Chapter 2
Looking Out

2.1 Lonely Earth

Try to imagine a Lonely Earth in a universe very different from ours, where the night sky is almost empty. To the naked eye, there appear only seven celestial objects which slowly move around the night sky in bizarre and complex ways. Some rare nights would be utterly black, others—equally rare—would reveal all five visible planets and the moon. In such a world, the history and practical use of astronomy would have followed a course very different from ours, even far back into ancient times—just think of the effect on early navigators of there being no orienting stars, such as the conveniently located 'north star'.[1] Without the field of fixed stars to provide a background frame of reference, it would have been very difficult for proto-astronomers to wrestle order out of the apparently unruly planetary behaviour. And very likely more than astronomy would have suffered. Conceivably, mathematics itself would never have really gotten off the ground and perhaps Plato's vision of an eternal, unchanging realm of perfect truth and beauty would have been almost unthinkable.

But for the sake of this thought experiment, let us instead suppose that at least science and technology advanced in our imaginary world pretty much as they did in ours, so that Galileo's twin could, in the realm of observation, eventually turn his crude telescope onto the few available celestial objects and, in the realm of theory, could apply Euclid and read the language of mathematics in the great 'book' of the natural world. This imagined world would present no impediment to Galileo's earth bound experiments on motion and gravitation. And it seems that this observer could more or less duplicate many of our own Galileo's astronomical discoveries, such as the mountains of the moon and the system of Jovian satellites.

It is true that without the fixed backdrop of stars it would be a lot more difficult to measure the position of the planets accurately, but it would not be altogether impossible (we can envisage using the horizon and time of year as the basis of a system of celestial measurement). So we might be permitted to go on to imagine figures akin to Brahe and Kepler, who led the way to the mathematical understanding

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of planetary motion via universal gravitation which was perfected by Newton (it is hard to see, though, how—lacking the supreme regularity of the stellar 'sphere' as an anchor—the Ptolemaic system would ever be devised in our imaginary world).

Now let the people of our imagined lonely Earth continue their scientific development in parallel to actual progress, up to modern times. Visual access to a starry sky does not seem crucial for this development. But as their science moves towards the equivalent of our twenty-first century physics, severe strains would appear with respect to the science of cosmology. Even in the actual world, this is a strange science, with no prospects for direct experimentation and reliant on disturbingly long and complex chains of argumentation linking its hypotheses with the relatively few observations to which they are relevant. Nonetheless, our cosmologists have managed to produce a grand and beautiful account of the overall structure of the universe, from its inception (minus a few picoseconds) to its possible end states.

But how could any kind of a scientific cosmology get off the ground on Lonely Earth? We can assume that as their telescopes increased in quality and power, they would discover Uranus, Neptune and Pluto; in fact, they would have the advantage in spotting new planets and dwarf planets (if they thought to look and had the patience) for there would be no field of stars with which to confuse a planet. But even measuring the size of the solar system would be difficult. We did it by using trigonometry and parallax, the apparent displacement of a nearby object against a distant background caused by the motion of an observer (you can readily observe parallax by holding up a finger at arms length and viewing it through each eye in turn). Without the fixed stars, our imaginary astronomers would have had to devise a notional celestial coordinate system, and instruments of sufficient accuracy that reliable assignments of location could be made without the guide of any visible background (notably, it would require exceptionally accurate clocks, which took a long time to develop in our world). At the very least, this would have made their distance measurements far more uncertain than ours were.[2]

In any case, once they had their solar system mapped out, no further advance in cosmology would seem to be possible. On the theoretical side, the development of relativity theory and quantum mechanics could proceed (on Earth, astrophysical data had very little to do with the creation of either special or general relativity, and nothing to do with the creation of quantum mechanics). As theoretical curiosities—even in our world they were little more than that for some time—general relativists could create the various cosmological models, such as Einstein's static universe or the Friedmann/Lemaître expanding universe model. But these theoretical exercises would lack any contact with sources of evidence relevant to cosmology. One of the very few (and highly influential) early tests of general relativity was the 1919 measurement by Eddington of how starlight is bent by the gravitational field of the Sun. In our imagined world, such a test would be impossible (the other early test however, the relativistic explication for the behaviour of Mercury's orbit, could have been accomplished, at least in principle, given that they could measure the position of Mercury with sufficient accuracy).

What could the scientists of that world say about the creation and evolution of the universe? Next to nothing. I would venture to guess the best account they could come up with would barely go beyond Laplace's 'nebular hypothesis'.[3] In the absence of any of the stellar nebulosities which so piqued the curiosity of our astronomers and set the stage for crucial debates about the extent of the Milky Way galaxy and the overall size of the universe, even that would take real creative genius. The nebular theory of solar system formation states that in the beginning was a slowly revolving (at least in the sense that it had some net angular momentum) amorphous cloud of gas and dust which gradually collapsed due to its own internal gravitational attraction. The increase in spin caused by the collapse would produce a disk of material, out of which would form the planets as the sun formed at the disk's centre. Powerful basic evidence for some such process lies in the two simple facts that all the planets revolve around the Sun in the same direction and their orbits lie pretty much in the same plane.

Being in possession of quantum mechanics, our imagined scientists could discover why the sun shines and they would then, perhaps, have a reasonable account of the formation of their solar system from the assumption of a primordial gas cloud. Their chemistry and biology could be as advanced as ours; they would have as much reason as we do to believe that life is a complex chemical process driven by evolution so they might well conjecture that life emerged from an earlier lifeless state.

But the whole system would remain deeply puzzling. The initial cloud of gas and dust from which their solar system formed would have to be simply postulated as, in the first place, *existing*, and then as containing just the mix of elements which they would observe in the current form of their solar system. But then, assuming our imaginary scientists discover how the sun can forge new elements through a host of possible nucleosynthetic pathways, they would have an elegant solution to a non-existent problem. For there is nothing in their world that could generate these elements.

Yet I don't think our Lonely Earth scientists could reject the nebular hypothesis in favour of the conclusion that their universe was eternal and essentially unchanging. Several lines of thought and evidence would lead them to the opposite conclusion. In the first place, they could calculate how long the sun should be able to generate energy via nuclear fusion, given its composition and mass. This would tell them that sun could only be a few billion years old. Second, from the rate of radioactive decay of various elements present within the bodies of the solar system, they would find that none were more than 4 billion or so years old (this would be in concordance with the age limit of the Sun). They could also note that the face of the moon, for example, reveals a violent history of impacts which no longer occur at high frequency, obviously suggesting that the solar system is not in some kind of equilibrium state as would be expected if it were eternal. Finally, even if they allowed for some unknown physics which permitted the Sun to shine indefinitely and which somehow eliminated the evidently finite age of the material in the solar system, very fundamental dynamical considerations would reveal that the system itself was unstable over extremely long periods of time (see Lecar et al. 2001).

Thus our imaginary scientists would have good reasons to believe that their solar system had a finite age of 5–10 billion years. This would put them in a difficult position, for the evidently finite age of their solar system would be coupled with no evidence whatsoever of any kind of 'initial state' from which the solar system could have evolved. Ultra-speculative theory sketches might be invoked to ease their minds. Theorists might argue that the universe is really a system of causally disjoint realms in which every possible configuration exists somewhere (there are stronger and weaker versions of 'every possible configuration'; for examples of the ultra extreme end of the scale see Tegmark 2007b; Lewis 1986). Such a view is a radical extension of theories that many of our cosmologists hold, but it is quite a stretch to believe in arbitrary creation events which generate isolated nebula, already properly stocked with the right mixture of light and heavy elements so as to generate a life creating solar system. Nor would the so-called anthropic principle be of much comfort, for our imaginary thinkers find themselves not just in a universe suitable for life, they find themselves in an exceptionally bizarre world that, among its many other oddities, also happens to support life. It is not a world that observers would expect to find themselves in, if one takes into account only the necessity for that world to support intelligent observers, which is the most the anthropic principle could license.

It might well be that the most reasonable response would be to accept that the particular world configuration in which they discover themselves was somehow an explicit target of a mysterious creation event.

Thus, while at first it does not seem difficult to pretend that the universe might consist of nothing but our solar system and indeed such a world does not in itself seem to violate physical law, its existence would be exceedingly puzzling to its inhabitants.

2.2 Galactic Cosmology

What a contrast to the situation that *we* find ourselves in! As we'll see, in our world, at every turn Nature has provided more clues which lead to a grand and unified account of the structure, and possibly, creation of our universe. So far, we have worked out a still incomplete but nonetheless remarkably detailed and coherent picture of the cosmos. In complete contrast to our imaginary scientists of Lonely Earth, no sudden complete explanatory roadblocks are ever thrown up against our theorists. How curious.

No one knows when our ancestors started to think seriously and reflectively about the nature and structure of the world, but it must have been a very long time ago. Evidence of sophisticated astronomical knowledge goes back thousands of years—for example, the Egyptian pyramids are exquisitely constructed to line up with compass directions, with interior shafts that point to particular stars (as they would have appeared at the time of construction). Such knowledge must itself have descended from a long history of observation and thought. Possibly some (literally) hard evidence of this early time comes from various peculiarly carved bones and antlers; for example, the approximately 30,000 year old 'Blanchard bone' appears to represent the lunar cycle (see Kelley and Milone 2005, pp. 95–96). These ancient efforts to wring order out of the evident complexity of the night sky were immeasurably magnified through the self-conscious application of mathematical representations of planetary motion and the 'heavenly spheres'. The codification of Ptolemy—the culmination of a long history of Greek geometrical astronomy—managed to encompass the entire visible universe in one rational system, albeit based upon a fundamental heliocentric misconception, and set us on the path to modern scientific cosmology.

The result, some 2,000 years later or more, is a spectacularly comprehensive and beautiful account of the universe. In parts it remains tentative and more or less hypothetical, but that befits a cosmology wishing to call itself *scientific*. Both its grand scope and fully detailed intimate links with all the physical sciences are breathtaking. If I could, I would have every child learn all their science via the study of this cosmology, which could easily be retold with increasing depth at every level of education and would naturally include everything from basic physics to biology. Of course, our cosmology butts up against its limits at various places, and mystery there intrudes. Why does anything exist at all? Why are there laws of nature? Why does mathematics do such an amazing job of describing our world? But, arguably, these aren't even parts of cosmology as a scientific discipline, although they are of course questions that need consideration. Perhaps they are unanswerable, purely philosophical in the good sense of being 'ultimate questions'. The status of another question, which is the topic of this book, remains unclear. Why and how does consciousness appear in the universe? Is this question ultimate and philosophical or empirically answerable and destined to be the crowning achievement of our scientific picture of the universe?

What seems so striking is how far off mystery can be pushed, especially as compared to the imaginary situation of Lonely Earth discussed above. Let's work backwards from the situation in which we find ourselves. We have worked out the structure of the Solar System by observation and already quite a bit of impressive direct physical investigation (every planet save Pluto has been visited by at least one robot probe, and the New Horizons spacecraft is scheduled to arrive at Pluto in 2015[4]). We find that the Solar System cannot be much more than 5 billion years old. But that's no great mystery. Our Solar System is embedded in a giant stellar system in which we can now observe the kind of dust and gas clouds surrounding budding proto-stars upon which the nebular hypothesis of solar system formation depends.[5] We have discovered a large number[6] of extra-solar planets; solar systems are not rare. Ours may be especially well behaved and well endowed to support life, but it is hardly surprising that life will only appear in those solar systems conducive to it, and so, out of the myriad of diverse solar systems in the galaxy, we must obviously expect to find ourselves in one that is suited to our kind of life.

Our galaxy—the Milky Way—is also a dynamic and evolving system. While one might have conjectured that it was eternal, it could not be considered as unchanging. If eternal, it must be following some kind of grand cycle of star death and rebirth. For we know that the stars cannot shine forever—they depend on a finite supply of nuclear fuel, mostly hydrogen, which they 'burn' through nuclear fusion. Paradoxically, the more fuel a star begins with the shorter its lifetime. The big stars' own gravitational force compresses the hydrogen fuel, forcing it to burn more vigorously. What happens to a big star that runs out of fuel? Before burnout, it is the pressure from the energy released via atomic fusion that prevents a star from collapsing under its own weight. When its main fuel source is expended, a star shrinks and heats by compression, initiating a new wave of atomic fusion, this time not of hydrogen but of many heavier elements, from helium through to iron. Eventually there are no new fusion routes left and the star suffers a catastrophic collapse. The compression and shock wave from the collapse generates a truly immense amount of energy in a very small amount of time. Such supernovas can briefly produce more energy than entire galaxies. But more important from the cosmogenetical point of view is that the exploding star spews forth almost the whole periodic table of elements into the interstellar environment. The twin discoveries of stellar nucleosynthesis and the seeding mechanism of supernova are two of the most significant discoveries of twentieth century astronomy and astrophysics.

These discoveries answer one of the questions that would simply stump the astronomers on Lonely Earth. They show how the complex mix of light and heavy elements found in the initial nebula which seeded the Solar System was both formed and put into our galactic interstellar space. Once we have the solar nebula in place and properly stocked, we can look in two directions: forward towards the creation of the planets, or backwards.

Looking back, we face the awkward question of the existence of the Milky Way galaxy itself. For the supernova-condensation-supernova recycling of stellar material would eventually lead to most stars being too small to explode. Material would thus be locked away in low mass, cool ancient stars and white and brown dwarfs. A certain percentage of higher mass stars would also lead to such lockup, since they will evolve into neutron stars or black holes. But the galaxy we observe is not like that. It has an interesting and varied mix of stars of all kinds with ages that seemingly do not exceed about 10–15 billion years. A curious feature of the galaxy is that the oldest stars are concentrated in a set of vast spherical collections of stars, called globular clusters, that themselves orbit around the periphery of the galaxy. These stars present two very striking properties: they contain extremely small amounts of heavy elements and appear to be very old.[7] The obvious reason for this is that they are largely stars that formed early, out of primitive material that had not yet been recycled through many generations of star formation and explosion. If the galaxy was truly old and somehow could regenerate star formation, we would expect to see the heavy elements spread more or less evenly throughout the stellar population. Since we don't it is hard to escape the conclusion that the galaxy itself was created somewhat more than 10 billion years ago.

After its formation, the evolution of the galaxy proceeded as outlined, with successive waves of star formation (which may be linked in complex ways to the rotation of the galaxy and its internal, spiral arm structure), leading to supernovas which enriched the interstellar environment with heavier elements, which then condensed into later generation stars, one of which is our Sun. But how was the galaxy itself formed? Our best theories are, in essence, upscaled versions of the nebular hypothesis of solar system formation; early stars and other condensations of mass in a universal gas cloud presumably condensed into proto-galactic structures from which the hugely diverse range of galaxies and types of galaxies we now observe were created. There now exist computer simulations of galaxy formation that do a pretty fair job of recovering the kind of galactic forms we actually observe from primordial clouds of gas and dust.[8]

2.3 Universal Cosmology

Our knowledge of galaxy formation is far from complete (the nature, role and even the existence of so-called dark matter is just one area of intriguing ignorance), and creation events are hard to observe since they happened so long ago (which is to say, they are very far away and thus faint or obscured). But we can pursue our general question nonetheless. The universe we can observe is a giant system of galaxies, perhaps a quarter trillion or so in total (so roughly speaking there are about as many galaxies in the observable universe as there are stars in our galaxy). Is this system eternal? If so, then there must be some mechanism of galactic 'recycling' else all the galaxies should be populated only with very old stars. We observe no such thing. Much more significant than this however, is the fundamental observation that the fainter a galaxy is, that is, the farther away from us it is, the more rapidly it is receding from us. Now, in fact we cannot directly measure the speed at which a galaxy is moving away from us. What is observed is that the light from certain galaxies is reduced in energy or 'red shifted', a phenomenon somewhat analogous to the Doppler shifting of the pitch of a sound source that is moving away from us. And there is a systematic correlation between the amount of red shifting and various indications of distance.[9] This correlation between distance and recession speed was discovered by Edwin Hubble and Milton Humason back in 1931, though at the time it was viewed with suspicion, not least because Einstein had devised a model in which the universe was static.

But other theorists—Friedmann and Lemaître—had already developed models of an expanding universe which could fit the increasingly convincing and accurate determinations of the expansion rate (codified in a number somewhat peculiarly named the 'Hubble constant', though it is neither fundamental nor constant). Since the 1930s evidence has mounted in support of the expanding universe hypothesis and against the idea that the galactic structure of the universe is eternal. For example, if we survey very distant galaxies (that is, galaxies that exhibit a very high red shift) we find that the statistics of galactic morphology are notably different from those of closer, older galaxies. In particular, there seem to be very few spiral galaxies in the survey which itself suggests that perhaps the typical spiral arm structure evolves from the evidently less structured elliptical forms.

If we take the Hubble constant seriously it is natural to think that all the galaxies were closer together in the past and that if we trace back far enough, all the matter in the visible universe must have been confined in a very small volume. It is then not difficult to conceive of the universe as coming into existence from a very small but, to understate it rather severely, highly energetic event. This hypothetical event came to be called the 'big bang' (originally a pejorative term coined by Fred Hoyle, who championed a theory in which the universe was infinitely old). In fact, it is a striking fact that the form of the relation between increasing velocity and distance is linear, which has two interesting consequences: no matter where you are it will look as if everything is moving away from you as the centre, and there must have been a time in the past when everything was close together (for a nice discussion of this and other aspects of Hubble's work see Sandage 1989).

However, the expansion of the universe as evidenced by galactic recession is far from proof that the big bang occurred or that the universe is not eternal. Hoyle and others accepted the expanding universe but denied the existence of any creation event (for Hoyle at least, this was in part motivated by an anti-religious sentiment which decried the possibility of something like a 'creation event'). The cost was to posit the continuous low level creation of matter and some sort of cosmic repulsion that drove expansion. The amount of fresh matter needed to maintain the universe in a Steady State (as the theory of Hoyle, Hermann Bondi and Thomas Gold came to be called) is actually very small—about 10^{-40} g/cm^3/s—and if uniformly spread out would be completely undetectable. You would certainly not expect to see tangible lumps of matter just appearing out of nowhere every so often. From whence derives the energy which through all eternity drives the 'matter creation field' remained an open question. Any genuine scientific theory must posit observable consequences, and the steady state theory implies that any uniform sample of galaxies visible to us will have the same mix of ages. It is the Hubble law which allows us to take such a sample. A large collection of galaxies with the same red shift will form such a uniform sample, and thus should exhibit the same mix of characteristics as a large collection of nearby galaxies. But, as noted, they do not; rather they exhibit characteristics which are highly suggestive of a prior state of galactic evolution. There is a fair amount of other evidence leading in the same direction.

The most decisive evidence against an eternal universe turned up before the kind of galactic evolutionary observations we have been discussing were very numerous or robust. This is the famous Cosmic Microwave Background Radiation or CMB.[10] The CMB was accidentally discovered (although it had been predicted by some astrophysicists) by Arno Penzias and Robert Wilson of Bell Laboratories in 1964 as they worked on a radio astronomy project with an antenna released from corporate needs. The CMB is a bath of electromagnetic radiation which can be observed emanating from everywhere in the universe—no matter where you point your antenna you will observe it (some of the snow on an empty television channel is caused by the CMB). The CMB is a direct prediction of the big bang model; what is more the prediction is that the 'structure' of the CMB should be identical to the electromagnetic emissions of an object in thermal equilibrium at a temperature of about three degrees above absolute zero. This very low temperature represents the remnant of the big bang which has been cooling down for the last 10–15 billion years. The cooling is the result of the billions of years of expansion of the universe in a process somewhat analogous to the cooling of an expanding gas. The thermal nature of the CMB is also one of the most spectacularly accurate predictions ever made. In 1989 the Cosmic Background Explorer (COBE) spacecraft was launched with the aim of measuring the CMB much more precisely than ever before. Figure 2.1 shows the spectacular result of one of the COBE instruments which provides the overall spectrum of the CMB.

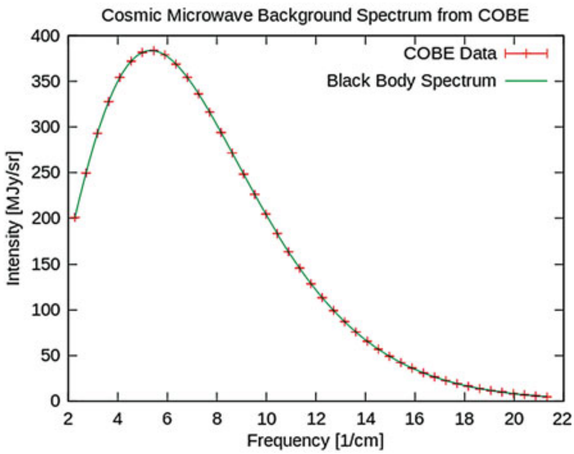

Fig. 2.1 Cosmic background radiation spectrum

Actually, the curve portrayed in the figure is the theoretical spectrum for a black body (an object that absorbs all radiation perfectly, emitting only thermal radiation). The COBE data consisted of many data points strung out along this curve, as illustrated. The data points themselves should by rights be invisible since the error in the measurements is far less than the width of the curve at this scale![11]

Of course, there are no crucial or decisive experiments in science. Although the CMB is exactly what a hot big bang would lead us to expect, versions of the steady state theory can always be maintained in the face of this evidence. Theorists can postulate that not only matter but radiation is continuously being created and that it is, somehow, being 'thermalized' so as to take on the characteristics of black body radiation. For example, a universe in which tiny iron 'whiskers' are uniformly scattered about would serve to thermalize background radiation (see for example Narlikar et al. 2003).

Such a model seems rather *ad hoc*, but there remains some observational evidence against the standard big bang model, of which the most interesting (both scientifically and from a 'science studies' point of view) is the problem of discordant red shifts. Halton Arp is infamous in astronomy for persistently discovering what he claims to be physical associations between objects that the big bang model asserts cannot be associated, typically a low red shift galaxy seemingly coupled to a high red shift quasar.[12] Arp has cataloged a host of discordant red shifts (see Arp 2003) of various kinds and personally believes that some kind of 'new physics' is necessary to explain them, and that the standard big bang model must be rejected. He—and a few other mavericks—remains adamant, but nowadays receives little attention from mainstream astronomers.

For the big bang model has many other fundamental pieces of evidence in its favour. A rather bizarre one which nicely reveals how seemingly disparate aspects of physical theory interact is the supernova decay dilation effect. Supernovae have been studied in sufficient numbers that we have mapped out certain characteristic patterns of light emission that the various types tend to produce. There are two main kinds of supernova (types I and II) and they each have their own light curves. In crude terms, a schematic example of the comparison of a 'nearby' type I curve with that of two high redshift supernovae would reveal that the latter curve is stretched out.[13]

Why should this effect occur? Are the laws of physics different a long way away, or a long time ago? That's always possible, but there is no other evidence for revising physics in a spatial and temporal way. On the other hand, if the universe is expanding, so that distant supernova have a very high relative velocity to us, then we would expect to see the effects of special relativity. Famously, one of these is time dilation: the faster an object moves relative to us, the slower its 'clocks' will run relative to ours. By 'clocks' here is meant any physical process by which time could be measured (including ordinary clocks, the human body as it ages—hence the 'twin paradox', or any other process of change). The expanding universe hypothesis provides a very elegant explanation of the otherwise anomalous light curves of distant supernova (see Leibundgut 1996).

Yet another crucial piece of evidence is the big bang model's prediction of the ratios of the light elements, especially the hydrogen to helium ratio (see Peebles, Chap. 6). Stars can and do produce helium but the same ratio of hydrogen to helium is found both in galaxies with lots of heavy elements (hence galaxies which have a long history of nucleosynthesis) and those with very small amounts of heavy elements. So the amount of helium observed does not seem to be a product of the gradual creation and dissemination of helium from successive stellar generations. However, under the hot big bang model, we can deduce that there was a period (about 1 s after the big bang event) when neutrons and protons were no longer transforming into each other under various high energy processes, but were instead 'free' particles, though still highly energetic, mixing in an extremely hot gas.

The initially almost exactly equal numbers of neutrons and protons would begin to tip in favor of the proton as neutrons naturally decay (into a troika of a proton, electron and neutrino), but as soon as the temperature dropped enough there would also be rapid neutron–proton fusion into deuterons, which would in turn fuse with protons into helium three and, by gaining another proton, into helium four (the stable form). The prevalent conditions ensured there was little or no fusion of any heavier elements through incremental processes then at play, though traces of lithium and a few other elements were formed. From the rate of neutron decay and the temperature bounds permitting fusion to begin, the ratio of protons to neutrons in place when fusion begins can be calculated. The ratio turns out to be about 13 protons for every 2 neutrons, which means that once all the neutrons are safely ensconced in helium nuclei (where they are safe from decay), for each helium nucleus—which contains two protons—there will be around eleven hydrogen nuclei (each a lone proton). By mass, helium will end up forming just under 25 % of the total, hydrogen around 75 % with a few light elements and deuterium (the isotope of hydrogen which contains one neutron in addition to one proton) filling up the rounding errors. It is a spectacular confirmation of the big bang model that this does indeed seem to be the primordial ratio of hydrogen to helium (the observed ratio is a little higher because of the contribution of extra helium from fusion occurring in stars since the big bang).

The present amount of deuterium in the universe is also significant for the big bang model. It is a highly curious fact that deuterium exists in the universe at all. Deuterium is easily 'ignited', which is why it is a favoured fuel for our perennially prospective fusion reactor programs (as the old saw has it, 'fusion is the energy source of the future…and always will be'), and hence is rapidly consumed by the fusion processes within the stars. If the universe was eternal, there would have to be some process of deuterium creation (the random creation of neutrons and protons would not suffice, since they would not likely be able to combine and free neutrons decay in about 15 min). But if the conditions of the big bang are appropriate, a small amount of deuterium can remain after the helium has 'frozen out'. There doesn't seem to be any other recognized process by which deuterium could be created. Observations of inter-galactic dust clouds, which hopefully represent the primordial distribution of matter, suggest that the early universe ratio of deuterium to hydrogen was about 1 to 10,000.[14] That deuterium had to come from somewhere, and it is hard to see where except for a period of nucleosynthesis of exactly the sort predicted by the big bang hypothesis.

Compare once again the situation of our astronomers and astrophysicists with their counterparts on Lonely Earth. They were driven by the data to embrace a picture of the universe in which the conditions for the development of the solar system simply appeared out of nowhere within a universe in which that appearance made no sense at all. The discussion above highlights how the imaginary scientists would find a kind of ultimate mystery almost everywhere they looked, once they looked deeply enough at any rate. They would find, since we supposed that their Earth and ours were qualitatively identical, that the water in their oceans contains not insignificant amounts of deuterium (about one 1 water molecule per 5,000 would be 'heavy water'). They would have no explanation for where this deuterium came from—it was just salted in the initial solar nebula. Perhaps they would infer that a beneficent god must have stocked the oceans in preparation for the shift towards fusion power.

In spectacular contrast to this, our scientists have found a rather grand, deeply complex and inter-related account of the creation of the solar system as part of an entire cosmos, in which a great many lines of evidence all point in the direction of the hot big bang hypothesis. Mystery remains, of course, as well as any number of scientific puzzles. But it appears that the mystery is being driven into that small corner of the room where rather abstract and philosophical issues get discussed. Why is there something rather than nothing? Why do we have laws of nature, and why did we get just *these* laws of nature? These mysteries face the Lonely Earth scientists too; it is just that they also have an elephant in the room.

As our scientists close in on the big bang via current remnants of the early stages of the universe another feature becomes apparent. I will call this the *simplicity* of the early universe. All science except for physics ceases to apply to the universe as we move back towards the big bang event. Thus between the creation of the universe and the present time the objects, processes and, perhaps, the laws of all the sciences beyond physics must have *emerged* out of conditions to which those sciences do not apply. This is a significant fact to which all the lines of evidence we have been considering point.[15]

The extremely early stages of cosmic evolution are not well understood because they require physics not yet in our possession. Thus there is one cosmological 'epoch' which remains completely mysterious; it takes up the time from 0 to 10^{-43} s, a duration called the Planck time, and an associated size of about 10^{-35} m called the Planck length. The density of the universe during this time is so high that gravity would be expected to have significant effects even at the ultra microscopic level of particle physics. But we have no theory which integrates gravitation with quantum mechanics, though there are several candidate approaches (see Smolin 2001; Greene 1999 for popular expositions).

However quantum gravity works, it takes almost no time at all for the universe to expand (and thus for its density to fall) sufficiently that gravity no longer has any microscopic effects, as its strength is swamped by the strength of other forces (of which, after a peculiar cascade of emergence we will consider, there are eventually three: the strong nuclear, the weak nuclear and the electromagnetic). We then enter what is sometimes called the GUT epoch. GUT stands for Grand Unified Theory, which sounds impressive. Unfortunately, there is no such theory which has been empirically verified. But it is thought that we know quite a bit about how such a theory should look. Supposedly, this is the period when there are but two forces, gravitation and a single GUT force which incorporates the nuclear strong force, the nuclear weak force and the electromagnetic force. This period lasts for only a very short time, until about 10^{-35} s after time 0. The GUT ought to be some kind of extension of a theory we do have in place, the electroweak unified theory independently developed by Sheldon Glashow, Abdus Salam and Steven Weinberg (for which they won the 1979 Nobel prize). The most disquieting prediction of GU-theories is that the proton is not stable, though possessed of a half-life trillions of times longer than the age of the universe. Current observations show no sign of proton decay however,[16] and the traditional GUT construction is no longer seen as very promising, but there are other candidate theoretical approaches that promise the same kind of unification.

As the GUT epoch began another rather bizarre and mysterious process seems to have taken place: cosmic inflation (see Guth 1997 for a first hand account of the development of this idea). This was an almost instantaneous increase in the scale of the universe by many orders of magnitude. The main evidence for inflation stems from both the overall and the detailed structure of the CMB. Overall, the CMB is almost perfectly isotropic, as if the system from which it emerged was pretty much in thermal equilibrium. Without inflation this is hard to fathom. We sit at the notional center of a universe which has been expanding for, say, 12 billion years. So, ignoring some relativistic niceties, photons from the CMB from regions on opposite sides of the universe which we capture today are separated by 24 billion light years. Since no causal influence propagates faster than the speed of light it is impossible for these photons to have been in causal contact since their creation. No matter how far back in time you go, if the universe has expanded uniformly—as the Hubble relation suggests—there could never have been a time when these regions were causally connected. Yet they have almost identical characteristics (to about one part in 100,000). This is called the horizon problem. Inflation solves it on the assumption that a huge expansion occurred after an initial thermal mixing. But this early state did not, and could not, reach perfect equilibrium and thus whatever residual inhomogeneities remained would themselves have been stretched out during cosmic inflation. As Andrew Liddle rather quaintly puts it: ‘inflation is trying as hard as it can to make the Universe perfectly homogeneous, but it cannot defeat the Uncertainty Principle which ensures that there are always some irregularities left over’ (Liddle 1999). Inflation predicts that, roughly speaking, the fluctuations in the CMB should be very nearly the same at all frequencies. So far, our observing instruments have verified the isotropy of the CMB to a high degree, and have more recently turned to examining the minute fluctuations (notably via the densely acronymic COBE and WMAP spacecraft and DASI instruments as well as the BOOMERANG balloon laden instruments in Antarctica). What we see thus far is quite in line with the predictions of cosmic inflation.

Inflation neatly answers another question: why is the universe ‘flat’ (that is, why is the current geometry of the universe very near, if not exactly, Euclidean)? The anthropic principle gives one answer: a ‘typical’ non-flat universe would either collapse too quickly for life to form, or have such a sparse matter density that the preconditions for life (such as stars and solar systems) would not be able to arise. Therefore, it is to be expected that we shall observe ourselves to be in a flat cosmos. Like all anthropic ‘explanation’, this does not in fact explain why the universe is flat. Cosmic inflation does. Just as blowing up a balloon makes regions on its surface more nearly flat, so too inflation’s blowing up of the cosmos make its regions more nearly Euclidean. Without inflation the density of the universe must be postulated (it is not fixed by the big bang itself so far as anyone knows) as being between 0.999999999999999 and 1.000000000000001 times the critical density at the age of 1 s (see Guth 2002).

Inflation blew up the scale of the universe by a huge amount, perhaps 70–100 orders of magnitude. One might wonder how come the universe was not left a virtually empty and cold vacuum after blowing up some 10^{100} times in size. Inflation itself deposited huge amounts of energy into the universe,[17] leaving it a fairly dense, roaring hot stew of elementary particles, just as in the basic big bang model (it has thus been said that inflation is thus a ‘bolt on accessory’ (Liddle 1999) to the hot big bang theory). The inflation happened so fast that it did not extend across any significant physical changes. Inflation began in the GUT epoch and ended as the quark epoch began. This marks the time when the temperature fell low enough to permit the appearance of the most elementary of particles, the quarks and their gluons which mediate the strong nuclear force. The quark-gluon plasma characteristic of this epoch has been recreated on Earth (in ultra small measure for a fleeting instant), initially at Brookhaven Laboratories in New York state[18] and now at the Large Hadron Collider in Europe. Further cooling reduced the energy of particle interaction and the universe passed through various epochs (cosmologists differ somewhat on the number of these worth distinguishing).

First, at about a millionth of a second after the big bang, comes the hadron epoch, in which quarks bound into the class of composite particles called baryons, such as the familiar protons, neutrons as well as a host of mesons. While the laws of nature appear to be almost perfectly symmetrical with respect to the production of matter and anti-matter, there is a very slight, and not well understood, asymmetry which led to the overproduction of matter baryons (by convention, what we are made of is called matter rather than anti-matter). Next—approximately 1 s after the big bang—comes the lepton epoch, in which electrons, neutrinos and muons take on an independent rather than the merely ephemeral existence they enjoyed before (during which they were being continuously created and destroyed). At this point neutrinos more or less stop interacting with other forms of matter. The electrons are now free to combine with protons to begin the formation of atoms. This leads to the epoch of nucleosynthesis, as discussed above.

2.4 Cosmology and Emergence

Of special interest is a sequence of 'phase transitions' that occur through these epochs, each one marking a loss of symmetry and the separation of forces that were heretofore unified. During the initial, almost entirely mysterious Planck epoch at the very beginning of things, all the forces were unified as described by the elusive 'theory of everything'. The decoupling of the forces occurred via a complex process of spontaneous symmetry breaking and mass creation. This is best understood in the case of the decoupling of the electromagnetic and weak forces. When unified, according to electroweak theory of Glashow, Salam and Weinberg, the weak nuclear and electromagnetic forces have the same strength, and form a single electroweak force. The phase transition occurs via a transformation of a field, called the Higgs field after its inventor,[19] which imbues the particles (three kinds of bosons) mediating the weak nuclear force with mass. The range of a force is inversely proportional to the mass of its exchange bosons, and one distinguishing characteristic of the weak nuclear versus electromagnetic force is that the latter has infinite range whereas the former is effective only over very short ranges. The exact mass acquired via the Higgs mechanism is not directly fixed by the theory but depends upon a free parameter (the Weinberg angle) whose value can be measured empirically. But the electroweak theory does tell us how to relate this parameter to the ratio of the expected masses. It was a great triumph of the electroweak theory when the predicted bosons were found—with the proper masses—in 1983/1984 (a first hand account of the complexity and difficulties of this experimental episode can be found in Watkins 1986).

It is conjectured that via similar processes all the forces decoupled sequentially as the universe cooled from an initial unified state. Two features of this cascade are particularly important to us. The first is that it seems there will be no way to predict from knowledge of the unified state the exact values of the relevant parameters of the post-unified state. The process of 'spontaneous symmetry breaking' involves a random element. By way of analogy, consider the properties of a bar magnet. An iron bar magnet will lose its magnetism if heated above 770 °C (what is called iron's Curie temperature). The atomic/electronic spins are disordered by thermal agitation above this temperature. As the bar cools magnetism returns and the magnetic field of the iron will be oriented in a definite direction, though there is nothing which forces any particular magnetic orientation. Certain patches of order appear and begin to crystallize, forcing order upon nearby regions, until eventually a single magnet orientation emerges. That is, there is spatial symmetry which is broken by the imposition of a definite magnetic orientation. The laws of nature do not distinguish any spatial direction as 'special' even after the magnetic orientation is fixed by accident (or design).

The creation of the magnetic field of a bar of iron by spontaneous symmetry breaking is thus a case of emergence which is unpredictable in principle. Similarly, the ratio of the relative strength of the four forces and the masses of the force carrying particles may not be set by nature but emerge through a random process. No matter how much one knew about the symmetric phase, it would be impossible to predict these values. Of course, we do not really know that these values are randomly fixed by the free evolution of the early universe. It is possible that deeper theory will show how they are dictated by physical law (for example, typical GUTs fix the free parameter of the electroweak theory mentioned above, while leaving other parameters unfixed).

It is far too early to have any confidence about what the final theory of everything will look like or even whether we shall be able to construct one. The mechanism of spontaneous symmetry breaking discussed here serves to illustrate one possible kind of emergence. More important, the discussion illustrates the status of the post-lepton epoch physics. No matter what form the theory of everything takes, a strong constraint on it will be to generate the state of the universe a few seconds after the big bang. Short of a truly revolutionary shift in astronomy and astrophysics, the big bang model of the 'later' universe (after 1 s that is) is now a part of standard knowledge.

And we have seen how our astronomers, in such stark contrast to the imaginary scientists of the lonely Earth thought experiment, have at every stage found both satisfying answers to current questions about the nature and structure of the universe and Earth's place within it as well as answers that fit together into an elegant total picture.

Picture then the state of the universe when approximately 1 s old. Is there anything missing from our cosmological picture? Considered from the standpoint of the recognized scientific disciplines, almost everything. There is no chemistry (organic or even inorganic), no biology, no psychology and no sociology. Is this surprising? From a purely physical point of view, not at all. Conditions of the universe at this time are, by Earthly standards, very extreme. The temperature was something like one billion degrees and it was quite impossible for atoms to form. The formation of stable atomic nuclei was just becoming possible as the temperature dropped below 1 billion. There was then a small window of opportunity where density and temperature permitted the synthesis of hydrogen and helium nuclei (as described above). Thus it is a natural fact that the only science which applies to the universe at the age of 1 s is physics. As we move back in time closer to the big bang itself, we encounter more exotic, eventually frankly speculative, physics, but it's physics all the way back.

However, as we pursue time away from the big bang towards the present, we obviously enter the domain of application of all the other sciences. Thus, for example, chemical and biological entities and processes (such as molecules, bonding, living organisms and natural selection) must be in some sense emergent phenomena. A little more precisely, any phenomenon which appears in a system which heretofore did not exhibit it can be labeled *diachronically* emergent. The cosmological tale as we now conceive it must be a tale of diachronic emergence.

My labeling naturally suggests a second form: *synchronic* emergence, which can be roughly defined in terms of properties possessed by a system which are exemplified by none of its components. The cosmological story told here supports synchronic emergence no less than the diachronic form. It seems quite evident that the physical entities which exist at 1 s after the big bang have no biological properties. Yet some 12 billion years later we know that at least a few systems possess such properties.

The extent of biology in the universe is one of the most interesting unanswered questions facing science today. People have wondered about exobiology for a long time, but before long we will be mounting serious efforts to grapple with this issue. It is on the edge of technical feasibility for us to launch space based observatories that will be able to analyze the atmosphere of the planets of nearby stars. As James Lovelock pointed out some time ago (Lovelock 1965), the presence of life, at least life as we know it, on a planet has profound effects on its atmosphere, maintaining it in a non-equilibrium state that is a signpost of biological activity. As I write this, the presence of methane in the atmosphere of Mars has been detected. Because of inevitable chemical reactions, methane cannot remain for long in a planet's atmosphere unless it is being replenished. Since Mars shows no signs of active volcanism (one of the few possible alternative sources of methane), it is possible that we have already indirectly detected life on Mars.

In any case, the obvious diachronic emergence of biology is coupled with its synchronic emergence: we do not think that the physical components of living things are themselves carriers of biological properties. This assumes that the basic structures of the world have not themselves acquired biological properties at some time after the big bang. Does it seem plausible to suppose that although the protons that existed 1 s after the big bang did not exemplify any biological properties, these very same protons now do carry biological properties? On the contrary, there is no reason at all to think that the properties of protons have changed in the slightest across the billions of years since the big bang.[20] There is no need to ascribe the properties of any science save physics to the early state of the universe. It follows that all scientific properties save those of physics are at least diachronically emergent and in all probability synchronically emergent as well.

Emergence will be extensively discussed below. The lesson of this chapter is that the overall scientific picture of the universe to which we have been led by abundant evidence strongly supports emergence—in some sense yet to be fully clarified. But before turning to the nature of emergence itself, I want to examine another line of evidence that also supports emergence, but this time in the narrower domain of life and mind rather than the whole universe.

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