Scientific Insights into the Evolution of the Universe and of Life
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WHAT WE KNOW, AND WHAT WE DON'T KNOW, ABOUT THE UNIVERSE

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We live in a universe that is incredibly beautiful, enormously large, and very complex. It is also evolving. As stars evolve and age, they act as chemical factories, transforming their light elements into heavier ones; as galaxies evolve, they acquire more mass from their surroundings; as cluster of galaxies grow, they gravitationally attract nearby galaxies. Only in the last 100 years have we understood this evolution of the Universe.

'The progress of astronomy during the past 100 years has been rapid and extraordinary'. These were the opening words in *A Popular History of Astronomy during the Nineteenth Century*, a book written one hundred years ago by Agnes Clarke (1). It is an equally valid description of progress in the 20th century, and it will surely describe progress one hundred years from now.

Early civilizations had myths about the sky. When Galileo turned his newly constructed telescope to the sky in 1609, he not only initiated modern observational astronomy, but he also solved a mystery that had occupied civilizations past: he learned that the Milky Way is 'nothing but a congeries of stars arranged in clusters.' His discovery that the planet Jupiter has moons orbiting it helped to displace the Earth from its unique position in the universe. He accurately timed balls sliding down inclined planes to learn how objects fall. Stillman Drake's book (2) describes Galileo's experiments and makes fascinating reading.

Isaac Newton has been called the 'chief architect of the modern world' (3), certainly the modern world of science. He identified and defined gravity as a force; he explained the orbits of the known planets as the combination of their gravitational attraction by the Sun and their forward motion.

He recognized that each planet has its own gravity; the Earth's gravity attracts its moon and Jupiter attracts Jupiter's moons. He understood that the planets would perturb each other; he extended this to universal gravity. He included comets in his gravitational theory, and he understood the tides. Newton studied the eye, vision and colors, and he constructed a reflecting (rather than refracting) telescope, to avoid the colored rings that plagued refracting lenses.

At the start of the 20th Century, scientists knew the astronomy of Galileo, Newton, and more. They knew that we live in a galaxy of stars. They did not know that the Earth was not located at the center of the Galaxy. They did not know if the small, faint galaxies detected with telescopes were located in our Galaxy, or if they were larger objects much farther away. A combination of observations and theories has given us the model of the Universe we know today.

A very simplified sketch of our Universe is shown in Figure 1 (see p. 593). Our sun, carrying the planets (A) with it, is one of more than 100 billion stars in our Galaxy. The planets orbiting our Sun formed from the rotating disk of debris that remained after the Sun formed some 4.6 billion years ago. We, sun and planets, are located about one-half of the way out from the center of our Galaxy (B), a center that harbors a black hole. It takes our Sun and planets about 200 million years to orbit once about the center of our Galaxy, even though we move with a speed of 500,000 miles per hour. Our Solar System has made this circuit only a few dozen times.

In a galaxy, stars are very far apart, relative to their diameters. Thirty million stars would fit between our Sun and Proxima Centauri, the nearest star to our Solar System! In contrast, galaxies are very close to each other relative to their diameters. Our nearest large galaxy is the Andromeda galaxy, only a few galactic diameters away. Andromeda, our Galaxy, plus dozens of smaller galaxies in our celestial neighborhood, comprise the Local Group (C) of galaxies. The Local Group may ultimately merge with the Virgo cluster (D), a collection of several thousand galaxies. But before this happens, our Galaxy and Andromeda will spend several billion years merging with each other, a galactic ballet that has been mathematically choreographed for computer by John Dubinski and John Kameel Farah (4).

When we look in any direction in space, we detect clusters of galaxies that are billions of years old, whose light is currently reaching our telescopes and/or our eyes. These clusters form web-like structures across our Universe (here white) separated by voids (E). Our view of the earliest Universe comes from cosmic microwave background radiation, produced almost 14 billion years ago, about 400,000 years after the Big Bang (our name for the origin of the Universe). The Universe, initially exceedingly hot, has been expanding, cooling, and evolving ever since. The cosmic microwave background radiation presently arriving at our detector has cooled to a cold 2.75 degrees above absolute zero (5).

Tiny temperature fluctuations in the cosmic microwave radiation are shown here (F) as color variations. From these, first sub-atomic particles, then simple elements, hydrogen, helium, some lithium, evolved, and eventually stars. During their lifetimes, stars transform light elements into heavier elements. From these heavier elements come more stars producing more elements, and with time come planets, geology, ultimately biology and life. We understand some parts of the evolution of the universe. Future generations will know more.

Astronomy advanced rapidly in the 20th Century. In 1913, Albert Einstein wrote to George Ellery Hale, Director of the Mount Wilson Observatory, to ask if the deflection of light rays from a distant object, distorted by passing near the Sun, would be bright enough to be detected without an eclipse (6). This deflection is predicted by relativity theory. The answer was 'No'; the bright Sun would mask the faint light from the background object. An easier experiment was successfully conducted with the Sun darkened during the 1919 solar eclipse. Enormous publicity followed the observation that the Sun had distorted background starlight. The publicity made Einstein a celebrity. Earlier, in 1915, Einstein used relativity theory to explain the 'not quite right' timing of the orbit of Mercury, the planet closest to the sun (7). Newton's laws of planetary motion had to be modified for the first time. In Einstein's words 'matter tells space how to bend; space tells matter how to move'. Thus science progresses.

It was not until the 1920s that astronomers learned that our Sun and its planets reside far from the center of our Galaxy, and that the small galaxies viewed with telescopes are large galaxies comparable to our own, but located at enormous distances. These galaxies have surprisingly high velocities with respect to our galaxy; this is the evidence that the universe is expanding.

In 1933, Fritz Zwicky, an astronomer at Mount Wilson Observatory, noted that the 7 galaxies in the Coma Cluster of galaxies with known velocities have velocities that range from 6600 to 8500 km/sec (8). This large range of velocities implies either that the cluster is dispersing, or that matter that we do not see is holding the cluster together. Zwicky named this 'dark matter'. Surprisingly, his discovery was mostly ignored for about 40 years, perhaps in part because some astronomers thought that clusters could be dissolving.

From the 1950s to the 1980s larger telescopes were built, sophisticated detectors could observe a wider region of the electromagnetic spectrum, and rockets and space telescopes returned new images and data. Celestial objects were imaged in various spectral regions, some not visible from Earth: radio, microwave, infrared, ultraviolet, x-ray, and even gamma-ray regions. These images showed astronomers and the public the great beauty in some formerly 'invisible' objects.

Millions of stars in our Galaxy are imaged in Figure 2 (see p. 594). The whiter regions are uncountable numbers of stars along our line-of-sight. These distant stars define the northern Milky Way, the central plane of our Galaxy. The red blobs are Hydrogen clouds. A real treasure is the small bright object at the bottom. This is M31, the Andromeda galaxy, the nearest large galaxy to our Galaxy.

In 1965 I moved from teaching at Georgetown University to DTM, the Department of Terrestrial Magnetism of the Carnegie Institution of Washington. There I joined Dr. Kent Ford, a young scientist who had built an image-tube spectrograph for use at a telescope. This early electro-optical device reduced telescope exposure time by a factor of ten. Kent's interest was in demonstrating what such a device could do. My interest was in studying the motions of stars far out from the centers of their galaxies, a difficult task with conventional photographic plates.

Kent and I started observing the velocities of stars and gas clouds in M31, as they orbit the center of that galaxy. Before going to the telescopes (at Lowell Observatory and Kitt Peak National Observatory), I spent months measuring deep photographic images of M31, in order to measure accurate distances from bright stars to each faint region for which we wanted a velocity. These regions were too faint to be seen in the telescope. With our new equipment we obtained a spectrum of a region in one or two hours; each showed bright lines of various chemical elements. By measuring the exact position of the H alpha (hydrogen) line and comparing it with the laboratory rest position of the line, I could determine the velocity of that region.

When Newton plotted the velocities of the planets orbiting our Sun versus their distances from the Sun, he produced a figure much like Fig. 3, except that here I also include the outer planets not known to Newton. The planet Mercury, whose distance from the Sun is 1/100th that of Pluto, orbits with a velocity that is 10 times (e.g., the square root of 100) as rapid as Pluto's velocity. Kent and I expected the velocities of stars in M31 to exhibit a similar 'inverse square law' falling pattern; galaxies farther from the nucleus would orbit with slower velocities.

We were surprised. In 1970 Kent and I published (9) velocities for about 70 regions (Figure 4, open circles and points with error bars), velocities in

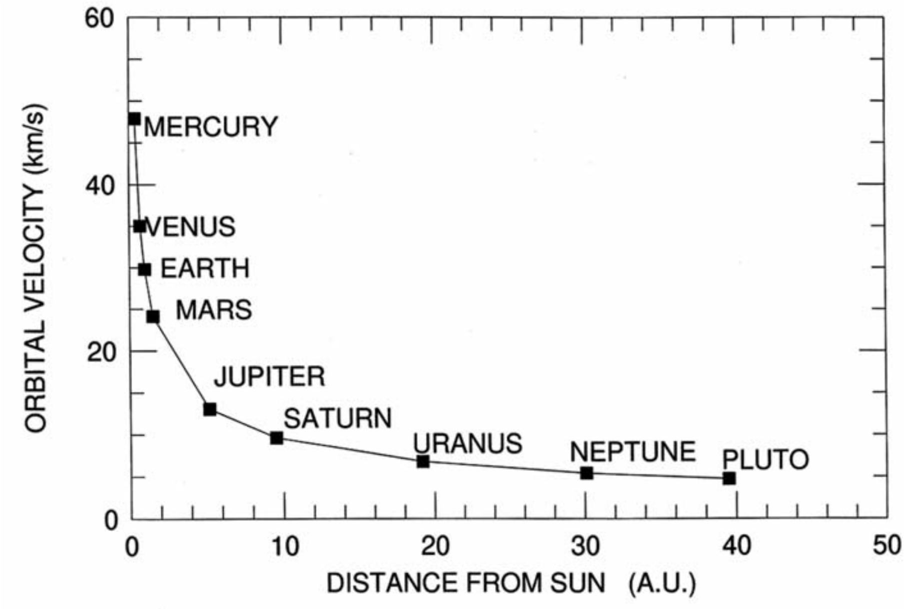

Fig. 3. The orbital velocity plotted versus distance from the Sun, for the planets in our Solar System. The AU (astronomical unit) is a unit of distance; the distance of the Earth from the Sun is one AU. Data for the first five planets come from Newton's *Principia*. When I plotted these data some years ago, Pluto was still a planet.

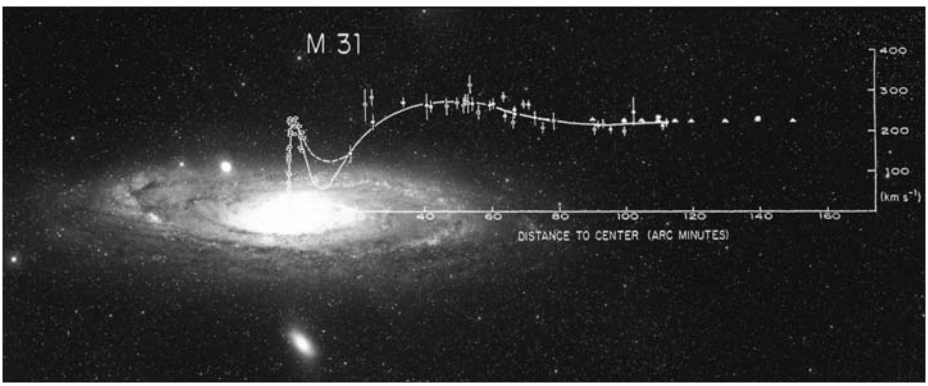

Fig. 4. The orbital velocities of stars and gas clouds in M31, the Andromeda galaxy, superposed on a Digital Sky Survey photo of M31(9)(10). The curve connects the optical data points (1970); the outer triangles are data from radio observations (1975). This flat rotation curve was one of the first to attract astronomers' attention.

the nuclear region and velocities well beyond the apparent optical limits of Andromeda. As plotted here, velocities from one side of the galaxy center are flipped over and plotted along with the other side. The drawn curve connects these optical velocities. In 1975, Roberts and Whitehurst (10) published velocities of more distant regions using a Green Bank Radio Observatory telescope. Optical and radio observations, superposed on the galaxy image, show that beyond the inner regions, stars and gas clouds in M31 orbit with remarkably constant velocities. The expected velocity decrease with distance, as observed in the Solar System, is not seen.

It took a decade, and rotation curves of about 100 more galaxies, for the subject of flat rotation curves to seem real and important. A brilliant review of the available galaxy data by Sandra Faber and Jay Gallagher (11) was important in convincing scientists that we must modify our concepts of the Universe. It is disappointing that after 40 years, and rotation curves for tens of thousands of other galaxies, the composition of the dark matter is still a dark mystery.

We lack important knowledge about our Universe for we lack knowledge of most of its mass. The current generally accepted model is (1).

(1) There is much dark matter (DM) in a galaxy; the amount increases linearly with radius and extends several diameters beyond the galaxy optical image to produce the observed flat rotation curve. It is known that dark matter interacts with matter only gravitationally, so it cannot be baryonic, e.g., composed of conventional atoms and sub-atomic particles. Dark matter constitutes about 95% of the mass in the Universe; conventional matter that we see and know contributes less than 5% of the Universe mass. This model has been adopted by most of the scientific community.

(2) An alternative, less conventional explanation is that there is no dark matter. Instead, Newton's inverse square law must be modified, for it does not apply at distances far from the centers of galaxies. A few dedicated scientists, initially Jacob Bekenstein and Moti Milgrom (12), have modified Newton's gravitational theory so that flat rotation curves result. Their modified Newtonian dynamics (MOND) accounts for the observations. An October 2008 email to me from Bekenstein states: 'Despite widespread doubts by DM aficionados, it has become possible to cast the essence of MOND into relativistic form (TeVeS and now various imitations of it) so that one can begin to confront it with gravitational lenses and cosmology'.

Richard Feynman presents a brilliant discussion of gravity in his little book, *The Character of Physical Law* (13). He notes that it is not exact, that 'Einstein had to modify it' to account for Mercury's orbit, and that 'there is always an edge of mystery always a place where we have some fiddling around to do yet'. This was before we knew of flat rotation curves.

Still other puzzles accrue. About 10 years ago, astronomers started gathering evidence that suggests that the universe is currently expanding faster than it had been expanding in the past. This phenomenon is named dark energy. However, dark energy is unrelated to dark matter, except that the observations were unexpected and the explanation is still unknown. Observations continue, and we will know more in the future.

Einstein knew that light from a background object would be gravitationally distorted by passing behind a massive foreground object. His 1913 query to the Mount Wilson Observatory Director was answered in the positive in 1979, with the discovery of the first gravitationally lensed image (14). In Figure 5 (see p. 595), the Abell 2218 cluster of galaxies at a distance of about 2 billion light-years from Earth has distorted the light from more distant galaxies into arcs and rays of various colors. The background galaxies are 5 to 10 times more distant than the Abell 2218 cluster. Our most distant views of the Universe at present come from *very* distant objects that are gravitationally lensed by distant objects.

Astronomers and physicists attempt to answer the many questions that arise from observations of the Universe. For astronomers, the second half of Century 2000 was remarkable for the instrumentation that it produced, and for the new knowledge that was uncovered. One of the great surprises came with the understanding that chemistry, physics and sciences in general are similar throughout the Universe. Although we understand that important surprises lie ahead, we are not wise enough to imagine what the new discoveries will be. With over 200 billion galaxies in our Universe, many with more than billions of stars, the likelihood of stars and planets with similar evolutionary paths is not small. It is likely that we will learn that other Universes exist and that we will learn to communicate with them. But distances are large, and finances are limited, and communication methods must speed up to be faster than light.

In the year 984 A.D. astronomer Al Sufi produced the first known image of the Andromeda galaxy, the faint fuzz in the sky that the fish is about to swallow (Fig. 6). Al Sufi could never have imagined what we know today about his fuzz, about the Andromeda galaxy and about the Universe. It seems likely that some of our science of 2000 will appear equally quaint to astronomers in the year 3000. But there is something remarkable about being a scientist and learning unimagined things about our Universe. Science truly is *The Endless Frontier* that Vannevar Bush (15) wrote about in 1945.

Fig 6. On this oldest known image of the Andromeda galaxy, Andromeda is about to be swallowed by the fish.

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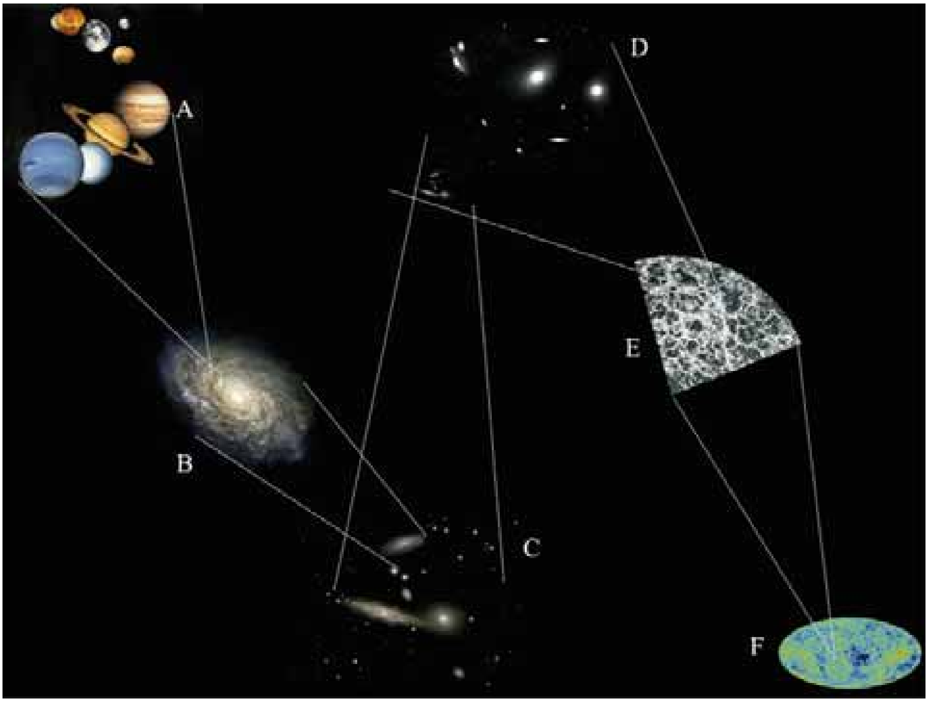

Fig. 1. This is a one-page sketch of our Universe, from nearby to distant. (A) The planets in our Solar System; (B) a galaxy similar to our Galaxy, with the 'location' of the sun and planets indicated; (C) a cluster of galaxies similar to our Local Group of galaxies; (D) the center of the Virgo Cluster of galaxies. The Local Group is currently moving away from the Virgo Cluster, but slowly. It may ultimately halt, then start moving toward the Virgo Cluster, and finally become gravitationally bound to the Cluster; (E) distribution of distant clusters of galaxies (white), with voids between; (F) our view of the very early universe showing the tiny fluctuations in the cosmic microwave radiation 400,000 years after the Big Bang. This microwave radiation traveled for almost 14 billion years to reach our detectors.

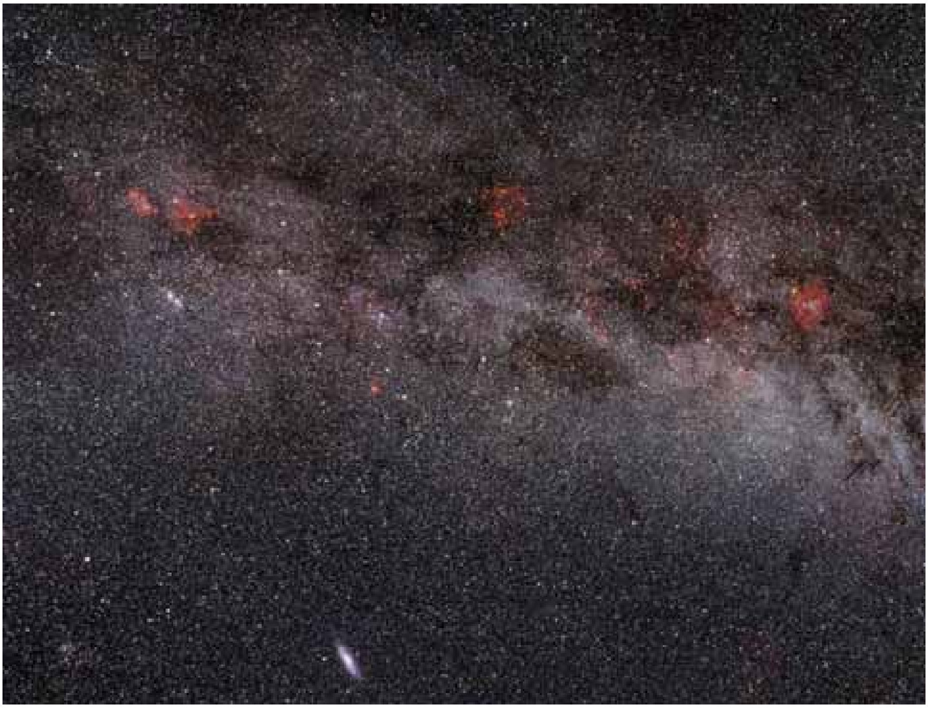

Fig. 2. A view of the stars and gas clouds in our northern Milky Way, the central plane of our Galaxy. The white regions contain billions of stars; the red blobs are hydrogen gas clouds; all in our Galaxy. The small white blob, lower left, is the Andromeda galaxy, the nearest large galaxy to us. [Photo by Wei-Hao Wang].

Fig 5. The massive cluster Abell 2218 acts as a lens, and distorts and magnifies the images of background clusters and galaxies moving them into the line of sight of the observer. The arcs are the distorted background galaxies; the color of an arc depends on the distance and the type of galaxy.