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**The First Three Minutes of Creation**

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The essence of life as we know it was produced in the first three minutes after the beginning of the universe. By this, I mean the stuff that we and the Earth are made of, particles of matter that we call baryons. But well before the baryons were created, the universe began from virtually nothing. There was empty space, and time, but no more. Yet within instants, thanks to the occurrence of quantum fluctuations, it attained its huge size, homogeneity and isotropy. The universe is enormous, it is relatively uniform when we smooth over the galaxies, and it looks the same in all directions. More remarkably, during this enormous inflation of space, the universe very early on developed the seeds from which all structure eventually formed.

Let us look back in time. We can think of this as cosmic archaeology. We have two tools. One is indirect: it is the search for local fossils from the past.

Historically, this was particularly important. Indeed interpretation of fossils, taken in a general sense, formed the basis of the cosmology of the ancients.

The second is direct: the telescope. Modern technology has revolutionized the power of telescopes to probe the past.

Historically, local fossils included geological estimates of the age of the earth. Clearly the universe must be older, but this was not the case with the age inferred from Hubble’s measurement of the recession of the galaxies. This led to an existential crisis among the cosmologists of the time, Hubble’s contemporaries. Some, led by Lemaitre, opted for the cosmological constant and the possibility of a prolonged stationary phase in the past to prolong the age of the universe. Others, including Hubble himself, denied the reality of the expansion, and preferred to think in terms of “tired light” or other, unspecified, physics that might simulate the observed Doppler shifts.

Matters improved as the expansion rate was revised by improved data. The real breakthrough came only with the work of Walter Baade in the years when LA was blacked out following the entry of the US into World War II. He succeeded, observing on Mount Wilson with the then largest telescope in the world, in showing that there were two distinct types of Cepheid variable stars, used as distance markers, and that the distance to nearby galaxies had been underestimated by a factor of two. Overnight, the Hubble constant shrank to an acceptable value for a cosmological age and origin of the universe.

Helium is the second most abundant element in the universe, amounting to about 30 percent of its mass. It was first discovered not on the earth where it is rare but in the sun. The sun shines because it is fusing hydrogen into helium by thermonuclear reactions in its core. B The four particles of a nucleus of helium, two protons and two neutrons, weigh slightly less than 4 hydrogen nuclei. It this mass difference that is converted into energy via Einstein’s equation E=mc2. We exist on earth because of the release of solar thermonuclear energy. However the thirty percent of helium that is observed in the sun cannot possibly have been created by the sun, there is far too much of it. Moreover, all stars seem to possess a similar amount of helium, once we correct for the small amount that they have synthesized. This prestellar helium fraction must have been produced long before there were any stars.

During the first minutes of the Big Bang, the universe went through a phase when it was as hot as the centre of the sun and about as dense. The genius of George Gamow was to realize, in the late 1940s, that here was the ideal furnace where helium may have been synthesized. At a second, the Big Bang consisted of protons, electrons, positrons and neutrons in a sea of photons and neutrinos. Indeed, much earlier, there were no protons or neutrons, just their constituents, quarks.

Let us begin with the neutrons, since they are critical for the chemistry of the universe. A proton captures an electron and emits a neutrino, forming a neutron. At the same time a neutron captures a positron, emitting an antineutrino, to form a proton. This leads to an equilibrium until the first second, with one neutron for every six protons.

As the universe cools, the neutrinos, which are very weakly interacting, decouple completely from the cosmic plasma. At the same time the electrons and positrons combine together, into photons. After another minute, the temperature cools sufficiently that a proton could capture a neutron. This is a nucleus of heavy hydrogen, or deuterium. This in turn captures another neutron to form tritium, a short-lived isotope of hydrogen. More reactions followed, including deuterium nuclei capturing protons and tritium capturing deuterium nuclei. The net result is the formation of helium, whose nucleus contains 2 protons and 2 neutrons. It is very stable and is the culmination of early universe synthesis of nuclei. One–third of the mass of the universe is helium, the rest is hydrogen, at least until, millions of years later, when the first stars form.

Observations confirm the universality of the primordial helium abundance. After allowing for the relatively small contribution from stars, the helium abundance is the same wherever we look. It was produced long before any stars had formed. The Big Bang is the only place it could have formed and resulted in such a uniform abundance.

The first minutes of the universe were as hot and dense as the interior of the sun. But the universe was expanding rapidly. This is why heavier elements such as carbon were not synthesised in the Big Bang. To achieve this, three helium nuclei must fuse into a carbon nucleus. Nature does not allow any short cuts: for example two helium nuclei cannot fuse into a beryllium nucleus of atomic mass 8, as there is no stable isotope of beryllium of this mass. So the only way to arrive at a carbon nucleus of mass 12 is by a 3-way encounter, which simply is rare and takes time. Such 3-body interactions happen only over millions of years in the cores of stars like the sun.

One remarkable consequence emerged from the helium prediction. This was that the universe should still retain a fossil glow, despite the 14 billion years of elapsed time over which the expansion and cooling occurred. Here is a curious historical footnote. Gamow’s graduate student, Ralph Alpher, predicted the temperature of the universe today to be about 5 degrees Kelvin. This was in 1952. However he failed to make the following connection.

Cosmologist Richard Chase Tolman had nearly two decades earlier predicted that the fossil radiation from the early universe should be blackbody radiation, from a perfect furnace. He had no idea what temperature to expect, however. At a temperature of 5 Kelvin, the radiation should predominantly be microwave radiation. Gamow and his colleagues failed to make this connection.

The first to do so were two Russian physicists, Andrei Doroshkevich and Igor Novikov in 1964. But they were too late. Two US groups were already hot on the pursuit of fossil radio waves from the early universe. One group, led by Robert Dicke, knew what to look for, and mounted an experiment in Princeton, NJ. But they were beaten in the race by two radio astronomers, Arno Penzias and Robert Wilson, who discovered the relic glow by pure serendipity, working at nearby Bell Laboratories in Holmdel, NJ.

The perfect furnace of the Big Bang lasts for the first month or so. The COBE satellite in 1990 measured the blackbody spectrum of the cosmic microwave background to near perfect precision. The Big Bang was now unchallengeable. The three pillars of the theory are the expansion of space, the primeval helium abundance and the relic cosmic microwave background. The Big Bang is confirmed back to the first second of creation.

This is not good enough however. We would like to know what happened before the first second. Here is where theory soon takes over. Early means higher energy. With our most powerful particle accelerators, we can smash protons together at energies of hundreds or thousands of times their rest mass energy. This means we can study collisions at energies of above 100 GeV. We are now approaching the regime where the electromagnetic and the weak nuclear reactions are indistinguishable. Electromagnetic forces control the orbits of electron in atoms. They are responsible for chemistry. Weak nuclear forces control radioactive decays, and are important for interactions by electrons and neutrinos. Unification of the two occurs at an energy of about 100 GeV.

Eventually at sufficiently high energies the strong nuclear force is no longer distinguishable. Strong nuclear forces hold together protons and neutrons to form atomic nuclei, and hold quarks together to form protons and neutrons. Today the weak nuclear force is a million times weaker than the strong force.

But there is a problem to be solved at lower energies. Where do the baryons come from? There is a subtle problem here. The universe is most naturally symmetric in its matter content. There should be as much matter as antimatter. But this cannot have been the case. As it cooled down, the matter and antimatter would have annihilated, leaving little behind. And whatever was left behind would consist in equal parts of matter and antimatter. This simply is not the case. Antistars and antigalaxies simply do not exist in any significant numbers, otherwise there would be vast amounts of gamma radiation produced as they encountered nearby galaxies of ordinary matter. The universe was borne with an inherent asymmetry that allowed matter to be dominant.

We do not know the precise conditions that led to this asymmetry. It is a small effect, about 1 part in a hundred million. But if it were much smaller, we would not be here. Too few baryons, essentially protons and neutrons, would have survived. However physicists are searching among the particle interactions studied at the LHC for ones that are inherently asymmetric and could eventually lead to an improved understanding of our baryonic origins.

At much higher energies, the physics seems simpler. We can’t measure this directly, the very early universe is our only laboratory. Unification of the electromagnetic and nuclear forces occurs at about ten thousand TeV. The Large Hadron Collider, the world’s largest particle accelerator, smashes protons together at about 100 TeV, a long way from testing grand unification of the fundamental forces, gravity apart. The very early universe provides a unique laboratory for particle physics.

Our greatest breakthrough in understanding the beginning of the universe came in 1980 with the theory of inflation. It was driven by the need to better understand particle physics in the context of the cosmic laboratory of the very early universe. There are four fundamental interactions in physics: These are the electromagnetic force, the weak nuclear force, the strong nuclear force and gravity.

Above an energy of ten trillion TeV, the forces are unified, apart from gravity. This is the scale of grand unification, or a theory known loosely as GUT. This occurs at an instant of a trillionth of a trillionth of a trillionth of a second after the beginning, known as the Planck time. Gravity only is unified at an energy one thousand times higher, the Planck scale. Above this energy, there is no longer any theory: we are in the realm of quantum gravity, where gravity and the quantum theory merge together.

Inflation occurred when the universe cooled below the GUT scale. As the phases separate, just as when ice melts, energy is liberated. In the cosmological situation, energy is injected into the expansion rate of the universe, which accelerates for a brief instant. This is enough to illuminate the universe, via the propagation of light and hence information, to a vastly larger scale than the actual horizon when this begins. By the time inflation comes to an end and the horizon returns to its normal extent determined by time elapsed since the Big Bang, there is more matter than we even see today in our current horizon that has entered briefly into causal contact. Inflation provides a means of understanding why the universe now looks the same in all directions. It also accounts for the immense size of the universe, and for the fact that space is indistinguishably close to Euclidean as a consequence of the enormous expansion. Finally, inflation accounts for the fluctuations that seeded galaxy formation, by arranging for statistically indistinguishable density fluctuations to be present on scales that were totally out of communication in the first instants of the universe.

All of this is great news for theorists, but how can we prove any of this? It all happened so long ago. Our best bet is to study the tiny temperature fluctuations. First there is their distribution of strengths on different scales. It’s almost the same, but there is a tiny systematic increase towards the short or blue end of the spectrum. What inflation tells us is that there should be deviation but it could be anything. So this demonstrates the principle of inflation but doesn’t do much more.

There are two other tests however that are predicted by inflation. And these are fairly generic to all inflationary models. One is that gravitational waves are produced at the end of inflation. These are imprinted as a distortion of the shapes of the temperature fluctuations. Many experiments are underway to search for the tiny polarization induced in the cosmic microwave background. The foregrounds induced by scattering of microwave photons by galactic dust has proved to be a major obstacle. Another prediction is that the temperature fluctuations are not totally random, but have some slight asymmetry in their distribution of strengths. Neither effect has yet been measured.

The ultimate question is what happened before the Big Bang. Let us go back to the 5th century for an answer that rings true today. Aurelius Augustinus, Bishop of Hippo, in what now is Algeria, and who died in 430 AD and was canonized in 1298, developed into a remarkable philosopher and theologian.

He contemplated many deep issues about the nature of the universe that have survived in his writings. Of especial relevance to the creation of the universe, he posed the question: what did God do before he created the universe?

St Augustine did not reply, as often cited: *He was preparing Hell for people who asked such questions.*

But more pertinently, he actually wrote:

*there can be no doubt that the world was not created in time but with time. An event in time happens after one time and before another, after the past and before the future. But at the time of creation there could have been no past, because there was nothing created to provide the change and movement which is the condition of time.*

***— Saint Aurelius Augustinus Augustine***

*De Civitate Dei (The City of God) [413-426], Book XI, chapter 6)*

Fast forward to twentieth century modern cosmology, and views about the earliest instants of the universe are most coherently expressed by the father of the Big Bang, Monsignor Georges Lemaitre. In 1927, Lemaitre published his theory of the expanding universe, and demonstrated that it was consistent with data on redshifts and distances of nearby galaxies.

Hubble was to re-derive this result two years later, unaware of Lemaitre’s pioneering work. A year later, Eddington had Lemaitre’s paper translated from French, and Lemaitre became well known as the discoverer, along with the Russian Alexander Friedmann, of the expanding universe cosmology.

Interestingly, as an ordained priest, and later science advisor to Pope Pius XII, Lemaitre reconciled the Big Bang with his religious beliefs by arguing that

*it appeared to me that there were two paths to truth, and I decided to follow both of them.*

Indeed Hubble never accepted the interpretation of the galaxy redshifts as proof that space is expanding. However, Lemaitre believed that his equations expressed the physical origin of the universe, while they said nothing about its creation. He argued that scientific discussions of what might have happened before time zero were a matter of metaphysics or even philosophy. For him, space and time were emergent. The beginning of the universe was:

*the first instant at the bottom of space-time, the now which has no yesterday because, yesterday, there was no space.*

One finds a similar view expressed by many modern string theorists that indeed that time and space began in the first instants of the Big Bang. To echo Lemaitre, there was no day before yesterday. However there is still no consensus theory on how this is actually achieved. The final theory that unites quantum theory with gravitation is still beyond our reach.

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