwise difficult to reveal in the youngest systems. Decades of multiwavelength studies of protostellar jets increased our understanding of their importance and the physical conditions that they experience. ALMA and single-dish tele-

Figure 1. Three-colour image of HH211 outflow with NIRCam instrument on JWST, F335M (blue), F460M (green), and F470N (red) filter (Ray et al., 2023). Credit: ESA/Webb, NASA, CSA, Tom Ray (Dublin).

scopes revealed the molecular content of protostellar jets (Tafalla et al., 2010; Tychoniec, et al., 2019; Podio et al., 2021). However, the atomic and ionized components are much harder to study in young, embedded systems. Those tracers are present in the optical and infrared regime where young protostars are heavily embedded in their natal envelopes. Therefore, they are best studied in the mid-infrared wavelength regime where extinctions are lower than at the optical range. Only with JWST, launched in December 2021, are studies of this component at sufficient spatial resolution and sensitivity possible. Below, we discuss key discoveries in this area.

One of the key questions is how jets and outflows evolve across protostellar lifetimes. JWST pushed the limits of those studies, discovering an ionized jet in a protostar in a quiescent accretion state. IRAS 16253 is a protostar with bolometric luminosity of 0.2 $L_\odot$. Both JWST instruments with capabilities of integrated field unit (IFU) – MIRI and NIRSpec, detected and mapped ionized iron [Fe II] launched at velocities of 170 km s^{-1}, within the program Investigating Protostellar Accretion (IPA) – an open time JWST Cycle 1 program (PI: Tom Megeath) aiming to study protostars across the bolometric luminosity parameter space. Narang et al. (2024), studied the shock conditions in this jet and quantified the jet ejection rate to be on the order of 10^{-10} $M_\odot$ yr^{-1}. With a corresponding study of accretion rate based on OH emission, Watson et al. (in prep.) quantified the amount of material accreted by a protostar at 10^{-9} $M_\odot$ yr^{-1}. This is very low compared to typical accretion rates of Class 0 protostars in the range of 10^{-6} – 10^{-7} $M_\odot$ yr^{-1} (Yen et al., 2017). Despite this quiescent accretion status, the protostar launches a jet nonetheless. This is an important piece of information: even the most quiescent protostars can propel a fast, ionized jet.

Interestingly, the IRAS 16253 outflow shows no traceable molecular emission, neither with JWST nor at longer wavelengths with ALMA. The contrasting example is another Class 0 object, HH211, in Perseus. This protostar is known for its knotted, high-velocity jet in CO and SiO, observed with sub-mm facilities (Lee et al., 2007). JWST images taken with NIRCam revealed a new, spectacular face of this iconic flow (Ray et al., 2023, Fig. 1). It appears that the jet, in this case, is mostly molecular, not showing a prominent ionized component. This suggests that shock velocities in this flow are very low. These observations also allowed us to shed new light on a more than decade-long mystery. With the aid of the NIRSpec instrument, the extended emission observed with Spitzer at 4.5 μm, called 'green fuzzies,' are now confidently attributed to the carbon monoxide (CO) rovibrational band.

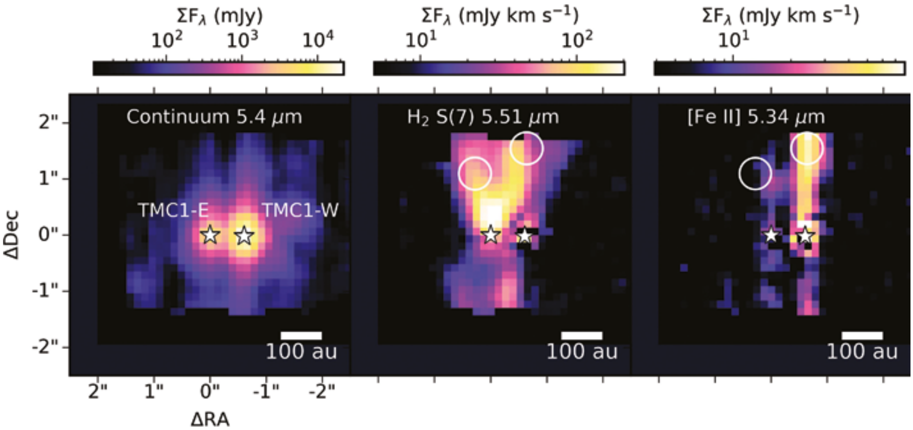

Figure 2. Continuum emission at 5.4 μm, integrated emission of H2 0-0 S(7) line at 5.51 μm in colorscale and [Fe II] line at 5.34 μm in color scale (Tychoniec et al., 2024).

More outflows from young stars are being observed as part of the CORINOS open-time program (PI: Yao-Lun Yang), with a first example of IRAS 15398, showing extended emission from [Fe II], [Ne II], and compact emission from [S I] (Yang et al. 2022, Okoda et al. in prep.). The largest sample of protostars in the first Cycles of JWST is observed with a guaranteed time observation program of the MIRI European Consortium JOYS (JWST Observations of Young protoStars; PI: Ewine van Dishoeck). First results on the high-mass protostar IRAS23385 reveal that such more massive sources share similar characteristics in jet and outflows tracers as the low-mass protostars (Beuther et al., 2023; Gieser et al., 2023).

An exciting example from the JOYS sample is a more evolved protostar TMC1, which shows the potential of the MIRI instrument to resolve action in close binary systems and promises studies in outflow time evolution. Tychoniec et al. (2024), show that the two companions propel strikingly different outflows: TMC1-E shows prominent H_2 emission, indicative of disk wind, while TMC1-W reveals a collimated and ionized jet (Fig. 2). With the aid of ALMA, able to trace colder, infalling gas, the difference in the outflow mechanism can be attributed to different accretion processes – TMC1-E dominated by inflow from the envelope to the disk, fueling the disk wind, and TMC1-W powering the jet that is related to the disk-to-star accretion process. The accretion can be traced with MIRI, covering several hydrogen recombination lines. This capability will enable studies of accretion in very embedded sources (Beuther et al., 2023).

TMC1 is also an excellent showcase of the sensitivity of the MIRI instrument, enabling detailed studies of the chemical composition of protostellar jets. Refractory elements like carbon, nickel, and cobalt are detected in TMC1-W. Neon and argon – noble gases with high ionization potential prominently detected in TMC1-E – suggest that the chemical content of jets can dramatically vary from source to source (even at the same evolutionary stage), either due to different launching radius or chemical composition at the launching point. Mapping jet tracers along the axis will be particularly powerful in revealing shock conditions along the flow and is being done for several targets (HH211, Caratti o Garatti et al. in prep.; BHR71, Tychoniec et al. in prep., L1448-mm, Navarro et al. in prep.).

2. Embedded disks

Seeds of planets are likely formed in the embedded disks around young protostars (Tychoniec et al., 2020). Knowing the conditions in those disks is therefore important to constrain the initial chemical and physical conditions of planet formation. They are vastly different from their older counterparts: warmer, more compact, and showing very few dust structures (van 'tHoff et al., 2020; Maury et al., 2019; Ohashi et al., 2023). ALMA provided a wealth of information on the structure and chemical content of those young disks. However, the innermost regions remain elusive because warm gas there is not well probed by ALMA cold gas tracers. Infrared wavelengths are crucial to uncover those inner few au regimes, most importantly, as those are expected regions where planet formation kicks off.

Here we present key results on the molecular lines from the embedded disks with JWST. JWST/MIRI delivered the first detection of the 7.3 µm SO_2 ro-vibrational transition in a protostar (van Gelder et al., 2024). While sulfur-bearing species are typically associated with shocked gas, suggesting an accretion shock from the envelope onto the disk, in the case of IRAS 2A, the emission from a warm disk heated by the central protostar is most likely. Importantly, infrared emission lines show clear signs of radiative pumping. Warm CO and H_2O gas has been detected in IRAS 15398 (Yang et al. 2022, Salyk et al. in press.), possibly coming from the inner regions of the disk although a more extended outflow or wind origin is not excluded. In a high-mass protostar example Francis et al., (2024) detected large reservoirs of hot organic gas (CO_2, HCN, C_2H_2). However, the temperatures and emitting areas indicate an extended warm disk's surface instead of the inner disks. In the case of CO, only high-energy transitions can be detected with MIRI. It is much better sampled in the NIRSpec wavelength range. In work of Rubinstein et al. (2023), IPA sources are studied with the CO emission lines in NIRSpec. So far, the picture emerging from the young disk observations with JWST is very different to that from Class II disks, which are very rich in water and small organic molecules (Grant et al., 2023).

3. Concluding remarks

Studies of the first stages of star and planet formation are experiencing an impressive boost with JWST observations. Unlocking the complete atomic and ionized content of protostellar jets opens studies of the physics and chemistry of shocks around protostars. Powerful synergies between observatories at different wavelengths, especially ALMA, will lead to a better understanding of accretion and ejection processes. At the same time, observing the evolutionary changes of the inner disk gas content from younger to older disks delivers insights on the onset of planet formation.

Acknowledgements

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SESSION 5: SOCIETAL IMPACT OF THE JAMES WEBB SPACE TELESCOPE

Session 5: Societal Impact of the James Webb Space Telescope

Massimo Stiavelli
Space Telescope Science Institute, USA

Panel discussion members

- Matt Mountain, *Association of Universities for Research in Astronomy, USA*
- Gillian Wright, *UK Astronomy Technology Centre, UK*
- Kevin Govender, *IAU Office of Astronomy for Development, South Africa* (Remote)

Introduction

JWST is a flagship mission, one that can be done only once in a generation. The former NASA Associate Director for Science, Dr. Thomas Zurbuchen, referred to flagship missions such as the James Webb Space Telescope (JWST) as "civilization-scale science", i.e. science that not only changes what we know, but also how we think about our place in the cosmos. It is then not a surprise that there are multiple dimensions to the societal impact of JWST. First of all, building something on the scale and complexity of JWST requires an extraordinary effort. In his contribution, Matt Mountain reviews the type of support that was needed to build JWST. JWST is extremely visible and its great success and visibility enables societal impacts in technology and inspiration as discussed by Gillian Wright in her contribution. Finally, JWST and astronomy in general can be inspiring and have a broad impact on education and using astronomy as a tool for development, especially in the global south. This is discussed by Kevin Govender in his contribution.

Matt Mountain's contribution leaves open the key question "*what kind of society builds something like JWST*?" I think it is a society that still values truth and beauty. The world around us is increasingly divided. However, the science results of JWST seem to unify people and give a positive example of international collaboration and show what we can do if we set our minds to cooperation and positive goals. Clearly, this is a powerful starting point to attempt to improve education and society.

Societal Impact of the James Webb Space Telescope and Astronomy

Matt Mountain
Association of Universities for Research in Astronomy, USA

The phenomenal success of the James Webb Space Telescope has not just impacted astrophysics but has reminded all of us that audacious science missions undertaken by our space agencies (NASA, ESA, and the CSA) can also have considerable public impact. None of this was a foregone conclusion. The original costs of JWST were greatly underestimated, as were its technical complexity and the program management challenges. Dennis Overbye later wrote in the New York Times, *"I have a confession to make: I underestimated the James Webb Space Telescope. For years, as NASA struggled to build the designated successor to the Hubble Space Telescope, I came to think of the Webb as a problem child, ever-delayed, swallowing dollars that could have gone to other telescopes and space missions… It was an infrared telescope, which would give astrophysicists a new angle on what was going on out there, but I didn't think it could have the impact Hubble had. I was wrong" (NYTimes, 23rd August 2022).* This summary for The Pontifical Academy of Sciences meeting on JWST summarizes three lessons I have learned from being with the mission since 2003, which I believe reflect JWST's societal impact. I then posed a question at the end, which we needed more time to cover in our discussion.

1. Humility

As Figure 1 below shows, we considerably underestimated what it would take to get JWST launched. At any one moment, after each crisis, there was a genuine belief that the costs had been estimated corrected – until we had not. Realizing and funding audacious, one-off missions like this requires considerable programmatic humility.

Surveying the recent results coming from JWST: the confirmation of the Hubble Tension, the unexpected nature of early galaxy evolution, and the difficulty of detecting the thin atmospheres of rocky planets around M-stars, the Cosmologist Joseph Silk's wise adage rings true (which I have modified): "*Humility in the face of the persistent great unknowns is perhaps the true contribution JWST has to offer*".

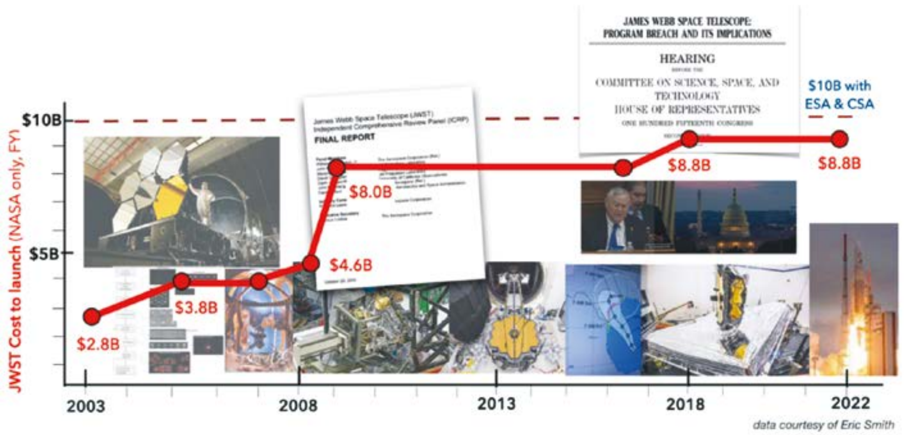

Figure 1. The time evolution of NASA's costs to launch JWST, courtesy of Eric Smith, NASA HQ.

2. It takes a village, which, in JWST's case, is a small town

Designing, building, commissioning, and now using JWST took, and now takes, multiple teams – multidisciplinary teams. It is now common for teams to apply for, use, and exploit JWST data and science –more so than in the Hubble era. Notably, the type of team needed today is critical for JWST-scale endeavors (Figure 2).

In his blog *My Little Hundred Million*, the author Malcolm Gladwell identified two types of teams: a "strong-linked team" where the strength of the superstar matters, as in basketball. However, our experience on JWST has demonstrated again and again that success takes a "weak-link team" (as in non-US Football) where the strength of the overall team is key, dependent on the "weakest link". Modern science at the JWST scale is very much a weak-link team undertaking.

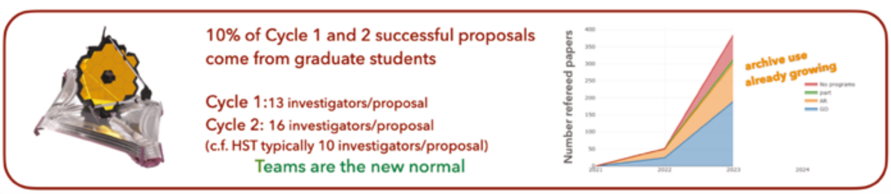

Figure 2. Flattening Science: lowering barriers to participation, dual anonymous review, open archives, and teams.

3. The importance of the Idea

An estimated 20,000 people worked on JWST, and for some, this program consumed most of their professional careers: why? Why do JWST images and results inspire its creators to look to art and awe people from all walks of life? Walter Isaacson, in his book *The Innovators*, claims it takes *"arts [to] intersect with the sciences"* and *"a rebellious sense of wonder"* for innovation to flourish and draw people in. And a constant churning of innovation has been characteristic of the JWST endeavor. However, given the long periods of just "sheer slog" to get through endless reviews, constant testing, and continual technical and programmatic audits, simply having the opportunity to "be innovative" has not held people to JWST; it has taken something more. In talking to the engineers, programmers, technicians, program managers, and all the other people drawn to JWST and its results, the sentiment is (I believe) captured in this verse from The Fleet Foxes, *"I was raised up believing I was somehow unique. Like a snowflake distinct among snowflakes, unique in each way you can see. And now, after some thinking, I'd say I'd rather be a functioning cog in some great machinery serving something beyond me".*

Constantly and consistently articulating the scientific promise of JWST, describing the role the mission will play in unraveling some of the most profound questions we have about our Universe, and committing to sharing JWST's challenges and (finally) its results widely, has been critical to getting JWST launched and working. This story has been as essential as its science requirements, technology breakthroughs, and our various Nations' willingness to fund such a unique project. The "idea" of JWST was the key to its resiliency and success.

Conclusion

These are personal reflections, but as Ewine van Dishoeck and I discussed at the airport lounge in Rome, a key question was left unanswered, *"what kind of society builds a JWST?"*

Societal Impact of Astronomy and JWST

Gillian Wright
UK Astronomy Technology Centre, UK

Excited by our scientific results and the accessibility of the night sky for everyone, we instinctively think of the public engagement, outreach, and educational opportunities that astronomy and JWST provide when asked about societal impact. All stakeholders in the JWST mission have highly effective programmes in this area. In public talks and school programmes people clearly relate to the inspirational nature of the images and science now being produced and to the team work and international collaboration needed to bring JWST to launch. In this summary to set the scene for discussing the societal impact of JWST and astronomy, I indicate some of the other types of societal impact. For our governmental agencies that invest in missions the interest is very often societal impact in the sense of economic impact and progress. Below some are some examples of different types of such economic impact.

A good illustration of the importance of economic impact from astronomy missions to our governments is the ESA "Juste Retour" system. Each ESA member state contributes to ESA with the expectation that this investment is returned to their country via industrial contracts and economic impact. ESA operates an accounting system that tracks these benefits in relation to the investment over a number of years which is carefully monitored by the member states. Corrective actions are implemented by ESA in terms of which countries contracts are placed in, or the nationalities of people recruited into ESA employment, to keep the national returns in an acceptable degree of balance.

Historically, of course, astronomy has been a key and well-known enabler of agriculture, the measurement of time and navigation. Now the technologies we develop to study the Universe still have many applications and benefits, with a relatively recent and on-going example of very broad societal-economic impact being underlying protocols which enable Wi-Fi having their origin in radio astronomy (https://blog.patentology.com.au/2012/04/story-behind-csiros-wi-fi-patent.html).

Considering JWST in the context of economics, the construction of the mission was a high-tech investment by government agencies in skills and people. An estimated twenty thousand engineers, technicians and scientists contributed to the mission for 25 years, spread across hundreds of distinct companies, institutes and universities in 14 countries, 29 US States and Washington DC. Through their work solving the complex engineering challenges of JWST, all of these people developed skills and knowledge that moves into other areas when people move to new employers, or the companies win more or different contracts. To trace this in specific detail at the level of an individual's career is very difficult, but perhaps it would be helpful to try and develop some examples or case studies?

More broadly, companies sometimes aggressively compete for contracts from NASA/ESA/CSA because the work is seen as prestigious, challenging and it both develops and demonstrates their capabilities. This means that the societal impact in terms of the economic value of a NASA contract to a company can be substantially greater than the nominal contract value if it helps the company to compete for future work. Anecdotal evidence for this type economic importance and impact can be seen in the numerous small parts of the MIRI instrument that have appeared on the "glossy front page" of marketing brochures and at trade fairs around Europe.

To build a mission like JWST that can explore fundamental questions about the universe requires the development of new technologies, pushing at the frontiers of engineering, and new expertise. Societal impact comes from numerous multidisciplinary applications of such "astronomy techniques" in other areas of science. This is more extensive, and can be more subtle, than simple re-use of "a technology" and is not necessarily the creation of a "spin out company". Collaborations between engineers and scientists working in astronomy instrumentation or data with those in other fields of research bring the expertise and skills from space missions such as JWST to help solve problems in other areas of science. All of these ways of using the expertise are important sources of economic and societal benefit.

There are numerous examples of multi-disciplinary collaborations with the astronomy community, particularly towards medical and environmental sciences. I described examples that I am familiar with, but there are many others. In a project led by Cardiff University UK ATC staff helped to develop a new design of Retinal Densitometer to make quantitative measurements of retinal function, via multi-spectral reflectance measurement of the retina over time with a view to early detection of age related macular degeneration, one of the leading causes of blindness in the elderly (Margrain, T.H., Atkinson, D., Binns, A.M. et al. "Functional Imaging of the Outer Retinal Complex using High Fidelity Imaging Retinal Densitometry". Sci Rep 10, 4494 (2020), https://doi.org/10.1038/s41598-020-60660-9 describes the project). It benefitted from skills in scattered light analysis, design of optical chains for simultaneous imaging in several bands, and adaptive-optics which were developed for JWST and ground-based observatories. Simple parallels between infrared observations of exoplanets and our own planet, led to the GHOST project with Leicester and Edinburgh University and the design of a Hyperspectral IR imaging spectrometer to measure greenhouse gases in the troposphere/stratosphere. Although used in a scanning mode, the data cubes would look familiar to users of the MIRI ("GreenHouse Observations of the Stratosphere and Troposphere (GHOST): a novel shortwave infrared spectrometer developed for the Global Hawk unmanned aerial vehicle", Neil Humpage, Hartmut Bösch, Paul I. Palmer, Phil M. Parr-Burman et al., Proc. of SPIE Vol. 9242, 92420P·doi: 10.1117/12.2067330 describes the instrument).

Data skills are important too, for example the ASTROTROP project fostered collaborations and common approaches for managing tropical forest information and astronomical data. In both cases software to combine information from 100s of sources and overlay information on different attributes have similar inter-operability data problems. Could there be new applications for the techniques being developed in fitting molecular and ice features in JWST data?

We can see societal impacts in action through the spontaneous use and reaction to the public release images such as the Deutsche Gesellschaft für Photographie (DGPh) awarding the 2023 prize for Science in honour of the outstanding scientific images of the James Webb Space Telescope (JWST) and the associated developments in imaging technology. The press release Wissenschaftspreis 2023 der DGPh: James-Webb Space Telescope | Deutsche Gesellschaft für Photographie e.V.[1] notes that "Images play a central role in the media, in science and art and have a diverse impact on society – be it in education, business or politics". However, as the community develops the case for the new facilities that will follow the rich capabilities of JWST and the under construction SKA and Extremely large Optical-IR telescopes, do we all need to become better and more familiar with enunciating and promoting the economic and multi-disciplinary benefits of astronomy?

1 https://dgph.de/presse/wissenschaftspreis-2023-der-dgph-james-webb-space-telescope

Societal Impact of JWST and Astronomy: the IAU and Africa

Kevin Govender
IAU Office of Astronomy for Development, South Africa

The scientific impact of JWST speaks for itself. The images captured by the telescope in turn captured the imagination of people all around the world. JWST serves a purpose to expand human knowledge. The question that arises is whether such an impact on humanity is truly universal, or whether it is only the few that benefit from it. In a global society as unequal as ours it is inevitable that the impact of a project such as JWST will be more pronounced in some parts than others. It remains our responsibility to be intentional about maximising those impacts and enabling them to reach as much of humanity as possible.

Astronomy as a whole has embarked on initiatives that try to maximise the positive impact of the entire field on society. The International Astronomical Union (IAU) (www.iau.org), representing the world's astronomers, has made it its mission "to promote and safeguard the science of astronomy in all its aspects, including research, communication, education and development, through international cooperation". In realising this mission it has established several global offices: (i) the Office for Astronomy Outreach, to communicate the science of astronomy to as many people as possible; (ii) the Office for Young Astronomers, to train the next generation of professional astronomers; (iii) the Office of Astronomy for Education, to stimulate the use of astronomy in the science education landscape; and (iv) the Office of Astronomy for Development, to use astronomy to realise developmental benefits to society. The latter is the main subject of my contribution.

The Office of Astronomy for Development (OAD) (http://www.astro4dev.org) was established in 2011 through a partnership between the IAU and the South African National Research Foundation. Its vision from the start was simply "Astronomy for a Better World" and it aimed to help further the use of astronomy as a tool for development by mobilizing the human and financial resources necessary in order to realise the field's scientific, technological and cultural benefits to society. In order to achieve this, it was essential that it be built on foundations rooted in humility. There is no way that one office, or one field of science, could possibly achieve the envisaged benefits to society on its own. As such the OAD established 11 regional offices and language centres which would drive these goals within a particular geographic or cultural region of the world, with each regional office understanding better the local needs of communities "on the ground". The OAD also established partnerships across fields, bringing in the social sciences as much as possible to help formulate and implement activities aligned with the goal of using astronomy to benefit society.

Out of over 200 projects funded through the OAD (with IAU funding exceeding a million Euro over the last decade) emerged three so-called flagship projects which are being driven with extra attention: (i) astronomy for economic development, including areas such as astronomy tourism in rural communities; (ii) astronomy for mental health, involving psychology and mental health expertise; and (iii) astronomy knowledge and skills, using especially data tools, techniques and infrastructure to address development challenges. These have all been ways in which astronomy as a field in general has been set up to enable a positive impact on society. Any astronomy project including JWST is thus able to contribute to some of these areas.

Taking a look at the special case of Africa, it is clear how a field such as astronomy can be used intentionally to drive societal development. The African astronomy community has been steadily growing over the years, with numerous major infrastructure projects across the continent. The most significant of these has been the Karoo Array Telescope (MeerKAT) in South Africa which has generated some of the most significant radio astronomy images in the world. Other countries hosting astronomy infrastructure include Algeria, Burkina Faso, Egypt, Ethiopia, Ghana, Morocco, Namibia and others. What has been significant with the growth of astronomy on the continent, as seen through the rise of the African Astronomical Society (the continent's professional body of astronomers), is the intentional inclusion of societal impact along with the growth of the field of astronomy. This is highlighted in the preparations towards the first IAU General Assembly on the African continent (Cape Town, 6-15 August 2024), which has three main pillars: (i) accessibility, including making the entire meeting open access; (ii) impact, specifically with regard to societal benefit from hosting the meeting in Africa; and (iii) sustainability, ensuring that the environmental footprint is kept to a minimum and in any event "worth it".

JWST has influenced us all. It is clear that a project as large as JWST can have a significant impact on society, and we are already seeing it in many parts of society. We just have to be intentional in driving such societal benefit globally. And in order to do so, humility is imperative.

Preservation of Dark and Quiet Sky

Piero Benvenuti
International Astronomical Union

Abstract

While providing important benefits to society, swarms of small satellites (also called satellite constellations) in Low Earth Orbit create sunlight streaks impacting optical/infrared observations and radio transmissions against which the highly sensitive systems at radio observatories can be unprotected. The International Astronomical Union's Centre for the Protection of the Dark & Quiet Sky against Satellite Constellation Interference (IAU CPS),[1] co-hosted by NSF's NOIRLab and SKA Observatory, is taking multiple approaches to mitigate negative impacts. At least twelve operators meet under their auspices to share best practices and understand astronomical concerns. Technical recommendations[2] from four expert workshops have been consolidated to provide targets for reducing reflected sunlight, defining the accuracy needed for position and optical brightness predictions, and technological approaches to limiting radio interference with astronomical observations. CPS-affiliated policy and space law experts have developed and are refining recommendations for ultimately turning best practices into a regulatory framework to be endorsed internationally and adopted by national agencies in licensing and oversight. Because the IAU raises awareness, the United Nations Committee on the Peaceful Uses of Outer Space (COPUOS) is now adopting a five-year agenda item to consider astronomy and satellite constellations. As a critical mode of exploration and use of outer space, astronomical observations merit protection as an integral part of long-term space sustainability. The high visibility that astronomy has gained, thanks to the impact of the constellations, may be used to extend its role beyond the science realm, recovering its relevance in philosophy, poetry, and theology.

[1] https://cps.iau.org/

[2] https://noirlab.edu/public/media/archives/techdocs/pdf/techdoc021.pdf

Since the dawn of civilization, the vision of the starry night sky has inspired poets, philosophers, theologians, artists, and scientists. With the introduction of optical instruments, pioneered by Galileo's *cannocchiale* in 1609-10, the observation of the sky acquired a new dimension: while keeping its aesthetic fascination, it opened the path to a progressive understanding of the physical reality. The latter role has become even more evident today thanks to space technology's possibility to access the entire electromagnetic spectrum and observe physical phenomena that would be impossible to reproduce in a terrestrial laboratory.

While technological evolution was instrumental in expanding our knowledge of the Cosmos, it also negatively affected the night sky's naked-eye appearance. The spreading of artificial illumination in densely populated regions makes it increasingly difficult to see the stars in the bright background. Entire generations of young people may grow up without knowing the magnificence of an undisturbed starry sky. Professional astronomy is also affected by the increasing artificial brightness of the sky, but, fortunately, the best astronomical sites that host the major telescope facilities succeeded in protecting them by adequate local regulations that limit the use of ALAN, the Artificial Light At Night. Similarly, an increasing number of Countries are creating "Dark Sky Oases", i.e. touristic protected areas that offer their visitors the possibility of enjoying an almost pristine vision of the night sky.

The most recent advances in understanding the universe and its 13,8 billion years of evolutionary history are very much indebted to space technology. The possibility of observing the cosmos from outside the terrestrial atmosphere allowed astronomers to detect signals over the entire electromagnetic spectrum, unveiling phenomena that were previously unthinkable.

It is, therefore, somehow ironic that the same space technology is today threatening the very same astronomy and cosmology. We are witnessing an epochal change in space activities: the so-called New Space Economy is driven by private companies that have reached the same, if not superior, technological capabilities of the historical Space Agencies but whose main goal, differently from the latter's, is pure profit.

One of the most visible consequences of this epochal transition is undoubtedly the massive increase in the number of communication satellites operating from the so-called LEO (Low Earth Orbit). The purpose of these large constellations, which may be composed of tens of thousands of satellites, is to offer high-speed internet connectivity from any location in the globe, including deserts and open oceans. Considering the additional high resilience of this space connectivity to external disturbances or attacks, it is clear that they represent an important progress in worldwide communication. Indeed, they will contribute to reaching the UN Sustainable Development Goals.

The other side of the coin is a significant impact on sky visibility and astronomy. Satellites reflect sunlight and, depending on the season and observer's location, can be visible for a large part of the night. Many are visible to the naked eye, and professional astronomers' highly sensitive telescopes can detect them all. The high density of satellites in the sky may make it impossible for telescopes with a wide field of view to avoid capturing satellite traces, potentially affecting up to 30% of collected images.

The situation is also challenging for radio astronomical observations. Satellites must transmit towards Earth in microwaves to fulfill their task. Although their frequencies are outside the radio astronomical protected range, the power of their beams, which is orders of magnitude stronger than the feeble cosmic signals, will inevitably disturb the astronomical observations.

The International Astronomical Union, founded in 1919, promotes and safeguards the science of astronomy in all its aspects. The IAU could not have remained inert in the face of threats, so it decided to take two initiatives. The first is to use its position as Permanent Observer in the UN Committee for the Peaceful Use of Outer Space (COPUOS) to raise international attention on the impact of satellite constellations on astronomy and propose voluntary mitigating measures. The second initiative was the creation of a coordinating Centre (CPS)[3] with the specific tasks of interacting directly with the constellations companies and with space industries to study and implement hardware and software solutions that can effectively lower the negative impact.

Both lines of action have produced positive results, albeit more is needed to solve the problem. At the UN COPUOS, we succeeded in including a specific Item called "Dark and Quiet Sky, astronomy and large constellations: discussion on emerging issues and challenges" in the agenda of the Scientific and Technical Subcommittee (STSC) for the next five years. That would ensure the possibility of discussing the progress and effectiveness of the mitigating measures and adopting internationally agreed-upon best practices. The interaction with the space industry and the operating companies has also been constructive. The second generation of Starlink satellites

[3] https://cps.iau.org/

is built and operated in a way that makes them appear less bright when reflecting sunlight. Progress has also been achieved in determining the satellites' real-time position with the necessary accuracy to avoid the crossing of their trace on the astronomical images. As for the satellites' interference on the radio astronomical observations, the most promising mitigation can be achieved by deviating their microwave emission beam when hovering over major radio astronomical facilities.

The issue created by the advent of the large constellations is having some positive outcomes that partially compensate for their impact on astronomy. Never, in recent times, has astronomy enjoyed such high international visibility. At the last session of the COPUOS Scientific and Technical Subcommittee, in February 2024, a significant fraction of the time was dominated by discussing the impact of the constellations on astronomy and the Delegations of about 50 Countries (on a total of 102) declared that astronomy is a fundamental science and its progress must be protected.

Astronomers should take stock of this fortunate favorable situation and use it to protect their research and foster it internationally, extending and improving the presence of astronomical teaching and training in schools and universities. To effectively achieve these goals, as the recent experience at the UN level has taught us, we need to convince the governmental policymakers that astronomy is (as it has always been) a unique science. As mentioned in the introduction, it explores phenomena that cannot be reproduced in terrestrial laboratories and that are fundamental to progress in our understanding of physical reality.

However, it is much more than that. The natural, mythical relationship with the cosmos that inspired so many philosophers and poets in the past is now supported by the unexpected scientific discovery that the main characteristic of the universe is its holistic evolution, out of which our consciousness finally emerged after a 13.8-billion-year journey. We are not just living under the same sky: we are the sky! Our very existence is linked with a golden braid to every phase of cosmic history, and now that we have reconstructed it, we are its witnesses. We bear the responsibility of being its conscience.

The power and reach of this cosmic awareness are hard to grasp. It may produce a universal sentiment of fraternity and peace that philosophers and theologians, following the seminal thoughts of George Lemaître and Pierre Teilhard de Chardin, should use to offer a glimmer of hope for humanity's future.

SESSION 6: PROTOPLANETARY DISKS

JWST Observations of Protoplanetary Disks

Colette Salyk
Vassar College, Poughkeepsie, NY, USA

Abstract

The study of protoplanetary disks allows us to better understand our origins. Protoplanetary disks provide a direct view of planet formation in progress, allowing us to refine our solar system-centric planet formation scenario. But protoplanetary disks also allow us to directly observe the more varied paths that planet formation might take. The incredible sensitivity of JWST, coupled with its instrumentation well-suited for studying planet formation chemistry, is allowing us to explore the diversity of planet formation pathways.

1. Introduction

1.1. The study of protoplanetary disks helps us understand our origins

The study of protoplanetary disks – the disks of gas and dust out of which planets form – is motivated, at its heart, by two questions fundamental to humans: Why are we here? and, Are we alone? One approach to answering these questions is to search for an Earth analog elsewhere in the galaxy. However, this type of work requires long exposures, unsuitable to large surveys, and getting sufficiently detailed information about Earth analogs will remain difficult for the foreseeable future.

As an alternative, we might try to understand several key steps in the origin of humans, and understand how likely each of those steps are to occur. We might perhaps begin with understanding the origin of the universe, then the origin of Earth, then the origin of life, and, finally, the origin of human life. If we want to understand whether the production of an Earth-like planet is common or rare in the universe, it is essential to not just hypothesize about Earth's formation. Instead, we need to understand the varied ways in which planets can form, and figure out which of those ways produces Earth-like vs. other types of planets.

The study of protoplanetary disks therefore aims to illuminate all of the planet formation pathways that occur in our universe. If we can study the varied pathways, we can understand which environments are likely to form Earth-like planets (or not), and why.

1.2. The solar system story

The solar system has a wide array of planet types, from gas giants, to tiny Mercury, with only our planet Earth seemingly habitable. For the solar system, the key variable that influences the type of planet formed seems to be distance from the sun, which is also a proxy for temperature. The standard formation story for our solar system (e.g., Grossman 1972) envisions a well-mixed solar-composition gas, known as the solar nebula, condensing into planetary building blocks according to the local temperature. Therefore, terrestrial planets and planetary cores close to the sun are composed of relatively more refractory-rich materials, while those far from the sun are composed of relatively more volatile-rich materials. In addition, the condensation of water ice at the so-called *snow line* allows for the formation of more massive planetary cores, aiding in the formation of gas giants (e.g., Hayashi 1981).

1.3. Wrinkles in the solar system story

However, the solar system story has some wrinkles, notably the influences of non-equilibrium chemistry and mixing processes. Meteorite and cometary compositional analyses have shown that solid materials can be mixed across large radial distances (e.g., Nakamura et al. 2008); in addition, cometary analyses suggest that some materials, especially in the outer solar system, may have been inherited directly from the solar system's birth cloud, rather than being vaporized and then thoroughly mixed about (Pontoppidan et al. 2014, and references therein).

One potential cause of mixing is the radial migration of solids that occurs in the presence of pressure gradients. In a smooth solar nebula disk, pressure is expected to decrease uniformly with distance from the sun, which would result in inward radial migration of solids (Weidenschilling et al. 1977). However, the relatively recent discovery that a majority of protoplanetary disks have radial structures indicative of many localized pressure bumps (Andrews et al. 2018, Long et al. 2018} suggests that migration is much more complex – grains might move in or out, or even stop altogether, depending on the local conditions. When this radial migration of solids occurs, local chemistry can vary depending on how much solid material was delivered to a region. Thus, planet composition won't just depend on distance from the sun, but will also depend on the detailed radial structure of the early solar system, and how it affects the transport of solid materials.

1.4. Multiple dimensions of planet formation

While the solar system provides a way to explore how distance from the sun affects planet formation, there are many other factors that could affect planet formation processes throughout the galaxy, or the universe (see Figure 1). Studying protoplanetary disks, as opposed to just the solar system, allows us to see how the formation process proceeds across many different *axes*.

It is important to understand how stellar mass might affect planet formation, given that low-mass stars are the most common types of stars. Metallicity may play an important role in planet formation efficiency since solids are the seeds of planet formation (e.g., Johnson et al. 2010), and this would affect the formation of planets at the edges of our galaxy, and in the early universe. Radiation environment may play a role by eroding disks and shortening planet formation timescales (e.g., Mann et al. 2014) affecting planets forming in large clusters containing massive stars. Stellar multiplicity can also dynamically shape disks, likely affecting planet formation when binary separations are similar to disk size scales (e.g., Kraus et al. 2012).

If all of these axes of planet formation are taken into account, there might still be stochasticity inherent to the planet formation process. Can we ever fully predict a planetary system from initial conditions, or might very different planets arise from similar disks? Whether or not there is inherent

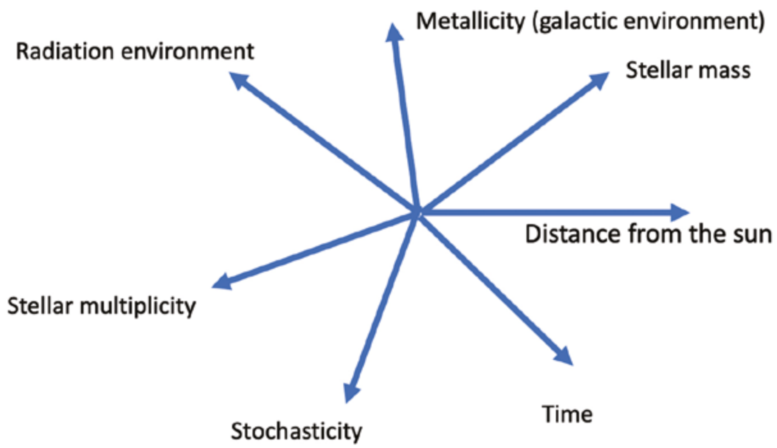

Figure 1. The many axes of planet formation. While the solar system provides insight into how distance from the sun (a proxy for temperature) influences the types of planets that form, we must look to other systems to understand more varied starting conditions and their outputs. JWST is finally allowing for a deep exploration of these many axes.

stochasticity in the process can only be understood once the other factors are fully explored.

A final axis inherent in all studies of planet formation using protoplanetary disks is the time axis. Studies of the solar system only allow us to look at the final result of planet formation, long after it occurred. Instead, studies of protoplanetary disks can allow us to study the planet formation process as it progresses. In addition, multi-epoch studies can allow us to study rapid changes in real time.

2. The JWST Advantage

JWST offers several advantages over ground-based facilities and its space-based predecessor, Spitzer, for the study of protoplanetary disks.

2.1. Spatial resolution

The increased mirror size of JWST as compared to Spitzer, coupled with the use of integral field unit (IFU) spectrographs, enables spatially-resolved spectro-imaging of some disk structures. JWST's diffraction limit corresponds to ~30 AU at the 150 pc distance of nearby star-forming regions. Thus, terrestrial planet-forming regions are not resolvable, but the outer parts of protoplanetary disks are. Also resolvable are jets and outflows, which regulate disk evolution, ultimately setting the timescale available for planet formation.

2.2. Sensitivity

The greatly increased sensitivity of JWST as compared to its predecessor, Spitzer, is allowing a fuller exploration of the many axes of planet formation. In particular, with greater sensitivity, we can now study the fainter disks around low mass stars, and lower-metallicity disks in the distant outer galaxy.

JWST's sensitivity also aids in the detection of less abundant molecular species, and weaker atomic and molecular emission lines in general.

2.3. Infrared spectroscopy

JWST's presence in space places it above the obscuring effects of Earth's atmosphere; ground-based observations struggle particularly in the study of important chemical building block molecules like H_2O that are also common in our atmosphere. Although JWST's spectrographs do not provide resolving powers as high as high-resolution ground-based spectrographs, they still provide substantial improvement over Spitzer's resolving power.

The increased resolving power provides greater sensitivity to weak lines, as the line strength scales with resolving power for unresolved lines. In addition, the increased resolving power allows for the disentangling of emission from the multiple overlapping energy levels of water and other molecules.

3. First results

3.1. Spectral imaging

Spectral imaging is only beginning to be highlighted by the planet formation community, but it bears mentioning that the IFU data from JWST provides *free* spatial information on size scales of 10's of AU. So far, emission lines from most molecules commonly studied in inner protoplanetary disks (including CO, H_2O, HCN, C_2H_2 and OH) show no resolvable spatial extent, consistent with our understanding that they arise from the few AU region of the disk. However, some atomic transitions and H_2 rovibrational transitions, both of which trace jets and outflows, are demonstrating interesting structures.

Pontoppidan et al. (2024) show an example of spectral imaging revealing an unidentified ring-like molecular hydrogen structure surrounding the protoplanetary disk FZ Tau. Its physical origin is not yet understood. Sturm et al. (2023), observing the edge-on HH 48 disk, demonstrate how a combination of tracers can map out the disk structure, plus a wide angle outflow, and a more collimated jet. In edge-on disks, it may also be possible to use line-of-sight probes to measure ice abundances as a function of disk radius; however, Sturm et al. caution that the optical paths can be complex, so simplistic interpretations should be avoided.

3.2. The distance axis, including the transport wrinkle

JWST continues to explore the solar system-based formation story, as well as the important caveats regarding transport of solids. A key take-away from JWST results so far is that protoplanetary disk chemistry in the few AU region can vary significantly from source to source. The reasons for these differences, however, are still being teased out. For some disks, various gaps may preferentially reveal different radial regions of the disk, and their specific chemistry. In others, radial transport, or its inhibition, may affect the inner disk C/O ratio. In all disks, the chemistry we see is also influenced by the local radiation field, and radiative transfer effects.

Pontoppidan et al. (2024) report strong water emission from the disk around FZ Tau, and show how JWST can allow for the decomposition of the spectrum into multiple temperature components. Gasman et al. (2023) take a similar approach, deriving temperatures for a series of water-emitting regions from the disk around Sz 98. Both studies thereby use the JWST spectra to empirically derive a disk radial temperature structure – the key input into a solar nebula-like chemical model. In addition, Pontoppidan et al. show how the full disk chemical abundance structure might be revealed by coupling JWST inner disk data with data from facilities probing the outer disk.

Several studies are revealing a variety of line strength ratios between H_2O and C-bearing species, including CO_2, HCN and C_2H_2, and discussions in each of these works highlight the continuing attempts to disentangle the multiple processes discussed above (revealing radial chemistry, vs. disk transport, vs. radiative effects). Grant et al. (2023) detect strong CO_2 emission, including from the $^{13}CO_2$ isotopologue, indicating high CO_2 abundances in the GW Lup inner disk. While this could reflect inward transport of CO_2 rich solids, Grant et al. (2023) argue that the transport should bring in H_2O as well. Instead, they suggest that an inner cavity might be preferentially revealing a region between the H_2O and CO_2 snowlines. Schwarz et al. (2024) and Gasman et al. (2023) find, instead, a relatively low C/O ratio in the inner disk of SY Cha and Sz 98, respectively. This could be caused by inward transport of O-rich icy grains, although Sz 98's gapped structure should prevent or at least slow such transport. Perhaps the C/O ratio is sometimes a relic of an earlier time when transport was more feasible, or perhaps other radiative transfer effects are affecting the observed ratio of C- to O-bearing molecules.

Results from Perotti et al. (2023) also remind us of the importance of large disk gaps on chemistry, in their observations of the gapped (and planet-bearing) disk PDS 70. As first noted in past work using Spitzer and ground-based facilities (e.g., Salyk et al. 2015), the presence of large disk gaps indicates depletion of the grains needed to shield molecules from photodissociation; therefore, gapped disks can show extreme reductions in molecular emission, even if gas is present in the inner disk. However, using the incredible sensitivity of JWST, Perotti et al. (2023) were able to detect water line luminosities in PDS 70 nearly two orders of magnitude below that seen in typical protoplanetary disks, and estimate water abundances in this planet-bearing disk. The impact of a disk gap on inner disk chemical signatures, however, is highly dependent on the exact properties of the gap (Salyk et al. 2015). As an example, Schwarz et al. (2024) show that the SY Cha disk, which has a mm-wave cavity but a *full disk* SED indicating the presence of micron-sized grains, has a more typical molecular emission spectrum.

Banzatti et al. (2023) report results from a program specifically designed to study the possible effects of radial transport. Comparing water vapor emission spectra from four disks, two large (indicating restricted radial transport) and two compact (indicating efficient radial transport), they find stronger water vapor emission in the compact disks. With the excellent spectral resolution of MIRI-MRS, however, they are further able to attribute the strength differences to the presence (or absence) of a cool water component. This component could be evidence for the inward transport and subsequent sublimation of water vapor at or near the snowline.

3.3. The (real) time axis

Although current programs are not focused on variability, JWST is already finding some variability in molecular emission. While continuum variability was detected commonly with Spitzer, especially in gapped disks (e.g., Espaillat et al. 2011), molecular line variability has typically only been detected in unusually active systems (e.g., Banzatti et al. 2015). Muñoz-Romero et al. (2024) find significantly weaker water vapor emission in the disk around AS 209, as compared to Spitzer observations, while Schwarz et al. (2024) find continuum variability and tentative line variability from the disk around SY Cha. The cause of the line variability is not yet known.

3.4. The stellar mass axis

Spitzer revealed notable differences in observed chemistry between lower mass T Tauri disks and their higher mass Herbig Ae/Be counterparts (Pontoppidan et al. 2010), and also hinted at differences between solar-mass and very low mass stars (Pascucci et al. 2009, Pascucci et al. 2013). Thanks to JWST's sensitivity, it is now possible to more deeply explore the lower stellar mass regime, to better understand how planets form and develop around such stars. First published JWST results for the low-mass (M4.75) star 2MASS-J16053215-1933159 (Tabone et al. 2023) were in line with past results, in that this disk showed a high ratio of C-bearing to O-bearing species. However, the disk has a dramatically rich spectrum of C-bearing species never seen in Spitzer spectra, including C_2H_2 (and its main isotopologue), C_6H_6, and possibly CH_4, with such molecular emission covering wide swaths of the MIRI-MRS band. On the other hand, Xie et al. (2023), studying the M5 star Sz 114, found a more T Tauri-like emission spectrum with significant amounts of water, and moderate amounts of organic molecules. Pinning down the origin of these differences likely requires expanding our sample beyond two objects (which will be tackled by S. Grant's cycle 2 program 3886); nevertheless, there may be a complex interplay between differences in chemistry due to the lowered stellar mass (which may, for example, speed up radial migration; Pinilla et al. 2013), and differences due to the presence or absence of gaps (Xie et al. 2023).

4. Conclusions

In short, JWST is revolutionizing our ability to study chemistry in protoplanetary disks, and therefore to better understand the diverse pathways of planet formation. So far, JWST has clearly revealed that the chemical environments in which planets form are diverse. However, the origins of this diversity are still being elucidated, and may reflect different radial migration histories, different radiation environments, different stellar masses, or some combination of effects. The sensitivity, as well as spectral and spatial resolution provided by JWST spectroscopy, are allowing us to fully explore the multiple axes of planet formation for the first time. The work has just begun, but it is clear that there will be many lessons learned.

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JWST: A New Window into the Chemistry of Planet-Forming Disks

Inga Kamp

Kapteyn Astronomical Institute, University of Groningen, The Netherlands

Abstract

A brief overview of JWST observations of planet-forming disks taken as part of the MINDS guaranteed time program is presented.

Introduction

Over the past decade we have revised our picture of when and how planets form in disks around young stars. The Atacama Large Millimeter Array (ALMA) is measuring how much mass resides in disks in form of solids and gas (Drazkowska et al. 2022, Bae et al. 2022) and showing a plethora of substructure that we generally associate with ongoing planet formation processes. This has now convinced the community that the first steps of forming planetesimals and planetary cores must happen very early, within

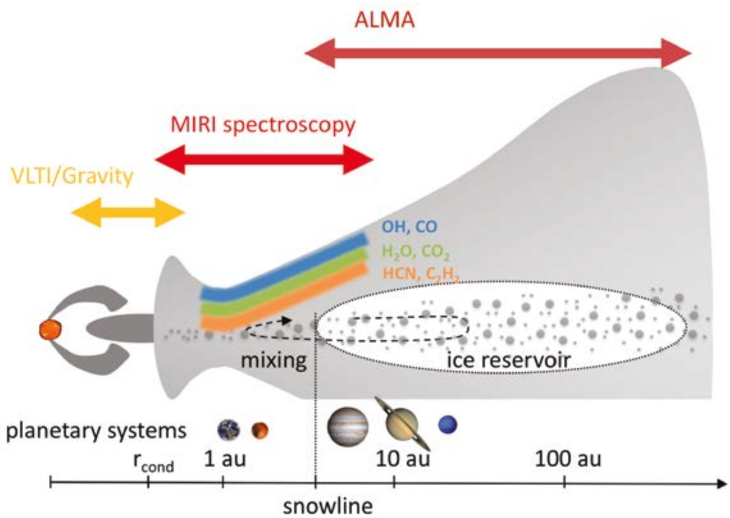

Figure 1. Sketch of a typical disk around a young T Tauri star. The MIRI instrument on board the James Webb Space Telescope probes the inner (≲ 10 au) warm disk surface (figure modified from Kamp et al. 2023).

~1 Myr. A similar conclusion is also reached by studying the Solar System evidence from Asteroids (e.g. Kruijer et al. 2014, Mezger et al. 2020).

Based on our own Solar System, we think of the inner few au as the terrestrial planet-forming region around a young Solar-type star. For stars with masses of ~1/10th of the Sun, this region could even be closer. With the advent of JWST, we can study the dust and gas composition in these regions around large samples of young stars with unprecedented sensitivity, thus enabling us to confront our theories of disk evolution during the main planet formation phase with detailed observational data. The mid-infrared wavelength range covers rovibrational emission of many simple abundant molecules such as CO, OH, H_2O, CO_2, HCN, C_2H_2, which had already been detected by the Spitzer Space Telescope (e.g. Carr & Najita 2008, Salyk et al. 2008, Pascucci et al. 2009, Pontoppidan et al. 2010). However, that wavelength range also contains emission from less abundant molecules such as the rarer isotopologues of these molecules, NH_3, CH_4, and a large range of simple hydrocarbons. Thermo-chemical disk models suggest a layered molecular structure with OH and CO at the top, followed by H_2O and CO_2. HCN and C_2H_2 peak in abundance deeper in the disk (e.g. Woitke et al. 2018, see Fig. 1). Hence, the potential richness of these mid-infrared spectra provides also an excellent testbed to study the warm and dense chemistry in these inner regions of planet forming disks.

The JWST GTO MIRI Mid-INfrared Disk Survey (MINDS, PI: Th. Henning) observed 5 Herbig disks (two of which close to edge-on), 33 T Tauri disks (four of which edge-on), 10 disks around very low-mass stars (VLMS, one close to edge-on, 2MASS- J04381486+2611399), and 5 young debris disks with detected CO sub-mm emission (Henning, Kamp & MINDS team 2024). The ages of our disks span ~1 Myr to several 10 Myr. At these ages, terrestrial planet formation is likely still ongoing, based on Earth studies who show that ~40-50% of its mass was accumulated late (>4-5 Myr, Lammer et al. 2021).

No two disks are alike

Based on Spitzer data, we already knew that the disks around VLMS differ from those around T Tauri stars, having a higher C_2H_2/HCN ratio (Pascucci et al. 2009, 2013) and lacking clear signs of water emission. With MIRI, we achieve typical S/N ratios of 200-500 within 30-minute exposures for T Tauri stars (e.g. Temmink et al. 2024), leading to mJy noise levels.

Besides confirming this strong dichotomy in spectral appearance (see Fig. 2), the very high S/N and the sensitivity achieved with JWST/MIRI

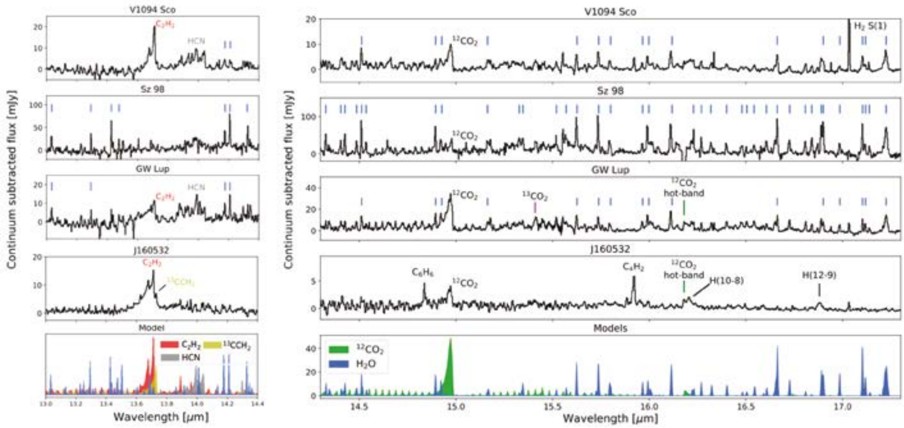

Figure 2. Continuum subtracted MIRI/MRS spectra of the T Tauri stars V1094Sco, Sz98 and GWLup and the VLMS J160532. The lowest panel on each side shows LTE slab models of the respective molecules and blue tickmarks in observed spectra indicate H_2O lines. Note that the flux scale changes between objects. This figure is a compilation based on van Dishoeck et al. (2023) and Kamp et al. (2023).

led us to the conclusion that no two disks are the same, even not within the group of T Tauri stars (Fig. 2, van Dishoeck et al. 2023, Kamp et al. 2023).

The analysis of the spectra has so far been done doing a (semi-)manual continuum subtraction and using 0D slab models for the gas emission. An overview of the approach can be found in Kamp et al. (2023). Most notably, for molecules with high column densities, line overlap can lead to a quasi-continuum (Tabone et al. 2023), thus making the placement of the continuum and the analysis of the line emission a coupled problem. On the other hand, 2-layer dust models such as Juhasz et al. (2009) have difficulty retrieving the dust continuum and features in the presence of now visible broad molecular emission bands (Jang et al. in prep.). Solutions have to be found in the simultaneous Bayesian fitting of dust and gas such as proposed by Liu et al. (2019) and Käufer et al. (2024).

The results of the 0D slab model analysis are the column densities, excitation temperatures and equivalent emitting areas of each molecule. In general, degeneracies are high, but temperatures (shapes of Q-branches) are often more robust than column densities. Thermo-chemical disk models clearly show that many of these molecules are not expected to be co-spatial. However, we can look for first trends in the retrieved data of T Tauri disks, i.e. which molecules share the same temperature regime and which ones are different. Even though it is still small number statistics, there could be a trend that CO_2 tends to be somewhat cooler (100-400 K) than the other molecules and that HCN is often very warm (>500 K). Thermo-chemical models without inner disk substructure often show that CO_2 emission extends to larger radii (up to ~10 au) compared to e.g. mid-IR water emission at the same wavelengths, and that HCN tends to be more compact (e.g. Bosman et al. 2017, Woitke et al. 2018, Anderson et al. 2021, Kamp et al. 2023). This very preliminary comparison paves the way to the use of more complex thermo-chemical disk models to be applied to JWST/MIRI data.

A first study was recently done by Woitke et al. (2024) on the disk around EX Lup. Two-dimensional radiation thermo-chemical disk models assume a radial gas and dust structure, allow the dust grains to settle depending on grain size, solve the continuum radiative transfer based on the dust opacities and then solve the gas chemistry (in this case using a network of 235 species connected by ~3000 reactions) and energy balance (heating/cooling) iteratively. These models take hours instead of milliseconds (like 0D slabs, Bayesian retrievals); hence, we have to use alternative ways to match observed mid-IR spectra. Based on the DIANA project (Woitke et al. 2019), we use an evolutionary algorithm, define the free parameters of the 2D disk model, and define the χ^2 to be minimalized. This approach can provide more context compared to the 0D slab modelling as we can study whether or not the physical conditions retrieved by slab models can exist based on our current understanding of the physical and chemical structure of such disks. Figure 3 shows the resulting fit after ~200 generations (~60000 CPU hours) for a model that uses the solar C/O ratio (0.46). Compared to the results achieved with slab model fitting, where each molecule is fitted separately, the emission shown here is from a ray tracing of the final thermo-chemical disk model using the Fast Line Tracer FLiTs (developed by M. Min, Woitke et al. 2018). In such models, the molecular emission of CO, H_2O, CO_2, C_2H_2 originates spatially in very different regions of the disk dictated by a combination of density, UV field (e.g. scattering by dust, dust+gas shielding) and temperature (chemistry and heating/cooling are intertwined). Based on such an approach, one cannot rule out that there are not equally well-fitting alternative disk structures, but it is an amazing achievement to have 2D disk models that do reproduce the observations at this level. This would not have been possible without many of the insights of past years highlighting the importance of dust processing, settling, rounded inner rims, molecular self-shielding and mutual shielding and the wealth of molecular data now available through databases such as HITRAN2020 (Gordon et al. 2022) and Geisa (Delahaye et al. 2021).

The dichotomy found earlier with Spitzer between the T Tauri and VLMS disks is even more clear now with JWST/MIRI spectra. The four VLMS objects analysed so far by MINDS (Tabone et al. 2023, Arabhavi et al. 2024, Kanwar et al. submitted, Morales-Calderon et al. in prep.) span spectral types M5-M7.5 and show an incredibly rich spectrum of small hydrocarbon molecules such as CH_4, C_2H_2, $^{13}CCH_2$, C_4H_2, HCN and in some cases also C_2H_4, C_2H_6, C_3H_4, C_6H_6, CH_3, as well as HC_3N, while water and OH are likely absent (or very weak); the only oxygen bearing molecule routinely found is CO_2 and its isotopologue $^{13}CO_2$. In one case (Tabone et

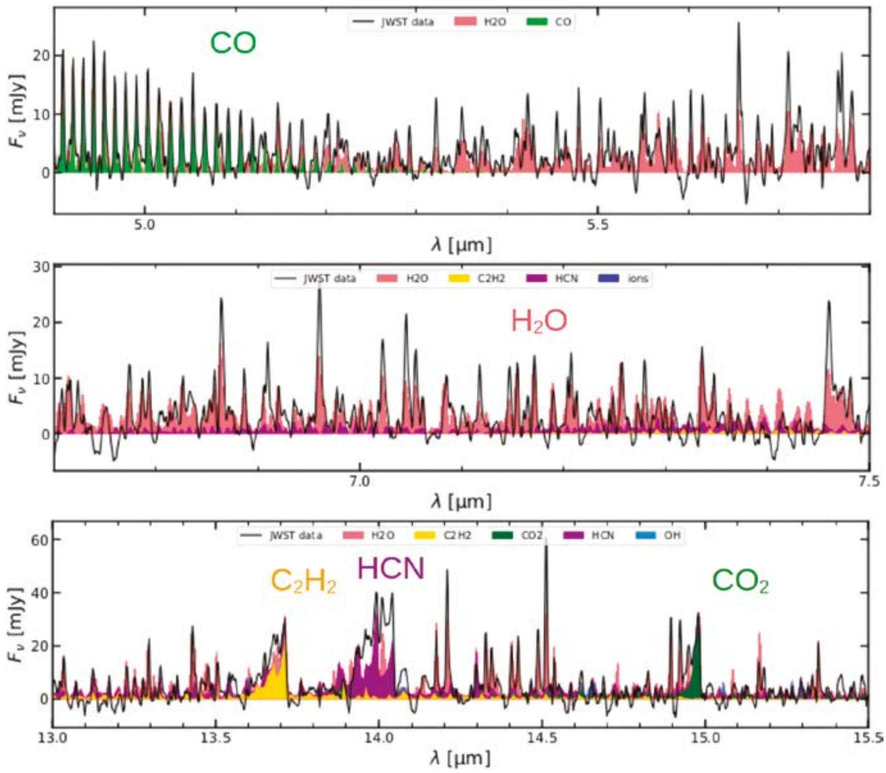

Figure 3. Full 2D thermo-chemical fit of the JWST/MIRI spectrum of EX Lup using ProDiMo. Modified figure based on the results from Woitke et al. (2024).

al. 2023), we detected CO, but often the short wavelength regions (5-7 μm) are dominated by the molecular absorption from the VLMS, making the search for CO disk emission very difficult. Such a rich hydrocarbon chemistry clearly points to an elemental abundance ratio C/O > 1 in the gas inside ~1 au of these VLMS. Interestingly, Xie et al. (2023) analysed another M5 VLMS disk and detected clear H_2O emission next to C_2H_2, CO, CO_2 and HCN. So, it could be that we still have a strong selection bias in our samples and that eventually we will find a gradual change in the inner disk composition from oxygen dominated to carbon dominated. This has recently been proposed based on models of ice transport in viscously evolving disks by Mah et al. (2023).

Warm inner disk chemistry

In the inner disks (~1 au) around young stars, we find densities up to 10^{15} cm^{-3} and temperatures between a few 100 and a few 1000 K. The conditions do overlap thus with warm planetary atmospheres. Woods & Willacy (2007) already demonstrated that the simplest cyclic hydrocarbon, benzene (C_6H_6) can form under these conditions through ion-molecule gas phase chemistry. Recently, Kanwar et al. (2024a) revisited the formation of small hydrocarbons expanding the large DIANA chemical network (Kamp et al. 2017) with 92 hydrocarbons with up to eight carbon atoms. We show that there are two main pathways to form the simple hydrocarbon C_2H_2 in the

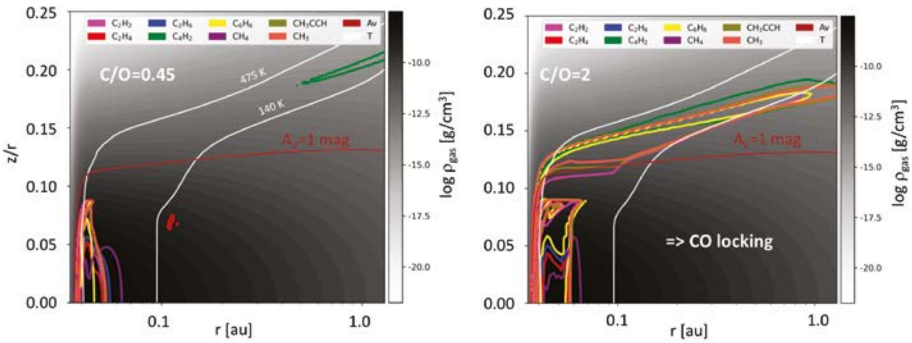

Figure 4. Abundance contours corresponding to 10% of the maximum abundance of the hydrocarbons detected in disks around very low-mass stars in the fiducial model with C/O=0.45 (left) and the enhanced C/O=2 model (right). The white contours correspond to the gas temperatures of 140 K and 475 K. The A_V =1 mag contour is shown in brown. The greyscale in the background is the gas density in g/cm³ (figure based on Kanwar et al. 2024a).

disk surface layers of T Tauri stars, the ion-molecule pathway starting with C^+ (unlocked from CO via He^+, cosmic rays/X-rays) and CH^+, and the neutral-neutral pathway unlocking C from CO via UV photons. This surface layer drives an efficient hydrocarbon chemistry, because it coincides with the H/H_2 transition and contains non-negligible abundances of atomic/ionized C. Its location is hence tied to the details of the warm H_2 formation on dust grains (Cazaux & Tielens 2010). Benzene forms inside 0.2 au, in a reservoir that is well below the A_V~1 mag line and extends down to the midplane. This means that under normal C/O circumstances, it can only be exposed if the dust opacities differ from the canonical ones.

Inspired by the richness of the disks around VLMS, we investigated the impact of a C/O ratio larger than 1 in such disks and found that many hydrocarbons will be enhanced in the optically thin surface layers. This happens because for a C/O larger than 1, all oxygen is locked in CO and the remaining C can drive additional carbon chemistry. In fact, we find all hydrocarbons detected in JWST/MIRI spectra to reside in our model inside a few au above the A_V~1 mag layer (Kanwar et al. 2024a, Fig. 4). The temperatures fall into the same range as the observations (~150-500 K). This demonstrates that if there is a mechanism enhancing the elemental abundance ratio inside 1 au, gas-phase chemistry will proceed on short timescales and form the entire observed range of small hydrocarbons, including benzene. The models also show the presence of a deeper hydrocarbon reservoir which exists independent on the C/O ratio. In case dust opacities are very low due to e.g. efficient dust growth in the inner disk, that warm reservoir inside 0.05 au could become observable.

The JWST/MIRI spectra still show a few unidentified features and our thermo-chemical disk models would predict species such as C_2, C_2H, C_3, CH_2CCH, both cyclic and linear isotopomers of C_3H_2, C_5H_2, CH_3C_4H, C_6, C_6H_2. None of them have spectral data in HITRAN2020 or Geisa. More work and collaboration with our colleagues from physical chemistry and/or laboratory spectroscopy is required to expand the existing molecular databases.

Unseen substructure, radiative transfer, and/or transport processes

We are just at the beginning of the interpretation of JWST/MIRI spectra of disks around young stars. Other contributions at this conference put forward detailed evolutionary scenarios, which will be further tested once larger unbiased samples of disk spectra have been analysed. Many theoretical works have already investigated how specific ‘local’ effects change the mid-IR appearance of disks, e.g. the C/O ratio (Najita et al. 2011, Woitke et al. 2018, Anderson et al. 2021), disk (sub-)structure and dust transport (Antonellini et al. 2015, Greenwood et al. 2019, Antonellini et al. 2023, Kamp et al. 2023, Vlasblom et al. 2024), photochemistry and shielding (Bethell & Bergin 2009, Bosman et al. 2022 a, b). This has increased the complexity and number of parameters in thermo-chemical disk models. The natural next step to couple these to transport models is being explored right now (e.g. Krijt et al. 2020), but more work is required to capture the aforementioned complexity also in these transport models. Figure 5 shows a sketch of the complexity that arises when trying to build a coherent modeling framework for the interpretation of JWST data. In fact, the outer disk, which is in many cases well characterised by ALMA data, provides a complementary view of the full story. Hence, in the future it will be crucial to interpret these two datasets within a single model framework to progress in our understanding of how planets are growing in these disks and how they acquire their final elemental compositions.

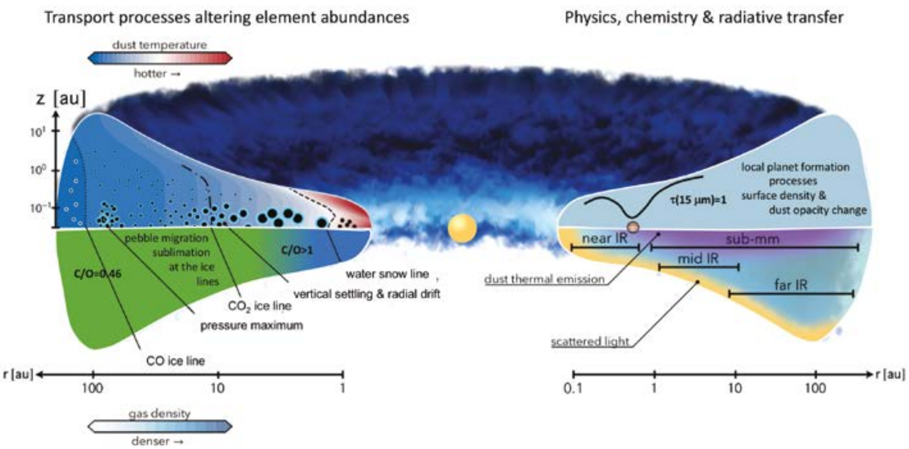

Figure 5. Disk sketch modified from Miotello et al. (2022) to illustrate the transport processes and the physical, chemical and radiative transfer aspects that need to be combined to confront our understanding of planet formation processes with JWST and ALMA data.

Acknowledgements

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Using JWST to Study the Delivery of Water and Solids to Rocky Planets

Andrea Banzatti
Texas State University – San Marcos, Texas, USA

Abstract

The formation and properties of our inner Solar System bodies have long been proposed to have required the delivery of icy solids from the cold regions away from the Sun, regions where comets originate from today. Recent observations of protoplanetary disks around other stars, the young analogs of the "Solar Nebula" that formed our Solar System, have confirmed that icy solids can either be retained in systems of rings at large distances from the star, or be efficiently delivered into the inner region where rocky planets are forming. Together with the solid mass necessary to build up planetesimals and planet cores, the drifting solids carry water ice into the inner warm region of disks, which will sublimate and produce large amounts of water vapor. While this fundamental dynamical process is included in theories of planet formation, its confirmation has been elu-

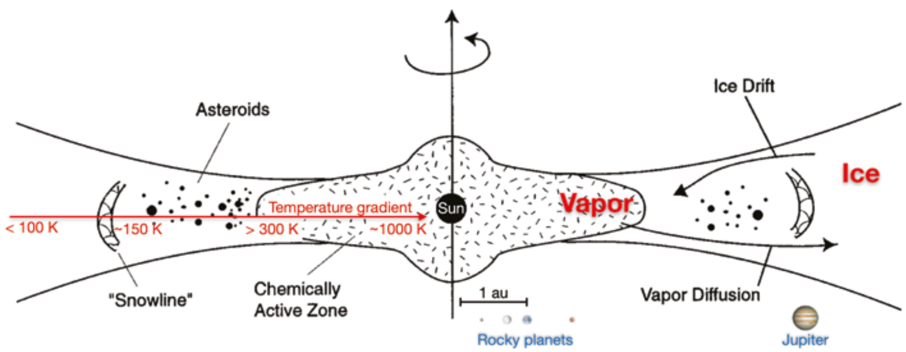

Figure 1. Schematic illustration of the "Solar Nebula", the protoplanetary disk around our Sun when it was about 1 million years old [16]. The front section of the disk is shown, to illustrate the global temperature gradient as a function of distance from the Sun defining the separation of water ice and vapor across the "snowline". The process of "ice drift" has long been proposed to be necessary to deliver water and solids to build planets in the inner 10 astronomical units (au) from the Sun.

sive for decades due to the extreme angular resolution needed to observe planet-forming regions around other stars. With the deployment of the James Webb Space Telescope (JWST), the long-awaited test has arrived. By providing an unprecedented sharp view of water vapor spectra, JWST has revealed that disks expected to have a large flux of icy migrators do indeed have excess cold water vapor near the ice sublimation front. Observing this fundamental ice migration process has exciting implications for using JWST to estimate the mass in solids and water that is delivered to the disk region where rocky planets are forming and clarify the origins of different types of planets and their potential habitability.

1. A fundamental problem: how planets get their essential ingredients

Planets are formed in disks of dust and gas that rotate around young stars. These circumstellar or "proto-planetary" disks are feeding mass to their central stars until nuclear fusion is ignited in their core and they begin their mature life on the Main Sequence, the current phase of our Sun. By then, the natal disk is gone and a new planetary system is formed. While this general picture is now accepted and supported by multiple lines of evidence, some of its fundamental steps still challenge current planet formation theories. Two such fundamental problems are: 1) how planets build up their solid mass, or how solids grow hugely in size from interstellar dust grains up to planetary cores and rocky planets, and 2) how planets obtain their water to possibly host liquid oceans and life.

These questions have first and for long been analyzed in the context of the formation of our Solar System. A global temperature gradient must have been present in the "Solar Nebula" (the protoplanetary disk of dust and gas that formed our Solar System) with a hotter inner region and increasingly colder outer regions (Figure 1). With this structure, the inner region is populated with dust particles and gas, while at larger distances the disk is cold enough to be populated with ice. The separation between these two global regions has been called the "snowline". The water snowline has long been proposed to have had a fundamental role in shaping the structure of our Solar System, because by being made of two of the most abundant elements (hydrogen and oxygen) water is very abundant and provides a large fraction of solid (ice) mass available to planets.

One fundamental process proposed early on in studies of the Solar System is that solid particles in disks should migrate efficiently towards the star due to gas drag forces [42]. This global process would cause an "ice drift" effect (Figure 1) bringing icy solid particles from the outer disk into the snowline region and within it. After crossing the snowline, ice sublimates in the inner hotter region producing an increase in water vapor abundance, which would in turn partly diffuse outward. This global process could solve two problems at the same time: 1) deliver enough solid mass at ~5 au to explain the rapid formation of Jupiter's core, and 2) radially mix the ice and vapor content across the snowline to explain chemical gradients measured in asteroids as a function of their distance from the Sun [28, 38, 16, 14].

Yet, the solution came with a new critical problem: the drift of icy solids, later called "pebbles", that have the right size to be marginally decoupled from the gas (i.e. not too small or they are completely coupled, not too large or they are completely decoupled) should be so fast to deplete the inner disk in as short as 100 years [42]. The particle size that maximizes drift efficiency depends on the gas density and is about 1 meter at a distance of 1 astronomical unit (and 1 millimeter at a distance of 100 astronomical units), so that this problem came to be known as the "meter-size barrier": no solids larger than 1 meter should have been formed in the Solar System, and protoplanetary disks should disappear before planets may form in them. However, the existence of planets demonstrates the opposite.

New observations of protoplanetary disks from modern millimeter interferometers, which observe the cold thermal emission from pebbles and reveal their distribution as a function of distance from the star, later came to help in finding a solution to overcome the barrier problem. They demonstrated that another process must be slowing down the drift, retaining peb-

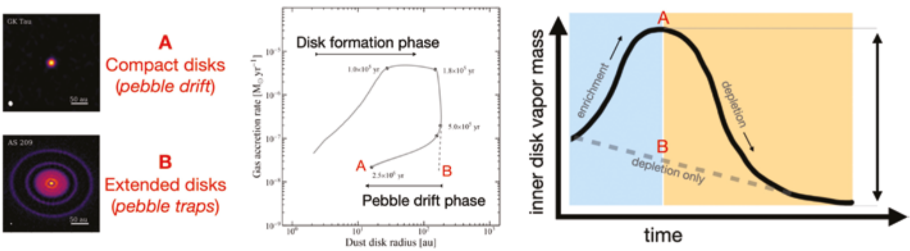

Figure 2. *Left*: ALMA observations of protoplanetary disks with different sizes and structures [18, 26]: drift-dominated compact disks (A) and extended disks with pebbles trapped in rings (B). *Center and right*: model predictions for pebble drift and water transport in protoplanetary disks. Dust disks shrink and become compact if pebbles are not retained in systems of rings (center, adapted from [3]), and ice delivery to the snowline produces a large mass of water vapor in drift-dominated disks (right, [21, 22]).

bles in the disk for a longer time, and even accumulating them in specific regions where the growth of solids towards planets would become more efficient. This process was proposed to be the formation of local pressure enhancements, or "bumps", that would trap pebbles in systems of rings preventing their rapid drift into the star [24, 32]. While being only a theoretical prediction at first, new sharp images from the ALMA interferometer in 2015 and onward demonstrated its reality: protoplanetary disk can indeed be carved by systems of rings where pebbles are trapped (Figure 2) [1, 18, 27, 2].

The radial distribution of pebbles observed in disks recently became a proxy for the relative efficiency of the drift process in different disks (Figure 2): some disks are observed to retain pebbles in systems of rings out to 100-200 au, while other disks are very compact and are proposed to have had a very efficient inward drift delivering a large mass in icy pebbles to the inner planet forming region [e.g. 35, 3, 44]. The radial drift and accumulation of pebbles are now considered fundamental processes that shape the mass architecture and chemical composition of planetary systems [e.g. 19, 10, 11, 15] and determine which type of planetary system would form in a given disk,

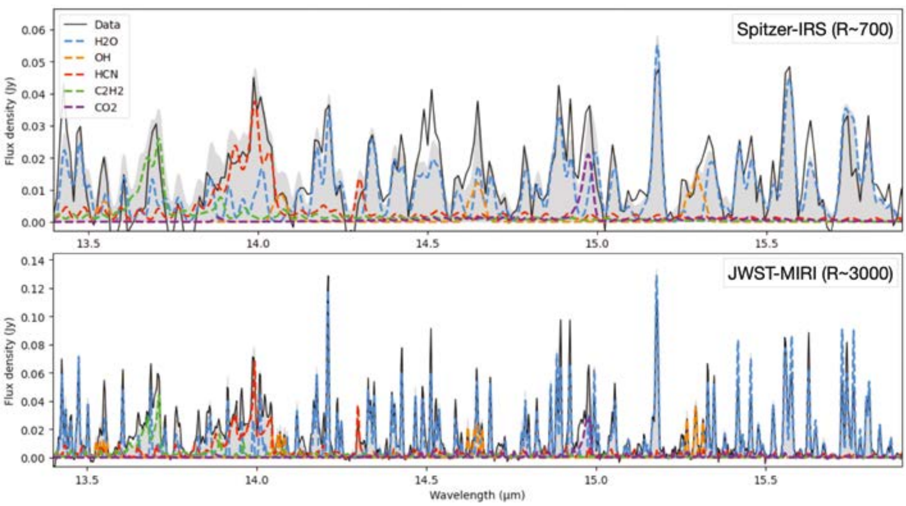

Figure 3. Comparison of molecular emission spectra from a protoplanetary disk, as observed with the Spitzer-IRS in 2008 (top) and JWST-MIRI in 2023 (bottom) [34, 6, 7]. The two spectra come from the same disk in the Taurus star-forming region, but the analysis of Spitzer spectra was critically limited by the strong blending of different molecules and lines. JWST now provides a much sharper view of the temperature and density of multiple molecules. The plots are made with the public tool iSLAT [20].

whether composed of super-Earths (in disks with efficient pebble drift delivering a larger solid mass to within the snowline) or of small terrestrial planets (in disks where pebble traps retain solid mass in the outer disk) [25, 40].

Despite how fundamental the process of ice drift in disks is, both from the physical point of view as well as for its implications for planet formation, its confirmation has long eluded direct observations due to the extreme resolution needed to observe planet-forming regions around other stars. An observable consequence of ice drift, if truly happening in disks, was however already known from previous Solar System studies, as described above: the rapid drift of large amounts of icy pebbles should produce an enrichment in water vapor in the region within the snowline (Figure 2) [22, 21].

2. A long-awaited answer: JWST reveals excess water emission near the snowline

Spectroscopy of water and molecular emission from planet-forming regions has become possible only about 20 years ago, with observations from the NASA Spitzer Space Telescope [12, 36]. The first analyses of these spectra suggested that water and organic molecules are abundant in planet-forming regions, but our understanding of the distribution, temperature, and density of molecular gas has been critically limited by the low resolution of Spitzer instruments, which was not optimized for this type of observations [34, 13, 37, 31, 9]. Yet, these spectra provided first hints that the drift of icy pebbles might indeed deliver large amounts of water to the rocky planets region in disks [4, 30, 6]. Even in this case, the interpretation of results was severely limited by the low resolution of Spitzer spectra that blended emission lines together, providing a "blurred" vision of their properties (Figure 3).

With the deployment of JWST, the view of the molecular environments of planet formation has significantly sharpened. Figure 3 demonstrates how the factor ~4 increase in resolving power ($R = \lambda/\Delta\lambda$, where $\Delta\lambda$ is the spectral detail that can be distinguished in the spectrum) results in the effective de-blending of emission lines from different molecules that overlap in the spectra. The possibility to separate different lines and measure their individual strength provides a "thermometer" that is most essential to researchers in all fields of astronomy: the population of different energy levels, which produce the different emission lines observed in the spectrum, is indeed dictated by the temperature of the gas in addition to other properties (including the gas density and the irradiation spectrum).

Equipped with this sensitive thermometer, JWST spectra observed from planet-forming regions have been used to test the fundamental predictions described in Section 1: that drift-dominated, compact protoplanetary disks should have more water vapor than the extended disks, which instead trap icy pebbles in systems of rings and prevent them from drifting to the snowline and feeding rocky planet formation. A mixed sample of compact and extended disks was observed in the first cycle of observations with JWST in February 2023, providing spectra of astounding quality thanks to improved data calibration techniques [33]. The comparison of their water spectra revealed a strong difference between the two types of disks: while both had similar emission in the higher-energy lines emitting from the inner, hotter region of the disk, the compact disks have excess emission in the lower-energy lines emitting from colder disk regions that extend to the water snowline ([7] and Figure 4). A fit to the excess emission provided temperatures of 400 K extending down to 170 K, matching the sublimation temperature of

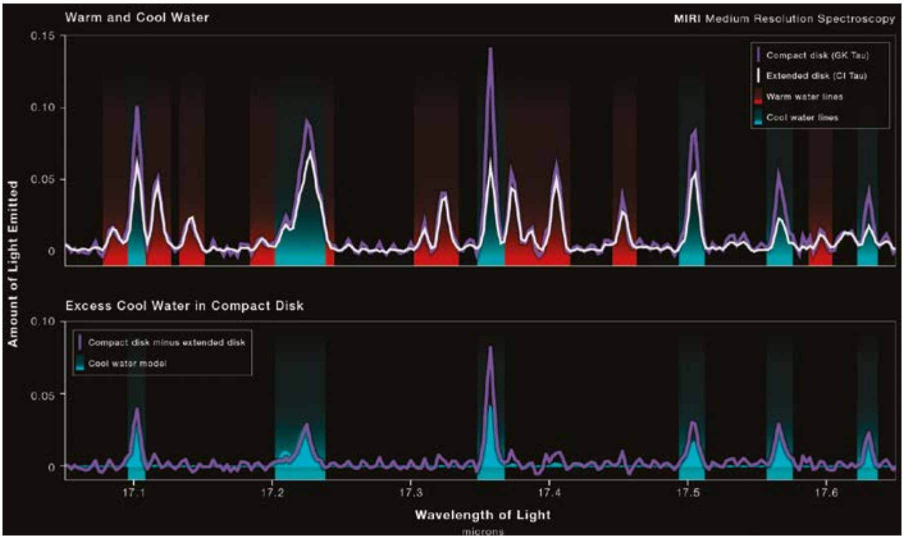

Figure 4. Cool water excess spectrum detected with JWST in compact, drift-dominated disks. The superposition of a representative portion of the water spectra from extended and compact disks is shown at the top, their difference at the bottom. The excess spectrum at these and longer wavelengths is well reproduced by a water emission model with temperature in the range 170–400 K [7]. Adopted from the NASA press release (https://www.nasa.gov/missions/webb/nasas-webb-findings-support-long-proposed-process-of-planet-formation/) featuring results published on November 8th, 2023 [7].

water ice in inner disks. The snowline region in compact disks indeed seems to be enriched in cold water vapor supplied by sublimation of icy pebbles that have drifted inward (Fig. 5).

3. Conclusions and future prospects

The discovery of the cold-water excess in drift-dominated disks [7] is a major achievement that comes directly from the increased resolving power, sensitivity, and data quality of JWST. The picture emerging from JWST spectra of molecules in planet-forming regions now supports the long-proposed, fundamental process describing the dynamics and re-distribution of solids and water in protoplanetary disks first proposed for the Solar Nebula and later applied as a standard for planet formation theories in general (Section 1). The implications from using JWST to study such a fundamental process are multiple, from aiding the analysis of other processes that impact the chemistry of planet-forming regions to providing essential input to planet formation models.

From the point of view of the global chemistry in planet-forming regions, the analysis of water and organic molecules from the past 20 years has already demonstrated that the problem is multi-dimensional by nature. Multiple factors determine which molecules will be formed and destroyed as a function of disk radius and time: irradiation from stars of different temperature and the high-energy radiation from shocks where disk gas is feeding the central star, the evolution of dust grains that are shielding molecules from dissociation from high-energy radiation, the relative abundance of molecules delivered as ice from the outer disk which can be stopped by

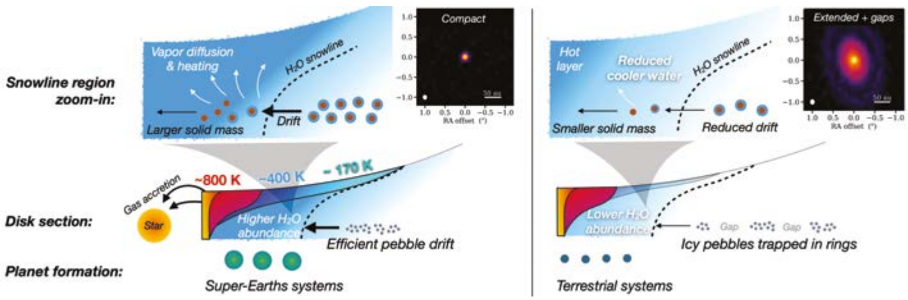

Figure 5. Interpretation of the cold-water excess in the context of pebble drift and ice delivery to inner disks [7]. The larger solid mass delivered in compact disks would form systems of super-Earths [25].

traps at different radii [e.g. 37, 31, 41, 43, 9, 5, 8]. This multiplicity of factors is emerging from the first JWST observations too [e.g. 39, 17, 23], and larger samples of disks are now being observed to explore some of them, including stellar mass and irradiation, age, dust evolution, and environment (see papers by C. Salyk and I. Kamp at this conference).

From the point of view of planet formation models, the solid mass delivered to inner disks through icy pebble drift is proposed to be a critical factor determining which type of planetary system will form [25]. The possibility to now extract ice mass estimates from JWST spectra of the cold water vapor emission from disks is supporting the scenario that drift-dominated disks may deliver a few 100s Earth masses of solids into the rocky planet region [29], which would support the formation of systems of super-Earths; on the contrary, disks with multiple pebble traps provide estimates of only a few 10s Earth masses, which would only sustain the formation of smaller terrestrial planets [25]. Determining which disks may form which types of planetary systems has the potential to significantly advance our understanding of planet formation in general, the origins of different planet types (including their water content and potential for habitability), and the place of our Solar System in the broader context of exoplanet populations in the galaxy.

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Planetary Debris Disks: Another Perspective on Exoplanetary Systems

George Rieke, Andras Gaspar, Kate Su,
Schuyler Wolff, Jarron Leisenring
Steward Observatory, The University of Arizona

Abstract

A brief summary of pre-JWST and new JWST observations of debris disks is presented, with a focus on Fomalhaut. These disks provide the opportunity for a detailed look at processes in exoplanetary systems that are not observable by other means.

Although the planets get most of the publicity, the Asteroid and Kuiper Belts are two additional major components of the Solar System. The planets finished their episodes of orbital migration and collisions long ago (thankfully), but collisions have not completely damped out in these two belts of small bodies.

The occasional collisions in the Asteroid belt break up the participants into smaller scraps that are put onto related orbits that can be traced back to the collision sites. This process creates "families" of asteroids with similar composition as well as related orbits. The collisions are messy, creating a very broad range of fragment sizes, and as these fragments continue to collide (particularly when the orbits bring them back to the original collision site) they yield clouds of dust. Snapshots of the resulting dusty bands around the sun were dramatically captured by the IRAS all-sky infrared survey (Sykes & Greenberg 1986, Sykes 1990, Nesvorny et al. 2003). There must be occasional collisions and generation of dust in the Kuiper Belt also, although it is too far away and the dust emission too faint to be detectable.

A fascinating aspect of these dust belts is that they reflect not only the processes within the Asteroid and Kuiper Belts, but the planets can imprint signatures on them, as shown in Figure 1. In this figure, the particle densities have been weighted by the inverse square of the distance from the sun to simulate a hypothetical brightness distribution as if the Solar System were being observed from outside. Uranus and Neptune as well as Jupiter and Saturn have profound effects on the distribution of dust. In fact, the role of Jupiter in shaping and carving the Asteroid belt is very well known. This

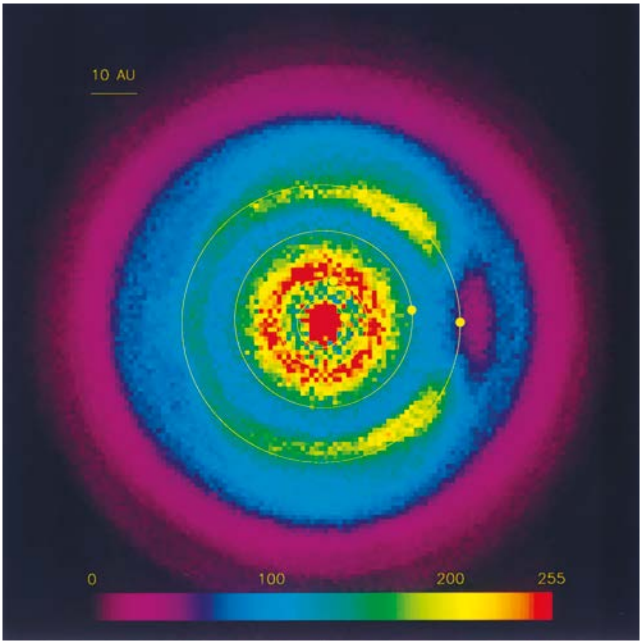

Figure 1. Hypothetical view of the brightness distribution produced by small grains in the Solar System under the gravitational influence of the giant planets (shown as yellow disks on their respective orbits). From Liou and Zook (1999), reproduced by permission.

suggests an indirect way to study planetary systems around nearby stars, as Liou and Zook (1999) pointed out:

"If an extraterrestrial intelligence were observing our solar system and had the image in Figure 1, it would know (if its knowledge was similar to or better than ours) that at least one giant planet at about 30 AU exists in our solar system [i.e., Neptune]." That is, the structures in circumstellar dusty debris can be used to infer the existence of the planets that are molding them.

It took many years to fulfil this prediction, and we will return to it later. The dusty circumstellar disks are of great interest in themselves also, since they show the presence of belts of smaller bodies analogous to the Asteroid and Kuiper Belts and can reveal processes occurring within them. They are also more readily detected than planets. This is illustrated by the analogy that it is easier to see the paint when it is spread on the wall (i.e., the dust) than when it is in the can (i.e., collected into a planet).

The Solar System belts are very tenuous and would not be detectable around another star with our current technology (Wyatt 2008). However, this pessimistic view was swept away when it was discovered with the IRAS all-sky infrared survey that Vega is about 15 times brighter than expected in the far infrared (Aumann et al. 1984). Like most scientific discoveries, this one was made by accident. A-type stars like Vega had served astronomy well as reliable calibration sources for the 60 years since they were originally suggested for this role by Henrietta Leavitt (1917), and the IRAS observation was planned for routine calibration purposes. The dust responsible lay in the analog to the Kuiper Belt around this star, far enough away that the star heats it only to about 85 Kelvin (that is 85 degrees above absolute zero). This is about 100 times lower temperature than that of the star, resulting in the peak of the emission being at 100 times longer wavelength than that of the star, i.e., in the far infrared near 60 μm. The result is very dramatic in the far infrared because the stellar output has fallen to only a few percent of its value in the visible, making it possible for the cold dust to be dominant. We could say that IRAS discovered the Kuiper Belt around Vega before Jewitt and Luu (1993) found the true one around the Sun (although a footnote might be needed to explain that at the time Pluto was the "ninth planet" but is now classified as the first discovered member of the Kuiper Belt). Originally, this behavior was termed "the Vega Phenomenon," but it is now known by the more generic term of planetary debris disks, or just "debris disks."

Several hundred debris disks were found in the IRAS data and many more have been discovered with ISO, Spitzer, and WISE. Their study has become a significant chapter in the astronomy of the past four decades. The results are far too extensive to cover here, but are described in a number of review articles (Wyatt 2008; Matthews et al. 2014, Hughes et al. 2018, Wyatt 2021, Marino 2022). Cold telescopes in space have played the dominant role because sufficient sensitivities are not possible from the ground where the infrared emission from the warm telescope partially blinds detectors.

Rather than describing all of this work, we will track developments in the study of the debris disk around Fomalhaut, a hot star (8600 Kelvin) in the southern hemisphere and at about 25 light years (7.7 parsecs) distance. Among debris disks, Fomalhaut has been kind of a show-off, placed ideally for ALMA and with all the components of other debris disks prominently represented and relatively easily observed. The disk was first well resolved in the submm (Holland et al. 1998, 2003) followed quickly by resolved images in the mid- and far-infrared with Spitzer (Stapelfeldt et al. 2004) and

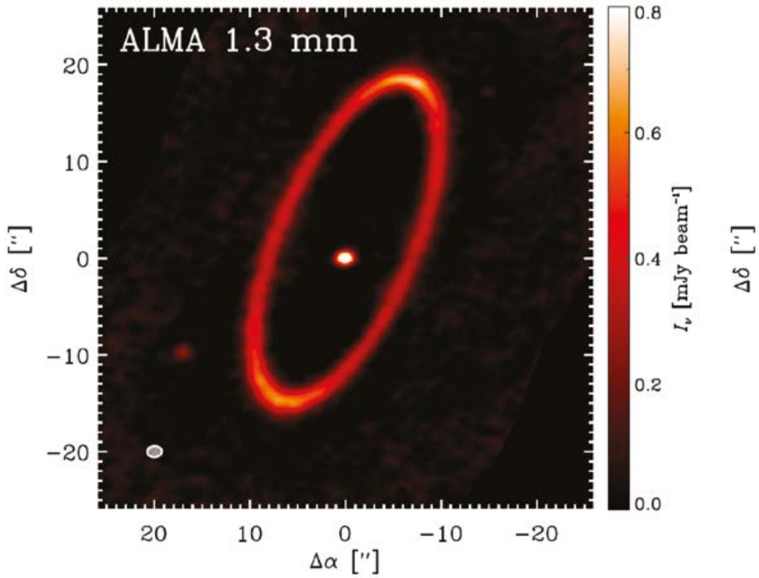

Figure 2. Mm-wave image of Fomalhaut, from MacGregor et al. (2017), with permission.

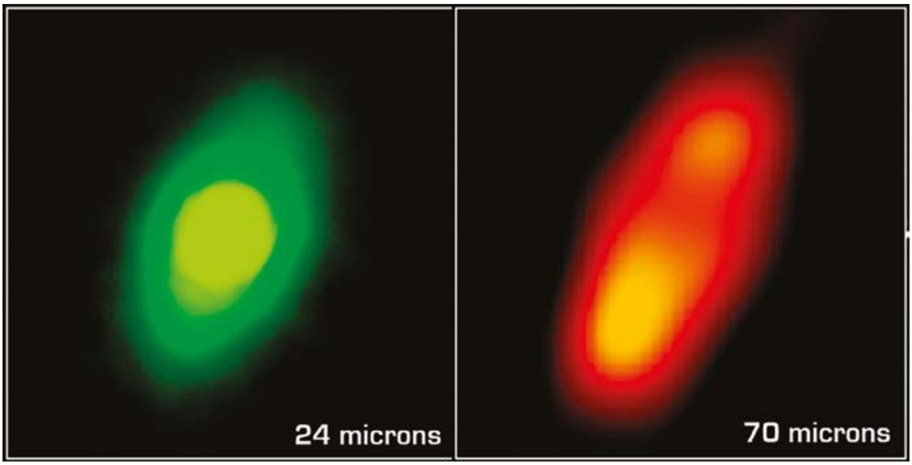

Figure 3. Images of the Fomalhaut debris system with the MIPS instrument on Spitzer. At the time, the 24 μm image was considered to be a sufficiently spectacular new result to be featured in the initial press release about the mission.

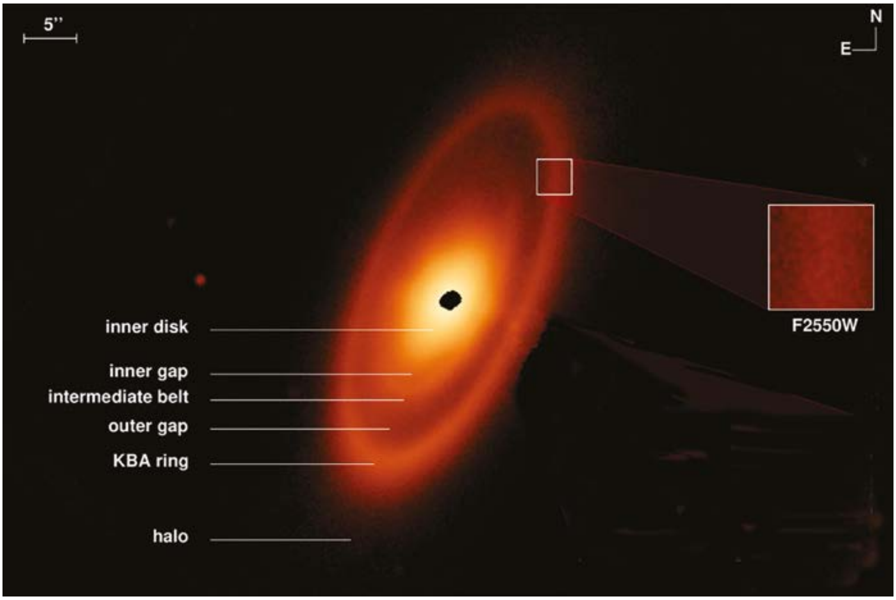

Figure 4. Image of the Fomalhaut system at 25.5 μm with MIRI on JWST (Gaspar et al.2023). The square to the upper right covers the area where the possible planet Fomalhaut b was found.

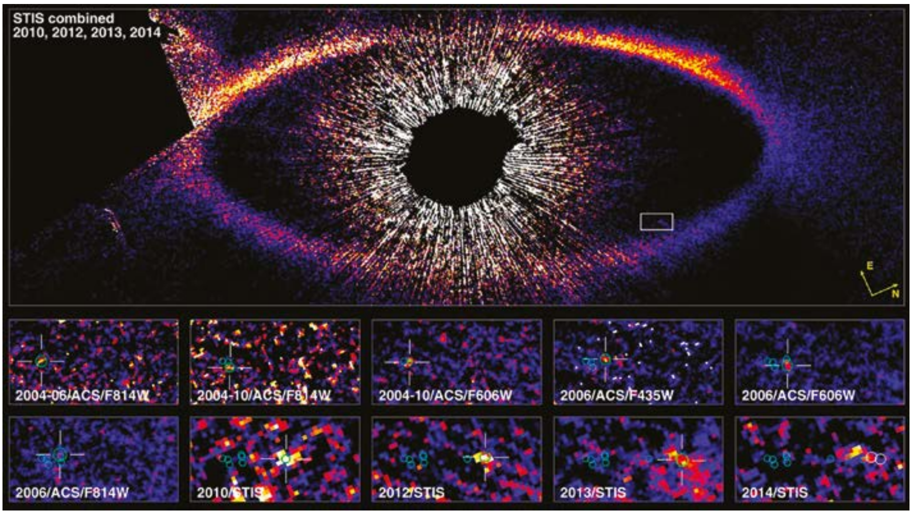

Figure 5. The Fomalhaut debris disk imaged with HST (Gaspar & Rieke 2020). The individual images across the bottom are the view in the rectangle to the lower right in the ring image, covering the position of the possible planet, Fomalhaut b.

optical (Kalas et al. 2005). As a foundation for the discussion, we will first assemble the highest quality imaging information, proceeding from long wavelengths to short ones.

Figure 2 shows the debris ring as seen by ALMA at a wavelength of 1.3 mm. The ring is at a radius of 143 Astronomical Units (au – the radius of the orbit of the Earth) from the star and only 13.5 au wide. We show Figure 3 for historical reasons – it is the view at 24 and 70 μm with the Spitzer telescope. For the first time it demonstrates that the structure at the shorter wavelength falls inside the outer ring seen with ALMA. Since this image was obtained, the Herschel telescope has obtained higher resolution images in the far infrared, from 70 through 500 μm (Acke et al. (2012) that show the ring in greater detail, i.e. at 70 μm similar to the Spitzer resolution at 24 μm. Figure 4 is the image obtained with JWST (Gaspar et a. 2023). A comparison with the left image in Figure 3 illustrates the huge leap in resolution and understanding. The debris ring was first imaged in the optical with HST by Kalas et al. (2005); Figure 5 combines those data with all the data obtained subsequently with HST into a more complete optical image. The ALMA, JWST/MIRI, and HST images are the only ones available with arcsec or better resolution. They are combined into a single one in Figure 6, which is the basis for a discussion of the processes sculpting the system.

The confinement of the mm-wave flux to such a narrow ring was surprising, leading to the suggestion that two planets, one inside and one outside it, "shepherd" it (Boley et al. 2012), in a way reminiscent of how shepherds over millennia have tended and kept order in their flocks of sheep. This is a realization of the prediction of Liou and Zook (1999) quoted at the beginning of this article, that ring structures carved by the gravity of unseen planets could reveal the presence of those planets. To understand the ring images in general, the other forces on ring articles need to be invoked. The gravitational forces on the particles go as their masses, which are proportional to their volumes. The radiation forces (when they absorb or scatter photons of light there is a resultant push in the direction the photon was going) are proportional to their projected areas. Consequently, there will be a particle size below which radiation is dominant and above which gravitation has the largest influence on their motion; for Fomalhaut and typical particle materials, this division is at a size of about 2 μm (Arnold et al. 2019). The ring seen with ALMA is described as containing "parent-bodies," meaning particles large enough to have stable orbits under gravity, and that collide destructively with each other to generate smaller debris. Since

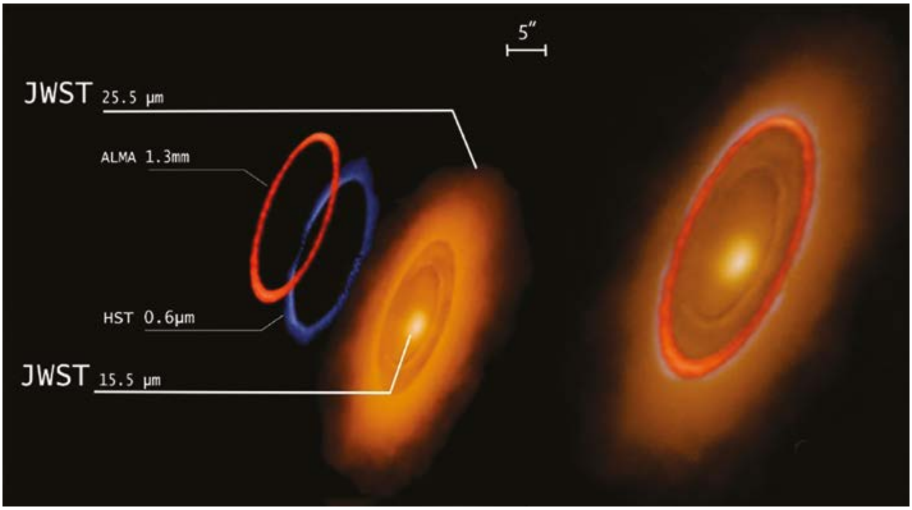

Figure 6. The relation of the high-resolution images of the Fomalhaut system to each other (image by Adam Block and Andras Gaspar). The left image is a kind of assembly diagram showing the three images separately, while they are combined into a single false color image to the right.

particles emit and scatter efficiently at wavelengths close to the particle sizes, this indicates the emission is from roughly mm-sized grains, something like beach sand. As they collide and break each other down into fine dust, these sand grains need to be replenished, which occurs when larger bodies collide destructively, breaking each other up into smaller particles. The colliding bodies are in turn replenished through collisions of still larger bodies. For obvious reasons, this process is called a collisional cascade.

In contrast to the mm-wave image, the HST optical image traces scattered light – scattering is efficient for photons similar in wavelength to the grain size, so the grains responsible are of size less than a micron (i.e., a thousand times smaller than the particles dominating the ALMA image). Since the outer ring lights up in the optical, we can conclude that the collisional cascade operating in this ring extends down to these small sizes. The photon pressure force on grains less than about 2 µm exceeds the gravitational force, so the smallest grains are blown away from the star; a careful look at Figure 6 reveals a thin halo outside of the ALMA-imaged ring illustrating this process.

For more than a decade, we had the beautiful HST and ALMA images, and had to content ourselves with the Spitzer image in Figure 3 as our best view at 24 μm and images at similar resolution from the Herschel Telescope at 70 μm and beyond. We resorted to building theoretical models to imagine what was happening with the dusty debris. These models leaned heavily on the structure of the solar system, with an inner ring analogous to the Asteroid belt and an outer disk like the Kuiper Belt, and nothing between (e.g., Su et al. 2013). We pointed JWST/MIRI at Fomalhaut expecting to confirm this picture but, as Figure 4 shows, got quite a shock. Virtually the whole region between the star and outer ring is filled with emitting dust that shows evidence for an inner ring and more. This complex structure is most likely signaling that there are more planets circulating the star.

Inside all this complexity there is another mystery: extremely hot dust confined to a few tenths of an au, revealed through interferometry (Absil et al. 2009) – a technique combining the images from multiple telescopes widely separated, to achieve the kind of sharpness we would get if we could afford a telescope as large as their separation. We are struggling to understand how this dust can be kept in place but does not evaporate so close to the star (e.g., Stamm et al. 2019).

We now have JWST/MIRI images of a number of additional debris disks and the shock in finding emission filling the region between the star and outer disk is no longer even a surprise. A dramatic example is Vega itself, a star very similar in properties to Fomalhaut and at virtually the same distance.

However, the dust in the Vega system is very smoothly distributed without the dramatic structures revealed around Fomalhaut. This disk – it does not resemble a ring – seems to have an inner edge at a few au and a modestly deep groove at about 60 au, just inside Vega's outer ring at 85 au that started the whole area of study. Vega seems to share the other debris properties of Fomalhaut, i.e., the very hot dust right around the star, the far infrared ring (although more diffuse and perhaps not shepherded by any planets), and the sub-micron-sized grains streaming out under the influence of photon pressure. Yet the differences in the JWST/MIRI images signal that its planetary system may be quite different.

Debris disks are interesting in their own right, as this discussion shows. As we image more, we may get glimpses of the influence of unseen planets as with Fomalhaut. Planets as massive as Jupiter are found around only about 3% of stars (Rowan et al. 2016). The most common "giant" planets have masses less than 10% the mass of Jupiter, more similar to Neptune and Uranus than to Jupiter and Saturn (Ananyeva et al. 2023). The great majority of exoplanets have been discovered through their small effects on the

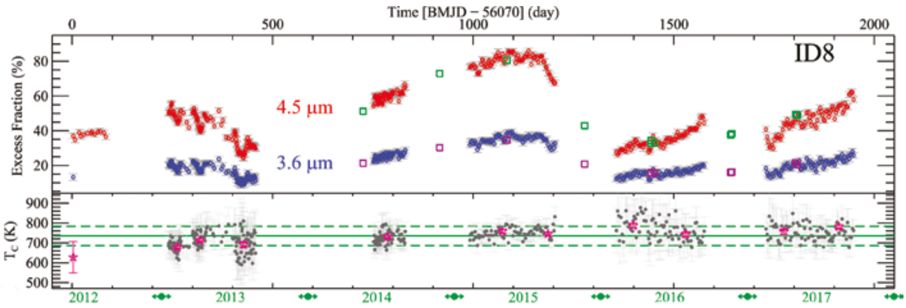

Figure 7. Infrared signal (the stellar fraction of the total has been subtracted) of the star "ID8" in NGC 2547, a young stellar cluster about 30 Myr old. The variations indicate asteroid collisions. The constancy of the temperature shows that these collisions are all occurring at about the same distance from the star, i.e., in something like a belt of asteroid-sized objects, and infrared spectra show mineralogical features proving that the behavior is generating lots of silicate-rich dust.

radial velocity of their stars as the orbit and gravity pulls the stars in synchronism, or by the minute dimming of their stars as they transit in front of them. Even Jupiter could be detected directly by JWST only at distances within about 25 light years (e.g., Ygouf et al. 2024). The current examples of directly imaged planets are of objects more massive than Jupiter; specifically, no Jupiter-mass planets have been spotted among the nearby stars. Within 25 light years, there are only eleven stars known to have exoplanets within the habitable zone (Wikipedia 2024), so detecting directly planets in a configuration in any way resembling the Solar System seems to be a remote possibility.

It was therefore exciting when inside the ALMA-imaged ring around Fomalhaut, a faint dot was found that seemed to be a planet orbiting Fomalhaut (Kalas et al. 2008). However, subsequent observations seemed to show it growing a bit in size until finally by 2014 it had blurred out and was undetectable, as can be seen from the bottom set of small cutouts in Figure 5 (Gaspar and Rieke 2020). The most plausible explanation is that it is the result of a devastating collision between two asteroid-sized bodies, with the resulting creation of a copious cloud of dust that masqueraded for a while as a planet (Kenyon et al. 2014, Lawler et al. 2015, Gaspar and Rieke 2020). Perhaps as exciting to the small band of debris disk aficionados as a planet, this object (if this hypothesis is correct) may well represent on a small scale the type of process that creates and sustains debris disks.

In our own asteroid belt, strong episodes of dust generation are associated with asteroid collisions (Sykes & Greenberg 1986, Sykes 1990, Nesvorny 2003). Similarly, in very young debris disks (generally around stars less than 100 Myr old) there are wide excursions in the infrared emission above the stellar photosphere. They indicate that their asteroids are colliding at a high rate and that the dust these collisions create is getting cleared rapidly (e.g., Melis et al.2012, Meng et al. 2012, Su et al. 2019, Su et al. 2022). Figure 7 is an example (from Su et al. 2019). The rate of collisions around the young stars is indicative of the chaotic events as planets and large asteroids are assembled. The infrared emission can help to reveal details of this process. For example, the infrared spectra usually are dominated by either crystalline silicate material (e.g., Olofsson et al. 2012, Su et al. 2019), or by silica (e.g., Rhee et al. 2008, Lisse et al. 2009), a simpler silicon-oxide compound. Both materials are direct indicators of the extreme temperatures reached as kinetic energy is released in a violent collision, and silica in particular is produced in extremely violent hyper-velocity collisions (Johnson et al. 2012). New JWST spectra indicate some variations on these two dominant dust compositions, so once these data have been fully understood we will have some understanding of compositional variations among asteroids orbiting other stars.

The rapidity of the variations contrasts with the behavior of traditional debris disks around older stars, which tend to fade at ages of about 500 Myr (Gaspar et al. 2013, Sierchio et al. 2014). In addition, there can be periodic modulations on top of the general light curve – you can almost see them if you look closely at the 4.5 μm curve for ID8. Explaining the full range of variations has been very challenging. The rapid drops in output require that the emitting dust be very small, so that radiation pressure blowout can expel it quickly. This rules out the conventional concept of generation by collisional cascades, since by definition they operate from a population of larger bodies. Instead, we may be seeing violent collisions from which tiny grains are condensing out of vaporized minerals. The incidence of these collisions around an individual star is extremely high, indicating that the zone where they are occurring is in a state of turmoil. There are a number of possibilities for this condition, but a likely one is that planets in the system are undergoing a scattering event or that a planet is migrating – situations that should be relatively common at the 30 Myr age of the ID8 system. Perturbations from such behavior will deflect planetesimals onto eccentric and inclined orbits, creating a chaotic situation in a formerly peacefully orbiting asteroid family and with an elevated rate of collisions (see Su et al. 2023 for discussion of this process in another highly variable system). Initially some of the resulting dust clouds may be optically thick, slowing their dissipation, but as they clear the fine grains will be ejected by radiation pressure force, yielding a rapid drop in their infrared emission.

In summary, debris disks offer a detailed look at processes in exoplanetary systems that are not observable by other means. This includes the presence and dynamical state of asteroid and Kuiper belts, and even the presence of unseen planets. These disks are a key aspect in our increasing understanding of planetary systems in general.

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SESSION 7: OUTREACH AND PUBLIC ENGAGEMENT IN ASTRONOMY

Session 7: Outreach and Public Engagement in Astronomy

Lars Lindberg Christensen
NOIRLab, USA

Panel discussion members

- Lars Lindberg Christensen, *NOIRLab, USA*
- Claudia Mignone, *INAF-Istituto Nazionale di Astrofisica, Italy*
- Teresa Paneque, *European Southern Observatory, Germany*

Introduction and summary

Lars Lindberg Christensen spoke about how advancements in astronomical technology, particularly in imaging from telescopes on the ground and in space, have had a transformative power in altering our view of the Universe and fostering a profound sense of connection to the cosmos. The astronomical images kindle our curiosity and sense of wonder and inspire a deep appreciation for the vastness and complexity of the Universe — as long as we uphold strict scientific standards and ethical production.

Claudia Mignone shared news headlines with popular questions on how JWST images are made and the meaning of colors in infrared astronomical images, an indication of genuine curiosity from the public and an opportunity to address data literacy and promote digital skills while sharing the beauty of the cosmos. Different sonification examples to map data into sound were also shown, along with activities from a project exploring astronomical images with children in a Brazilian favela.

Teresa Paneque gave some scary examples of the scientific literacy of the younger generations and talked about how to use information and science outreach against conspiracy theories and misinformation.

There was concern about the proliferation of fake news and general mistrust of science/scientists by certain parts of society. It was recommended to speak with such individuals and communities with curiosity and openness, not condescension. Their questions and skepticism can actually be great ice-breakers for a discussion. We were also reminded that the landscape may not be as grim as we believe. What we see online is not a reflection of reality, and science literacy and trust in science/scientists is actually increasing in many places. Trust comes from dialogue, two-way engagement with society, and it takes time, care, effort and emotional energy to build it collectively. Furthermore, astronomers are greatly privileged, being well-liked and well-trusted by the general public (more so than many other kinds of scientists). We must thus see it as our responsibility, given this privileged platform, to have an open (two-way) dialogue with the public about science and increase their sense of awe, wonder, curiosity, and trust.

Colorful Cosmos: Transcending our Worldviews through Astronomical Imaging

Lars Lindberg Christensen
NOIRLab, USA

The Universe, a canvas of celestial wonders, has captivated human imagination for millennia. Advances in astronomical technology, particularly in color imaging from telescopes on the ground and in space, have served to transform our understanding of the Universe and foster a profound sense of connection to the cosmos.

When we stargaze outside under a clear sky with lay people today, the most frequent question is: "Is there life out there?" It is more frequent than the questions about black holes, Mars and lunar landings that were common 30 or 40 years ago. I believe this is a result of our worldview slowly changing.

The answer to the question about life is, of course, tricky. On the one hand, we know that there are billions of worlds out there and likely life as well, but on the other hand it took a long string of seemingly improbable events to produce life. Among them, a mature galaxy billions of years into its life span forming a mature Solar System with sufficient metals to form a rocky planet where water and life appeared. And later, a Moon creating tides, enabling the right conditions for life to emerge from the oceans. And

Figure 1. This NASA/ESA/CSA James Webb Space Telescope MIRI image of N79 in the Large Magellanic Cloud shows a region of interstellar atomic hydrogen that is ionized. Credit: ESA/Webb, NASA & CSA, O. Nayak, M. Meixner.

then the meteorite impact some 65 million years ago which altered animal life on the Earth profoundly, as the dominant reptiles were largely replaced by mammals...

And now we are gathered here in the Vatican, with JWST and other telescopes preparing the canvas for the most exciting time of scientific progress! Very fitting to be reflecting in this place.

Over the last 25 years, I've had the privilege to work with a talented crew of image processing experts in Europe and the US, like my co-author Mahdi Zamani, working on data from the NASA/ESA/CSA Hubble Space Telescope, the European Southern Observatory, the NSF NOIRLab, the NSF National Solar Observatory, NASA/ESA/CSA James Webb Space Telescope and more.

The journey from monochrome to vibrant, high-resolution color images (Fig. 1) has been a pivotal element in broadening our cosmic perspective and redefining our place in the grand tapestry of the cosmos. To highlight some examples of what I find to be some of the most pivotal visuals, at least from western science, through history:

1. In 1543 *De Revolutionibus* by Copernicus showed the Sun at the center of the Solar System and the planets orbiting around it.
2. In 1572 Tycho Brahe's bright supernova in Cassiopeia showed that the heavens are changeable and nudged a revolution in astronomy (Fig. 2).
3. In 1613 Galileo Galilei's observations of sunspots showed that the Sun is not perfect, but flawed.
4. In 1785 William Herschel carefully counted the stars in different regions of the night sky and his sister Caroline produced the first drawing of the shape of our star island, the Milky Way.
5. In 1859 Richard Carrington sketched an intensely bright flare on the Sun. This led to what became known as the Carrington Event, the most intense geomagnetic storm in recorded history, that caused fires in telegraph stations. Today it would have resulted in electrical blackouts and widespread damage to satellites and other sensitive systems.
6. In the 1890s pioneering astro-photographer E.E. Barnard imaged the Barnard nebulae, clouds of gas and dust that obscured the more distant stars in the background as he mapped the heavens.
7. In 1919 two expeditions, led by Dyson and Eddington, used a total solar eclipse to measure the position of stars near the Sun so as to verify the minute two-arcsecond bending of light by its gravity — a visual

proof of Einstein's mind-bending general theory of relativity.

8. In 1968 astronaut William Anders photographed the Earthrise during the NASA Apollo 8 mission. By some accounts "the most influential environmental photograph ever taken". It moved our vantage point and worldview from the Earth *to space*.
9. In 1990 Voyager 1's Pale Blue Dot took our vantage point even further out.
10. Around 1992 David Malin, known as the *Man Who Colored the Stars*, was still using photographic emulsion and gave us views of cosmos that moved us even closer to the stars.
11. In 2015 NASA's New Horizons spacecraft captured a high-resolution color view of the dwarf planet Pluto, exploding our perception of the diversity of worlds in the outer parts of the Solar System.

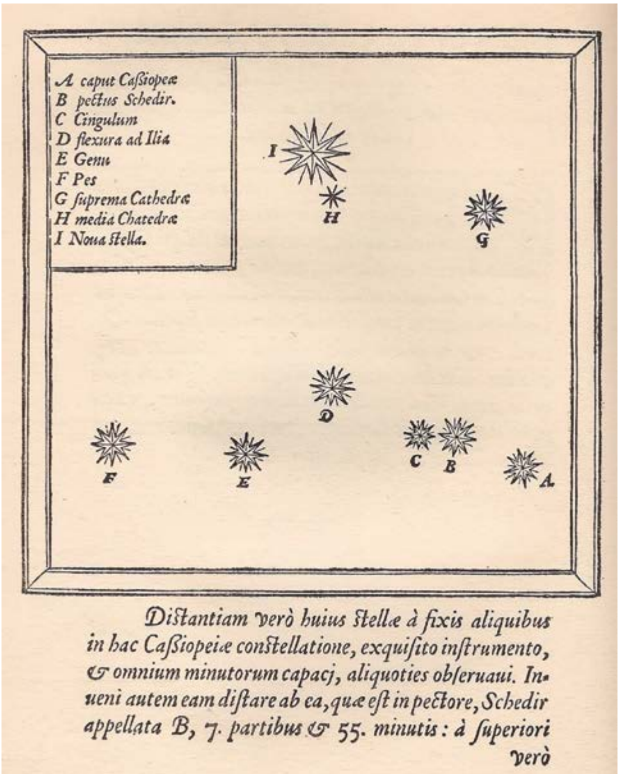

Figure 2. Star map of the constellation Cassiopeia showing the position (labeled I) of the supernova of 1572; from Tycho Brahe's *De Nova Stella* (On the New Star) of 1573. Credit: Tycho Brahe.

Of course, the observations and the scientific papers in many ways speak for themselves but there's a lot going on under the hood when it comes to visualizing the data in color and removing all instrumental artifacts. Our decades of experience in creating color images from data from telescopes in space and on the ground has given us our significant expertise – however, with the forthcoming data deluge from Rubin and JWST, we are entering a new era in data visualization.

The process involves some design choices – and because of that we have developed rigorous scientific standards for generating ethically correct images for the public.

It is *almost* possible to make a recipe for the six steps, or components, that go into these images:

1. Resolution – not just angular resolution, but Photogenic Resolution that we defined in 2013 – field of view divided by angular resolution. Large ground-based imagers can also make amazing images if the number of resolution elements is large! A good example is one of the first big Hubble mosaics – 15 pointings by the WPFC2 of the Crab Nebula that we put together in 2005 (Fig. 3).
2. To get definition and contrast the compression of the immense dynamic range in the astronomical FITS files is, in many ways, the secret sauce.

Figure 3. One of the first big Hubble mosaics done with 15 HST/WFPC2 pointings of the Crab Nebula. Credit: NASA, ESA, A. Loll/J. Hester (Arizona State University).

After the astronomical processing the stretch function brings the many nuances into view, before compositing and post-processing. This work is performed in our own interactive tool called the FITS Liberator, now used by most image processing experts. The inverse hyperbolic sine is our go-to function and is flexible enough to handle most objects.

3. The colors are usually assigned as close to the astronomical filters as possible, but for JWST we use chromatic ordering where the least infrared filter is assigned blue and the most infrared is red.
4. Composition, of course, plays a huge role. Books have been written about framing. The classical example is Jeff Hester's Eagle Nebula from 1995 with Hubble, carefully prepared to work with WFPC2's bat shape.
5. Signal-to-Noise can be improved in a number of ways – exposure time, good weather, large pixels etc. but also in post-processing through sophisticated use of modern noise-reduction and sharpening tools in frequency space.
6. Experience has taught us that lay people need images that are pristine depictions of space. We invest a significant amount of manual labor into removing artifacts from the telescope and detector – sometimes hundreds of hours for gigapixel images. A case in point are the diffraction spikes – artifacts from the secondary mirror mount that are almost impossible to remove in the cosmetic cleaning and which have somewhat incorrectly become the four-spiked stars we see in popular culture. Maybe we will start seeing more six-spiked stars now, inspired by JWST images.

The full overview of our image processing pipeline is shown below in Fig. 4. No need to go into the details but in recent years especially the post-processing and artificial intelligence tools have led to significant improvements and the ability to cope with gigapixel-sized images.

In conclusion, we have evolved from an understanding that *we* are the center of the Universe, to the *Sun* being the center of the Universe, to having *no center* of the Universe – and are now potentially on the cusp of *discovering other worlds with life*. And when we do, our worldview will change profoundly again. All eyes will pivot to that world. For a time at least, that may become the center of our Universe.

There is no doubt these are exciting times, and images are arguably the best way to share these momentous discoveries with the public. The huge datasets from JWST and soon Rubin, translated into color images, do not only provide astronomers with invaluable information enabling us to grasp the intricacies of cosmic phenomena. Astronomical images also kindle our curiosity and sense of wonder and inspire a deep appreciation for the vastness and complexity of the Universe – as long as we uphold strict scientific standards and ethical production following the recipe laid out.

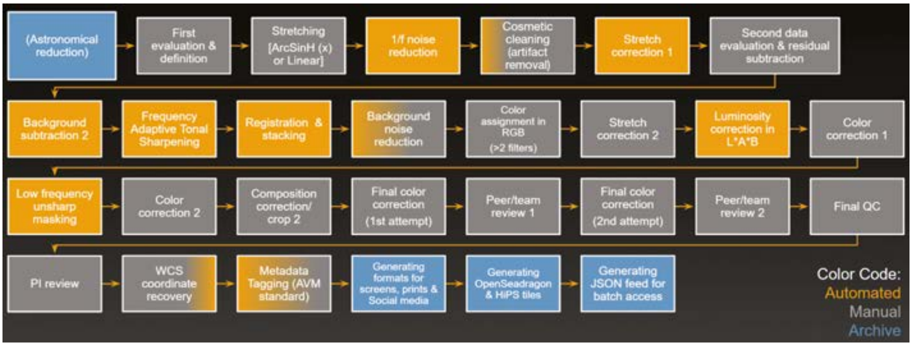

Figure 4. Pipeline for Post-processing of EPO Images (detailed). Credit: M. Zamani & L.L. Christensen.

"But Are the Colors Real?"— Opportunities for Data Literacy, Art Collaborations and Social Justice

Claudia Mignone
INAF-Istituto Nazionale di Astrofisica, Italy

Introduction

JWST images have achieved resounding success worldwide. A frequent question with the general public concerns how such images are made, triggered especially by the fact that JWST observes in the infrared. This curiosity can, in turn, be used to explore the topic of digital color image processing, promoting computational thinking and data literacy "through the backdoor". This is also a fertile area for art-science collaborations and an engaging subject for projects co-creating scientific knowledge with marginalized communities.

An evergreen question: How are astronomical images created?

In today's image-dominated digital landscape, astronomical images enjoy a very fortunate reputation thanks to the fascination enticed by the cosmic subjects they depict. For science visualization purposes, astronomical images are processed via a layering technique that allows multiple data sets to be combined into a color image (Rector et al., 2007). This is however not readily known by the non-expert public, often eliciting questions on how such images are created, for example during public talks, in online forums and on social media. A wide range of multimedia content has been produced to address this question, a classic for Hubble Space Telescope (HST) imagery that was revamped since the JWST Early Release Observations (Pontoppidan et al., 2022) in July 2022.

Online news outlets have covered the topic with in-depth articles and interviews to mission experts, featuring headlines such as: "How the James Webb Space Telescope's first color images were made",[1] "The Colors in the

[1] By Will Gater, *New Scientist*, July 11, 2022 https://www.newscientist.com/article/2327954-how-the-james-webb-space-telescopes-first-colour-images-were-made/ (last retrieved on 10 March 2024)

James Webb Space Telescope Photos Are Fake. And that's OK",[2] "Yes, NASA Did Manipulate The Webb Telescope's First Color Images Last Week—But Don't Call Them 'Fake'",[3] "The James Webb Space Telescope images aren't what your eyes would see. But that makes them science, not faked",[4] "What color are the stars? The story behind the James Webb telescope images",[5] "Are the Colors in Webb Telescope Images 'Fake'? Humans can't see infrared light, so what makes Webb Space Telescope images so dazzling?",[6] "The art behind NASA's scientific space photos. Welcome to the aesthetics of space photography",[7] "How is color added to the JWST images? An astronomer explains".[8]

The abundance of content on the topic, which was still popular even several months after the first JWST images were released, indicates a genuine curiosity by the general and interested public to understand science at a deeper level. After all, as the mission was rightfully presented as an infrared observatory, catching light humans cannot see, the question of how these beautiful images were made arose quite naturally. Whereas some of the headlines may contain the word "fake", suggesting possible disbelief around the images and their scientific truthfulness (this might be linked to the unfortunate expression "false-color" from photography jargon, the use of which is discouraged by the astronomical community), the headlines themselves, and the articles in greater detail, do a pretty good job explaining the process of creating such scientific visualizations from the observatory data.

[2] https://slate.com/technology/2022/07/james-webb-space-telescope-photos-colors-infrared.html By Sarah Braner, *Slate*, July 15, 2022 (last retrieved on 10 March 2024)

[3] By Jamie Carter, *Forbes*, July 18, 2022 https://www.forbes.com/sites/jamiecartereurope/2022/07/18/yes-nasa-did-manipulate-the-webb-telescopes-first-color-images-last-week/ (last retrieved on 10 March 2024)

[4] https://qz.com/2188123/the-james-webb-space-telescope-images-arent-faked-theyre-designed By Tim Fernholz, *Quartz*, July 19, 2022 (last retrieved on 10 March 2024)

[5] Translated from Italian: "Di che colore sono le stelle? La storia dietro le immagini del telescopio James Webb" by Matteo Marini, *Repubblica.it*, July 20, 2022 https://www.repubblica.it/tecnologia/2022/07/20/news/ecco_come_nascono_i_colori_del_james_webb-358387567/ (last retrieved on 10 March 2024)

[6] https://gizmodo.com/webb-space-telescope-image-colorization-1849320633 By Isaac Schultz, *Gizmodo*, August 6, 2022 (last retrieved on 10 March 2024)

[7] By Jay Castello, *The Verge*, October 10, 2022 https://www.theverge.com/2022/10/10/23393194/nasa-image-processing-jwst-astrophotography (last retrieved on 10 March 2024)

[8] Dr Alastair Gunn, *BBC Science Focus*, February 15, 2023. https://www.sciencefocus.com/space/how-is-colour-added-to-the-jwst-images-an-astronomer-explains (last retrieved on 10 March 2024)

Opportunities for public engagement

Such a widespread expression of interest is an opportunity for public engagement, not just to delve into the physical processes behind the astronomical objects depicted in the images, but even further, to explain how digital images are made, thus promoting data literacy "through the backdoor" and practicing computational thinking, a vital skill in the current digital age (Wing, 2006). An example of an online tool to explore the topic in the classroom is the Rubin Observatory's investigation "Coloring the universe"[9] which lets users practice with ordinary color digital images before moving to astronomical image processing. This is also a fertile area for science-art collaborations. An example is the lenticular print of the famous HST Pillars of Creation image created by artist Melanie King in 2017: the choice to use this printing technique, which makes use of a zig-zag texture to feature two images at once, wishes to highlight the levels of mediation that an astronomical image goes through when produced for public consumption.[10]

Another way to explore the extra dimension offered by multi-wavelength astronomical observations is through sonification: transforming the data into sounds rather than images. This approach can be used to make data accessible to visually impaired people as well as providing an additional, multi-sensory layer for people with clear vision. A wide range of astronomical sonifications have been produced, but there is still not a common "grammar" as the one used for image processing. Nevertheless, as sound offers many more parameters to map a data cube rather than images, there is great potential for both public engagement and research. One of the most used conventions is to map wavelength onto pitch, intensity onto volume, and position through a stereo surround system, but research is ongoing to investigate which astronomical parameters are best mapped onto which sound parameters (Zanella et al. 2022). A platform for astronomical sonifications is Chandra's "A Universe of Sound",[11] which features some of the JWST ERO images as part of their collection. There is also the option to let users "play" images in real time. An example is the freely available Herakoi[12] software, a motion-sensing sonification experiment that uses machine learning for hand recognition to track in real time the position of the user's

9 https://investigations.rubinobservatory.org/coloring-the-universe (last retrieved on 10 March 2024)

10 https://www.melaniek.co.uk/pillars-of-creation (last retrieved on 10 March 2024)

11 https://chandra.si.edu/sound/ (last retrieved on 10 March 2024)

12 https://github.com/herakoi/herakoi (last retrieved on 10 March 2024)

Figure 1. Cooperative student work comparing life phases of stars and humans. Credits: Closer to the Sky.

hand in the scene observed by a webcam connected to a computer screen, converting into sounds the visual properties of the "touched" pixels (Guiotto Nai Fovino et al. 2023). An exhibit based on this software to explore the JWST image of the Carina Nebula is also part of the "Time Machines" exhibition, created and produced by INAF at Palazzo Esposizioni Roma.[13]

Exploring the raw data underlying astronomical images in an interdisciplinary way can also be an empowering tool to practice science with marginalized communities. This is being done as part of "Closer to the Sky",[14] an IAU-OAD funded project run by astronomers and community organizers to co-create scientific knowledge in the Cantagalo Pavão Pavãozinho (PPG) favela complex of Rio de Janeiro (Cortesi et al. 2024). Figure 1 shows a cooperative student work created at Ninho das Águias, the local library

[13] https://macchinedeltempo.inaf.it/index.php/en/home/ (last retrieved on 10 March 2024)

[14] https://www.astro4dev.org/closer-to-the-sky-co-creating-astronomical-knowledge-in-the-favela-complex-of-cantagalo-pavao-pavaozinho-ppg-in-rio-de-janeiro/ (last retrieved on 10 March 2024)

that hosts the project, during a workshop led by Prof. Denise R. Gonçalves, an Afro Brazilian woman astronomer at Valongo Observatory of Federal University of Rio de Janeiro, sharing her research on planetary nebulae, which also includes JWST observations of the NGC 3132 nebula (De Marco et al. 2022). This is an example of a public outreach project engaging a marginalized and fragile community, meeting the community where they are, presenting scientist role models in which they can identify themselves and co-designing the project according to the community needs.

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Astronomy Outreach — Reaching for Representation and Visibility

Teresa Paneque-Carreño
European Southern Observatory, Germany

Scientific outreach is an activity that can be developed through different platforms, by institutions or individuals, using a variety of tools and towards multiple objectives. It affects not only the target audience, but also those who are involved in the effort of communicating the scientific content. In the following I will address four key points highlighting the importance of promoting scientific culture and relatable stories in historically underrepresented communities within science, such as the global south and women in general.

Outreach as a way of promoting critical thinking

In 2021, when asked about four conspiracy or science statements it was shown that people born after 1981 (classified as Millennials and Gen Z) were more likely to believe or be unsure about statements such as "Vaccinations implant microchip", "Earth is flat, not round" and "NASA did not land on the moon".[1] These are generations that have grown with or been heavily influenced by the access to the internet, therefore an alternative explanation is that they may be prone to frequent conspiracy groups online.

It is a clear necessity to actively fill these corners of the internet with scientifically accurate content. Going beyond a public that is already eager and interested in learning from academic institutions in traditional settings is the current challenge for outreach endeavors. Scientific outreach should not present itself as the absolute truth or only answer, but rather push the audience to learn more, to question itself and transmit the importance of a scientific method based on proving a hypothesis in a consistent manner. The scientific community must not fall into believing that because the internet has democratized the access to educational material everyone is using it in this way or that certain topics are "common knowledge".

[1] https://carsey.unh.edu/publication/conspiracy-vs-science-a-survey-of-us-public-beliefs

Outreach for policy makers, the importance of knowing what is being funded

Communication of scientific results must also be angled towards government institutions in a way that makes it appealing to fund further investigations in various topics. Current investment in research and development is below 2.5% of the GDP in most OECD countries.[2] For countries in South America, such as Chile and Argentina this value is below 1%.[3] Understanding the scope of the scientific research and technologies developed under public funding both from the governments and from the taxpayers is crucial towards pushing for larger investments and career development opportunities in academia.

Outreach gives tools to become better scientists

It has been documented that participating in outreach activities has an impact not only on the public, but also on the people that create and present the activity. Most scientists that participated in projects such as "Present your PhD thesis to a 12-year-old" and "Shadow a Scientist" reported that the opportunity had increased their interest in outreach, helped them become better speakers, gave them new perspectives on research and considered it a valuable addition to their formal graduate training.[4]

Even though it shows to be a productive and positive experience, less than 30% of scientists report to frequently addressing schools, mass media or journalists.[5] While outreach should not be left to be an individual task, but rather an institutional effort that supports and helps individuals communicate their findings, it is important that as part of the academic tasks we consider time for these activities. A possible reason for this is the idea that it is necessary to be a perfect communicator or a highly renowned academic to actively engage in outreach activities. It is however important to show the diversity of people in academia and the various stages of scientific accomplishment. If only the highly successful cases are shown, then the stereotypes and social biases are enhanced and science drifts further away from people outside academia.

[2] https://www.oecd.org/sti/inno/researchanddevelopmentstatisticsrds.htm
[3] http://data.uis.unesco.org/Index.aspx?DataSetCode=SCN_DS&lang=en#
[4] https://journals.plos.org/plosbiology/article?id=10.1371/journal.pbio.1002368
[5] https://www.nature.com/articles/s41550-018-0633-7

Outreach can change stereotypes and scientific culture

Showcasing women in science or other people from underrepresented communities that are participating in academic research is key to inspire the younger generations. The motto is, "If she can see it, she can be it": by setting the example the impact is higher and transcends social stereotypes. However, it is important to not fall into only showcasing highly successful people from underrepresented communities, as this builds into the super-person figure. An example of this would be constantly promoting only Nobel Laureates as inspiring characters; while their science is great, they represent a small percentage of the academic field and particularly in respect to women laureates in science, they are mostly (except for one) from the northern hemisphere.

The use of social media can aid in showcasing in a familiar way the experiences and realities of scientists from different backgrounds and stages in their careers. Several individuals currently use popular platforms like Instagram and TikTok to share their paths, inspiring younger generations and diversifying the image of what an academic/scientist looks like.

Several institutions have also taken part in outreach through social media; in this case, as they represent the work of many scientists from a variety of backgrounds, they can help in highlighting that science, particularly astronomy, requires an international and multidisciplinary effort. Through the use of communication platforms these institutions can shape the view of how scientists work as a collective and send a powerful message of unity and diversity in a complex time of our history.

Communication of science is a powerful tool: how we communicate, what we communicate and who communicates sends a message that leaks into society and its effect must not be underestimated. The task of doing outreach must be valued as a job in itself. Scientists will participate, but they should be led or assisted by professionals in areas of communications. Institutions are ultimately responsible for producing quality outreach materials. Those who partake in outreach should not only be the most highly accomplished scientists (by current academic standards), at every stage science should be shown and the teamwork effort behind each discovery highlighted. The message matters: scientific outreach should not move away from discussing topics of diversity and migration which are fundamental to scientific progress and also relevant in the current world political context. Overall, outreach helps us build bridges and move forward within both academia and society; it must be prioritized and evolve together with the new technologies and platforms to reach vast audiences.

SESSION 8: PHILOSOPHICAL PERSPECTIVES, NEW WORLD VIEWS

Philosophy and Religion in the Age of JWST

Introduction to the session on "Philosophical perspectives, new world views"

Guy Consolmagno
Vatican Observatory

Our understanding of the nature of science compared to the nature of philosophy is subject to many of the same misunderstandings as can be found in science-religion debates. As with religion, however, one hopes that we can go beyond naive concepts of conflict or replacement.

It is important to recognize that while science and philosophy can interact, each must be given its own due. In this, one is reminded of what St. John Paul II wrote in his 1987 letter to the director of the Vatican Observatory, Fr. George Coyne SJ, about science and religion: "Both religion and science must preserve their autonomy and their distinctiveness. Religion is not founded on science nor is science an extension of religion. Each should possess its own principles, its pattern of procedures, its diversities of interpretation and its own conclusions." One could substitute "philosophy" for "religion" and the statement would remain valid.

But while both science and philosophy each represent an independent mode of searching for truth, this does not mean that the one cannot provide motivation and inspiration for the other. The immensity of the universe revealed by JWST makes it difficult to be satisfied with a narrow, parochial understanding of reality, just as it forces the believer to look beyond an Earth-bound God. Indeed, the ability to observe the universe in a new way, as has been granted to us by the James Webb Space Telescope, means that we can be inspired to deeper questions about the nature of the reality behind these images.

In the face of astronomical data, a philosopher must confront a universe larger than the common-sense experience of our quotidian experience, just as a believer must confront the fact that the only possible sort of creator-God is one even bigger than that observed universe. And just as by seeing the nature of the universe one can begin to deduce and appreciate the "personality" of such a Creator — one who is both eminently logical and yet transcendently beautiful, so the philosopher can begin to ask what principles remain constant even as the nature of space and time itself becomes bent beyond recognition.

Science, in turn, can be inspired to reflect on the nature of its limits, even as it is inevitably directed toward the unbounded possibility of a universe that exists beyond the borders of what we can observe. And science can perhaps be guided by the expectation that the more elegant its understanding, combining both logic and beauty, the closer it comes to truth. The person of faith can put it this way: the author of Truth is the One whose essential being is reflected (however faintly) in the elegance of any theory that we poor creatures can devise.

It is perhaps worth recalling another phrase of St. John Paul II, introducing his 1998 encyclical *Fides et Ratio*: “Faith and reason are like two wings on which the human spirit rises to the contemplation of truth.” Again, one could substitute “metaphysics and physics” for “faith and reason” in that statement. The essential insight is this: our goal is Truth. Physics and metaphysics are both wonderful tools; but the goal of our efforts is neither science alone, nor philosophy alone. No human understanding or expression that is guided toward any goal other than Truth will ever satisfy the urge within us that drives us to be scientists, or give us the faith that an accomplishment like the JWST could even be achieved.

In the discussion that follows, we find an eloquent discussion of the shifting boundaries of physics and metaphysics in light of the JWST results; a discussion of how the Catholic intellectual tradition has pondered the apparent directedness of the human mind towards truth and beauty; and how our understanding of theoretical cosmology, especially in the work of Stephen Hawking, may be motivating a fundamental paradigm shift in our understanding of our place in the universe.

Astronomy and Religion Dialogue in the Age of JWST

Karin I. Öberg
Harvard University

Religion and science in general, and Catholicism and astronomy in particular, are often presumed to be in natural conflict with one another. This conflict model often uses the Galileo affair as evidence, ignoring the complex human conflict at the heart of it, Galileo's dubious evidence for the geocentric model, and Galileo's continued allegiance to the Church [1]. This conflict model is also deeply ahistorical, erasing the religious origins of universities, as well as the many scientists who were not just religious, but whose scientific investigations were motivated by religious beliefs. This does not mean, however, that fruitful dialog between astronomical and religious communities, and between astronomical and religious ideas is always easy, but it does suggest it is worth having.

Religious commitments remain important to many, and in the Global South a majority of people hold that their religious belief is *very* important [2]. Engaging with religious beliefs is therefore often needed to remove barriers to entry into the scientific project. A dialog implies that teaching and learning flows in both directions, however, and one of the things I have learnt from engaging with the Catholic intellectual tradition, is that religiously-inspired or motivated thought often provides powerful interpretative frameworks to connect scientific discoveries to human purpose and meaning. In the remaining text I briefly outline what such exchanges of ideas can look like using astronomical images and astronomical discoveries by the James Webb Space Telescope (JWST) as the starting point.

During the past two years the JWST has given us stunning images of the Universe, from nearby star forming regions to distant galaxies [3]. Beauty alone is not what is ultimately so attractive about these images, however, but rather it is that they are also true. This, I think, helps explain why laypeople so often worry about 'false colors' in astronomical images; they want to be sure that what they are seeing is 'real'. When deployed effectively these images can break down barriers between different communities and attract new people into the scientific conversation. For people of faith, contemplating these beautiful truths can be profoundly spiritual, drawing them closer to their Creator, as well as to science.

But why are we, religious and secular alike, so attracted to JWST's images? Why is it so important that they are true? The Catholic intellectual tradition has pondered the apparent directedness of the human mind towards truth and beauty for millennia. In the process, the tradition has developed understandings of the human person that can be appreciated also by those who do not share Catholic beliefs. Among these is the idea that human flourishing can only be achieved if we first understand that to be human is to be a seeker of truth, and therefore to abhor being lied to. This idea is grounded in a deeper idea that the human person has a rational soul, which has as its end truth itself [4].

Two specific truths addressed by the JWST are the origin of the Universe's structure, and the origins and presence of other worlds. The JWST was especially designed to explore our Universe's early moments and how its strange and exotic first stars and galaxies evolved into the present-day cosmos. It is natural to want to bring these discoveries into conversation with religious claims about creation of the Universe. The origin of the Universe as described by Big Bang cosmology is, however, qualitatively distinct from the Catholic idea of the Universe being created by God out of nothing; when the Big Bang begins, the Universe is already there. As the father of the Big Bang, Catholic physicist-priest Lemaître, emphasized, the Big Bang does not prove the religious idea of creation, nor does it refute it. Still, the Big Bang cosmology presents an image of the beginning of time and space, and as such can help the faithful imagine what the theological concept of creation out of nothing entails, and what it does not.

Even for the non-religious, Big Bang cosmology and the intense historicity of the Universe, which is made manifest by the JWST, can inspire questions about the contingency and origins of the Universe. The apparent beginning of the Universe seems to beg the question of where did it come from, and what gave it existence. Already in the Middle Ages Thomas Aquinas taught that we cannot know with philosophical or scientific certainty whether the Universe had a beginning. He also taught that God had the power to create a Universe without a beginning [5]. Yet, one of the teachings coming out of the Bible is that cosmos has a beginning, and Thomas Aquinas argues that, in part, this is to make the existence of a creator more apparent to us: 'For the world leads more evidently to the knowledge of the divine creating power, if it was not always, than if it had always been;

since everything which was not always manifestly has a cause; whereas this is not so manifest of what always was.' [6]. In other words, contemplating the beginning of the Universe can be a path to contemplating the divine.

The other way around, contemplating the divine, may also have helped in conceiving of the beginning of the Universe. It is tempting to speculate that the Catholic teaching of the contingency of the Universe, that it did not need to exist, helped to give birth to the idea of the Big Bang cosmology. Lemaître's seminal paper on the Universe's beginning [7], seems to carry echoes of St Augustine: 'For if eternity and time are rightly distinguished by this, that time does not exist without some movement and transition, while in eternity there is no change, who does not see that there could have been no time had not some creature been made, by which some motion could give birth to change?' [8,9]. It is tempting to speculate that Lemaître's theological understanding that time and space did not need to exist helped him imagine a beginning of space and time for our Universe, especially in the context of a societal and academic environment that otherwise took the eternity of the Universe for granted.

A second question addressed by JWST with deep spiritual reverberations is the characterization of exoplanets with an eye towards finding habitable, and perhaps even inhabited planets outside of the Solar System. Superficially such discoveries may seem to pose a threat to traditional religious belief. First, the discovery of alien life would suggest that the origins of life both here and elsewhere happen naturally, removing God as an explanatory cause. Second, the possible presence of life elsewhere appears to make us less special, completing the Copernican revolution, and hence making the Biblical account of God's intense interest in Earth and humanity less plausible. If not addressed, these objections will be obstacles towards fruitful dialog. So let me briefly address them here, using tools from the Catholic intellectual tradition. Catholic theology emphasizes that God typically acts through instrumental causes, however, and that a process being 'natural' does not mean that God is absent, any more than an author is absent from the book he has written. Furthermore, if God is truly infinite in power and goodness, as taught in the Catholic tradition, the expanse of the Universe and the amount of life in it has no impact on the intensity of his care for humanity – only if God was limited could there be competition between God's care for others and his care for us. Exciting future exoplanet discoveries should hence not provide obstacles to religious faith. That does not mean that such discoveries would be without theological significance, however. In a Christian context, studying the cosmos provides understanding of its creator, and it matters whether the Universe is a garden, or an empty sea where we constitute the lonely ark that carries all life through time and space.

In conclusion, the beauty and truths about the Universe being gifted to us through the JWST offer multiple opportunities for dialogue between scientific and religious communities. Such dialogues will include the clearing away of both scientific and theological misconceptions, and they critically depend on the mutual respect and willingness to learn from one another. When successful, these dialogues can then help purify religious beliefs, provide fertile soil for theological contemplation, and assist all truth seekers in better exploring the big questions about the Universe and about the human beings trying to understand it.

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[2] Pew Research Center (https://www.pewresearch.org/religion/2018/06/13/how-religious-commitment-varies-by-country-among-people-of-all-ages/).

[3] https://webbtelescope.org/images

[4] See e.g. Thomas Aquinas, *Summa Contra Gentiles*, Book III, Chapter 25.

[5] Thomas Aquinas, *De Aeternitate Mundi*.

[6] Thomas Aquinas, *Summa Theologica*, Prima Pars, Question 46, Article 1.

[7] Georges Lemaître, *Nature*, Volume 127, Issue 3210, pp. 706 (1931).

[8] St Augustine, *City of God*, Ch 6; cf. St Augustine, *Confessions*, Book 10, and *The Literal Meaning of Genesis*, Book 1.

[9] Jonathan Lunine, 'Faith and the Expanding Universe of Georges Lemaître' in *Church Life Journal*, McGrath Institute for Church Life, U. Notre Dame.

At Home in the Universe?

Thomas Hertog
KU Leuven, Belgium

Thank you for the opportunity to speak here.

I would like to offer some thoughts on our understanding of our place in the universe in the light of a fundamental paradigm shift that is unfolding in theoretical cosmology. This shift concerns the epistemic roots of big bang cosmology. It has emerged from my work on quantum cosmology with Jim Hartle and Stephen Hawking, which I have elaborated on in my book *On the Origin of Time* (Hertog, 2023).

The idea that time began in a big bang goes back to the discoveries of Georges Lemaître, the illustrious former President of this Academy. Lemaître famously predicted the expansion of the universe on the basis of Einstein's theory of general relativity. Tracing the expansion backward, he speculated that time must have had a genuine origin in what he called a primeval atom. Remarkably, Lemaître realized back then that it required a rather special history of expansion, in casu an extended period of very slow expansion, for the universe to be habitable.

Since those early days, the strange biophilic character of the universe has become even more intriguing. We now understand that the effective laws of nature have a long list of life-engendering properties, from the strength of the particle forces to the composition of the universe, to the size of the fluctuations in the microwave background. Twiddle ever so slightly with any of these and habitability would often hang in the balance. It is almost as if the cosmos has known all along that one day, it would be our home. What should we make of this?

Traditionally, most scientists from Einstein to the earlier Hawking, regarded the mathematical relationships that underpin the laws of physics as transcendental Platonic truths. In which case, the answer to the riddle of cosmic design – to the extent that it is an answer – is that it is a matter of mathematical necessity. The universe is the way it is because nature had no choice.

Around the turn of the 21st century, an entirely different explanation emerged. This one had its roots in a series of surprising discoveries that suggested that at least some properties of the physical laws might not be carved in stone, but instead be the accidental outcome of the particular manner in which the early universe cooled after the big bang. From the species of particles to the strength of forces to the amount of vacuum energy, it became apparent that the universe's biofriendly laws were forged in a series of random transitions during its earliest moments of expansion. Reasoning along these lines, cosmologists began to envisage a multiverse, an enormous inflating space with a variegated patchwork of island universes, each with its own physics. This led to a sweeping change of perspective on the idea of our universe being fine-tuned for life. Even though most universes would be sterile, in some the laws of nature are bound to be just right for life. Multiverse aficionados argued that it is not a profound mathematical truth that renders the universe biofriendly, but simply excellent local cosmic weather.

Yet there is a problem buried in this reasoning: The multiverse is itself a Platonic construct. Multiverse cosmology postulates immutable metalaws governing the whole. But these metalaws do not specify in which one of the many universes we are supposed to be. Without a rule that relates the metalaws of the multiverse to the local laws within our island universe, the theory gets caught in a spiral of paradoxes that leaves one without verifiable predictions at all. Invoking the anthropic principle hardly helps, because your anthropic perspective might select one biofriendly patch, with this set of properties, whereas mine might pick out another patch, with a different set of local laws, and no objective rule at hand to decide which one is correct.

In the light of this conundrum, Hawking grew increasingly skeptical of the multiverse as the basis of a solid scientific paradigm. Can we do better? Yes, we found out, but only by relinquishing the idea, inherent in multiverse cosmology, that our theories can take a God's-eye view, as if somehow standing outside the cosmos. It is an obvious and seemingly tautological point: our cosmological theory must account for the fact that we exist within the universe. "We are not angels who view the universe from the outside," the later Hawking proclaimed. So we set out to turn cosmology inside-out and rethink its basic framework from an observer's perspective.

This required adopting a quantum outlook onto the universe. The key role of the observer has been recognised since the discovery of quantum theory. Before a particle's position is observed, there is no sense in even asking where it is. It doesn't have a definite position, only possible positions described by a wave function that encodes the likelihood that the particle, if it were observed, would be here or there. Of course, quantum observations are by no means restricted to those made by humans. Such observations could be made by a dedicated detector, the environment, or even through interaction with a lone photon.

Thinking about the universe as a quantum system introduces a subtle backward-in-time element into cosmology. The past exists as a wave function that describes not a single history but a spectrum of possibilities that morph into a definite reality only when the future to which they give rise has been fully settled, i.e., observed.

This leads one to view what went on in the very earliest stages of the universe as a process akin to that of natural selection on Earth, with an interplay of variation and selection playing out in this primeval environment. Variation happens because random quantum jumps cause frequent small excursions from deterministic behavior and occasional larger ones. Selection enters because some of these excursions, especially the larger ones, can be amplified and frozen-in through quantum observations, giving rise to new rules that help shape the subsequent evolution. The interaction between these two competing forces in the furnace of the big bang produces a meandering branching process in which dimensions, forces, and particles first diversify and then acquire their effective form when the universe expands and cools. It is as if the collective quantum observations retroactively fix the outcome of the big bang. For this reason, Hawking referred to our hypothesis as "top-down cosmology", to drive home the point that we read the fundamentals of the universe ex post facto, somewhat like how biologists reconstruct the tree of life.

Top-down cosmology ties in with remarkable developments in theoretical physics that have brought to the fore the holographic nature of gravity. For quite some time now, theorists have speculated that gravitational systems may be holograms made up of quantum entangled particles located on a surface in spacetime. In a cosmological setting, it turns out that it is the dimension of time that holographically pops out. From a holographic viewpoint, one ventures back in time by taking a fuzzy look at the hologram (Fig. 1). It is like zooming out, an operation whereby one discards more and more of the entangled information that the hologram encodes. Eventually, however, one runs out of qubits, and that would be the big bang. That is, holography suggests that Lemaître's primeval atom is an epistemic origin where not only time, but also the physical laws themselves disappear. This is very different to the old Platonist view that the laws of nature are immutable and transcendent. Holographic cosmology radiates the view that it is not the laws as such that are fundamental, but their capacity to change.

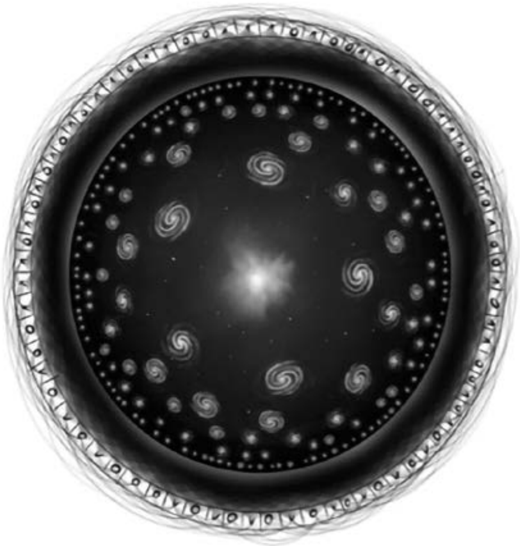

Figure 1. The evolution of the universe as it pops out holographically. Holographic physics envisages the boundary of the disk as a hologram made of entangled qubits from which the interior spacetime – our past history – projects down. Thus, holography builds in the top-down philosophy of cosmology, in which the past is in some sense contingent on the present.

The upshot of all this is a profound revision of what cosmology ultimately finds out about the world. For almost a century, we have studied the history of the universe against a stable background of fixed (meta)laws of Nature. But the quantum outlook that Hawking and I developed reads the universe's history from within and as one that includes, in its earliest stages, the genealogy of the physical laws (Fig. 2). By weaving observership into its mathematical fabric, quantum cosmology appears to encapsulate the limitations of what can be known about the universe.

A finitude of this kind has been anticipated by philosophers like Hannah Arendt. To Arendt, the pursuit of science and technology from an Archimedean standpoint, stripped from all anthropomorphic elements and humanistic concerns, was an alienating and ultimately self-defeating paradigm. She argued that if we begin to look down upon the world and our activities as if we are outside it, then our actions will ultimately lose their deeper meaning. "The stature of man would not simply be lowered by all standards we know of but will have been destroyed" (Arendt, 1958). This is the paradox. In our attempt to find the ultimate objective scientific truth, we risk ending up smaller, not larger.

The later Hawking's top-down cosmology, rooted in a profoundly quantum outlook onto the universe, amounts to a response to Arendt's concern. It is a call emerging from the depths of fundamental physics to view our universe as our home and the laws we discover to describe it anchored in our relation with the cosmos. One can hope this could be the seed of a new worldview in which man's knowledge and creativity will once again revolve around their common center.

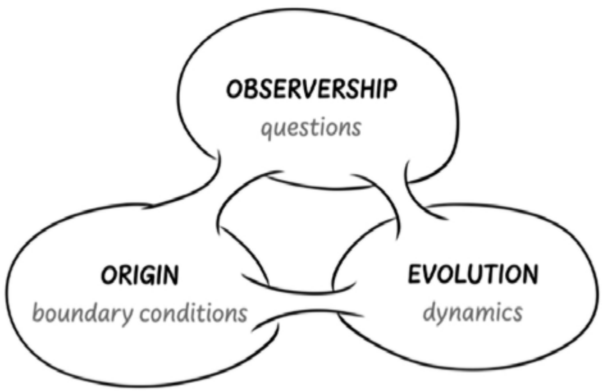

Figure 2. The usual framework for prediction in physics assumes a fundamental distinction between the laws of evolution, boundary conditions, and observations or measurements. For most scientific questions, this split framework suffices. But the apparent biophilic design in cosmology runs deeper, for it probes the origin of the nature of the laws. It necessitates a more general predictive framework that entwines these three entities. A quantum outlook on cosmology provides exactly that. The interconnected triptych sketched here constitutes the conceptual core of a new quantum theory of the cosmos in which evolution, boundary conditions, and observership are folded into a single scheme of prediction.

Is the 'Big Bang' Physics or Metaphysics?

Martin J. Rees
University of Cambridge, UK

Abstract

Cosmology is an exploratory quest; many ideas are tentative, and most will surely prove wrong – but it is speculative science, to be distinguished from metaphysics.

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The laws of physics established locally seem to apply everywhere we can observe – and also throughout cosmic history back to 1 second, when helium and deuterium form – indeed we can be confident back to a nanosecond. That is when each particle had about 50 Gev of energy – as much as can be achieved in the biggest particle accelerators – and the entire visible universe was squeezed to the size of our solar system. Were there not this uniformity, we would have made little progress in astrophysics.

But fundamental questions like "where did the fluctuations come from?" and "why the early universe contained the actual mix we observe of protons, photons and dark matter?" take us back to the even briefer instants when our visible universe was hugely more compressed still – if inflation theories are correct, down to microscopic size.

Lab experiments offer no direct guide to the relevant physics at these extreme compressions – though inflation is a consequence of specific (though still conjectural) physics and here is another basic question:

How much space is there altogether? How large is physical reality? We can, even in principle, only observe a finite volume – a finite number of galaxies. That is essentially because, like on the ocean, there is a horizon. Unless we take a very non-Copernican view, there are galaxies that are already beyond the horizon – and in our accelerating universe we can never (even in principle) observe them.

There is no perceptible gradient across the visible universe and that suggests it extends hundreds of times further than our horizon. But that is just a minimum. If it stretched far enough, then all combinatorial possibilities could be repeated. Far beyond the horizon, we could all have avatars.

Be that as it may, even conservative astronomers are confident that the volume of space-time we can ever observe even in principle is only a tiny fraction of the aftermath of our big bang.

And there is something else. Some scenarios like Andre Linde's "eternal inflation" suggest that the aftermath of "our" big bang could be just one island of space-time in a vast archipelago – one big bang among many.

A challenge for 21st century physics is to answer two questions: first, are there many "big bangs" rather than just one? Second, if there are many, are they all governed by the same physics or not?

Many string theorists argue that there could be a huge number of different vacuum states – different vacuum energy, different microphysics. Other big bangs may, when they cool down, be governed by different laws. What we call "laws of nature" may in this grander perspective be local bylaws governing our cosmic patch.

If physical reality is like this, then there is a real motivation for theorists to model "counterfactual" universes, with different gravity, different microphysics, and so forth, to explore what range of parameters would allow complexity to emerge – and which would lead to sterile or "stillborn" cosmos. This is what is called anthropic selection.

Some do not like the concept of such a vast and varied cosmos, because it would render the hope for neat explanations of the fundamental physical numbers as vain as Kepler's numerological quest to relate planetary orbits to nested platonic solids.

But our preferences are irrelevant to the way physical reality actually is – so we should surely be open-minded to the possibility of a 4th and grandest Copernican revolution – we have had the Copernican revolution itself, then the realization that there are zillions of planetary systems in our galaxy; then that there are zillions of galaxies in our observable universe. But we would then realize that our entire observable domain is a tiny part of a far larger and possibly diverse ensemble. We would live not in a typical part of the multiverse – but a typical domain in the subset that allows complexity to develop.

To address that question we have to know the probability distribution – and the correlations between them. That is a can of worms that we cannot yet open – and will have to await huge theoretical advances.

I must re-emphasise that we do not know if there are other big bangs. But they are not just metaphysics. We might one day have reasons to believe that they exist. Specifically, if we had a theory that described physics under the extreme conditions of the ultra-early big bang – and if that theory had been corroborated in other ways [by for instance deriving the unexplained parameters in the 'standard model' of particle physics] then if it predicts multiple big bangs we should take that prediction seriously. And there would be no reason to assign them different epistemological status from the un-observable domains beyond our horizon in our own big bang.

We cannot observe the interior of black holes, but we believe what Einstein's relativity says about what happens there, because his theory has gained credibility by agreeing with data in many contexts that we can observe. Likewise, we would believe the prediction of other big bangs if this was the consequence of applying to the early universe a "battle tested" theory that correctly predicted the values of some basic physical constants of our low-energy world.

It is now an open question – but how would you bet? About 15 years ago I was on a panel at Stanford where we were asked by the chairman, Bob Kirshner, how seriously we took the multiverse concept – on the scale "would you bet your goldfish, your dog, or your life". I said I was nearly at the dog level. Andrei Linde, who had spent 25 years promoting "eternal inflation" said he had almost bet his life. Later, on being told this, Steven Weinberg said he would happily bet Martin Rees's dog and Andrei Linde's life.

Andrei Linde, my dog, and I will surely all be dead before this is settled.

Indeed, some of the crucial physics of unified theories could be just too difficult for human brains – just as quantum theory is too difficult for monkeys.

It is conceivable that machine intelligence could explore the 10-D geometrical intricacies of some string theories, and spew out, for instance, the correct mass of the electron or other key parameters of the standard model. We would then have confidence in the theory and take its other predictions seriously. But we would never have the "aha" insight moment that is the greatest satisfaction for a theorist. Even worse, physical reality at its deepest level could be so profound that its elucidation and comprehension would have to await emergence of a posthuman species, or massive advances in AI.

But let me close with a plug for our field of astronomy. It is the grandest of the environmental sciences. Thanks to improved instruments, on the ground and in space, this subject is becoming broader. For instance, we know that most stars are orbited by retinues of planets. There are billions of planets in the Milky Way that could be abodes of life – but are they?

Astronomy is also a "fundamental" science: to understand the very beginning of our expanding universe will require advances in physics that may take us further from our intuitive concepts than quantum theory and relativity already do – indeed we must be open-minded that these concepts may be too deep for human brains to grasp.

So I end with an admonition from Hubble: "Only when empirical resources are exhausted should we enter the dreamy realm of speculation".

A Responsibility to Awe

Some Thoughts on the James Webb Telescope from the Perspective of a Dutch Poet

Marjolijn van Heemstra
Poet, Netherlands

The wonders of zooming out, gain in significance when simultaneously we zoom in.

Eye level. The daily realities of politics, society. In my country, The Netherlands, we had a devastating election outcome last November. For the first time in the history of our democracy, a far-right party won the most seats. And as you all know, this is not a Dutch phenomenon.

Worldwide, populist parties are feeding on the fear spiked by growing insecurities. The gaze turns inwards, the mind narrows. Otherness is framed as threat. In such dangerous times, the ultimate gaze of a telescope pointed to possible worlds far away can be an antidote. Showing us the enormity that we are still part of, even though nationalism grows. Showing us how strangely alien we are, all of us. Mysterious carbon-based lifeforms – unique and futile – full of contradictions, very much dependent on each other and the planet that sustains us.

The telescope is often presented as something a-political, a thing of objective science and facts, but it can be much more than that. In these times, searching for the furthest horizons is possibly an act of resistance and searching for life in alien form a way of staying open for the otherness that populist politicians try to make us fear.

Also, the James Webb telescope can help remind us of the intrinsic value of the universe we inhabit, which is no small feat in the light of the very fast developments in the commercialisation of space. More and more, planets, orbits and asteroids are seen as a commodity from which private companies can profit. This raises huge moral questions not only about ownership but also about how – once it is commercialized – we will relate to the night sky that throughout human has been a source of science, solace and spirituality.

By reducing forests, rivers and planets to nothing more than resources, we lose sight of their intrinsic value, until they no longer mean anything besides a product for consumption. This in turn reduces us to consumers of the world, no longer in conversation with our surroundings. A lonely way of living.

No wonder recent years have seen a worldwide explosion of feelings of alienation, especially among young people. There is a lack of a sense of belonging and relating to the world. For how can you relate to a world – a universe – that is primarily viewed as something for economic gain?

Staring into space with the huge communal eye of a telescope is a way of honouring the non-commercial values of the universe. Honouring the cosmos as a source of wonder and knowledge. The search for habitable planets and possible alien presence makes us understand the stars as a force of life, as something to relate to. It is, again, an antidote. *Aliens against alienation*.

Someone much in favour of relating to the universe was the Canadian astronomer Rebecca Elson. Working for the Hubble telescope in the ninety-nineties she combined her scientific work with the writing of poems. Like this one, perhaps my favourite, called 'Evolution'.

We are survivors of immeasurable events
Flung upon some reach of land
Small, wet miracles without instructions
Only the imperative of change.

In one of her poems Elson formulated something called a *responsibility* to awe. Saying we have a duty to honour the poetry of astronomy. I love that word, responsibility, for the response it carries inside. Seeing the pillars of creation, possible relatable planets, the birth of stars – we need to ask ourselves how to respond to all that magnificence. It is the only way to keep science where it belongs, right next to poetry, so near that it sometimes is impossible to distinguish between the two. For Rebecca Elson, astronomy asked for reciprocity. Gathering data through a telescope is not about finding facts, it is about starting a conversation that keeps us connected with the universe we inhabit.

In celebration of this meeting on the findings of the James Webb telescope, I tried to formulate my response to awe. Thinking about reciprocity, perhaps we should consider this question: what's in it for the possible alien we so hope to discover? In case we would be 'discovered' one day, wouldn't we at least want to know what our discoverers are about? This is not an original idea. With his Golden Record, Carl Sagan tried communicating about humankind to possible faraway forms of intelligence. You all know the story. It was beautifully poetic but he left out a few things. Sagan was convinced that a first impression had to be a good one. I believe aliens deserve the whole truth. So, here's my letter to the possible inhabitants of some far-off planet in a goldilocks zone.

Dear alien,
How long before you come into view? Conversely, you may
already have us in your sights for a long time. Us, a speck in your sky.
I can't speak for all of humanity, but in general
that possibility is hard to stomach here.
Our geocentric thinking forms us. Our myths are replete
with chosen-ness. We alone are the children of a sun.
We alone look back at God. It is crushing, the idea
that we might be a simple collusion of the right ingredients.
Not the pinnacle of creation, not guardians of the stars.
Random wanderers in a remote galaxy, with strange kin
around another sun. You force us to ponder
how we can think beyond our human selves.
Look at me writing 'you', assuming singular existence.
While you might be a thousand things, or a thousand things at once,
a collective movement, a large-scale happening in a twelfth dimension.

I once asked an astronomer: How can we recognise extraterrestrial life?
Her answer was: we probably can't.
The overly alien eludes a human. But you can learn, she said,
by unlearning all you learned. Make the strange familiar, the familiar
strange. Regard this world with permanent amazement.
Why this? Why so?
Her words made me think of all those earthly beings,
so close and yet misunderstood. The wild fish on our plates,
the wisdom of root systems, the slow language of metals
which we understand only as raw material for destructive growth.
Why this? Why so?
Our conversation with the world is a long and boring monologue.
But something resonates within us when we look upon the stars.
The remnants of some giant melody. Somewhere in that void
our song vibrates along.

If we meet you, I'm not sure if we'll acknowledge what connects us.
It can take ages for a human to recognise their neighbour,
let alone a relative from billions of years away.
And yet. We point lenses at the unknown. Like lost children, we peer into the dark. It's time someone finds us.

SESSION 9: GALAXY EVOLUTION

A (Non-Comprehensive) Overview of the On-going Galaxy Evolution Paradigm Shift with JWST at "Low" Redshift ($z \lesssim 8-9$)

Stacey Alberts
Steward Observatory, University of Arizona, USA

Abstract

JWST is reshaping our understanding of galaxy evolution, from pushing the frontier of the earliest galaxies known to probing the inner lives of nearby galaxies in exquisite detail. JWST's photometric and spectroscopic capabilities, reaching depths and spectral and spatial resolution never before achieved in the infrared, open up previously inaccessible diagnostics and parameter space that promise to broaden our understanding of the Universe. Here we present a non-comprehensive overview of how JWST is addressing the Big Questions in galaxy evolution – how do galaxies get their shapes? How do galactic ecosystems change over cosmic time? What is the role of black holes? and finally, when and why do galaxies stop forming new stars? – at what has facetiously become "low" redshift, $z \leq 8-9$, in the community.

Introduction

Globular clusters, ancient and compact spherical collections of stars, have long been one of our most enigmatic neighbors. Our own Milky Way contains 150 of these structures, putting them practically in reach astronomically speaking. Globular clusters likely formed in the very early epochs, witness to early galaxy assembly, yet how they formed and what role they play in the galactic ecosystem remains a mystery after decades of active research (e.g. Harris & Racine, 1979). Part of the challenge is exactly that globular clusters are so very old and the process of aging erases clues as to their origin. And these relatively small – again, astronomically speaking – faint structures have defied observation earlier in the Universe at higher redshifts,[1] where we can use the travel time of their light to Earth as a time machine.

[1] "Redshift" is a non-linear scale that corresponds to the amount of time that has passed since a photon left its galaxy and arrived at Earth. It is often represented by the letter "z".

Enter the James Webb Space Telescope (JWST; Gardner et al., 2023). When the CANUS[2] team was examining the first JWST deep field in SMACS J0723, taken in the first month of JWST science operations, they discovered something miraculous. Around a galaxy (named the "Sparkler") magnified by another foreground galaxy cluster are several compact sparkles (Figure 1), which they dated to be old stellar populations that probably formed only 500 million years after the Big Bang (Mowla et al., 2022) at $z > 9$! These stars, likely already ancient by the time their light began traveling to us some 9 billion years ago, present a unique new opportunity to

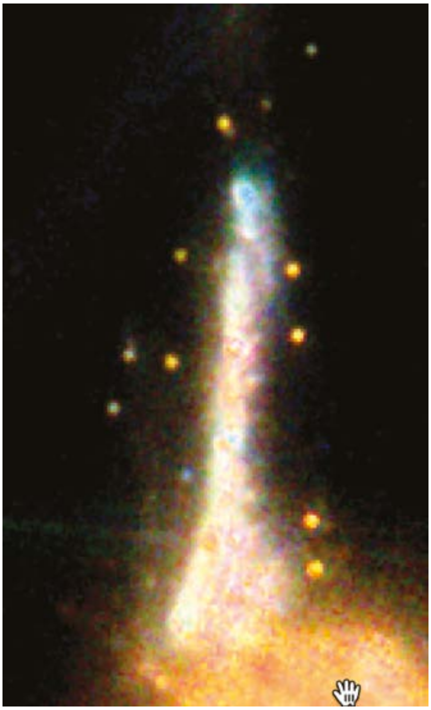

Figure 1. The "Sparkler" – a galaxy at $z = 1.378$ being lensed (magnified) by another foreground galaxy, resulting in a distorted image – was discovered early in JWST's mission to have several "sparkles" that are thought to be ancient globular clusters (adapted from Mowla et al., 2022), previously undetected so early in cosmic time.

[2] The CAnadian NIRISS Unbiased Cluster Survey (CANUCS).

push back the frontiers of our understanding of a previously inscrutable component of galaxies.

The study of galaxy evolution, established when the extended, fuzzy shapes of "spiral nebulae" were determined to be in fact be massive structures external to our own Milky Way, is a historical journey back to our origins. Across cosmic time, an individual galaxy will undergo dramatic transformations, accreting and consuming gas from the cosmic web which it processes into new stars, solar systems, and planets, growing in mass and undergoing structural changes. Understanding this process is one of the primary science drivers for JWST, which carries an instrument suite designed to peer back to the beginning of the Universe with unparalleled spatial and spectral detail. JWST's three near-infrared instruments – NIRCam, NIRSpec, and NIRISS[3] – and one mid-infrared instrument, MIRI,[4] each

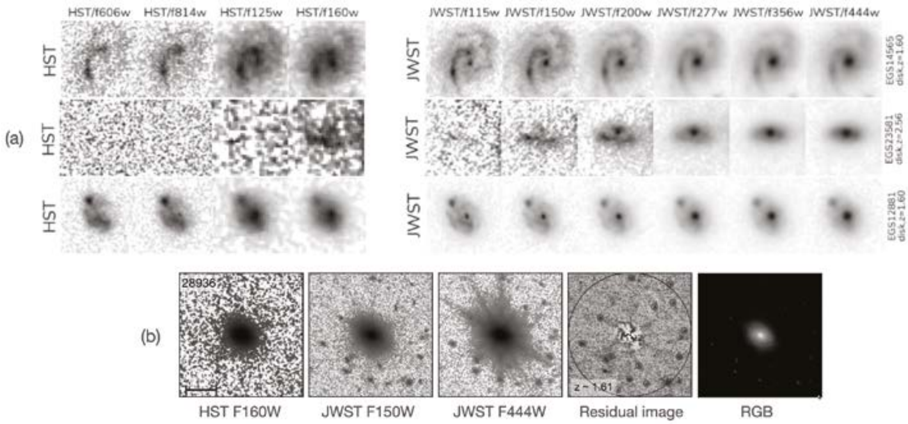

Figure 2. (a) A comparison of galaxy shapes seen at different wavelengths with HST (left) and JWST (right). Structures like spiral arms and central bulges are apparent in the longer wavelength JWST filters. Figure adapted from Ferreira et al. (2023). (b) HST and JWST images of a massive elliptical galaxy at $z = 1.61$ are shown in the first three panels. The fourth panel shows the residual after subtracting the bright elliptical, which reveals several companion galaxies. The final panel shows the F270W, F150W, F090W RGB image of the elliptical. Figure adapted from Suess et al. (2023).

[3] Near-Infrared Camera (NIRCam; Rieke et al., 2023), Near-Infrared Spectrograph (NIRSpec; Jakobsen et al., 2022), Near Infrared Imager and Slitless Spectrograph (Doyon et al., 2023, NIRISS).

[4] Mid-Infrared Instrument (MIRI; Wright et al., 2023).

provide a distinctive piece of the puzzle as we pursue the big questions in galaxy evolution: how do galaxies get their shapes? How does the galactic ecosystem within a galaxy change over cosmic time? What is the role of black holes? And finally, when and why do galaxies stop forming new stars?

From Hubble to High Redshift: The Shapes of Galaxies with JWST

A new era in astronomy was sparked with the Great Debate between Harlow Shapley and Heber Curtis, who disagreed on whether the un-star-like, extended shapes of "spiral nebulae" meant that massive structures existed outside of our Milky Way. The outcome was a literal redefining of our concept of the Universe and today we know that galaxies are not only independent structures, but that a galaxy's shape encodes critical information as to its assembly and evolution, which was codified in the Hubble Sequence classification[5] (Hubble, 1926). Increasingly powerful telescopes culminating with the Hubble Space Telescope (HST) chased this sequence back through cosmic time for bright galaxies, finding that the ordered spirals and spheroids Edwin Hubble cataloged for his Sequence exist as early as ~ 3 billion years after the Big Bang ($z \sim 3$), but they are accompanied by an increase in the fraction of disordered peculiar and irregular galaxies, perhaps pointing to turbulent origins. However, the types of light we could see arriving from these early galaxies, ultraviolet (UV) and optical, can be obfuscated by showing only recently formed stars, or redirected by cosmic dust. Only observations in the near-infrared show the true shape of a galaxy outlined by the older, bulk stellar population.

JWST's Hubble Sequence

JWST's sensitivity and HST-like spatial resolution in the near-infrared wavelengths is already putting our previous view of galaxy shapes to the test. As demonstrated in Figure 2 (a), JWST can identify spiral arms and central bulge structures within disks that are not obvious or even entirely invisible with HST. The results have been surprising: rather than the chaotic, irregular shapes we expected from HST to be abundant, JWST has quickly revealed there are far more ordered, familiar shapes even earlier in the Universe than we ever imagined (e.g. Jacobs et al., 2023; Kartaltepe et al., 2023; Ferreira et al., 2023). In fact, the Hubble Sequence seems firmly

[5] At base, the Hubble Sequence groups galaxies into spheroidal, disk-y or spiral, and irregular morphologies.

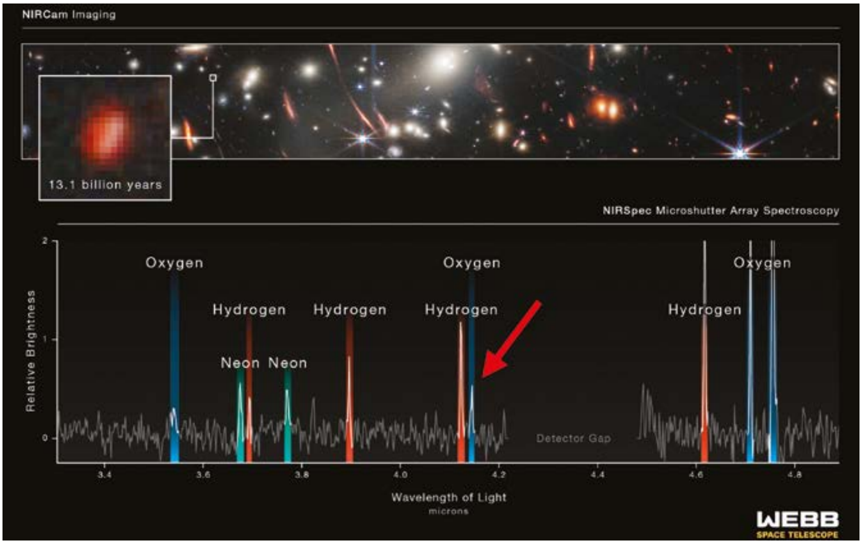

Figure 3. NIRSpec spectroscopy of a galaxy observed 13.1 billion years ago in some of the earliest JWST observations, the Early Release Observations (ERO). The red arrow highlights a relatively weak oxygen emission line that accurately traces the amount of heavy elements in a galaxy and previously was only detected in low redshift galaxies. Credit: NASA, ESA, CSA, STScI.

in place only 1 billion years ($z \sim 6$) after the Big Bang! This new challenge to the current paradigm is further enhanced by access to a previously unseen population: faint galaxies with low stellar masses can now be identified and studied with JWST at early cosmic times. These faint galaxies likely live very different lives from their massive counterparts; their smaller gravitational wells make them more susceptible to disruption, say through interactions with neighbors. They may also play an outsized role in shaping their more massive counterparts: JWST is also revealing that elliptical galaxies – massive spheroids that have stopped forming stars – have a retinue of previously-undetected companions 900x less massive (and nearly a 100x too faint for HST!) than themselves (Figure 2 (b); Suess et al., 2023), long suspected culprits in creating the spheroidal shape of elliptical galaxies.

The Tumultuous Inner Lives of Galaxies

The birth, lifecycle, and death of stars are fundamental to who we are as this process is responsible for "polluting" the Universe with heavier elements – essential for planets and people! – than the hydrogen, helium, and trace amounts of lithium produced in the Big Bang. The recipe for forming stars within a galactic ecosystem is still poorly understood, however, particularly in the early Universe. We know that at a macro level, the efficiency of forming new stars peaked some 10 billion years ago (the so-called cosmic noon era at $z \sim 1-3$) and then declined to present day (Madau & Dickinson, 2014), likely due to less availability of the hydrogen gas required to form stars. We also know from studies of nearby galaxies that the process of star formation is incredibly complex, sensitive to conditions and energy transfer on scales much smaller than the galaxy itself.

The galactic ecosystem: gas, metals, and dust

The revolution in our understanding of galactic ecosystems with JWST will come largely because of two factors: unprecedented sensitive spectroscopy and spatial resolution in the infrared.

Spectroscopy is the gold standard of astronomical observations: it finely bins the light from galaxies, revealing discrete features that contain a wealth of information about the energetic processes in a galaxy. Though not as enchanting as the gorgeous images coming out of JWST, a galaxy's spectrum is nevertheless the source of much excitement among astronomers, as was demonstrated when the very first press release of JWST data presented NIRSpec spectroscopy of a galaxy viewed just 600 million years after the Big Bang (Figure 3). Those in the know immediately spotted an innocuous little line of ionized oxygen that just so happens to be a gold standard for measuring the amount of heavy elements in a galaxy (Arellano-Córdova et al., 2022; Schaerer et al., 2022; Curti et al., 2023; Trump et al., 2023; Rhoads et al., 2023; Brinchmann, 2023; Laseter et al., 2024). This line was previously rarely used to track heavy elements over cosmic time because it was too faint for detection except in nearby galaxies and now, on its figurative first day, JWST was not only detecting this little line, but detecting it in a galaxy that emitted its light 13.1 billion years ago!

The unique capability of JWST to do sensitive spectroscopy in the near- and mid-infrared will give us new insight into several vital aspects of the galactic ecosystem. Using optical emission lines, JWST is measuring how many heavy elements are present in galaxies over cosmic time (e.g. D'Eugenio et al., 2023; Sanders et al., 2024; He et al., 2024), which tracks how stars are born and how pristine gas is accreted from the cosmic web. As we push earlier and earlier in the Universe, we expect these heavy elements to be increasingly rare, with huge implications for the first galaxies; and indeed, JWST is finding that these early ecosystems are harsh places of rapid star formation and extreme radiation fields (Cameron et al., 2023; Topping et al., 2024). JWST's spectroscopy is so detailed that not only can we measure the strength of spectral features (like the emission lines in Figure 3) but also their *shapes*. The shapes of spectral features have a lot to tell us about how stars and gas are moving through a galaxy (called kinematics); for example, whether gas is flowing *into* the center of a galaxy, compressing to form a burst of star formation, or flowing *out* of the galaxy, expelling heavy elements into the cosmic web and removing fuel for new stars (de Graaff et al., 2023). And this is only the tip of the iceberg, JWST's spectroscopy is going to be changing our view of the Universe for decades to come.

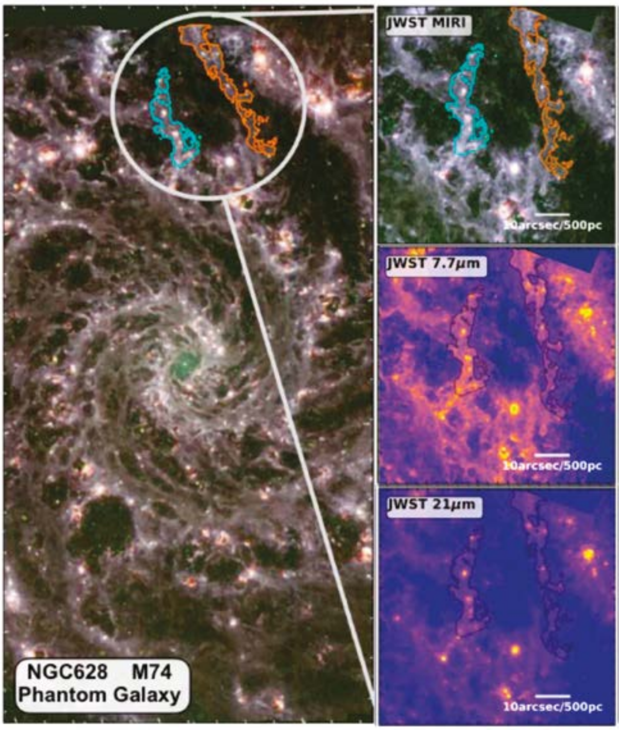

Figure 4. (left) A three-color MIRI image of local galaxy NGC 0628 in F770W (blue), F1000W (green), and F1130W (red) with Hα from HST highlighting young stars. The regions rich and deficient in molecular hydrogen are highlighted in cyan and orange. (right) The top panel shows the region zoomed in. The middle and bottom panels show the F770W and F2100W filters which show cosmic dust and young stars, respectively. Adapted from Williams et al. (2022).

This wonderous spectroscopy will team up with JWST's ability to take images with high spatial resolution, revealing the inner workings even in smaller, distant galaxies. As just one example, a small but integral component of the galactic ecosystem is cosmic dust, small to large carbon and silicate grains that are pervasive in massive galaxies at later times. Cosmic dust is known to be highly efficient at absorbing the high-energy photons emitted by young stars and other energetic processes and re-emitting lower-energy photons with infrared wavelengths. Because of this, much activity happening in galaxies has been "hidden", invisible to our UV and optical telescopes and even to HST's infrared capabilities at high redshift, including the birth clouds of new stars. JWST can peer through cosmic dust in the near-infrared and directly measure the photons from small dust grains in the mid-infrared. Such became exquisitely apparent with early observations of nearby galaxies from the JWST PHANGS team;[6] Figure 4 shows MIRI images of two very different regions where new stars are being born (Williams et al., 2022). These observations identify new stars in their dusty cradles, catching star formation in its earliest stages. Combining MIRI observations with those at even longer wavelengths in the far-infrared from the ground-based interferometer ALMA reveals that only one of these regions is rich in molecular hydrogen, the fuel for star formation. That both are forming stars speaks to the complexity of the galactic ecosystem and the power of JWST in unraveling this complexity.

The mystery of Little Red Dots

JWST's look at the inner lives of galaxies is not only testing our long-held models but also discovering types of galaxies that we never expected. Considerable excitement was sparked in the community with the discovery of Little Red Dots in the first billion years of the Universe using NIRSpec and NIRCam. These compact galaxies have peculiar 'v-shaped' spectra, emitting abundant photons at the short and long wavelength extremes (e.g. Matthee et al., 2023; Labbe et al., 2023). This shape defies our current models, as in normal galaxies, an excess of long wavelength photons seen by JWST would usually be caused by the aforementioned process of cosmic dust absorbing the high energy UV and reemitting in the near-infrared. Follow-up has only deepened the mystery: spectroscopy with NIRSpec has uncovered broad spectral features that signal active black holes among some

[6] Physics at High Angular resolution in Nearby GalaxieS (PHANGS; Lee et al., 2023).

of these Little Red Dots (as well as some brown dwarf stars just pretending to be galaxies; Kocevski et al., 2023; Harikane et al., 2023; Greene et al., 2023; Matthee et al., 2023; Maiolino et al., 2023a; Furtak et al., 2023; Kokorev et al., 2024). These moderately massive black holes are new territory; pre-JWST we could only see supermassive black holes in the form of luminous quasars this early in the Universe. That's not the last word, however: examination of Little Red Dots with MIRI reveals that many are lacking in even the longer-wavelength photons seen by MIRI, uncharacteristic of active black holes and more characteristic of old stars (Williams et al., 2023; Pérez-González et al., 2024). The nature of these previously unknown and surprisingly abundant galaxies – whether they represent the early population of galaxies with moderately massive black holes – has important implications for the origin and growth of black holes and their contribution to galaxy evolution.

The Origin and Influence of Black Holes

Actively accreting black holes have long been an integral part of our models of galaxy evolution, invoked to create the conditions that can influ-

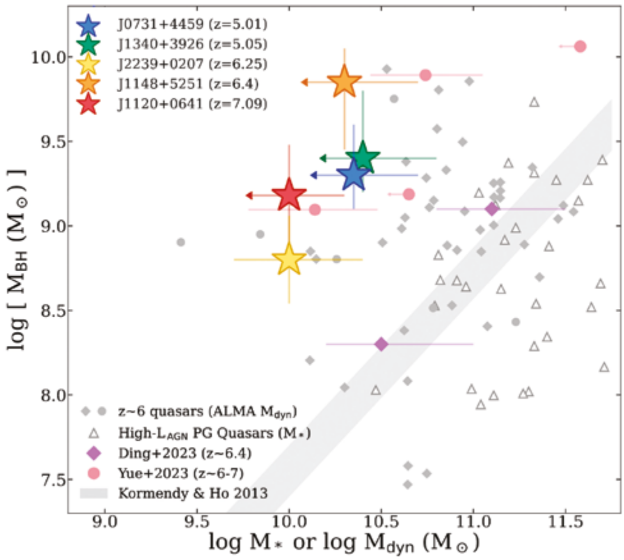

Figure 5. The relation between the black hole mass, M_{BH} and the stellar or dynamical mass for $z \sim 6$ quasars. The stars show measurements of stellar mass from JWST, which can detect the host galaxies under luminous quasars. Host galaxies at $z \sim 6$ are being revealed by JWST to be significantly off the standard relation (gray shaded region). Adapted from Stone et al. (2023b).

ence the gaseous contents of galaxies and ultimately shut down star formation. JWST now stands poised to revolutionize our understanding: from revealing the host galaxies of the most luminous quasars in the early Universe, to spotting moderately massive black holes for the first time beyond our immediate neighborhood, to finding long "missing" black holes, hidden by cosmic dust.

Which came first: the chicken or the egg?

A foundational relation in astronomy is the Magorrian relation (Kormendy & Ho, 2013), which tightly links the mass of a galaxy's black hole to its mass in stars. This relation is well established up to 11 billion years ago, implying that galaxies and their black holes evolve in lockstep and revealing a classic chicken and the egg dilemma: did galaxies or black holes form first?

While ground-based optical telescopes and HST have discovered about one thousand luminous quasars up to $z \sim 7-8$ (e.g. Mortlock et al., 2011; Bañados et al., 2018; Matsuoka et al., 2018, 2023), the brightness of the quasar precluded making measurements of their host galaxies, if they were detected at all. Discovery of black holes down to intermediate masses (such as the Little Red Dots in the previous section) and the robust detection of their host galaxies is only possible with JWST at high redshift.

Using NIRSpec, JWST quickly shattered our record of the earliest black hole known, discovering two within ~ 200–300 Myr after the Big Bang (e.g. Goulding et al., 2023; Maiolino et al., 2023b,a), and several more within the first billion years (e.g. Harikane et al., 2023; Larson et al., 2023). Such early, massive black holes challenge the idea that their "seeds" form from the collapse of the first massive stars (Fan et al., 2023). Do these surprisingly large black holes have correspondingly massive host galaxies? Careful subtraction of the quasar's light in NIRCam imaging has revealed no, their host galaxies are in fact rather wimpy (Figure 5; Ding et al., 2023; Stone et al., 2023a,b). The emerging picture is that the lockstep evolution of galaxies and their black holes breaks down in the early Universe; in other words, black holes may grow first and rapidly, leaving galaxies to play catch-up.

The missing population of AGN hidden by cosmic dust

A key thorn in the side of efforts to link active black holes to evolution on the scale of entire galaxies has been our inability to catalog all black hole activity. Like young stars, black holes can exist in an extended cocoon of cosmic dust which absorbs the high energy photons escaping the accretion

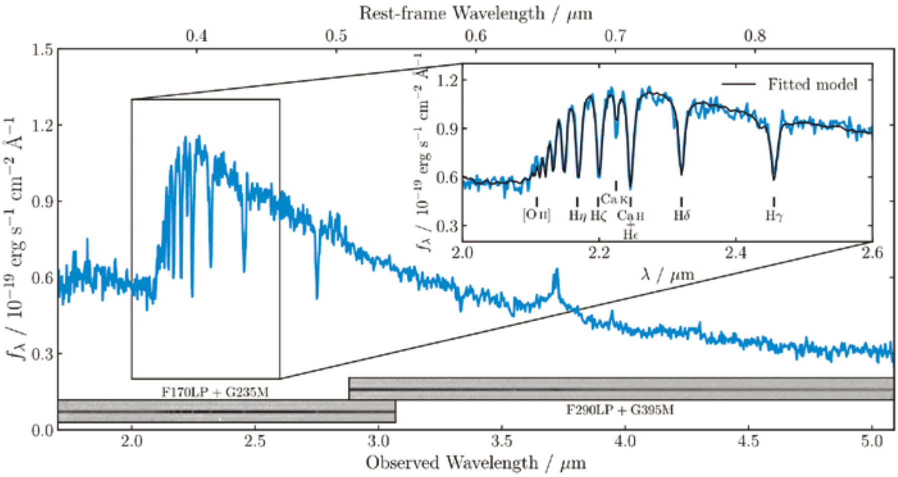

Figure 6. NIRSpec spectroscopy of GS-9209, a quenched galaxy observed in the first ~billion years after the Big Bang. The characteristic flat spectrum without strong emission lines is no challenge for JWST, which can see absorption features (inset) that tell us the history of this galaxy. Adapted from Carnall et al. (2023a).

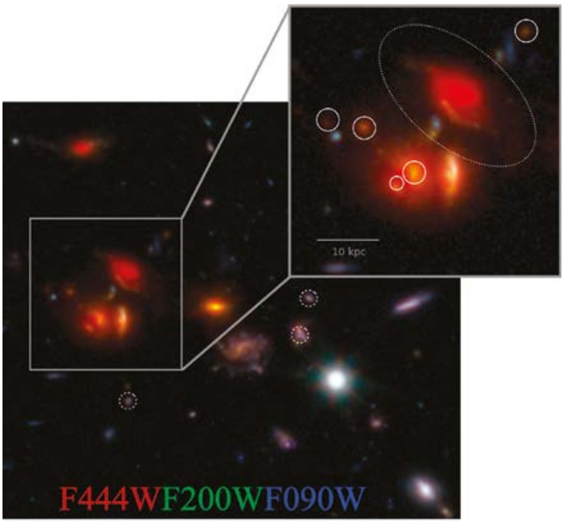

Figure 7. NIRCam three-color image of the Cosmic Rose, a grouping of galaxies at z ~ 3.7 including a massive, dusty star-forming galaxy (inset, dotted circle) and a massive and multiple low-mass quenched galaxies (inset, circles). Their close proximity, some closer than the Milky Way is from the Large Magellanic Clouds, suggests they influenced each other's evolution. Adapted from (Alberts et al., 2023).

disk – superheated material falling onto the black hole – and re-emits them in the infrared. JWST MIRI's spiritual predecessor, the Spitzer Space Telescope, was able to identify these hidden AGN if their infrared emission was very luminous, outshining the galaxy's stars. JWST now has the sensitivity to take a much more complete census, identifying small excesses in infrared light with MIRI and specific spectral signatures with NIRSpec and MIRI from less luminous and very dusty active black holes (e.g. Alberts et al., 2020; Lyu et al., 2023) even at high redshift (e.g. Scholtz et al., 2023). And particularly, MIRI can take this census at $z \sim 1 - 3$, when both the efficiency of forming new stars and the rate of accretion of material onto black holes peaked. Early results show that MIRI increases the number of black holes identified in massive galaxies by more than 2x over X-ray surveys and can discover black holes in low-mass and high redshifts galaxies, newly accessible populations with JWST (Lyu et al., 2023). The hidden black holes can hide no longer, giving us a more complete view of the galaxy-black hole connection (Bonaventura et al., 2024).

The Emergence of Quenched Galaxies

The endgame for galaxies is the cessation of their star formation, a process called quenching. How and why galaxies quench (and stay quenched; Dome et al., 2024) has been a driving mystery in the field of galaxy evolution, with an array of proposed quenching mechanisms (Man & Belli, 2018). An amazing effort using ground- and space-based facilities has been expended to push back the frontier closer and closer to the emergence of the first quenched galaxies; however, the faint and red nature of these sources has limited these efforts to the most massive quiescent galaxies at $z \lesssim 4$, ~ 1.5 billion years after the Big Bang.

The elusive first quiescent galaxies not only provide a boundary condition on the rapid assembly of early galaxy populations, they are not yet old enough that the signatures of their quenching mechanisms have been erased by aging and merger activity. Very quickly post-launch, JWST's high sensitivity in the near-infrared uncovered remarkable evidence of rapid early growth, including some candidates for early, ultra-massive galaxies which, if confirmed by spectroscopy, would be difficult to explain with our current cosmological models (e.g. Labbe et al., 2023). Given that we know galaxies cannot grow indefinitely to arbitrary masses in the later Universe, this implied rapid, permanent quenching as early as $z \sim 6$.

Quenched galaxies are relatively rare and thus need sensitive imaging over large areas of the sky. Even given this, searches for quenched galaxies in our first, limited area deep surveys have found tantalizing evidence that galaxies no longer forming stars are surprisingly abundant in the first 2 billion years of the Universe (Carnall et al., 2023b; Alberts et al., 2023). Among these, NIRSpec spectroscopy of a quenched galaxy at $z = 4.6582$ finds that this galaxy likely formed all of its stars very rapidly, in just 200 million years, before shutting down, likely for good (Figure 6; Carnall et al., 2023a). And continuing in our theme, JWST is not just changing our view of massive galaxies, but opening up a whole new view of low-mass galaxies up to high redshifts. Combining NIRCam imaging with some of the deepest MIRI imaging so far observed (46 hours of exposure time in one filter!) has uncovered a surprise: not only are there quenched low-mass galaxies at $z > 3$ but the proximity of other galaxies may play an important role in their quenching (Sandles et al., 2023; Alberts et al., 2023). This tests a long-standing theory that low-mass galaxies will happily go on forming stars for longer than the age of the Universe without outside influence, unlike their massive counterparts. A gorgeous example of this is the discovery of a so-called Jekyll and Hyde pair – a dusty, vigorously star-forming galaxy with a massive quenched galaxy companion – that has several low-mass quenched galaxy companions (Figure 7; Alberts et al., 2023); together these galaxies make up the Cosmic Rose, just one of many examples of JWST images that fire the imagination and leave us in awe of our Universe.

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New Views of Star Formation, Feedback, and Dust in Nearby Galaxies with JWST

Janice C. Lee*, Adam Leroy, Erik Rosolowsky, Karin Sandstrom, Eva Schinnerer, David Thilker & the PHANGS-JWST team
*Space Telescope Science Institute, Baltimore, USA

Abstract

This brief paper is an extended abstract adapted from the introduction to the JWST Physics at High Angular Resolution in Nearby Galaxies (PHANGS) JWST February 2023 Focus Issue for *ApJ Letters*[1] and the PHANGS-JWST survey paper.[2]

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JWST is revolutionizing fields across astrophysics, and chief among them is the study of the earliest stages of star formation and the dusty interstellar medium (ISM). Mid-infrared observations from space observatories, including IRAS, ISO, Spitzer and WISE, have been key to building our understanding of star formation during the phase when it is concealed beneath a shroud of dust that blocks the passage of visible light. JWST's order of magnitude leap in sensitivity and resolution are finally allowing us to step beyond the Local Group, and observe young embedded stellar populations and the ISM at 10-100 parsec scales across environments characterized by physical conditions not found locally. Combined with observations across the electromagnetic spectrum that capture all major stages of the star formation cycle, we can follow the progression of star formation – from molecular clouds to embedded and unembedded stellar populations – to provide new constraints on the process of star formation to inform theoretical models.

In the first year of science observations with JWST, we have carried out a Treasury survey to obtain 8-band imaging from 2 to 21 μm of a diverse sample of 19 nearby (D < 20 Mpc) massive star-forming galaxies. This survey is conducted in the larger context of the PHANGS (Physics at High Angular resolution in Nearby GalaxieS) program, which aims to study the multiscale processes of galaxy evolution, star formation, and stellar feedback by combining high-resolution panchromatic observations with the

[1] https://iopscience.iop.org/collections/2041-8205_PHANGS-JWST-First-Results
[2] https://ui.adsabs.harvard.edu/abs/2023ApJ...944L..17L/abstract

latest theoretical models. A rich set of data has already been obtained for each PHANGS-JWST target including CO(2–1) mapping (molecular gas), optical integral field spectroscopy (ionized gas and stellar populations), and high-resolution UV-optical imaging (star clusters and associations) through large programs with ALMA, VLT/MUSE, and Hubble, respectively. Our goals are to measure the timescales and efficiencies of the earliest phases of star formation and feedback, build an empirical model of the dependence of small dust grain properties on local ISM conditions, and test our understanding of how dust-reprocessed starlight traces star formation activity and gas, all across a diversity of galactic environments. As a Treasury program, the data have no exclusive access period, and we are providing higher level science products[3] for the full PHANGS JWST-ALMA-MUSE-HST datasets to maximize community science with the survey.

The JWST images of the galaxies in the PHANGS survey are extraordinary, and mind-blowing even for researchers who have studied the same galaxies for decades. The data have been on broad display, and the level of attention that the data have received took many of us by surprise. The STScI Office of Public Outreach reported that four days after the January 29 2024 press release,[4] media coverage was just over 1,000 articles with a potential reach of 4 billion. The images are not only aesthetically stunning, they also vividly illustrate the physics of star formation, stellar feedback, and the ISM. The composite mid-IR images (Figure 1) reveal how gas and dust in spiral galaxies are shaped by large-scale gas flows, star formation, and stellar feedback. Just as striking is where the dust is not seen; shells and bubble-like features, likely carved out by stellar feedback in the form of stellar winds, radiation, and supernova explosions, are ubiquitous. Star-forming regions appear as bright compact IR sources, due to heating by dust-enshrouded young clusters, within a larger diffuse filamentary network of dust. The images and data seem have taken a life of their own.

An initial set of 21 "First Results" papers based on the four PHANGS galaxies observed in the first two months of JWST science operations (NGC 628, NGC 1365, NGC 7496, and IC 5332) was published for a Focus Issue for the *Astrophysical Journal Letters*. The papers presented a broad range of results, ranging from the discovery of embedded star cluster populations and filamentary dust structures down to the smallest scales probed; a census of feedback-driven bubbles and shells; calibration of the dust emission as

[3] https://archive.stsci.edu/hlsp/phangs

[4] https://webbtelescope.org/contents/news-releases/2024/news-2024-105

a gas tracer; and new insights into how the properties of small dust grains (polycyclic aromatic hydrocarbons, PAHs) depend on local ISM conditions. Figure 2 compares the JWST images of NGC 628 and NGC 7496 with those previously obtained with Spitzer.

In particular, work with JWST to study the prevalence of the youngest invisible star clusters (Figure 3) builds on the PHANGS-Hubble effort which has recently released the largest census to-date of ~100,000 star clusters and stellar associations.[5] To search for embedded clusters, we have taken advantage of NIRCam imaging at 3.3 μm using the F335M filter, which is the highest resolution, dust emission dominated imaging filter aboard JWST. The filter captures polycyclic emission from small neutral aromatic hydrocarbons (PAH), and we have demonstrated that 3.3 μm PAH emission is an effective tracer of the youngest dusty clusters (Rodriguez et al. 2023).

Through a visual search for bright compact sources in the F335M image of NGC 7496 which had little to no emission in the Hubble visible images, a small set of 12 dusty clusters was first identified to determine selection criteria which could be used to select a larger sample.

All 12 sources show a F300M − F335M color excess, which indicates the presence of PAH emission (Figure 4). Application of a 300M − F335M color excess criterion results in a total of 67 candidate embedded clusters in NGC 7496. Cross-correlation with the PHANGS-Hubble cluster census shows that only eight of these are found in the Hubble catalog, and all are young (six have SED fit ages of ~1 Myr). This suggests that studies with JWST may significantly increase the census of young clusters in NGC 7496 from the PHANGS-HST catalog; the number of clusters younger than ~2 Myr could be increased by a factor of 2. Candidates are shown to be preferentially located in dust lanes and are coincident with the peaks in the PHANGS-ALMA CO (2–1) maps.

Initial results from expansion of the study to all 19 galaxies in Figure 1 appears to confirm these results. Constraints on the timescale of the dust embedded phase (and the 3.3 μm PAH emission) can be inferred and appears to be less than 2-3 Myr. If confirmed, such a timescale implies that pre-supernova feedback plays a central role to clear natal gas and dust from embedded populations. Next steps include investigation of the completeness of embedded cluster samples based on 3.3 μm PAH emission, which will also provide insight into the processes that heat and destroy small neutral PAHs.

[5] https://archive.stsci.edu/hlsp/phangs/phangs-cat

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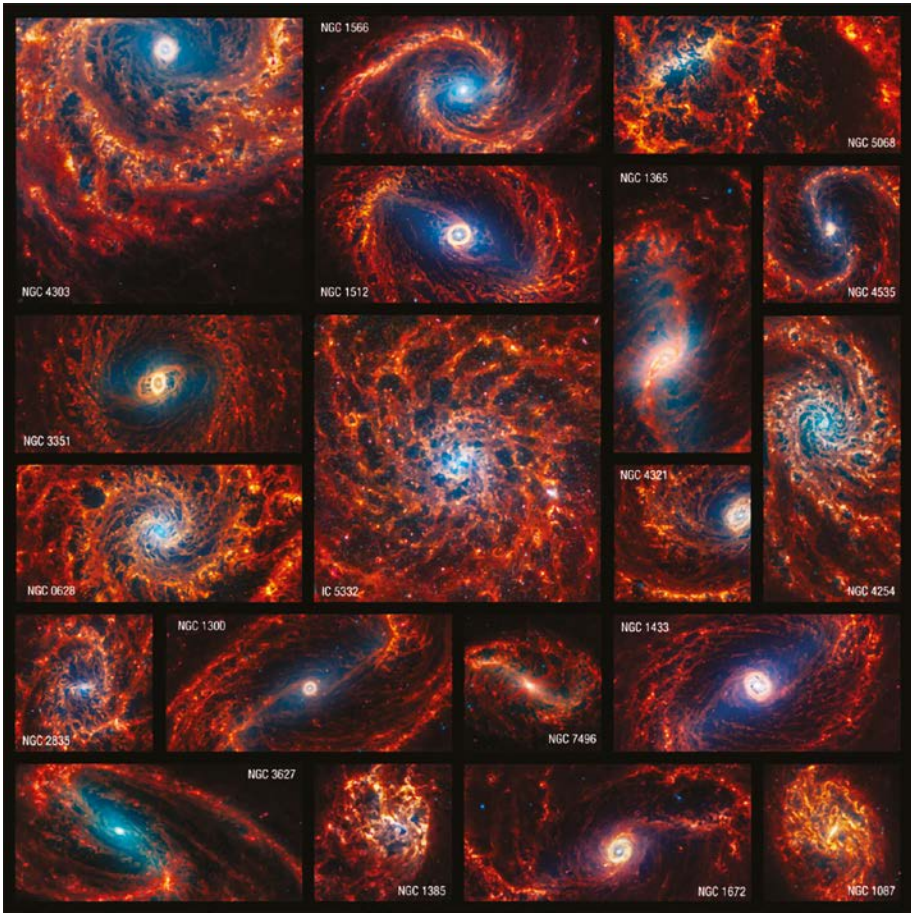

Figure 1. Color composite images from the PHANGS-JWST January 2024 press release[6] composed from data in seven of the eight near and mid-infrared filters used for all 19 galaxies in the survey. From Williams et al. (2024).

6 https://webbtelescope.org/contents/media/images/2024/105/01HM9KGGP1EWFFS-RRSKR8NZGWZ

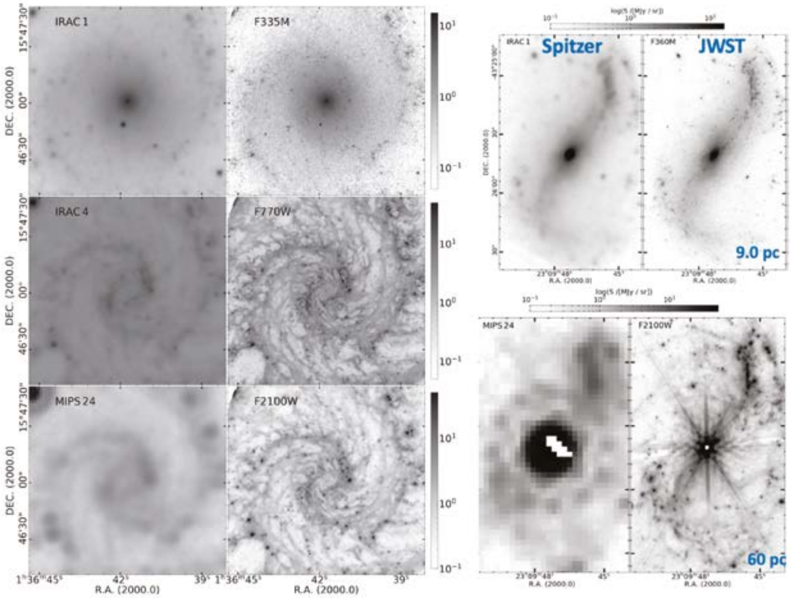

Figure 2. Comparison of PHANGS-JWST images of NGC628 and NGC7496 with previous Spitzer imaging. Adapted from Lee et al. (2023).

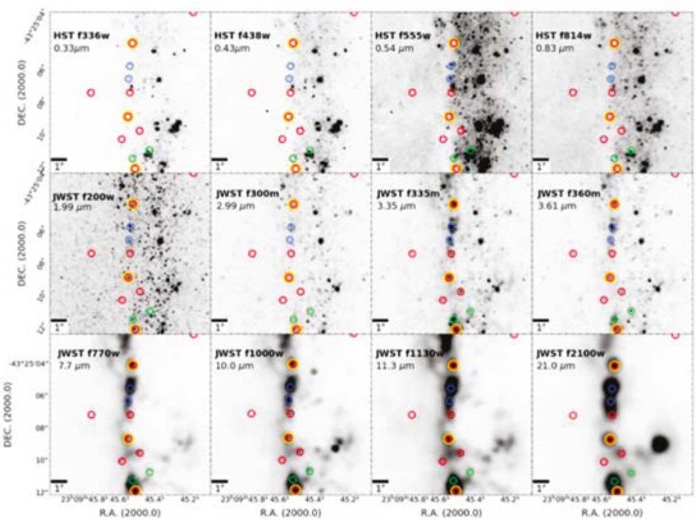

Figure 3. PHANGS-JWST 3.3 μm–selected star cluster candidates is shown with different colors according to their categories: embedded (red), partially embedded (green), and visible (blue). From Rodriguez & Lee et al. (2023).

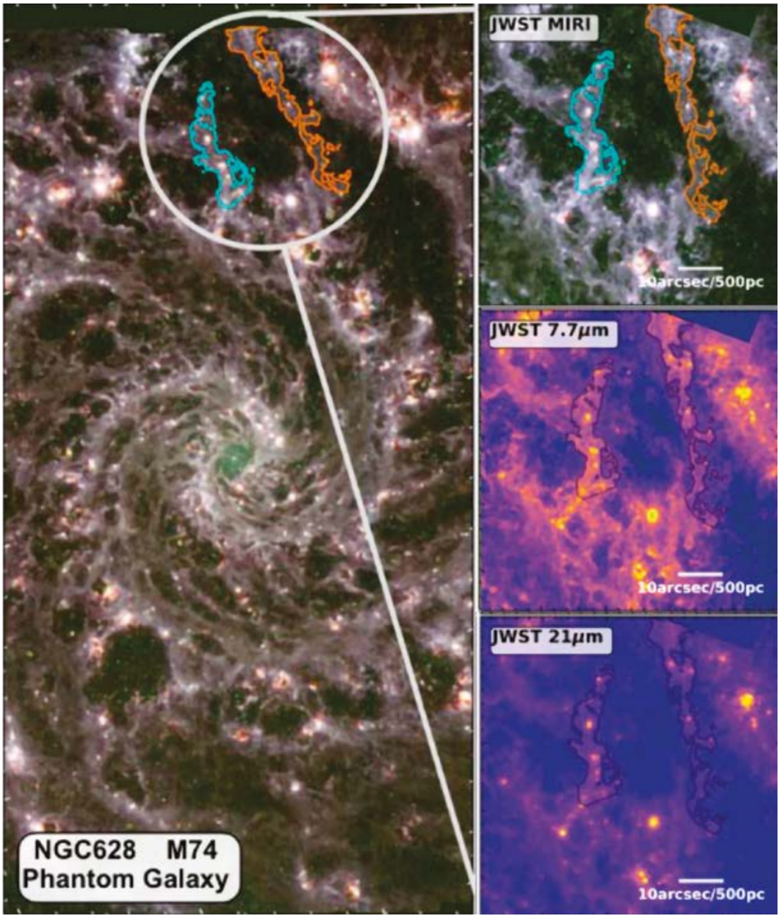

Figure 4. Color-magnitude diagrams which show that visually identified "prototype" dusty star clusters all have 3.3 μm PAH emission (first panel). Sources selected to be in this region of the diagram are then inspected for optical emission in the Hubble images (second panel). Cross-correlation with the PHANGS-Hubble catalog show that the vast majority of optically selected clusters with 3.3 μm PAH emission have ages that are 2 Myr or younger. From Rodriguez & Lee et al. (2023).

Star Formation in Galaxies across Cosmic Times

Karina I. Caputi

Kapteyn Institute, University of Groningen, Netherlands

1. Star Formation in the Present Day

Observations of our own Galaxy (the Milky Way) as well as the nearby galaxies that surround it, show us that new star formation happens slowly at present times. In spiral galaxies, the Milky Way included, the star-formation rate is of only a few stars like our Sun per year. This rate is very modest compared with the amount of stars that these galaxies have already assembled over cosmic history, which is typically tens or hundreds of billions of suns. This fact suggests that star formation activity must have been more important in the past, when the Universe was younger, because at the current formation rates galaxies would have never managed to build their current stellar content.

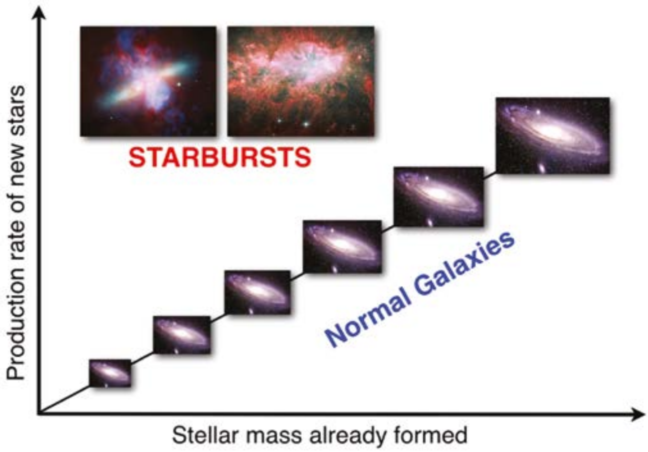

Figure 1. The relation between the ongoing star formation rate and the stellar mass already formed by previous star formation activity. For normal star-forming galaxies, in particular nearby spiral galaxies, the two quantities relate with each other, simply because larger galaxies have more assembled stars and also more gas, which is the fuel for new star formation. A minority of star-forming galaxies suffer temporary enhancements of their star formation activity, becoming starbursts. This phenomenon is very rare in the present day, but was much more common in the past, especially amongst small and young galaxies, like those seen in deep JWST images. Adapted from figure with credit: NASA/JPL-Caltech/K. Caputi (University of Groningen).

In the majority of star-forming galaxies, the production rate of new stars is directly related to the already assembled stellar mass, forming the so-called main sequence of star formation (e.g., Speagle et al. 2014; Fig. 1). This is simply a scaling relation: galaxies with large amounts of assembled stars also have larger cold gas reservoirs, allowing for higher star formation rates. Galaxies are expected to stay on the main sequence until their gas reservoirs are exhausted, or until flows of hot gas (coming from supernovae or active black-hole winds) prevent the gas from cooling down to form new stars. When this happens, galaxies become passive, as it is the case for red giant ellipticals in the nearby Universe.

On the contrary, galaxies with enhanced star formation activities, the so-called starbursts, are rare in the local Universe. Starbursts are defined as those galaxies whose birth rate parameter, i.e. the ratio between the ongoing star formation rate and the past average star formation rate, is large, namely $b \equiv \mathrm{SFR}/ < \mathrm{SFR} >_{\mathrm{past}} \gg 1$ (see Kennicutt 1983; Bergvall et al. 2016). This implies that their specific star formation rates (i.e., the star formation rates per unit of assembled stellar mass) are also large, which in turn means that their stellar-mass doubling times are short, of the order of 10 to 50 million years. The elevated star formation activity is expected to be temporary in these galaxies and can be triggered by galaxy-galaxy interactions (mergers) or internal instabilities. Starburst galaxies typically have irregular morphologies in the local Universe (Fig. 1; top left).

2. Star Formation in the First Half of Cosmic Time

Over the past two decades, a number of studies investigated the existence of distant starburst galaxies, in order to understand the importance of this phenomenon in the first 6-7 billion years of cosmic time (about a half of the Universe's current age). Most of these studies were conducted with far-infrared telescopes, as the most vigorous star formation was hidden behind dust clouds in the past (Sanders & Mirabel 1996; Dole et al. 2006). Contrary to the expectations, these studies found a small fraction of starburst galaxies (Rodighiero et al. 2011; Sargeant et al. 2012). The most intense dusty star-forming galaxies are quite massive and, thus, follow the relation described by the main sequence of star formation.

More recently, other works extended the search for starbursts to smaller sources and the more distant Universe, probing galaxies 10-100 times smaller than the Milky Way, whose light was emitted in the first few billion years of cosmic time. This was possible thanks to the availability of deep astronomical images taken with the Hubble Space Telescope (HST) and the Spitzer Space Telescope, over blank and gravitationally lensed fields of the sky showing thousands of distant galaxies of different sizes. These studies recognised, for the first time, that starbursts did make a significant fraction of the star-forming galaxies present in the past Universe (Caputi et al. 2017), accounting for more than 50% of the cosmic star formation rate density in the first few billion years (Rinaldi et al. 2022). Since then, many other works found examples of starburst galaxies in the distant Universe (e.g., Vanzella et al. 2018; Caputi et al. 2021; Casey et al. 2021; Finkelstein et al. 2022).

In the vast majority of these studies, the starbursts were identified amongst line-emitting galaxies. This is perhaps not surprising, as star-forming galaxies are typically characterised by line emission in their spectra and the presence of such lines facilitates the detection of these sources (Sun et al. 2023). A more systematic investigation of the link between the starburst phenomenon, star formation and line emission in the young Universe has not been done until recently, in the JWST era (Caputi et al. 2024).

3. New Results from JWST

The unprecedented sensitivity and spectral coverage of JWST images are allowing us to investigate star formation activity and other properties in galaxies as small – or even smaller – than the Milky Way satellites, up to very large distances. In such a way, we can now study, for the first time, how the seeds of today's bigger galaxies were formed in the young Universe.

3.1. Star formation in Lyman-α emitters

Lyman-α emitters, i.e., galaxies whose spectra show the Lyman-α transition line in emission, are some of the easiest-to-detect distant galaxies. This is because the Lyman-α line is emitted at λ wavelengths λem = 1216 Angstroms, so when it comes from very distant sources it reaches us redshifted to visible frequencies due to the expansion of the Universe (with λ = (1 + z)λem, where z is the redshift of the source). Thus, distant Lyman-α emitters can be identified in spectroscopic surveys conducted with traditional, ground-based telescopes, which operate at optical wavelengths. Tens of thousands of these galaxies were known even before the advent of JWST.

Instead, many of their most important properties were unknown in the pre-JWST era, especially for the most distant sources whose light was emitted in the first 1-2 billion years of cosmic time. In particular, one of the most important questions that astronomers had was if the Lyman-α emitters were really young galaxies forming their first stellar generations, or more evolved galaxies, whose newly formed stars coexisted with older ones formed in previous star-formation episodes.

This problem has recently been tackled by Iani et al. (2024) using JWST images taken with the Near-Infrared Camera (NIRCam; Rieke et al. 2005) and Mid InfraRed Instrument (MIRI; Rieke et al. 2015, Wright et al. 2015). They studied the stellar populations of 182 Lyman-α emitters identified in VLT/MUSE spectra, along with the stellar populations of 450 similarly distant galaxies without Lyman-α emission (the so-called Lyman-break galaxies), as control sample. They found that about 75% of the Lyman-α emitters are young galaxies with ages < 100 Myr, while the remaining 25% have older stellar populations, which suggests that they are experiencing a rejuvenation effect (Rosani et al. 2018). These older Lyman-α emitters are more massive and less dust-extinct than the younger ones, and are typically found on the star-formation main sequence. Instead, most of the young Lyman-α emitters are starburst galaxies. Remarkably, the properties of the control sample are quite similar: about a half of them are very young and classified as starbursts (based on their emitted UV luminosities), in spite of not having Lyman-α in emission, which is due to HI resonant scattering and/or dust-absorption.

3.2. Revealing Dust-obscured Star Formation in Optically Dark Galaxies

The new JWST data are also proving to be fundamental to understand the properties of galaxies discovered with previous infrared telescopes, but which are extremely faint (or completely undetected) at optical wavelengths, even in the deepest HST images. Early studies suggested that most of these sources were dusty star-forming galaxies in the distant Universe, whose light was emitted only a few billion years after the Big Bang, at redshifts $z = 3 - 6$ (e.g. Caputi et al. 2012, Sun et al. 2021). A number of recent JWST studies confirmed that this is the case (e.g. Barrufet et al. 2023, Williams et al. 2024). In some cases, JWST has enabled a detailed study of their internal dust distribution (e.g. Kokorev et al. 2023). Moreover, JWST has discovered many more, fainter examples of such galaxies (e.g. Nelson et al. 2023).

The dusty star-forming nature of these optically dark galaxies was confirmed in several cases with sub-/millimetre telescopes (e.g. Caputi et al. 2014; Smail et al. 2023). More recently, van Mierlo et al. (2024) studied a more extreme class of such sources, which were discovered in the mid-infrared, but extremely faint even at near-infrared wavelengths. Their JWST data analysis indicates that these sources are mostly prominent Hα emitters (indicative of new star formation activity), including a few which are bright sub-millimetre sources.

3.3. Star Formation around the Epoch of Reionization

With no doubts, one of the most important steps forward in the JWST era is the possibility of investigating star formation activity in galaxies around the Epoch of Reionization, when the atomic hydrogen present in the intergalactic medium became progressively ionised by the ultraviolet photons produced by the earliest stars and galaxies formed. Cosmic Reionization was a process that lasted several hundred million years and occurred within the first billion year of cosmic time. The exact nature of the sources of Reionization is still under debate, but a number of recent studies are now providing clear hints on their properties and their relation to the general population of star-forming galaxies present at those early cosmic times.

Numerous line emitting galaxies have been identified with JWST, in most cases Hβ+[OIII] emitters, towards the Epoch of Reionization, confirming that optical line emission was quite common even in galaxies with a damped Lyman-α line (e.g. Bunker et al. 2023). A major success was the finding of Hα emitters at these cosmic epochs for the first time (Rinaldi et al. 2023), as Hα is one of the most secure tracers of star formation activity. This discovery was possible thanks to the extended wavelength coverage provided by MIRI on JWST. Only MIRI can see the Hα line at such early cosmic times. In general, line emitting galaxies, either identified via spectroscopy or photometry, have been proposed as sources of Reionization. The corresponding line fluxes allow for an estimate of the photon production efficiency which, coupled with constraints on the escape fraction, indicates whether these sources are effective ionizers or not (e.g., Endsley et al. 2023, Rinaldi et al. 2024).

In parallel, other studies based on JWST data proposed that the process of Reionization could have been driven by low-stellar-mass, young starburst galaxies (Endsley et al. 2024, Simmonds et al. 2024), as theoretically proposed by Sharma et al. (2017). Starburst galaxies and strong line emitters have some properties in common. However, their relation at the Epoch of Reionization was not laid out until very recently.

In spite of their enhanced detectability, strong line emitters constitute less than a third of all star-forming galaxies at the Epoch of Reionization

(Rinaldi et al. 2023, Caputi et al. 2024), which indicates that these emitters alone do not provide a full census of the cosmic star formation activity in the early Universe. Interestingly, Caputi et al. (2024) also showed that a significant fraction of the prominent line emitters are starburst galaxies, but not all of them are. And the same happens with the star-forming galaxies which are not prominent line emitters. So, this suggests that *all* starbursting galaxies may have had a role in the process of Reionization, but it is unclear when their main contribution happened — either at the beginning of the starburst phase, during the phase of intense line emission, or after, when all the photons associated with the new star formation were emitted in the UV, qualifying as reionizing photons.

4. Conclusions

JWST is revolutionizing our understanding of the process of star formation in galaxies across cosmic times in two main ways: i) by discovering star formation activity down to very small galaxies, like the Milky Way satellites and even smaller units, which may simply be stellar aggregates on the way of galaxy formation; ii) by revealing the link between star formation activity and spectral line emission, and in turn the implications for cosmic Reionization. The pending challenges for the near future are to: establish whether prominent line emitters or non-emitter starbursts were the main sources of reionization; achieve a full understanding of the underlying physics that characterized the star formation process in these small systems.

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A New View of Galaxy Assembly Enabled by JWST Spectroscopy

Anna de Graaff
Max Planck Institute for Astronomy, Heidelberg, Germany

Abstract

Under hierarchical assembly, galaxy formation begins as haloes collapse in the very early Universe and gas subsequently cools sufficiently to form stars. How do galaxies grow into the diversity of colours and structures seen in the local Universe? The high sensitivity of JWST and its wavelength coverage offers a revolutionary new view of the high-redshift galaxy population and its evolution into the present-day population. Spectroscopy with the Near Infrared Spectrograph (NIRSpec) in particular has proven powerful, revealing the spectral energy distributions and emission line kinematics of up to 200 galaxies simultaneously. Spectral modelling provides crucial insight into the properties of the stars and interstellar medium, as well as signatures of black hole activity. Combined, these different measurements are beginning to paint the picture of the early assembly of today's massive galaxies and galaxies like our own Milky Way. Early results with JWST suggest a rapid growth in galaxy stellar mass and their central black holes in the early Universe, with morphologies and kinematics that are already surprisingly 'mature' and galaxy and black hole masses that are surprisingly high. Ongoing large spectroscopic surveys will obtain spectroscopy for nearly over 15,000 sources at redshifts $z>1$ by the end of 2024. These large statistical samples will be critical to place the early findings into a cosmological context, and unravel the evolution of the broader high-redshift galaxy population.

Introduction

In the local Universe there is a rich diversity of galaxies. Some look similar to our own Milky Way, with prominent, blue spiral arms where star formation takes place. Other galaxies are much redder in colour and also differ strongly in shape: whereas the spiral galaxies have disky structures, the reddest galaxies tend to be spheroidal. In contrast, current widely-accepted theories indicate that the very early Universe was more homogeneous. In the standard cosmological model, cold dark matter haloes collapse first, after which gas could cool and collapse to form stars (White & Rees

1978). These first haloes are thought to form the seeds of the massive galaxies observed at the present day. Therefore, a major open question in extragalactic astronomy is how galaxies grew from initially gas-rich structures to the great variety of systems seen today.

The early galaxies continue to grow rapidly after the initial formation of stars. Broadly, two growth mechanisms can be identified. Cold gas streams can efficiently provide fuel for star formation despite a hot circumgalactic medium in the halo (e.g. Dekel et al. 2009). At later times mergers between galaxies are thought to play a crucial role, with massive galaxies being almost entirely formed through the accretion of nearby galaxies (e.g. Oser et al. 2010). These two modes are difficult to distinguish observationally, and instead, the combined stellar mass growth is usually traced statistically. Observations from ground-based near-infrared instruments as well as with the Hubble Space Telescope (HST) have shown that the most massive galaxies were already in place at redshift $z \sim 2$ (only 3 Gyr after the Big Bang; Muzzin et al. 2013; McDermid et al. 2015), indicating that these systems formed or accreted their stellar mass on rapid timescales.

Our current understanding of the early Universe has been limited by the spectral coverage and sensitivity of the HST. At lower redshifts ($z<2$), HST has been tremendously successful in uncovering the structures, star formation activity and stellar masses of galaxies. However, at higher redshifts HST probes rest-frame ultraviolet (UV) emission and only has the sensitivity to map the very brightest high-redshift galaxies. A large population of objects has therefore been missed by HST due to the faint UV emission of high-redshift galaxies or obscuration of UV light by dust. The earliest phase of galaxy formation and growth thus still remains unclear. How did galaxies in the early Universe build up their stellar mass? When did galaxies start to resemble the colours and structures seen in the present-day Universe?

Spectroscopy with JWST

The James Webb Space Telescope (JWST) provides the observations needed to tackle these longstanding questions. With its extremely high sensitivity and wavelength coverage in the near- and mid-infrared, JWST has enabled the efficient and highly complete detection of early galaxies ($z>2$) by their emission at rest-frame optical wavelengths. Unique to JWST is its ability to perform spectroscopy in the near-infrared with the Near-Infrared Spectrograph (NIRSpec; Jakobsen et al. 2022; Ferruit et al. 2022). The multi-object spectroscopic mode of NIRSpec allows for the simultaneous observation of 200 high-redshift galaxies, thereby delivering an unprecedented number of spectra of early galaxies. These spectra are taken at different spectral resolutions: the low-resolution mode is ideal for obtaining the precise redshift of a galaxy and an overview of the galaxy properties, by revealing spectral breaks and a broad range of emission lines. The higher spectral resolutions de-blend individual emission lines, enabling a more detailed view of the chemical properties of the gas and stars within galaxies, and also provide insight into the internal dynamics of galaxies.

Rapid mass and structural assembly at high redshift

Within the first months of science observations, imaging surveys with the Near-Infrared Camera (NIRCam) onboard JWST detected several thousand objects that were previously missed by HST and ground-based telescopes (e.g. Finkelstein et al. 2023; Rieke et al. 2023; Weaver et al. 2024). In the context of the questions above, these observations yielded two major surprises.

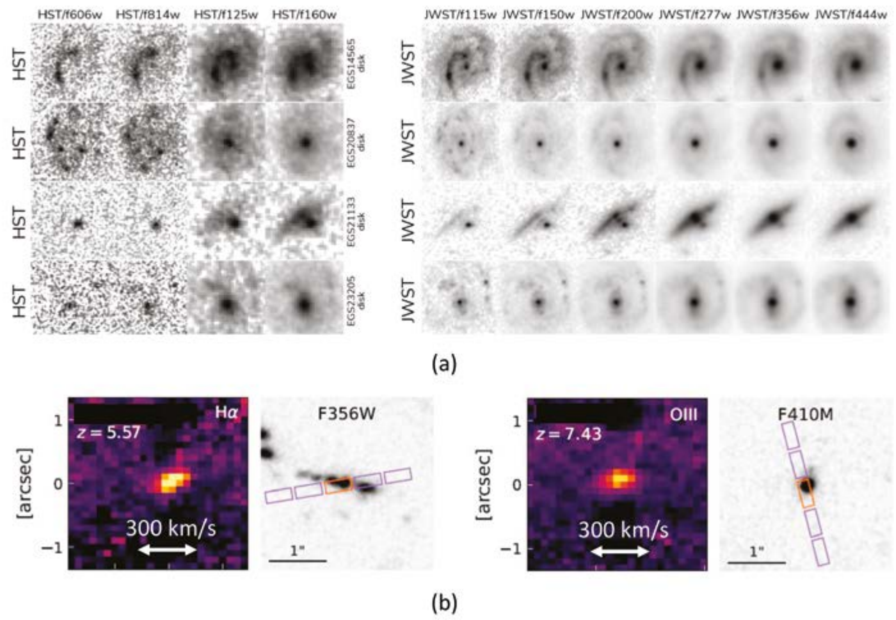

Figure 1. (a) HST (left) and JWST NIRCam (right) images of galaxies at high redshift (z~2), adapted from Ferreira et al. (2023). (b) NIRSpec observations of early galaxies at z~6 (adapted from de Graaff et al. 2023) provide insight into their kinematic structures.

First, multiple groups reported the discovery of highly 'mature' galaxies, as they found that the morphologies of galaxies at redshift z~2-4 (i.e. when the Universe was 1.5-3.0 Gyr old) already look like the well-organised galaxy structures observed at the present day (e.g. Ferreira et al. 2022, 2023; Kartaltepe et al. 2023). This is surprising, as previous studies with HST had indicated that the very early galaxies appear more clumpy, and less disky than galaxies in the local Universe. As shown in Figure 1, this may be due to the increased sensitivity of JWST: some objects that looked clumpy in HST imaging, appear as smooth disks with spiral arms in the JWST imaging, even when comparing at the same observed wavelength. However, imaging alone cannot answer whether these systems are truly like the objects we see at the present day: galaxies are projected at a random inclination angle on the sky, and it is therefore impossible to distinguish a rotating disk from an elongated structure with turbulent kinematics. Spectroscopy can reveal the kinematic properties of galaxies and answer whether the high-redshift galaxies have dynamical properties that are consistent with those observed at z~0. In de Graaff et al. (2023) we used NIRSpec in its multi-object spectroscopic mode to, for the first time, study the kinematic properties for a sample of 6 high-redshift (z~6-7) galaxies with low stellar masses and compact sizes. These early galaxies were found to have diverse kinematic structures: some show clear evidence of rotation, consistent with disky galaxies, whereas others are highly turbulent in nature. On the other hand, Nelson et al. (2023b) discovered a very massive galaxy with kinematic properties similar to that

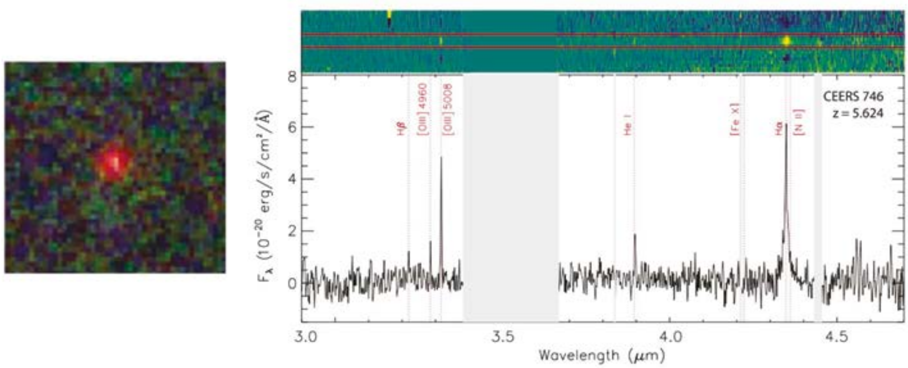

Figure 2. Left: false-color image from JWST/NIRCam of one of the candidate extremely massive galaxies identified by Labbé et al. (2023). Right: the NIRSpec spectrum reveals a broad emission line, indicative of an active galactic nucleus. Figure adapted from Kocevski et al. (2023).

of galaxies at much lower redshifts. These studies likely reflect an important dependence of the morphology and kinematics on the overall galaxy mass, and will require further investigation with larger samples.

Second, a substantial fraction of the newly-discovered sources with JWST were found to appear extraordinarily bright for their estimated redshift or to have unusually red colors and SEDs (e.g. Finkelstein et al. 2023; Nelson et al. 2023a; Pérez-González et al. 2023). The physical properties of these sources are still poorly understood, but many of these new objects have been suggested to be very massive already at a very early epoch. Of particular interest is a subset of high-redshift objects that have even been shown to be in tension with current well-established models of cosmology and/or galaxy formation (Labbe et al. 2023), because the estimated masses of these systems exceed all model predictions.

However, the imaging so far cannot determine the true nature of these sources, due to the coarse wavelength sampling of the different image filters. Only spectroscopy with JWST/NIRSpec can confirm whether these objects are truly at the claimed high redshifts (z~7) and reveal the stellar population properties. Kocevski et al. (2023) presented spectroscopic observations obtained for one of the sources from Labbé et al. (2023) as part of the Cosmic Evolution Early Release Science (CEERS) program (Figure 2), and revealed a slightly lower redshift (z=5.6) than estimated based on imaging alone (z=8.3). More importantly, the spectroscopy showed clear evidence for a luminous active galactic nucleus. This therefore showed that the stellar mass inferred previously was overestimated, as the light was assumed to originate solely from the stellar population.

Conclusions & Outlook

JWST observations thus far have demonstrated the great potential of the different instruments to transform our understanding of galaxy evolution at high redshifts. The NIRSpec instrument in particular has proven to be essential to provide insight into the growth of galaxies and their structural properties. Nevertheless, many studies have been based on early observations and hence on modest sample sizes. Future work based on spectroscopic samples covering a wider range in stellar mass and redshift will be crucial to establish the growth and evolution of the broader galaxy population.

Further observations are also critical to uncover the properties of newly-discovered sources. Although one candidate for an extremely massive early galaxy was shown to be at a lower redshift and of AGN nature, many massive galaxy candidates remain. It is still unclear if all objects will turn out to have actively accreting black holes, or whether some sources may indeed have masses that are incompatible with current theories. Follow-up observations with JWST/NIRSpec that systematically target these highly-sought-after sources are planned for Cycle 2 (program 4106, PI Nelson; program 4233, PI de Graaff) and will soon reveal their true nature.

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The Structural Evolution of Galaxies in the Early Universe

Jeyhan S. Kartaltepe
Laboratory for Multiwavelength Astrophysics, School of Physics and Astronomy, Rochester Institute of Technology, NY, USA

Abstract

One of the stunning surprises from JWST's first year and a half of observations of the extragalactic sky is that not only are we detecting large numbers of galaxies in the early universe but that many of these galaxies are resolved and show great structural detail. For the first time, we can quantify the morphological structure of galaxies well into the epoch of reionization and constrain how these galaxies grew over cosmic time. Here we present an analysis of the morphological and size evolution of galaxies in the early universe, from z=3-9, using deep multi-band NIRCam imaging from the public survey fields CEERS and COSMOS-Web. Our morphological measurements include quantitative measures, such as surface brightness profile fitting and non-parametric fits, visual morphologies, and machine learning approaches. We find that galaxies at this early epoch have a wide diversity of morphologies, including compact unresolved sources, disky structures, irregular features and multiple components, and a significant fraction that appear to be involved in a merger. Future work with larger surveys like COSMOS-Web will enable statistical analyses and the training of machine learning algorithms to classify galaxy morphologies and identify galaxy mergers.

1. Introduction

One of the most fundamental properties of a galaxy is its physical structure. We have known for about 100 years that galaxies in our nearby universe typically have two different structures: 1) disk galaxies with spiral arms and sometimes a bar through their center, 2) elliptical galaxies consisting of stars with more randomized orbits. Galaxies that do not fall into these two types are considered to be irregular. However, galaxies in the early universe are significantly different as these structures were in the process of forming. Galaxies were overall smaller, clumpier, and messier. However, it is still an open question of when the very basics of today's structures were put into place.

Over the age of the universe, while galaxies were evolving structurally, many other properties were also evolving in tandem. Their stellar masses grew as their gas reservoirs were turned into stars. Their chemical compositions changed as subsequent generations of stars formed heavier elements. Their central supermassive black holes grew, occasionally entering an active growth face and appearing as an active galactic nucleus (AGN). The overall level of star formation and AGN activity in the universe changed, ramping up to a peak from the early universe to a period known as cosmic noon ($1 < z < 3$) and then coming down from that peak to the present day level of star formation. Some galaxies grew passively on their own while others were involved in major or minor mergers that altered their properties. The structural evolution of galaxies over this time period provide clues to the physical processes at work driving all of these changes along their evolutionary pathways.

JWST has opened a new window in our understanding of galaxy structure. Prior to JWST, our observations of structural detail with Hubble were limited to $z \sim 3$, where Hubble could probe the rest-frame optical emission from galaxies. JWST's coverage of the near to mid-infrared wavelengths makes it ideal for investigating the rest-frame optical structure of galaxies, where the bulk of stars emit their light, out to very high redshifts. Additionally, the incredible sensitivity and increased resolution allow us to see

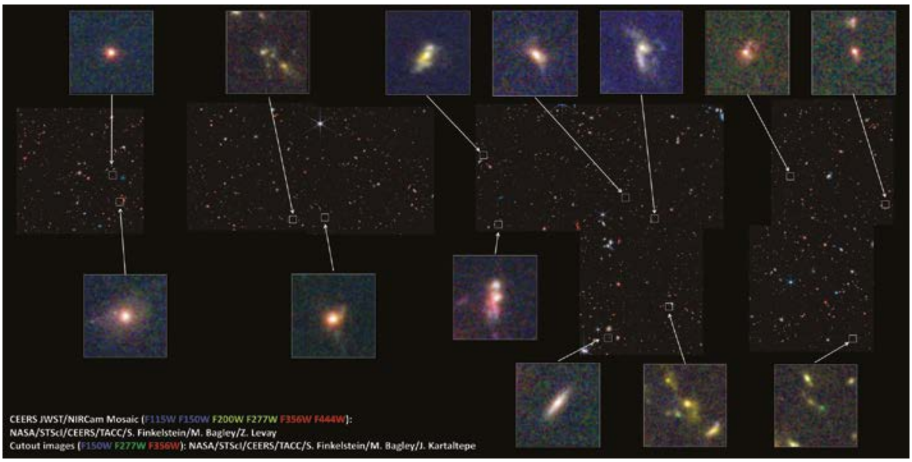

Figure 1. CEERS NIRCam RGB image of the first four pointings observed in June 2022 with a selection of F150W+F277W+F356W postage stamp cutouts of example galaxies in each of the seven morphological groups described by Kartaltepe et al. (2023). Each cutout is 2" on a side.

features that are smaller and fainter than ever before. JWST's first observations with surveys such as CEERS (Bagley et al. 2023) have revealed the detailed morphologies in the early universe for the first time, while large surveys such as COSMOS-Web (Casey & Kartaltepe et al. 2023) enable detailed statistical analyses of hundreds of thousands of galaxies.

2. Morphological Measurements

Our initial study of galaxy morphologies in the early universe was conducted using images from the CEERS survey's first observations taken in June 2022. We selected a sample of galaxies with previous measurements from HST to evaluate the improvement / change in morphologies as measured by JWST. These galaxies span the redshift range $z = 3 - 9$. We measured these morphologies visually, adapting the visual classification scheme of Kartaltepe et al. (2015), as well as quantitatively, using Galfit[1] (Peng et al. 2002; Peng et al. 2010), GalfitM,[2] and the Python package Statmorph[3] (Rodriguez-Gomez et al. 2019). Figure 1 shows the CEERS NIRCam mosaic with a handful of example postage stamp cutouts highlighting the range of morphologies observed with JWST at these redshifts.

3. Morphological Evolution

Our sample contains the full range of morphological types across all redshift and stellar masses. Over the entire redshift range, only 16 and 18 galaxies are classified as Point Source/Unresolved or Unclassifiable, respectively. Figure 2 shows the fraction of the total number of galaxies that each morphological class makes up as a function of redshift. Overall, 56% of the galaxies at $z > 3$ have a visually identifiable disk component, dropping from $\sim 60\%$ at $z = 3 - 4$, to $\sim 45\%$ at $z \sim 5$, to $\sim 30\%$ at $z > 6$. 38% of the galaxies at $z > 3$ have a visually identifiable spheroidal component, decreasing from 42% to 26% between $z = 3$ and 4.5, then varying between ~30-40% beyond $z = 4.5$. This is largely driven by the similar decrease and then increase in the Spheroid Only group. Part of this apparent trend at higher redshifts may be due to small number statistics and part may be due to a number of selection effects. For example, there is a possibility that we miss fainter extended features in some of these systems at high redshift. It is also possible that a

[1] https://users.obs.carnegiescience.edu/peng/work/galfit/galfit.html
[2] https://www.nottingham.ac.uk/astronomy/megamorph/
[3] https://statmorph.readthedocs.io/en/latest/

larger fraction of galaxies at higher redshift are small enough to be at the resolution limit of NIRCam, given the expected size evolution of galaxies, and are therefore more round and compact in appearance.

43% of the galaxies at $z > 3$ have irregular features and this fraction remains roughly constant across the full redshift range due in part to the fraction of Disk+Irregular galaxies being roughly constant at 20% and then decreasing while the fraction of Irregular Only galaxies is at roughly 10-15% and then increases to 20% by $z = 4.5$. Note that the total fractions of objects that are All Disks, All Spheroids, or All Irregular do not add up to one due to the overlapping objects in each of these classes.

Finally, we note that the fraction of point sources and unclassifiable objects remains at 0-2% across most of the redshift range. At $z > 6$, 13% of galaxies are unresolved and 8% are unclassifiable, corresponding to 5 and 3 individual galaxies, respectively, in this redshift bin. We remind the reader that the above percentages correspond to galaxies that were bright enough to be detectable with HST CANDELS imaging and may not be representative of the overall galaxy sample detectable by JWST at these redshifts.

Figure 3 shows the morphological fractions as a function of redshift based on CANDELS HST imaging and using the visual classifications of

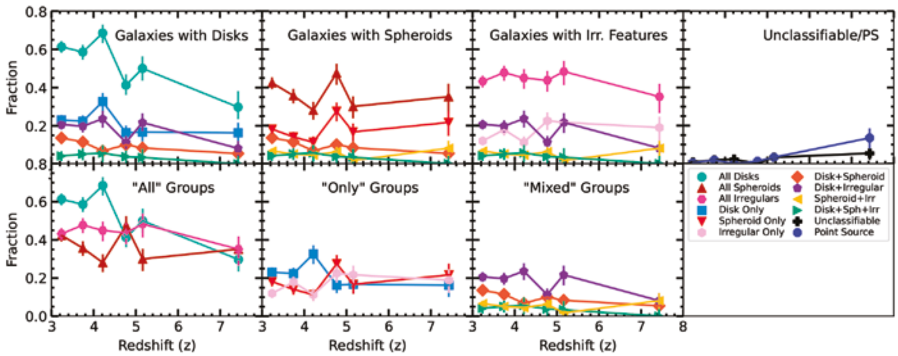

Figure 2. The fraction of $z > 3$ galaxies detected by both JWST and HST with $M_\star > 10^9 M_\odot$ as a function of redshift for each morphology class. The top row, from left to right shows galaxies with disks, galaxies with spheroids, galaxies with irregular features, and Point Sources and Unclassifiable galaxies. The bottom row shows all of the same morphological groups, but divided in different ways for easy comparison. From left to right, the combination of all disks, all spheroids, and all irregulars; the combination of Disk Only, Spheroid Only, and Irregular Only groups; and finally, the remaining mixed groups. Error bars represent the 1σ binomial confidence limits given the number of objects in each category, following the method of Cameron (2011).

Kartaltepe et al. (2015) for all z > 3 galaxies in all five CANDELS fields (1375 galaxies in total). Based on the HST imaging alone, a smaller fraction of galaxies at z = 3.0 – 4.5 have disks (~40%) and a larger fraction are pure spheroids (~20% at z = 3.0 – 5.0). The fraction of galaxies that are only irregular is small and drops with redshift, from ~5% at z > 6. The fraction of galaxies that are unclassifiable rises sharply, ~5% at z = 3.5 to ~35% at z=5.5 to~80% at z>7. Likewise,~30% are unresolved at z=5–7.

The large difference seen between the HST and JWST morphologies at these redshifts is expected and is due to the difference in depth and wavelength coverage. 488 galaxies were flagged by at least one classifier as having a different morphology in the JWST images compared to the HST images. A significant number of galaxies with disks were previously identified as spheroids because of their compact central morphologies, with low surface brightness disk features that only became visible with deeper imaging (see, for example, Conselice et al. 2011; Mortlock et al. 2013; Kartaltepe et al. 2015). This suggests that some fraction of the spheroidal galaxies observed with JWST, particularly those that are faint and/or at higher redshifts, possibly have unobserved disks as well. It is not likely that these disks would previously have been identified as irregular, except for some at the low red-

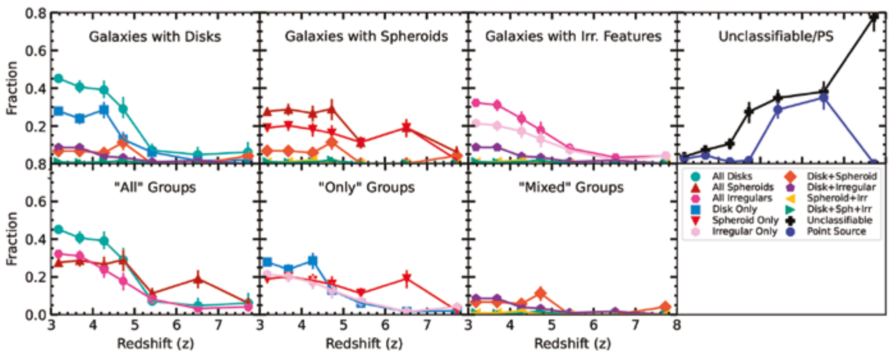

Figure 3. The fraction of z > 3 galaxies detected HST with $M_\star > 10^9 M_\odot$ as a function of redshift for each morphology class based on the CANDELS HST visual classifications of Kartaltepe et al. (2015). The top row, from left to right shows galaxies with disks, galaxies with spheroids, galaxies with irregular features, and Point Sources and Unclassifiable galaxies. The bottom row shows all of the same morphological groups, but divided in different ways for easy comparison. From left to right, the combination of all disks, all spheroids, and all irregulars; the combination of Disk Only, Spheroid Only, and Irregular Only groups; and finally, the remaining mixed groups. Error bars represent the 1σ binomial confidence limits given the number of objects in each category, following the method of Cameron (2011).

shift end, as these irregular features are also too faint to be easily identified at these redshifts with HST. At the low redshift end ($z = 3 - 3.5$), some disks may have been classified as irregular if the HST data only picked up the brighter star forming clumps rather than the underlying disk structure.

Figure 4 compares the distribution of the Sérsic indices and sizes of galaxies from the Santa Cruz Semi-analytic model (SAM, Yung et al. 2022a), TNG50 (Costantin et al. 2022), and TNG100 (Rose et al. 2023) to the distribution measured from CEERS galaxies. The distributions from the SAM have very similar peaks with a narrower distribution, which holds for all three redshift bins. The Sérsic index for both TNG50 and TNG100 peak at lower values than the CEERS galaxies and have narrower distributions at all redshifts. At $z = 3 - 4$, TNG50 galaxies have larger sizes than TNG100 galaxies and even larger than both the SAM galaxies and the observed CEERS galaxies. At $z > 4$ the distributions match more closely. At all redshifts, the simulations do not contain the smaller (lower Re) more compact (larger n) galaxies that we observe with JWST CEERS imaging.

Figure 4 also compares the measured axis ratio and asymmetry value for the TNG50 and TNG100 galaxies to the distribution from CEERS. In all three redshift bins, the axis ratios of the TNG50 and TNG100 galaxies match each other well, but peak at higher b/a (~0.6) and fall off more sharply at lower values than the observed CEERS galaxies. At $z = 3 - 4$, the asymmetry distributions for TNG50, TNG100, and CEERS are well-matched, but the TNG50 and TNG100 distributions shift toward lower (more negative) values at higher redshift. Negative asymmetry values are unphysical and typically result from low S/N sources, where the source is very close to the background level that is being subtracted when making the asymmetry measurement.

Overall, the agreement between our measurements for the $z > 3$ JWST CEERS galaxies and the various simulations is encouraging. The differences seen (for example, the difference in axis ratio and the lack of small compact galaxies in the simulations) are worthy of a more in-depth look in order to determine if there are selection effects impacting the results or if there is an actual physical difference between galaxies in these simulations and those in the real observed universe.

4. Merger Identification

Galaxy mergers are particularly difficult to identify, especially at high redshift where the low surface brightness merger signatures are lost. JWST's increased sensitivity enables the identification of major and minor mergers that would previously have been missed. New machine learning techniques can also be applied to large datasets and tested to quantify how well they work to identify galaxy mergers. We have identified mergers visually, and categorized them into Groups 1, 2, and 3 based on how many classifiers identified them as a merger, irregular, or marked various merger signatures (such as tidal tails and double nuclei). The Group 1 sample is the most confident, though has smaller numbers.

We then tested two different machine learning techniques: random forests and a convolutional neural network DeepMerge (Ćiprijanović et al. 2020). We first used the simulated CEERS imaging of Rose et al. (2023) to train and then test the performance using both the simulated images (where the merger history is known) and the visual classifications from CEERS. Overall, we find that each of the two methods hits a ceiling of ~ 70% at identifying both mergers and non-mergers correctly. The performance for identifying mergers can be improved, but only at the expense of incorrectly classifying non-mergers.

Figure 5 shows the Gini coefficient G vs. M_{20} for the observed CEERS dataset, color-coded by visual classification. G quantifies the relative distribution of the galaxy's flux, whereas M_{20} is the second-order moment of the

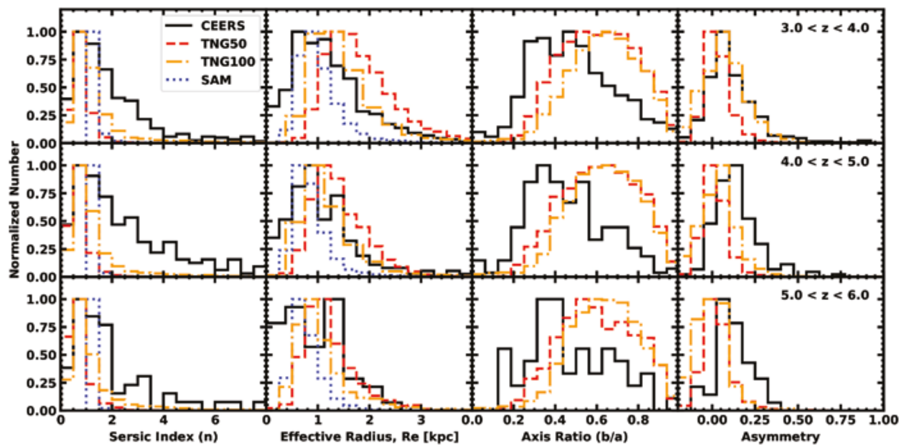

Figure 4. The distribution of Sérsic index, size, axis ratio, and asymmetry of the z › 3 CEERS galaxy in three different redshift bins compared to the distribution from the CEERS mock catalog derived from the Santa Cruz Semi-analytic model (blue dotted line; Somerville et al. 2015, 2021; Yung et al. 2019; Yung et al. 2022b), measurements from mock images based on IllustrisTNG50 (red dashed line; Costantin et al. 2022), and measurements from mock images based on IllustrisTNG100 (orange dash-dotted line; Rose et al. 2022).

brightest 20% of the galaxy's flux. G vs. M_{20} does not appear to effectively separate visually classified mergers and non-mergers, which is to be expected since $G - M_{20}$ is not sensitive to all stages of a merger. The second and third panels show the merger classifications predicted by the random forest and the DeepMerge network, respectively, color-coded by the merger probability. Probabilities higher than 0.5 mean the object was classified as a merger while probabilities lower than 0.5 mean the object was classified as a non-merger. The second panel shows a potential trend where objects with very low probabilities from the random forest are far below the merger discriminating line while objects with higher probabilities are closer to or above the line. The third panel shows that most galaxies were classified as mergers with relatively high probabilities, and there appears to be no clear trend in relation to the merger discriminating line.

Figure 6 shows the simulated CEERS and observed CEERS merger rates. In each panel, the black line is the theoretical Illustris merger rate derived from Rodriguez-Gomez et al. (2015) assuming a merger timescale of 0.5 Gyr, for comparison. The second and third panels show the simulated CEERS merger rate as determined by the random forests and by the DeepMerge network, respectively, and are in good agreement with each other. Like the simulated merger rates, the observed merger rates in the first and second panel are underestimated compared to the theoretical Illustris merger rate. The DeepMerge observed merger rate appears higher than the simulated CEERS merger rates, the theoretical Illustris merger rate, and the observed merger rates in the first panel due to the fact that DeepMerge overestimated the number of mergers. The random forest observed merger rate is in better agreement with the observed merger rates in the first panel. In addition, the observed merger rates all appear to decrease or remain constant at $z > 4$ while the simulated mergers rates increase at $z > 4$.

5. Next Steps

One and a half years after JWST's first observations, we now have a better understanding of galaxy structure in the early universe and how that structure has evolved with time. We know that early galaxies were diverse and structures such as disks and spheroids were already in place very early on in our Universe's history. However, many questions remain that can only be answered with large area surveys like COSMOS-Web that provide statistics for many thousands of galaxies, or very deep surveys such as NGDEEP that will be able to detect the faintest structures.

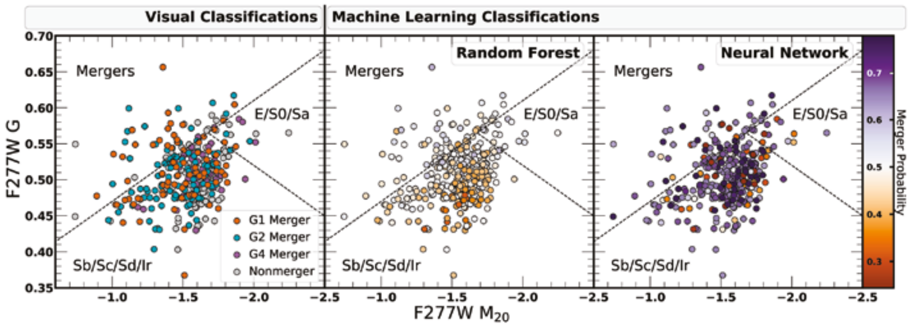

Figure 5. F277W G – M_{20} space for observed CEERS galaxies from 3 < z < 5. In the left panel, observed galaxies are color-coded by the visual classifications (Group 1 / G1: at least two out of three volunteer classifiers assigned an interaction class; Group 2 / G2: at least two out of three classifiers assigned the Irregular morphology class; Group 4 / G4: one of out three classifiers assigned an interaction class). In the middle panel and right panel, galaxies are color-coded by the merger probability output by the random forest or neural network, respectively.

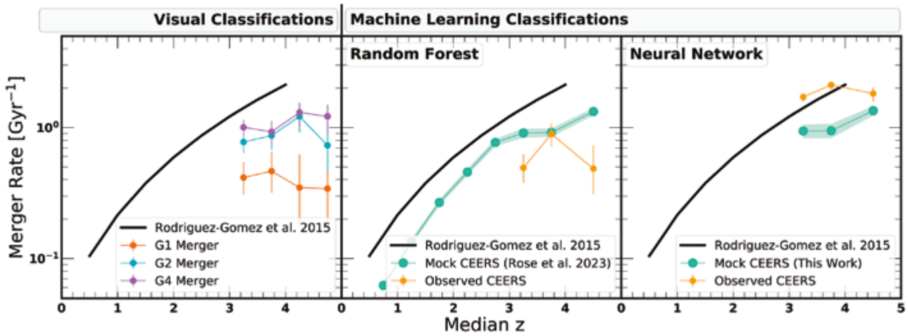

Figure 6. Merger rate based on visual classifications (left panel), random forest classifications (middle panel), and neural network classifications (right panel) as compared to the theoretical Illustris merger rate (black line) derived from Rodriguez-Gomez et al. (2015). The green shaded regions and the observed galaxy error bars indicate the binomial 95% confidence interval.

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SESSION 10: SOLAR SYSTEM

Solar System Science with JWST: Revealing the Volatile Ingredients for Planet Formation

Stefanie N. Milam

NASA Goddard Space Flight Center, Greenbelt, MD, USA

Abstract

The James Webb Space Telescope (JWST), now in full operation, has demonstrated unprecedented sensitivity and enabling observations of objects throughout the solar system and beyond. JWST has now glimpsed at the planets and their systems revealing new insights into atmospheric composition, activity, and origin. The first 3 annual cycles of science have also included multiple programs from specific targets to larger population studies of small bodies in the asteroid belt and beyond Neptune, deciphering their composition, activity, and origin. JWST has revolutionized studies of all small bodies in the solar system with its wavelength coverage and sensitivity to measure the composition of sometimes barely active objects – even in the farthest reaches of the known solar system. The more active or larger objects can usually be resolved with flyby quality imaging to disentangle the native composition and understand the pristine nature of these objects. Additionally, the search for biosignatures and studies of ocean worlds with JWST will provide an avenue to support the detection of habitability in the

Figure 1. Montage of JWST NIRCam images acquired during Cycle 1 from Early Release Science (Jupiter, ERS 1373), Guaranteed Time (Mars, GTO 1415; Saturn, GTO 1247; Europa, GTO 1250; Titan, GTO 1251; Comet 238P/Read, GTO1252), and Early Release Observations (Uranus, ERO 2739; Neptune, ERO 2739). A summary of press releases and publications for these images in provided in Villanueva and Milam (2023).

solar system. All of this coupled to the new, resolved observations of disks, star formation, and exoplanets will be revolutionary in deciphering how our solar system came to be and insights into star and planet formation/evolution throughout our galaxy and beyond.

1. Background

On 25 December 2021, JWST was launched into space on an Ariane 5 rocket to L2 flawlessly, conserving fuel after trajectory adjustment and orbit insertion to operate for up to 20 years. Six months of commissioning – including optical alignment, instrument mode check out, and operations testing – led to the release of images from a perfectly aligned telescope with performance that exceeded expectations (Rigby et al. 2023; McElwain et al. 2023).

JWST was designed to address four science themes (Gardner et al. 2006): The End of the Dark Ages, The Assembly of Galaxies, The Birth of Stars and Protoplanetary Systems, and The Planetary System and the Origins of Life. While considerably challenging, especially for a large space telescope

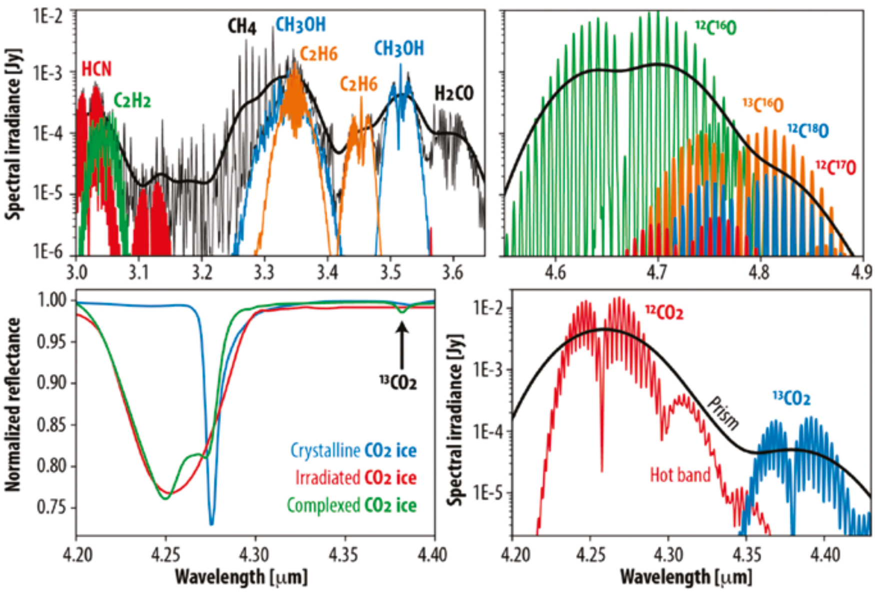

Figure 2. Simulated JWST spectra at near-infrared wavelengths from the Planetary Spectrum Generator (Villanueva et al., 2022) for solar system bodies including a slew of organics around 3 μm (upper left), rovibrational lines of CO isotopologues (upper right), CO_2 ice features (lower left), and CO_2 isotopologues (lower right). Figure adapted from Villanueva and Milam (2023).

designed to peer at the faintest objects in the infant universe, JWST began observing the biggest and brightest planets in our solar system and demonstrated its incredible capability, dynamic range, and tracking accuracy (Figure 1). The first year of images and spectra towards our solar system's planets and small bodies in the JWST field-of-regard (it cannot observe objects towards the Earth, Moon, and Sun due to the sunshield) have provided new views of these objects in the near-to-mid-infrared. Additionally, while it is generally assumed the search for "Origins of Life" with JWST is linked to habitable exoplanets – the solar system has several compelling worlds that just may be habitable as well beyond Earth.

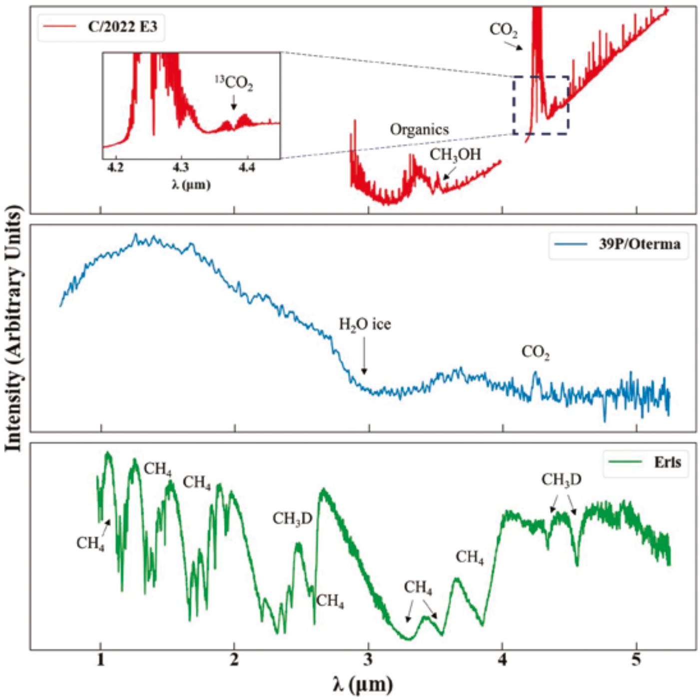

Figure 3. Variety of spectra from icy small bodies with JWST. Top panel: JWST NIRSpec data from comet C/2022 E3 (ZTF) (Milam et al., in preparation). Prominent emission lines of CO_2 and $^{13}CO_2$ (inset) as well as the organics region comprised of multiple volatile hydrocarbons. Intensity scale is exponential. Middle panel: JWST NIRSpec data of centaur 39P/Oterma showing the water-ice absorption feature as well as the first confirmed detection of CO_2 emission (Harrington Pinto et al., 2023). Bottom panel: JWST NIRSpec data from TNO Eris with multiple methane (CH_4) ice absorption bands as well as the CH_3D bands (Grundy et al., 2024). Intensity scale on lower two panels is linear.

When searching for habitability remotely (either in the solar system or towards other planetary systems), the accurate characterization of several volatile species (e.g., water, carbon dioxide, methane, ammonia, etc.) is critical as the primary building blocks of larger complex molecules but also key for life as we know it. Fortunately, these molecules have distinct and prominent infrared signatures that fall within the range of JWST. Understanding the distribution and origin of volatile species throughout the solar system and what processes may influence them (geologic or evolutionary, for example) is critical to piece together how the right ingredients came to Earth and contributed to our habitability here. This is also essential for understanding the processes occurring in other planetary systems and how the volatile chemistry will contribute to planet formation. Finally, understanding the ubiquitous nature of volatile chemistry and the possible inheritance of these volatiles from the interstellar medium, protostars, planetary disks, to planetary systems will guide our searches for other worlds similar to Earth or perhaps other extreme objects such as ocean worlds like Europa, Enceladus, or Titan.

The story of volatiles and their history in the solar system or even an origin prior to planet formation is best understood through isotopic signatures and detailed compositional studies. JWST's spectral coverage, unique instrumentation (including integral-field-unit, or IFU, spectrometers that offer spectral maps of molecules), unprecedented sensitivity, and resolution provides a powerhouse of combined methods to help disentangle the pristine nature of volatiles throughout the solar system from small bodies to planetary atmospheres, and ocean worlds. Figure 2 provides a simulated perspective of these tracers as JWST can measure them spectroscopically (adapted from Villanueva and Milam, 2023).

2. Small Bodies

JWST's incredible sensitivity and spectral coverage is well-suited for detailed compositional studies of small bodies – especially those in the outer solar system. All families of small bodies are being observed including near-Earth objects (NEOs), main-belt asteroids and comets, centaurs, comets, and trans-Neptunian objects (TNOs), and the science returned to date is revealing new insights into the relics of our solar system's formation.

The sensitivity of JWST is giving us access to some of the mysteries across our solar system. A notable finding was the detection of water vapor in a main belt comet, 238P/Read (Kelley et al., 2023). These active bodies in the asteroids have perplexed astronomers since their discovery in 2006 (Hsieh and Jewitt, 2006) and have eluded the detection of volatiles with attempts made with some of the largest telescopes in the world – until JWST. This finding is incredibly significant by 1) demonstrating the power of JWST to detect extremely low abundances of volatiles, 2) resolving the driving activity phenomenon of these bodies in the asteroid belt, and 3) identifying a presence of volatile material that is currently unrepresented in comets and the meteoritic record. This final point is critical for the further understanding of the early solar system's volatile composition, distribution, and evolution (Kelley et al., 2023). This initial finding has led to further studies of fainter and fainter targets (both near and far) with JWST to study their composition, activity, and origin.

The diversity of small bodies across the solar system is also being revealed in surprising ways and demonstrated by representative spectra of 3 targets observed with JWST in Figure 3 – a comet, C/2022 E3 (ZTF) (Milam et al., in preparation); a centaur, 39P/Oterma (Harrington Pinto et al., 2023), and a TNO, Eris (Grundy et al., 2024). Comet spectra from JWST across the near and mid-infrared have shown the wealth of molecular outgassing from sublimating ices in these bodies as they journey through the inner solar system, across major ice-lines, in their orbits. JWST's spectroscopic capabilities provide fundamental insights on the volatile composition, isotope and cosmogonic ratios (e.g., $^{12}CO_2/^{13}CO_2$ – see inset in Figure 3, ortho-to-para water abundance ratios), as well as insights into the heterogeneous nature of these icy relics with the 2-D images of each molecular species in the IFU (Milam et al., in preparation). Moving toward the outer solar system and peering at bodies that reside at distance around the giant planets, to a population known as Centaurs – objects transitioning from TNO to Jupiter-family comet. These objects reside past the water-ice sublimation distance in the solar system, but still have some activity. Like the main belt comet, 238P, the opportunity to study these "barely active" objects with the powerful JWST was a must. The first looks have been exciting, showing for the first-time carbon dioxide (CO_2) gas-phase emission. This is complemented by the water-ice absorption features that are consistent with other comets (Harrington Pinto et al., 2023). The centaur data are clearly more evolved with less ice than the TNO spectra shown in Figure 3 of Eris. Eris is a large TNO (comparable in size to Pluto) and has an extensive amount of methane (CH_4) ice across its surface as shown by the broad absorption peaks across the spectrum, as well as some contribution of N_2-ice (Grundy et al., 2024). The surprise in these data was the strong absorption features of deuterated methane (CH_3D). Analysis of these observations yield an isotope ratio of D/H ~2.5×10^{-4}, a value inconsistent with primordial D/H abundance estimates at ~2×10^{-3} and alluding to some endogenic activity from a rocky core (Glein et al., 2024).

The diversity and new evidence for activity, processes, and chemistry in these icy relics have complicated the story for understanding the volatile inventory of our solar system upon formation, but also providing critical insights into the true tracers of our molecular origins.

3. Ocean Worlds

The search for habitability in our solar system and beyond is focused on terrestrial planets with atmospheres and the presence of water, or in bodies known as ocean worlds that may or may not have an atmosphere but do have liquid on or beneath the surface with an internal or external energy source that could support a habitable environment. Different processes may leave molecular evidence that JWST is privy to by studying plumes of gas spewing from the subsurface, deposits of ice or minerals on the surface, or even variables in an atmosphere that suggest activity. JWST is observ-

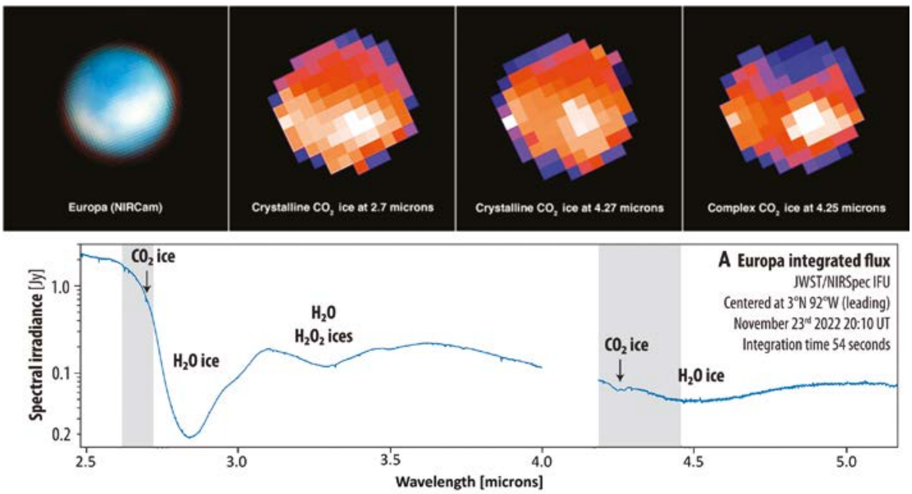

Figure 4. Top panel: JWST NIRCam observations of Europa and JWST NIRSpec IFU maps of Europa at 2.7, 4.27, and 4.25 microns, respectively, showing the distribution of CO_2-ice on the surface. Lower panel: JWST NIRSpec spectrum of Europa from 2.5-5.2 micron showing ice features identified. Figure adapted from Villanueva et al. (2023b).

ing a number of these objects and revealing details on composition and activity that even dedicated spacecraft to these bodies in the solar system had not identified. One such example is Saturn's moon, Enceladus. While a plume of water-rich gas was identified and studied with the Cassini mission, JWST measured the extent of the water vapor coming from this moon and its contribution to the torus and E ring (Villanueva et al., 2023a). This quick glimpse at Saturn's moon did not detect other species, though deeper searches with JWST are now underway.

Another world of keen interest with a known subsurface ocean is the Galilean moon, Europa. This moon has an elusive plume of water vapor, discovered by Hubble (Roth et al., 2014), though not confirmed with many other attempts at various facilities. The power of JWST would readily reveal plumes, if present, and provide insights across the surface if a subsurface plume re-deposited volatile material on the surface as a volcano does with lava. While a plume of gas was not confirmed with a first glimpse with JWST, multiple bands of CO_2 ice were detected and mapped across the disk of the moon (Villanueva et al., 2023b; Trumbo and Brown 2023) – see Figure 4. It was determined that the CO_2 is concentrated in a region that has no cratering, likely regenerated from subsurface geologic activity where material is transported to the surface.

JWST is also peering at other ocean worlds and revealing intriguing chemistry and dynamics that had not been observed before. The volatile content of these bodies provides insights into the primordial conditions from which they were formed.

4. Concluding Remarks

Since its launch in late 2021, JWST has already provided fundamental insight into the composition and dynamics of planetary/satellite atmospheres/exospheres and rings as well as the composition of small bodies, the distribution of volatiles and processed materials across the different reservoirs, and new insights into the formation of the solar system. The question of habitability throughout our solar system is of particular interest and the focus of many upcoming planetary missions – JWST is offering preliminary data to help guide those missions and complement their suite of instrumentation. More importantly, new phenomena and questions are already emerging, revolutionizing this area of research. The nominal launch and efficient operations in place ensure a JWST science mission lifetime of up to 20 years, enabling new discoveries and exploration for future generations.

Acknowledgements

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The Giant Planets in Our Solar System Observed by the James Webb Space Telescope

Henrik Melin
University of Leicester, UK

Abstract

Early JWST observations of the giant planets in our solar system are summarized, including both imaging and spectroscopy.

The giant planets in our solar system, Jupiter, Saturn, Uranus, and Neptune, share similar characteristics. They are dominated by hydrogen and helium, and are much larger than the Earth, without a solid surface, and they all have strong magnetic fields – see Figure 1 for an overview. However, these planets have significant differences that render each planet unique. Jupiter, the largest planet, is one of the brightest objects in the night sky, and its familiar stripes, known as belt and zones, define its visual appearance, along with the Great Red Spot, the largest storm in the solar system.

Saturn, with its striking ring-system, is the second largest planet in our solar system. It has been intensively studied over the past decades, driven largely by the presence of the Cassini-Huygens mission between 2004-2017. The mission revealed several intriguing features of the system, including active cryo-volcanicity at the moon Enceladus, the sixth largest moon (Dougherty et al., 2006). The mission characterised the seasonal change in the atmosphere, produced by the large axial tilt of the planet (Fletcher et al., 2016). Later in the mission observations of the aurora became a significant focus, trying to elucidate their origins (Badman et al., 2012; Lamy et al., 2013; Melin et al., 2016).

Uranus and Neptune are classed as ice giants, with significant amounts of methane, water, and ammonia, both being about four times larger than the Earth. Far away from the Sun, they receive little sunlight – at the orbit of Neptune, the solar flux is only ~0.1% compared to the flux received at Earth. Uranus stands out as the oddball in the solar system. It has an axial tilt of 98°, which means that its rotational axis is closely aligned with the ecliptic plane: the planet rotates on its side, perhaps because of a large collision during the formation of the solar system (Ida et al., 2020). This col-

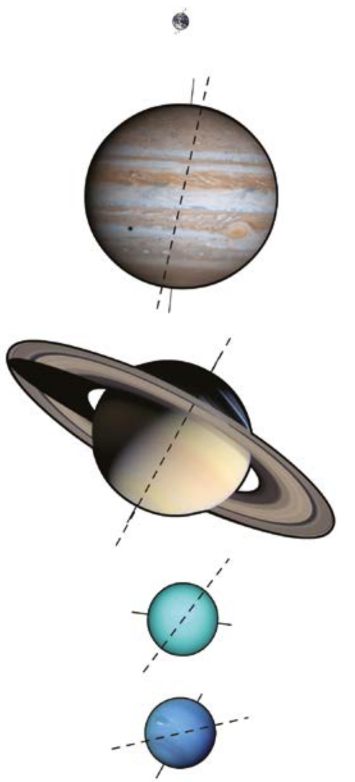

Figure 1. The Earth and the giant planets within our solar system, Jupiter, Saturn, Uranus, and Neptune, to scale. The solid line indicates the orientation of the rotational axis and the dashed lines shows the orientation of the magnetic dipole axis.

lision could also potentially explain the complete absence of any internal heat at Uranus. This is in stark contrast to Neptune, which has the largest internal heat flux of all. The internal heat has consequences for the atmospheres of these planets, since it drives their turbulent convection; the fastest tropospheric winds are seen at Neptune, largely driven by this internal heat.

Whilst emissions from the troposphere and stratosphere of these planets are relatively bright, the tenuous upper atmosphere is harder to observe from the ground. This region is an important interface region between the atmosphere, the magnetic field, and the surrounding space environment. The upper atmospheres of all the giant planets are observed to be several hundreds of degrees hotter than solar input predicts. This is one of the largest outstanding questions in planetary science and is colloquially referred to as the giant planet energy crisis. There are two main potential solutions to this problem. Firstly, the auroral process drives very strong currents at the magnetic poles, and heats it in the process, analogous to a current running through a resistor, which generates frictional heat. This renders auroral regions hotter than the rest of the planet, and this energy could potentially be re-distributed globally. However, the challenge is that these planets are very fast rotators, which generate very strong Coriolis forces, effectively prohibiting the redistribution of energy towards lower latitudes. Secondly, gravity waves generated in the turbulent lower atmosphere can propagate up in altitude where these waves break and release their energy. However, the efficacy of this process is still being debated (Yelle and Miller, 2004).

Whilst all four giant planets have been visited by numerous spacecraft, significant questions remain. In particular, very little is known about either Uranus or Neptune, having only been visited by Voyager 2, in 1986 and 1989, respectively. Given that these planets are the best analogues available for a vast number of exoplanets outside of our solar system, understand-

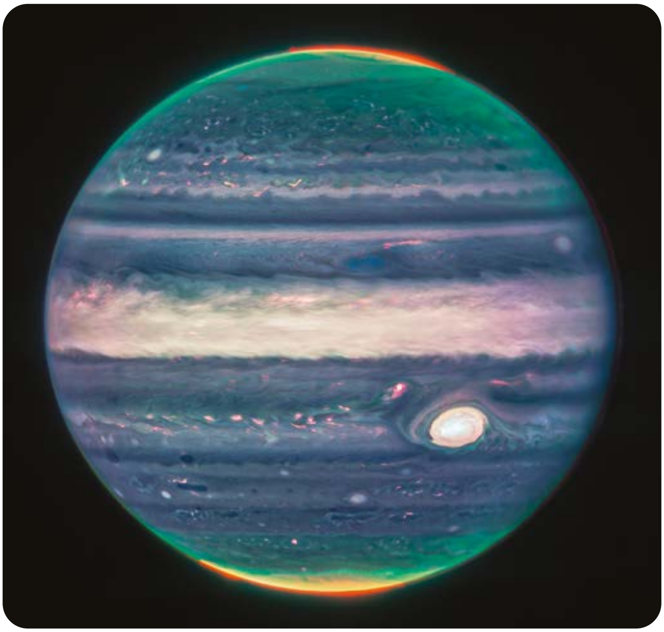

Figure 2. First composite JWST image of Jupiter from ERS programme #1373. Credit: NASA, ESA, CSA, Jupiter ERS Team; image processing by Judy Schmidt.

ing these worlds is a matter of priority. Both the 2022 US Planetary Science and Astrobiology Decadal Survey (National Academies of Sciences and Medicine, 2023) and the ESA Voyage 2050 (Fletcher et al., 2021) have given high priority to a flagship style mission to either Uranus or Neptune. This may take the form of an international collaboration between ESA and NASA, as well as other stakeholders, perhaps building on the highly successful Cassini-Huygens mission to Saturn and Titan.

Observations of the giant planets from the James Webb Space Telescope offer unique opportunities to understand these complex and dynamic systems (Norwood et al., 2016; Villanueva and Milam, 2023). The telescope offers capabilities that were not previously available, either via ground-based telescopes, or by in-situ spacecraft. Firstly, the unrivalled sensitivity of JWST offers access to very faint emission and absorption features currently invisible using existing facilities, and secondly, offers much higher spectral resolution than near and mid-infrared instruments flying on orbital missions (e.g., Cassini VIMS, Cassini CIRS, and Juno JIRAM). Consequently, JWST provides the only means to address some of the most pressing questions at these planets.

The first JWST images of Jupiter were released in July 2022 (ERS programme #1373), which are shown in Figure 2. This image reveals striking cloud structures within the belts and zones cutting across the disk of Jupiter, as well as stunning near-infrared views of the Great Red Spot. By comparing images taken on successive rotations, tracking the movement of

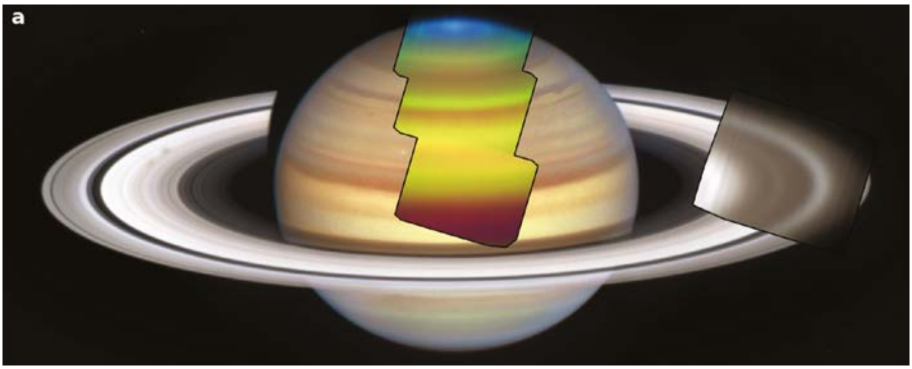

Figure 3. The Saturn MIRI observations obtained in November 2022 as part of the GTO programme #1247 (Fletcher et al., 2023). The color composite of Saturn contains the following wavelengths: red = 10.3 µm, green = 10.1 µm, blue = 11.6 µm and for the rings: red = 15.5 µm, green = 14.6 µm, B = 13.5 µm.

individual clouds, pole-to-pole stratospheric wind profiles can be derived. Hueso et al. (2023) discovered a new narrow equatorial jet, moving at a speed of 140 m s^{-1}, likely forming part of a stratospheric circulation system that varies over time. Figure 2 also shows the northern and southern aurora in red. These are emissions from the molecular ion H_3^+ in the upper atmosphere, which traces the ionisation of molecular hydrogen by precipitating auroral electrons, delivered by vast magnetospheric currents.

The first observations of Saturn were obtained by JWST MIRI in November 2022 (Figure 3) providing an opportunity to characterise the change in the planet's troposphere and stratosphere since the demise of Cassini-Huygens in 2017. Fletcher et al. (2023) found that ammonia was significantly elevated around the equator, suggesting that Saturn exhibit similar stratospheric circulation patterns as Jupiter does. They also observed atmospheric changes consistent with the changing seasons, with equinox occurring in June 2025.

This brief summary highlights that JWST observations of the giant planets provide insights previously impossible from any other facility, be it orbiting spacecraft or telescopes on the ground. These observations can sample altitudes from the troposphere all the way out to the upper atmosphere, highlighting the versatility of JWST in exploring these planets. In particular, Uranus and Neptune are ideally suited targets, given their small angular sizes, and faint emission features, which coupled with the fact that they are relatively unexplored, provides the exciting opportunity for uncovering fundamental features of these systems.

Acknowledgments

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Juno & JWST: Joint Journeys Judging Jovian Geneses

Jonathan I. Lunine
Cornell University, Ithaca, USA

Abstract

Constraints on the formation of giant planets are provided by comparing elemental and isotopic abundances from Jupiter via the Juno space mission and comets from various observing platforms, extending to other extrasolar Jovian planets thanks to abundance determinations by JWST. Very recent results from Juno suggest some interesting similarities and differences from comets, and from JWST a not-unexpectedly wide range of elemental abundances.

Introduction

Giant planets range in size and type from Jovian gas giants to Uranus/ Neptune ice giants (which might, as regards Uranus at least, be a rock giant; Feuchtgruber et al. 2013). The gaseous envelopes of the giant planets contained the residue of solid bodies that contributed to the growth of these planets during their formation, as well as possible post-formation contamination. Identifying the original composition of the planetesimals or smaller pebbles (Lambrechts and Johansen, 2012) and comparison with either nebular models or the measured composition of primitive bodies can constrain where the solid material came from and, to a limited extent, the processes by which it was delivered (e.g., Pacetti et al. 2023; Mousis et al. 2021).

In our own solar system, Uranus and Neptune would seem to provide the clearest signature of solid body accretion given that their hydrogen-helium envelopes are only a minor fraction (of order 10%) of their mass. However, scantily little data are available on their heavy element abundances. In fact, we have a complete inventory of the major elements only for Jupiter, and that was accomplished only over a long period of thirty years from the Galileo Probe to the Juno mission. For comparison with the Jupiter data, many comets and meteorites (as proxies for asteroids) have measured major element abundances and for the latter, noble gases, but noble gas data exist for only one comet.

Beyond the solar system, JWST is providing high resolution, high signal to noise spectra that are allowing major element abundances and metallicities to be determined for giant planets that range over masses from sub-Neptune to super-Jupiter. Of particular interest because of their high abundance as elements and their propensity to condense are carbon and oxygen. Predicting the C/O ratio in models of protoplanetary disks is an important way to connect such models with observations of planets (Öberg et al. 2011). Comparison of the carbon-to-oxygen ratio (hereafter, C/O) in Jupiter to that in comets and extrasolar giant planets is now illuminating how variable formation environments of giant planets might be.

Jovian C/O and metallicity

The ingoing assumption when the Galileo probe was designed and fitted with a mass spectrometer was that the 10-bar level to which the probe could transmit would be (i) sufficiently deep to be below the meteorological layer and (ii) representative of the heavy element abundances throughout a well-mixed hydrogen-helium interior (see Stevenson 2020 for a detailed review). Neither of these assumptions has been borne out by the data. With respect to assumption (i), while the carbon abundance in the envelope through the dominant molecular carrier CH_4 was constant with pressure and clearly representative of a non-condensable species with a 3 to 5 times solar value, the molecular carrier of oxygen, water, exhibited a subsolar value that increased weakly down through the 20-bar depth to which the probe operated (Wong et al. 2004). Since the Galileo probe fell by chance into a so-called 5-micron hot spot which is thought to be a region of overall subsidence, the subsolar value of water measured by the Galileo Probe Mass Spectrometer is generally regarded as reflective of meteorological drying out of water associated with its role as the major condensable in Jupiter's atmosphere.

The realization that assumption (ii) might be wrong has come much more recently and is a long and delicate argument covered in the following three paragraphs. The Juno mission, proposed and selected in the NASA New Frontiers program, had as a primary goal the measurement of the water abundance deep in Jupiter's envelope (hundreds of bars pressure) and over a range of latitudes by a microwave radiometer (Janssen et al. 2017). The determination of water is tricky, because the measured brightness temperature is a function of the abundances of microwave absorbers and the physical temperature profile. Ammonia is a very strong absorber of microwaves as well, and the physical temperature profile at any given latitude is not a priori known. After arriving in Jupiter orbit in 2016, Juno found that the ammonia vertical profile is not constant down to significant depths, tens of bars pressure, well below the expected base of the ammonia or mixed ammonia-water clouds. One model involves the formation of large water-ammonia hailstones ("mushballs") at high altitudes, which survive to well below the cloud base, releasing ammonia and water into the microwave-detected gas phase (Guillot et al. 2020).

As a result, a painstaking effort has been required to remove the vertically and latitudinally variable ammonia profile to reveal the water abundance at deeper levels, in an uncertain physical temperature profile. Being able to measure at different emission angles yields limb darkening which provides additional information to the analysis (Zhang et al. 2020). Only near the equator is the temperature profile such that it can be untangled from the opacity sources in the microwave data, yielding a water abundance between 1.5 and 8.3 times solar (Li et al. 2024).

Juno has other ways to determine the oxygen abundance. In particular, in the deep interior, the shape of the gravitational field measured to exquisite precision by Juno limits the abundance of O (excluding the core) to at most twice solar (Howard et al. 2023a), assuming no other heavy elements. However, the 3-5 times solar carbon measured by Galileo in envelope is, if representative of the deep interior, already the equivalent of twice solar O, or more, and so there is no room even for a solar abundance of water in the deep interior. Put simply, the Z-enrichment in the atmosphere appears to be too large to be consistent with the Z- composition of the deep interior (again, excluding the core).

Various explanations include problems with the equation-of-state, layering and non-adiabaticity, and a higher internal temperature (offsetting the density of the Z-elements). None of these seem to work. Another alternative is that the atmosphere and deep interior have not mixed and have different heavy element abundances. Leaving aside the dynamical challenges of maintaining a denser overlying layer for billions of years (Howard et al. 2023b), one may then ask the question of how the atmosphere became more enriched in Z-elements. The obvious answer given Jupiter's location is that it accreted solid material after formation, when the gaseous envelope had reached its full mass (Shibata and Helled, 2022).

What might this additional solid material have been? An obvious answer would be comets. By way of example, Lunine et al. (AGU meeting presentation, 2023) used the abundances measured in the Jupiter family Comet

67P/Churyumov-Gerasimenko ("67P") by the Rosetta mission from a variety of published papers. Normalizing relative to solar, they find C/O in the atmosphere to be consistent with that in 67P. Furthermore, 67P is unusual in having noble gas determinations (Ar, Kr, Xe) that are lacking for many outer solar system bodies, but the Galileo Mass Spectrometer measured these in Jupiter. The Kr/Xe ratio in Jupiter and 67P are consistent, but Ar/Xe is not – it is too low in 67P. One explanation is that the relatively volatile argon has been preferentially lost from 67P over time, such that when comets like it added Z elements to Jupiter's atmosphere, they contained more argon (Figure 1). What is not consistent between Jupiter and 67 P is the isotopic ratios of the stable xenon isotopes. Further, while a nitrogen isotopic ratio $^{15}N/^{14}N$ has not been published for 67P, the value for other comets is inconsistent with the Jovian envelope.

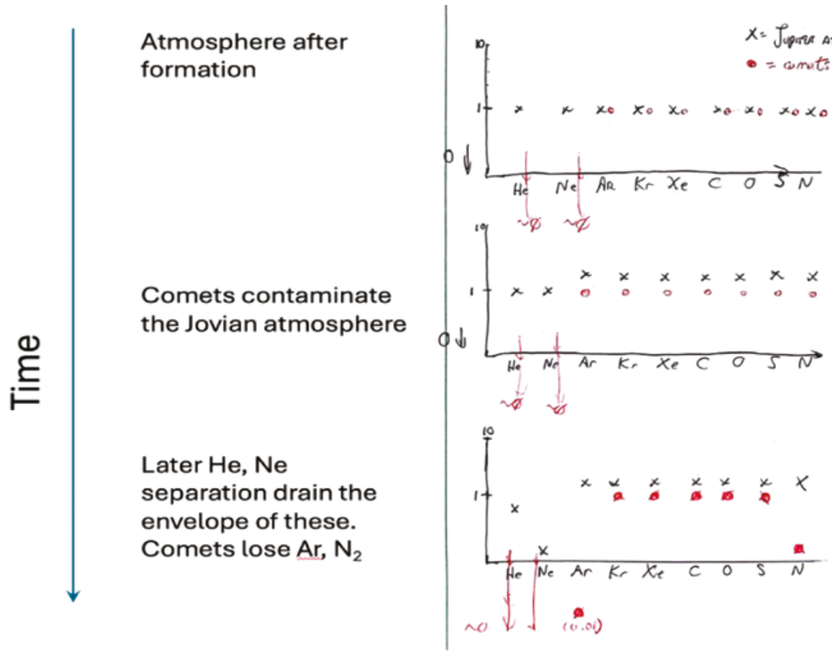

Figure 1. Conceptual model of the enrichment of elements in Jupiter's atmosphere. Three snapshots of Jupiter's atmosphere are shown. The vertical axis is enrichment relative to solar (=1). The elements are arrayed on the horizontal axis. X's are in Jupiter's atmosphere; red circles in the comet. The lowermost box is the present-day. The atmosphere stars out solar in composition. Comets add noble gases but themselves lose the most volatile ones over time so that argon in 67P is depleted today relative to early times. Helium and neon are taken out of the atmosphere as deeper down helium raindrops form. The final element set is consistent with the Galileo and Juno results as described in the text.

It is somewhat disappointing that one must contemplate the possibility that the atmospheric C/O ratio measured painstakingly from Galileo and Juno data might not be the bulk value in the deep interior, if the material that seeded the atmosphere with Z-elements were somehow different in that ratio from the bulk of the heavy elements that built up Jupiter. A sampling of many more comets would be helpful, but a perspective is also available now from JWST.

Extrasolar giants with JWST

Hot Jupiters are in principle more straightforward targets for determining C/O ratios because the molecular carriers in these high temperature atmospheres are all in the gas phase. However, results obtained with HST and Spitzer had large error bars in both the C/O ratios (where determined) and the total metallicity (Line et al. 2021). JWST's performance makes determination of these quantities much more precise (Figure 2). Here are three examples from the GTO program (Lunine #1274), where the data analysis has been performed in collaboration with the group of Professor Jacob Bean at the University of Chicago.

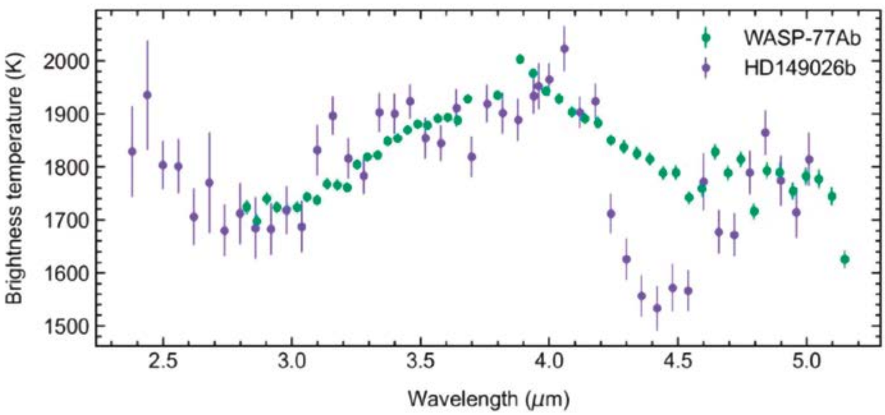

Figure 2. Beautiful JWST spectra of two exoplanets observed in our GTO program 1274, expressed as brightness temperature vs. wavelength. Note the strong CO_2 absorption feature in Smertrios but absent from WASP77Ab. Figure reproduced from August et al. (2023) by author's right to reproduce.

HD149026b, a.k.a Smertrios (Bean et al. 2023). This is a Saturn-mass planet exoplanet with known high bulk metallicity (280 ± 26 times solar) based on its density. JWST spectra obtained in secondary eclipse with NIRCAM allow us to obtain an atmospheric metallicity of 59-275 times solar and a C/O ratio of 0.84 ± 0.03. Note that the atmospheric metallicity is less than that of the interior, but this does not account for the possibility of a large and pure heavy element core which in the case of Jupiter is diagnosed from gravity data and removed from the comparison with the atmosphere. We cannot perform the same correction for Smertrios in the absence of any gravity data (beyond the radial-velocity-determined mass). We can at least say that the atmospheric and envelope mass could be the same, and that there is no evidence for an atmosphere with elevated metallicity relative to the deep interior. The C/O ratio is larger than the standard quoted value (Lodders 2021), but a recent novel approach to determining elemental ratios in the Sun might lead to an elevated value approaching that of Smertrios (Ngoc Truong et al., in prep. 2024).

Wasp 77Ab (August et al. 2023): This is a hot superJupiter (1.8 Jupiter masses) with a radius larger than Jupiter's. Our work yields improved metallicity and C/O values from earlier HST and Spitzer observations; our JWST NIRSpec dayside spectra yield a metallicity between 0.08-0.21 solar and a C/O of 0.36 (+0.10, -0.09). The very low metallicity is surprising even for an object with such a massive envelope, suggesting that the gaseous envelope was depleted of Z-elements before collapsing onto the core during formation. However, one might then expect the least volatile materials to be depleted from the gas by condensation, leading to a high C/O as water was preferentially depleted from the gaseous disk.

HD209458b (Xue et al. 2024): This iconic exoplanet was the first to be detected by transit, about 70% the mass of Jupiter and 1.35 times the radius of Jupiter. Conflicting pre-JWST determinations of the abundance of water and detection of other species have been resolved by our primary transit NIRCam observations. Water and carbon dioxide are present, as well as methane, acetylene and hydrogen cyanide. The metallicity is between 2-9 times solar and the C/O an astonishingly low 0.08 (+0.09, -0.05). Thus, the bulk of the metallicity is contributed by O and the resulting O enrichment relative to solar identical to the Juno-derived value for Jupiter.

Taken as a set, including Jupiter, there seems to be a wide variation in metallicity and C/O ratios from system to system. Only one of our objects fall on the atmospheric metallicity-mass trend seen for the solar system's giants (Figure 3), namely HD209458b. That giant planet, closest in mass to Jupiter, has an identical water enrichment to the equatorial value on Jupiter as determined by Juno. It appears to be one that compositionally would have been much at home in our solar system. Whether this is significant will require determination of O abundances in many more hot Jupiters. But assuming this to be more than coincidence, it argues that the water enrichment in the Jovian atmosphere is indeed the enrichment in the deep interior, and that the discrepancy between the gravity-determined metallicity and that of the atmosphere lies in something other than the metallicity itself – for example, in the equation of state of hydrogen and helium at high pressures. Thanks to the powerful observational capabilities of Juno and JWST, the field of giant planet compositional studies is greatly expanding and in foment.

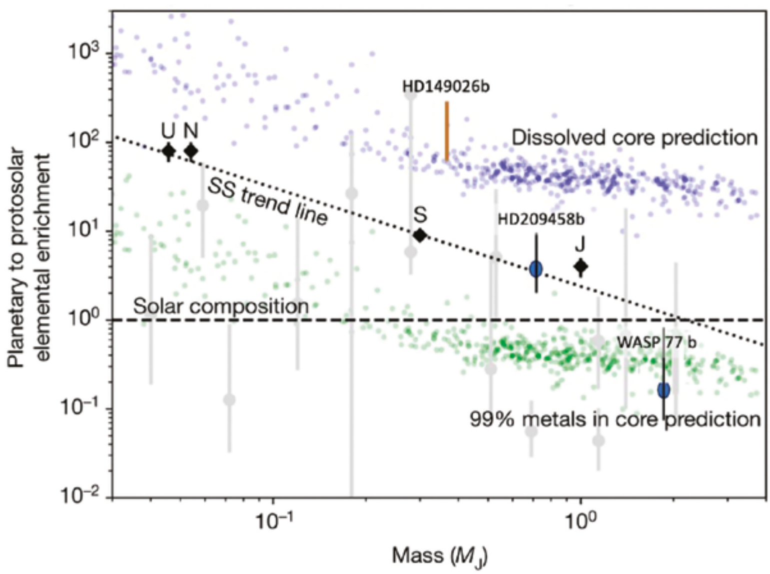

Figure 3. Plot of atmospheric enrichment vs mass in Jovian masses for the exoplanets in our study: HD149026b from Bean et al. 2023; WASP 77Ab from August et al (2023) and HD209458b from Xue et al. (2024). Solar system planets shown as black diamonds with an approximate trend line drawn through. Faint grey lines are pre-JWST enrichment determinations from other facilities. The blue and green dotted fields represent predictions for models in which the heavy element core contains 99% of the heavy elements (blue) versus all heavy elements dispersed in the envelope (green). Figure adapted from Line et al. 2021 by adding the three exoplanets described in this paper.

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List of Participants

Prof. Dr. Joachim von Braun
President
The Pontifical Academy of Sciences

Cardinal Peter K.A. Turkson
Chancellor
The Pontifical Academy of Sciences

Msgr. Dario E. Viganò
Vice Chancellor
The Pontifical Academy of Sciences

Prof. Ewine van Dishoeck
Leiden University

Rev. Brother Guy Consolmagno SJ
Director
Specola Vaticana

Dr. Stacey Alberts
Research Professor
University of Arizona

Prof. Andrea Banzatti
Assistant Professor
Texas State University

Prof. Piero Benvenuti
Interim General Secretary
International Astronomical Union

Dr. Olivier Berné
CNRS Research Scientist in Astrophysics
Institut de Recherche en Astrophysique
et Planétologie

Prof. Karina Caputi
Professor
Kapteyn Astronomical Institute
Groningen

Dr. Anna de Graaff
Max Planck Institute for Astronomy
Heidelberg

Prof. Rene Doyon
Professor & Director
Universite de Montreal - iREx

Dr. Adriana Fontana
INAF

Prof. Jonathan Fortney
University of California, Santa Cruz

Dr. Steven Gillman
DAWN - DTU Space

Mr. Kevin Govender
Director
IAU Office of Astronomy for Development

Mrs. Marjolijn van Heemstra
Space Poetry

Prof. Thomas Hertog
KU Leuven

Prof. Sasha Hinkley
Associate Professor
University of Exeter

Prof. Inga Kamp
Kapteyn Astronomical Institute
University of Groningen

Dr. Jeyhan Kartaltepe
Rochester Institute of Technology

Dr. Janice Lee
Project Scientist for Strategic Initiatives
Space Telescope Science Institute

Dr. Nikole Lewis
Associate Professor
Cornell University

Mr. Lars Lindberg Christensen
Director of Communication
NSF's NOIRLab/IAU

Prof. Jonathan Lunine
Professor and Departmernt Chair
Cornell University

Dr. Melissa McClure
Leiden University

Prof. Nikku Madhusudhan
Professor
University of Cambridge

Prof. Roberto Maiolino
Professor
University of Cambridge

Dr. Margaret Meixner
Astrophysics and Space Sciences Section Manager
Jet Propulsion Lab/California Institute of Technology

Dr. Henrik Melin
STFC James Webb Fellow
University of Leicester

Dr. Stefanie Milam
JWST Deputy Project Scientist for Planetary Science
NASA Goddard Space Flight Center

Dr. Claudia Mignone
Public outreach specialist
INAF

Dr. Michiel Min
SRON

Dr. Matt Mountain
President, AURA

Dr. Takahiro Morishita
Caltech/IPAC

Dr. Nathalie Nguyen-Quoc Ouellette
JWST Outreach Scientist Université de Montréal

Dr. Antonella Nota
Executive Director ISSI

Prof. Karin Öberg
Harvard University

Ms. Teresa Paneque-Carreño
Leiden Observatory

Dr. Klaus Pontoppidan
Jet Propulsion Laboratory

Prof. Martin J. Rees
University of Cambridge
Institute of Astronomy – PAS Academician

Prof. George H. Rieke
Regents' Professor of Astronomy and Planetary Sciences
Steward Observatory; & Professor, Lunar and Planetary Lab
University of Arizona

Prof. Marcia Rieke
Principal Investigator for The Near-Infrared Camera (NIRCam)
Professor of Astronomy
University of Arizona

Prof. Adam Riess
Bloomberg Distinguished Professor
Thomas Barber Professor of Physics
Nobel Laurete

Dr. Pedro Russo
Leiden University

Dr. Colette Salyk
Associate Professor of Astronomy
Maria Mitchell Chair Vassar College

Dr. Massimo Stiavelli
Astronomer and Head, JWST Mission Office
Space Telescope Science Institute

Dr. Sandro Tacchella
University of Cambridge

Dr. Łukasz Tychoniec
Postdoctoral Researcher Leiden Observatory

Dr. Yao-Lun Yang
Research Scientist RIKEN

Prof. Gillian Wright
Director - UK Astronomy Technology Centre