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Our Place in Space and Time

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Other speakers have talked eloquently about some of the contributions of the astronomical sciences to human progress and well being. We recognise that Einstein's special and general theories of relativity are essential for accurately functioning GPS and the guidance of satellite and probes dedicated to observation of the earth's topography, flora and fauna, predicting weather, and monitoring our vulnerability and responses to disasters of many sorts; lasers and masers were developed with astronomical uses in mind; sensitive receivers and mirrors, new materials, as well as optical instruments for medical and practical deployment have all emerged from astronomical imperatives; techniques for mining information from huge data sets; indirect astronomical determinations of the constants of nature that surpass the accuracy achievable by laboratory metrology, and limits on elementary particle physics that are beyond the reach of terrestrial experiments. All are by-products of astronomy.

Yet, I do not want to revisit those direct benefits from astrophysics and cosmology. Instead, I want to highlight the potentially larger impact on human thinking of the ideas of modern cosmology. Cosmology is an attractive shop window for all of science. It attracts the attentions of young school students and engages a far wider public. It is one of the few sciences that is able to rise above political and nationalistic wrangling to stress the unity of humanity and reveal our shared cosmic environment. It raises longstanding and outstanding questions about the nature of the universe and our existence within it that places it at a crossroads where physics, biology, philosophy and theology meet.

Cosmology is currently in a golden age of discovery. New developments in quantum electronics, optics, and satellite instrumentation have fuelled a succession of dramatic discoveries, culminating in the recent direct detection of gravitational waves from colliding black holes and neutron stars.

Cosmology shapes our worldview and defines the cosmic canvas on which we try to place ourselves. It not only tells us where we are and when we are, it helps us understand who we are and where we might be heading. Although cosmology is an ancient human speculation, it only became a branch of science after Einstein's creation of the general theory of relativity in 1915. Previously, there was no theory of gravity that allowed us to consistently describe entire universes, whether they were finite or infinite in extent [1]. Cosmology was really just a branch of art history. You could imagine any type of universe that took your fancy and there was no way to test whether it might be right or wrong.

For thousands of years, philosophers, astronomers and scientists thought of the universe as rather like a stage setting – a fixed, unchanging system within which the planets, stars and other heavenly bodies had been set in motion. Einstein changed all this and showed that space and time are dynamic entities whose nature, rate of change and flow are shaped by the material contents of the universe. Instead of a fixed stage, space is more like a trampoline, shaped by the movement of mass and energy upon it. Einstein's equations determine the link between the shape of space, the rate of flow of time, and the distribution of mass and energy upon them.

Every solution of Einstein's remarkable system of ten partial differential equations describes an entire universe: a map of space, time and matter. There are in principle infinitely many of them and only a few of the simplest, most symmetrical solutions can be found. Fortunately, one of the simplest solutions fits observations very well and provides an accurate description of an expanding universe with very high levels of symmetry and spatial uniformity on the average just like the one we see. The visible universe is almost the same in every direction and at every place to an accuracy of about one part in 100,000 over its largest scales of more than 14 billion light years.

Cosmology is not like laboratory sciences: we can't experiment on the universe so we look for correlations between properties that are predicted to coexist. Moreover, everything we see in the astronomical universe is,

to a greater or lesser extent, as it was in the past when the photons left their sources towards us. We see the universe as it was long ago. Some of the things we see will no longer exist.

The universe is expanding as Edwin Hubble, Milton Humason and Georges Lemaître first revealed to us by interpreting the shifting of spectral lines in light from distant stars towards the red end of the optical spectrum as a Doppler shift produced by a receding light source. This was arguably the greatest scientific discovery of all time – the expansion of the universe. It is important to realise that there is no centre and no edge to this expansion: the universe is not expanding into anything. We can't be at the centre of the universe because there isn't one. Nor are we, or the solar system, or our Milky Way galaxy, expanding. All of those structures are bound together by other gravitational or non-gravitational forces that are stronger than the effect of the expansion over their scale. You have to go out to the scale of great clusters of hundreds of galaxies before you find the markers that trace the expansion of the universe.

The visible part of the universe contains about 100 billion galaxies and each of them contains about 100 billion luminous stars. Yet there is evidence throughout the universe of another dark form of matter, unimaginatively dubbed *dark matter* – probably some weakly interacting elementary particle population as yet unknown to laboratory physics but suspected to exist by theorists – that contributes nearly seven times more material and gravitational pull that everything that shines in the dark.

In 1998, two large teams of astrophysicists led by Saul Perlmutter, Brian Schmidt and Adam Riess observed that distant supernovas were dimmer than expected, and hence much further away than predicted by existing models of the universe. This led to the dramatic (and ultimately Nobel Prize-winning) discovery that, instead of slowing down under the effect of gravity, cosmic expansion is now proceeding at an ever-accelerating rate. A new universal force had caused the universal expansion to switch from deceleration (governed by gravitational attraction) to acceleration (governed by some source of gravitational repulsion) when the expansion had proceeded to about 75% of it present extent. What is the reason for this mysterious force – the so-called *dark energy* – that makes up about 70% of the mass-energy in the universe today? Is it the quantum vacuum energy of the universe, some new type of matter with a very strong negative pressure, some feature of quantum cosmology, or simply another part of the gravitational force that Einstein knew to be a possibility back in 1915. All of these options are possible descriptors of the dark energy. Each has the challenge of explaining why it began to dominate the dynamics of the universe a few billion years ago. None has succeeded so far.

Modern cosmology has taught us that we should not longer expect our position in the universe to be privileged in every way. We couldn't exist anywhere in the universe, of course – the hot centres of stars are hardly conducive to living complexity. However, when it comes to *when* we exist we can see that we do live in a special cosmic time interval. This determines our entire picture of the universe and many of the philosophical and psychological responses we have to it.

As far as elements go, the early universe was almost exclusively made up of hydrogen and helium when it was three minutes old, with only tiny traces of everything else. Carbon, oxygen and all the other heavier elements that make up complexity and life today did not appear ready-made at the beginning of the universe. They were forged in the explosive nuclear furnaces of dying stars, where helium atoms combined into beryllium, beryllium and helium into carbon, and carbon and helium into oxygen. These reactions, which yielded the basic building blocks of biochemistry, took many billions of years to complete. Thus, we shouldn't be surprised to find ourselves in a universe that is more than 10 billion years old, since younger ones would not yet contain the building blocks needed for biochemical complexity.

Neither should the size of the universe surprise us; its immensity is simply a reflection of its great age. In fact, we could not exist in a universe that is significantly smaller than the one we find ourselves in. While a universe the size of the Milky Way, with its billions of stars and planets, might seem a sufficiently large setup for life to emerge, it would be little more than a month old – barely enough time for you to pay off your credit card bill, let alone evolve complex life. People often point to the vastness of the cosmos to argue that life surely must exist somewhere other than Earth. While this might very well be the case, it is striking that the universe would still have to be almost as big as it is just to support one lonely outpost of life.

The large time needed to produce the building blocks of living complexity leads not only to the large size of the universe but also to its low temperature (just 2.7K) and remarkable scarcity of matter. If all the atoms in the universe were evenly spaced out then there would only be about one atom in every cubic metre of space – emptier than any laboratory vacuum chamber on Earth. Gather atoms together, and this tiny material density corresponds to finding about one Earth-sized planet every 10 light years, or one star like the Sun every 1000 light years, and one galaxy like the Milky Way every 10 million light years. Thus we see why the other planets, stars and galaxies are so far away: there is too little material to form them with greater spatial density in the universe.

The last dramatic consequence of the low density of stars is that the sky is dark at night. There is too little matter and energy in the universe to make the sky bright as Edmund Halley first thought it should be, around 300 years ago. For if your every line of sight ends on a tree trunk when you look into a wood containing just a few hundred trees, why doesn't your line of sight end everywhere on a star when you look out into the countless field of stars in the universe? Why is the sky not completely bright all the time?

The large age of the universe needed for life has led to so much expansion that the density of matter and light is far too low today to illuminate the sky. There was a time when the sky was always bright but it was in the distant past, when the universe was about a million years old. But no one could be there to see it because the temperature then was too great for any atoms and molecules to exist. So, the dark night sky you see today, witnesses to the expansion of the universe.

Thus, we are faced with a curious, almost philosophical set of consequences: to develop the broad-brush ingredients required to produce biochemical complexity, the universe must be big and old, almost empty, dark and cold. Paradoxically, these stark properties, which do not sound at all conducive to sustaining living things, turn out to be necessary for the creation of the building blocks of life upon which evolution can act.

Since 1981, a unifying idea has been that the universe underwent a surge of *accelerated* expansion for a finite period of time in its very early history – this phenomenon is called *inflation* [2]. It can be caused by new types of matter with negative pressure (called 'scalar fields') that were predicted to exist in new theories of elementary particles that emerged after the emergence of gauge theories including asymptotic freedom 1974. The recently discovered Higgs boson is an example of such a scalar field.

The surge of early inflation accelerates the expansion to such an extent that it allows the whole of our visible part of the universe to be the expanded image of a part of space that at the time inflation began was small enough for light signals to traverse it and keep its properties correlated and smooth – up to quantum statistical fluctuations. In the absence of an early period of accelerated, this is not possible: the smooth regions would only have expanded to be a few metres in size today, far smaller than the size of the visible universe (about 1025 metres across).

This appealingly simple idea allows us to understand the expansion rate as well as the symmetry and smoothness of the expansion today; it also gives rise to quantum statistical fluctuations which seem able to produce the seed fluctuations that led to galaxies. These possibilities all allow the theory of inflation to make predictions and be tested by astronomical observations made from the ground and by satellites like COBE, WMAP and Planck.

Remarkably, our universe is expanding within about one per cent of the critical divides that separates a future of indefinite expansion (exceeding its escape velocity) from one (at less than its escape velocity) that will reverse into contraction back towards a 'big crunch' of ultra high density and temperature in the future. That our universe seems to be balanced on a knife edge separating two radically different futures is not the only unlikely feature of the cosmic expansion that inflation naturally predicts. The expansion of the universe is also isotropic, meaning that it proceeds at the same rate in every direction. In addition, the universe is extremely smooth, but not completely so – it has a graininess level of one part in 105, just lumpy enough for stars and galaxies to form. Had the universe been just ten times more or less grainy, it would host no habitable regions where stars could form and the chemical elements needed for life would be missing. The elegance of the inflationary picture is that a brief period of accelerated inflation drives the expansion so close to the critical divide that even after 14 billion years of subsequent expansion it should still be tantalisingly close to the divide. Moreover, any pre-existing directional asymmetries in the expansion rate, due to rotation or shear, will be driven to become imperceptibly small as the acceleration pushes the expansion rate in every direction towards the same rate of isotropic expansion [3]. Two of the longstanding problems of cosmology could therefore be solved and a third, the origin of the galaxies, might also be answered by the quantum fluctuations created during inflation which then grow by gravitational instability to become significant over-dense islands of matter billions of years later. This third hope can be checked to an accuracy of a part in 100,000 by observations of the pattern of variations in the background radiation temperature with wavelength. So far, there is a very impressive agreement between the predictions and the observations: some version of inflation seems to have occurred when the universe was about 10-35 sec old. It is remarkable that microwave receivers in space are now easily able to observe the effects of processes occurring so close to the beginning of the universe's expansion across the whole microwave spectrum. In the future, the detection of cosmological gravitational waves also produced by the surge of early inflationary expansion may contribute more information to our picture of the very early universe.

Cosmic inflation is now the standard working model for the earliest stages of the universe – the one that we try to shoot down. As we mentioned earlier, this requires that the whole of the visible part of the universe (and probably much beyond our horizon as well) grew from a tiny patch of space measuring about 10-25 cm across.

But what about the rest of the early universe that lay beyond that tiny patch when inflation commenced? We can imagine many (perhaps infinitely many) similarly sized regions, each internally coordinated but potentially very different from each other. They might have all inflated by different amounts to create a universe that was globally extremely different in structure from place to place (maybe also in its underlying physical forces and constants of nature in some versions of this scenario). This is called *chaotic inflation* [4]. It invites us to think of the universe during the period of inflation as being analogous to a great foam of bubbles, some of which get inflated a lot, others not very much, and others perhaps not at all. We live in one of those bubbles that has inflated enough, and over sufficient time, to become old enough and big enough for stars, biological elements, planets, and ultimately people, to form [5]. If we could see far enough in the universe, beyond our horizon imposed by the speed of light, 42 billion light years away, this elaboration of inflation predicts that we should find the universe to be very different from place to place. Geography is a much more complicated subject than when we were school! While the idea of a universe varying in space like this is not a new one, this is the first time that it has emerged as a positive prediction of a cosmological scenario.

Alarmingly, it seems that history may also be a more complicated subject than we are used to. For each one of those inflating 'bubbles' can rather easily create within itself the conditions for tiny sub-regions to undergo further inflation of their own. They, in turn, can create the further sites for continuing inflation, ad infinitum. This *eternal inflation* is a self-replicating fractal process that appears to have no end [6]. Whilst any bubble, like the one that expanded to encompass our entire visible universe, will have a beginning, the entire eternally self-reproducing network of which it is a (possibly infinitesimal) part has no end and need have no beginning – it may be continued like an exponential function ex forever into the past as x->-oo.

Our visible universe is just part of one of these inflating bubbles that has the features of large age and size needed for life to be possible. So, the question of "Did the universe have a beginning?" now has a much more nuanced answer. Our visible universe had a beginning, when some sort of quantum fluctuation initiated its career of expansion. But we don't know, and probably can never know, if the same was true for the entire (possibly infinite) multiverse of all the expanding or contracting bubbles.

Chaotic and eternal inflation have produced a multiverse perspective. They are simple extensions, that may be inevitable consequences, of the standard simple inflationary picture of the fate of a single inflating 'bubble' that has been astronomically so successfully tested by observations. Modern theories of high-energy physics, like string theory, need to tell us whether the classes of self-interacting matter fields, or particles, that give rise to these exotic behaviours do indeed exist with the right properties within their theories, or whether their existence would be in contradiction with other features of the elementary particle world that we know exist. In this respect, the recent study of the so called 'swampland conjectures' [7] is interesting. Particular constraints on the speed of change of the types of matter field that can give rise to inflation and eternal inflation have been proposed in order that the whole theory have an acceptable vacuum state. These constraints on the 'landscape' of all possible theories seem to be extremely restrictive. Their significance remains a research topic of great current interest.

The discovery that the universal expansion started accelerating again, a few billion years ago, has far-reaching consequences for the future of the universe and the extent to which it can be comprehended. The acceleration will ultimately bring to an end all information processing in the universe [5]. Structures will not be able to bind and survive in the face of acceleration that stretches all spatial separations exponentially rapidly in time. The acceleration also introduces a new feature. During the earlier stages of the universe's life, the distance that we can see with a perfect telescope increases steadily, in proportion to the product of the speed of light times the age of the expansion. Each day we can, in principle, see a little (one light-day) further. But the acceleration now imposes a fixed limit to how far we can see. Light can never beat the effect of the acceleration and reach us from outside this fixed horizon surface around us. After about 100 billion years all the other galaxies we see today will pass beyond this surface [8]. If we have descendants studying the universe at that time, they will no longer be able study cosmology like we do. They will not be able to see other galaxies or discover that the universe is expanding. Ironically, they will not be able to see the evidence we have for the accelerating expansion that is responsible for the horizon around them. Trapped in a nutshell they will be prisoners in a finite space. Their knowledge of the vastness of the expanding universe will have to come from books. For them cosmology will have become a branch of literary history.

Just as there is a period of cosmic history during which life can arise and evolve, so there is a period during which the universe can be studied and understood. It is strange and sobering to think that in the distant future, the only way to learn about aspects of the universe that are easily observed today would be to pore over old astrophysical books and journals from a long-gone era, when the galaxies were still within our reach.

Finally, we see how our conception of the universe has been elaborated and extended. This forms part of a familiar historical trend which see the particular become part of a wider spectrum of possibilities. For

example, once we believed that Euclidean geometry was the only logically consistent possibility – part of the absolute truth about reality – but an infinite number of non-Euclidean geometries can be consistently formulated (what mathematicians mean when they say that they 'exist'). Later, we found that there were many possible logics, unending scales of infinities [9]. None is unique. In the future we may have to find a place for human intelligence amongst a population of 'artificial' intelligences or see life on Earth amongst forms of life that evolved independently elsewhere in the universe. These challenges will require varieties of judgement that are broader and deeper than those provided by science alone.

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