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28 November 2018

# In the Beginning

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How did we get here? Some 13.7 billion years have elapsed since the Big Bang. This is as far as reliable physics takes us. But some might even add eons more in a previous phase before the Big Bang, referred to as the Big Crunch.

With our most powerful telescopes, we can peer back in time to when the first galaxies formed. Perhaps the most fundamental discovery of the twentieth century, along with quantum theory, was that of the expanding universe. The data had accumulated for a decade. Two remarkable scientists interpreted it. The best known of these was astronomer Edwin Hubble who in 1929 announced that distant galaxies were receding from us at a rate that increased with their distance, as in an explosion. But it was newly fledged physics PhD and seminarist Georges Lemaitre who used similar data two years previously to deduce that space itself was expanding, a conclusion that Hubble never himself comfortably accepted.

To quote Lemaitre, who should be rightly acknowledged as the co-discoverer of the expanding universe:

> The evolution of the world can be compared to a display of fireworks that has just ended: some few red wisps, ashes, and smoke. Standing on a cooled cinder, we see the slow fading of the suns, and we try to recall the vanished brilliance of the origin of the worlds.

Two years later, after Lemaitre's revelation appeared in an obscure French language journal, Edwin Hubble presented similar evidence for the rate of expansion of the distant galaxies and which subsequently was known as Hubble's Law. He was unaware of Lemaitre's paper which had been published in an obscure French-language journal. The International Astronomical Union is now agitating to rename the recession of the galaxies as evidence for the Hubble-Lemaitre law.

Lemaitre was a remarkable scientist who reconciled his religious views of creation with the wonders of nature. It was all a question of physics. For him, any higher authority was active only before the first instance of time as described by physics, that is, before the Big Bang. Hence for him, it could not be observable or experimentally testable. He dismissed notions of religious creationism, even more prevalent one or two centuries ago than now, by remarking about one of the most eloquent advocates of this type of reasoning, Blaise Pascal, who inferred from the otherwise supposedly incomprehensible beauty of nature, that '*when Pascal tries to infer the existence of God from the supposed infinitude of nature, we may think that he is looking in the wrong direction.'*

Lemaitre said, as a physicist and priest, '*it appeared to me that there were two paths to truth, and I decided to follow both of them'*. For him, physics took us back to time zero. He wrote that cosmological models of the expanding universe, now known as the Big Bang theory, took us back to *the first instant at the bottom of space-time, the now which has no yesterday because, yesterday, there was no space.* What happened before then, he affirmed, was a question of personal belief.

At that time, there was no physics alternative. Since then, there has been much progress in cosmology. The sticking point has been that the conditions are so extreme at the initial instant that quantum theory is needed. And not just the quantum theory that unveils the structure of matter, but a quantum theory that incorporates the force of gravity. This is an elusive theory that remains to be discovered in its full grandeur.

Indeed, Einstein spent most of his life fruitlessly searching for this union of the two fundamental theories of nature. After more than half a century, there may now be one, in the form of string theory. Or more precisely, superstring theory. This is currently highly disputed, as we will see. But it does provide novel insights into how our universe may have begun.

**Strings**

Dive into an atom. One finds a core, the nucleus, that consists of protons and neutrons. Keep on diving. One arrives at quarks, the ultimate constituents of matter in what we call the standard model of particles.

This might seem a speculative idea, but a prediction was made 40 years ago that all particles in the standard model acquire mass because of a new, fleetingly present, particle, called the Higgs boson. This was discovered just six years ago at the world's largest particle collider in CERN.

Solve one puzzle, and others arise. Why are there the particles we find in the standard model? There are precisely eight types of quarks, each with specific masses and flavours. Flavour denotes the different ways particles interact with each other. Think of it as analogous to the charge of an electron. Why?

String theory accounts for all of the particles of the standard model by interpreting them as vibrating one-dimensional loops of energy. That is an amazing achievement, although it does not necessarily mean it is the correct theory. For the moment, it is the best we have. String theory requires more dimensions than we are ordinarily accustomed to in 3-dimensional space. The existence of strings is hard to verify. Essentially, the extra dimensions have all rolled up or compactified. But, long ago, at the enormous energies at the beginning of the universe this was not the case.

In physics we are used to testing theories by their predictions. So far, string theory has made no testable predictions. However, there is an unanticipated outcome. String theory does provide an explanation of one of the most fundamental problems in physics.

One property of string theory is that it requires eight extra space dimensions.

We need to incorporate gravity. We achieve this by unifying all of the fundamental forces of nature into a single theory. This takes us to what have been called superstrings. This is our best theory of quantum gravity, absolutely crucial to getting insights into how the universe began.

It turns out that early on in the multidimensional universe, string theory predicts that space can have many shapes. When the extra dimensions in any patch are compactified, one can easily produce a universe that is nothing like ours. It expands, as a big bang. But it might end up being too big or too small. Or it might be just right. The number of possible shapes is immense. Each shape represents a different universe. They may or may not actually exist, and we will return to this question.

However, string theory is a beautiful, and even compelling, mathematical construction. The number of shapes has been calculated. It amounts to a number that is larger by far than the number of atoms in the visible universe. This is about ten to the power of 80. The number of possible universes, each corresponding to one of these shapes and with different combinations of particles and ages, is predicted to be 10 to the power of 500.

All of these options have led to the concept of the multiverse, the thesis that such universes might actually exist somewhere in higher dimensional space in all their diversity. Different patches compactified to give our universe of three spatial dimensions, but this happened in many different places in superspace, the higher dimensional entity in which everything must be embedded. This seemingly fantastic view of Nature might actually be relevant to understanding one of the most important issues in cosmology.

**The Acceleration of The Universe**

Half a century was to pass before there were new insights into the beginning of the universe. The major development in cosmology in the twentieth century, after the discovery of the expansion of space, was the discovery of its acceleration. The acceleration is remarkably small compared to anything that physicists might have expected as a relic of the early universe. This discrepancy has been called one of the greatest problems in physics.

The acceleration is due to the effects of repulsive gravity. That seems to be a contradiction. After all, gravity attracts, that's why Isaac Newton was supposedly inspired by an apple falling from the tree in his garden to develop the theory of gravity in order to explain the universality of orbits of the moon around the earth and the planets around the sun.

Now imagine a completely uniform substance. This won't necessarily be attractive. It would be if it exerted pressure such as that of a gas. Pressure equals energy equals mass, which attracts. But in fact, pressure, if it is negative, exerts repulsion, or antigravity. Here is why.

The vacuum contains a constant density of energy. This arises from tiny fluctuations due to the uncertainty in the positions of particles. These particles are predicted to come and go, according to the quantum theory, but last for so little time that they are not measurable. We say that even the vacuum is a bustling hive of activity that does leave a trace of energy behind. This energy must be constant and it is dark, since we can't actually measure or detect any of these dancing particles and antiparticles. They don't exit for long enough. It is what we call quantum pressure, and arises from uncertainty in where the particles actually are.

Now the more vacuum we have, the more there is of associated dark energy. But energy must in turn be associated with pressure. Normally as you compress a gas, the pressure increases. That's positive pressure, which acts, so Einstein says, as energy, hence mass, hence attractive gravity.

However, the situation is reversed in the vacuum. Expand the vacuum, there is more vacuum and so there is more pressure from the tiny fluctuations due to the uncertainties in particle positions. This is quantum pressure. And this is negative pressure. Positive pressure, our everyday concept, decreases when the volume of any container is expanded. Quantum pressure actually increases, hence it is referred to as negative pressure. Just as positive pressure reinforces gravity, negative pressure acts against gravity, it is intrinsically repulsive. And the repulsion drives the acceleration of space.

It was Lemaitre, who foreshadowed what was to come. He realized that what was said to be emptiness or vacuum was teeming with energy. In 1933 he reinterpreted the meaning of Einstein's introduction of the cosmological constant in 1916, originally designed to prevent the universe from collapsing but redundant once the expansion was announced in 1929. He was the first to realize that the cosmological constant could be interpreted as the energy of the vacuum.

Lemaitre discovered that the cosmological constant could account for his models of the accelerating universe. He wrote in 1933 that '*the cosmological constant…corresponds to a negative density of the vacuum.'* That's antigravity, and generates the acceleration of space.

We now call this invisible energy field of the vacuum the dark energy. The modern interpretation is a consequence of the quantum theory. Quantum theory postulates that vacuum can be full of particles that come and go on a time-scale too small to be measurable. We can never see these particles directly, but their coming and going, via creation and annihilation, creates a pressure in the vacuum. This pressure has the remarkable property of acting like a tension and pushing back against gravity.

Once Pandora's box is opened, it can't easily be closed. At the time, there was no evidence for acceleration and Lemaitre's hypothesis was generally ignored. Several decades later, two new discoveries were to revive Lemaitre's ideas. One was experimental: acceleration of the expansion was discovered and began about halfway back in time to the Big Bang.

Another was theoretical: the theory of inflation emerged. Inflation theory envisaged a brief but intense period of acceleration a mere fraction of a second after the Big Bang. We cannot directly see this phase of cosmic history, but its consequences left a profound imprint on the observed universe.

Acceleration was discovered because we had the means to obtain precision distances to remote galaxies. Armed with these, one could search for any deviations from a uniform expansion. Cosmologists expected a deceleration. After all, the universe might be expected to eventually recollapse. One should therefore see a slowing down of the expansion, by looking very far away and back in time.

The expansion is mapped by studying exploding stars, or supernovae, among the most luminous objects in the universe. The most distant ones, at about half the present age of the universe as we look back in time, were too faint, by about 20 percent. This is a big effect. Acceleration of the universe, meaning that the distances to the host galaxies are further than expected in a uniformly expanding universe, is the only explanation.

The conclusion seems inevitable, that the universe began accelerating a few billion years ago. The big surprise was the measured value of the acceleration. It required a density of dark energy smaller than anticipated by some 120 factors of 10.

**Inflation to The Rescue**

Discrepancies this large between theory and experiment worry physicists. The multiverse was soon advocated as a likely solution. It predicted a vast panoply of competing universes. Some would be too young, some too old, some too hot, some too cold, for life to have evolved. Some would be accelerating so much that all stars would be ripped apart.

Life is highly improbable. It takes rather special conditions, such as a planet with oceans and atmosphere, not too far from, nor too close to, a star like the sun. And no doubt many primitive cell mutations to arrive at complex beings. But given the vast number of possibilities, and vast number of predicted universes, the chances of life developing somewhere would be finite and even inevitable. The fact that we are here requires only that it must have happened once. It's like Goldilocks and the three bears, though with more possibilities, only one serving needs to be just right.

The origin of life somewhere in one of the universes is now compatible with the huge number of hostile universes in the multiverse. We could not be doing cosmology in most of these universes. However, what was missing from this explanation of the weakness of dark energy was a reality check. How can we be confident that the multiverse exists? Superstring theory says only that it once existed at the beginning of time, but might be totally irrelevant for the vastness of space. There would just be highly compactified knots of space-time, everywhere embedded in the favoured higher dimensional space. Something vital was missing.

Our universe is enormous, gigaparsecs across. Vastly larger than anything foreseen in superstring theory. If such an anthropic (or intelligent life-centred) explanation of dark energy holds any credence, we must explain how many of these primordial universes could be so large. The missing link came from the theory of inflation.

This theory was originally developed in the 1980s in order to explain the size of the universe. In fact, the natural value of dark energy early on did lead to a huge acceleration. This phase did not last long as the dark energy soon was diluted once the universe heated up with radiation. But for a tiny fraction of a second the universe expanded from an infinitesimal size to a scale immensely larger than our horizon today.

Inflation could explain why the geometry of the universe is Euclidean, it's like the expansion of a wrinkled balloon leading to a perfectly flat surface. And as a bonus, the infinitesimal fluctuations caused by quantum effects were stretched to very large scales. This enabled the seeds of galaxies to be explained as the fluctuations in density accreted matter during the later and cooler phases of the expanding universe.

And there is more. It turned out according to cosmologist Andrei Linde that inflation did not just occur once, it occurred many times, and each occurrence spawned a new universe. And this continued for ever and ever. Inflation is eternal. It explains the multiverse.

**The Swampland**

The multiverse cannot be viewed or even probed. By definition, there are universes outside our universe. We can never see them no matter how large our telescopes. That provides a certain amount of discouragement to many physicists would argue that an untestable theory is more philosophy than physics.

The only alternative to the multiverse explanation is to state that the cosmological constant observed is just a constant of nature. There are others, for example the value of Newton's constant of gravity. If gravity was much stronger, stars would not have had time to generate elements like carbon that are essential to life. If it was much weaker, stars and planets might never have formed. So gravity is also said to be fine-tuned. In fact what is fine-tuned is really the ratio of the gravitational to the electromagnetic forces; it is the latter that stops all stars from collapsing to black holes.

To add further fuel to the multiverse debate, recent developments in quantum cosmology have been highly critical of the multiverse. It turns out that the most natural prediction from quantum cosmology is that the cosmological constant should be attractive, not repulsive. In most cases it is a negative, not a positive constant. This undercuts the entire basis of anthropic reasoning that purports to explain the value of the cosmological constant by virtue of our existence.

The original anthropic argument for the cosmological constant went something like this. If it were too high, any larger than its observed value, galaxies would not have had time to form, because the acceleration would start too soon. Why it couldn't be smaller?

Reverend Bayes in the 18$^{th}$ century gave us the answer, or rather the means of obtaining this. His reasoning rested on a more subtle point, partly philosophical in nature. The outcome of Bayesian reasoning argues that the odds of any bet or prediction can be refined by using our beliefs or even our intuition. These additions to our reasoning of the odds can play a crucial role.
Such is the case for the cosmological constant. The larger the value of the cosmological constant, always denoted by the Greek letter Lambda, then there are more possibilities for different universes. This changes the odds. Lambda should be as large as possible, runs this argument, since that's the most likely outcome of any bet.

But we run into a natural limit. The larger the value of Lambda, the sooner the universe begins to accelerate. If the universe accelerates too soon there is no time for life to develop. Hence we have a prediction for the value of the cosmological constant: not too large and not too small.

While not overwhelmingly precise, the predicted value is within range of the measured value. Very different from the predicted number, some 120 factors of ten larger! This is considered to be a triumph of what we call anthropic reasoning, that is, inclusion of the existence of life in a scientific discussion of the values of any natural parameters. It is a way of explaining the highly unlikely occurrence of an observed phenomenon, in this case the fine-tuning of Lambda.

This was the state of affairs until 2017. Not the most satisfactory conclusion perhaps, as many physicists are reluctant to invoke anthropic reasoning as being beyond the domain of physics. Just as the masses of elementary particles and the numbers of their families are parameters that are part of our standard model of particle physics, and the strength of the gravitational force is a parameter in Einstein's theory of general relativity, it may be that the mystery of Lambda is due to yet another constant of nature. In short, nature is the way it is because that's the way it always was.

However recently new arguments were developed in quantum cosmology, the only, but still incomplete, theory of the beginning of the universe. These argued forcefully that quantum cosmology indeed predicted a vast number of possible universes at the beginning of time, but that most of them had the wrong sign of the cosmological constant.

All these alternatives were rapidly decelerating, rather than accelerating.

No strong case here for the odds favouring an accelerating universe. A decelerating universe is a disaster, it's not the one we inhabit. This new view of the origins of the multiverse has become known as the swampland, a place where essentially all theories of cosmology are doomed to fail.

So we have not made much progress in understanding the origin of the universe. There is the most generally accepted view, the Big Bang. It is the aftermath that could result in diverse outcomes.

If the dark energy density is too high, there is the Big Rip. This follows a big bang but with too much acceleration. If the dark energy density is too large but with a negative sign, or even if the dark matter density is too high, there is the Big Crunch. Our universe will collapse, perhaps sooner than we'd like in the most likely cases. And if our understanding of quantum cosmology is as incomplete as some believe, there could be a Big Bounce.

Getting through the singularity, that is the point of origin of the Big Bang when the density of matter was infinite, is a challenge for cosmology. There is no known solution. But we can happily speculate that a prior phase of contraction terminated in a bounce from which the Big Bang, phoenix-like, emerged.

Some elusive physics theory yet to be discovered, dubbed the theory of everything, will eventually provide explanations for the observed values of the fundamental constants of nature. This might be wishful thinking, but it could equally be the only physics way forward. There is no doubt that we have far to go in understanding the nature of quantum gravity, and the physics required to take us back to, or even before, the beginning of the universe.

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