A Cosmic Coincidence Resurrects the Cyclical Universe

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Over the past five years or so, scientists have finally converged on a model of the universe that explains (or at least permits) all of its characteristics. The new cosmological model has one very surprising feature, however, which is supported by several robust and unrelated observations. In addition to matter and radiation, it seems that the vacuum of space is filled with a mysterious ‘dark energy’ that pushes the universe apart. While the dark energy helps us explain a great many things, it also resurrects an old problem once thought buried—the idea that our universe is the product of a highly unlikely cosmic coincidence.

During the decades following common acceptance of the Big Bang model, physicists and astronomers tried very hard to measure the composition of the universe. According to theory, the average density of the universe would determine its ultimate fate. A universe with too little matter would expand forever, and its average density would eventually drop to zero. A universe with too much matter, on the other hand, would one day collapse under its own gravity (the ‘Big Crunch’). Only one special value, the *critical density*, could prevent both a Big Crunch and the unchecked expansion of the universe.

Those with philosophical objections to a dying universe had only three alternatives. One idea was that we actually lived in a *steady state* universe. In this model, the universe expands at a constant rate but produces an occasional atom out of the void to maintain its average density. A steady state universe is infinite, and need not have had a Big Bang at all. Another way out was to have a *cyclical universe*, whose every

Big Crunch is followed by another Big Bang. The cyclical universe model didn't improve our own long-term prospects, but it at least preserved the universe itself from extinction. Unfortunately, neither of these models survived under the pressure of improving astronomical observations.

By the 1970s, a critical density Big Bang model was the only viable solution for a stable universe. Unfortunately, even the most generous accounting of matter in the universe added up to only about half of the required density. Cosmologists were stuck with an unstable universe, doomed to end in cold and darkness. A universe that expands forever is not so bad, if the data require it; the future history of the universe might be disappointing to aesthetes, but a scientist will just shrug and accept the result.

The Big Bang model, however, still had a big problem: our low-density universe could only arise from a highly unlikely coincidence of initial conditions. An expanding universe is fine in principle, but it mustn't expand too quickly! For galaxies, stars, and planets to form, the average density of matter has to stay relatively high for at least a few billion years. To satisfy even this one vague constraint, it turns out that the initial density of the universe would have had to be very close to the critical value[1].

How close? The answer is a bit hard to swallow even to a disinterested physicist! A difference of one part in a million billion (10^{15}) would allow galaxies to form before the expansion of the universe pulls everything too far apart for new structures to form. This is known as a *fine-tuning* problem: to explain the observed properties of the universe under the Big Bang model, physicists had to assume a very specific value for its initial density.

If the universe were actually *at* the critical density, which has a clear physical significance, the fine-tuning problem wouldn't be so bad. A universe starting at the critical density remains at the critical density forever, which sounds like a clue to some deeper physical law. One might claim that an unknown physical process makes this the only possible value. But in knowing that the initial density was some other number, physicists had to admit that *any* initial density was possible. Although we live in a universe capable of supporting life, the probability that such a universe came into existence randomly seemed to be infinitesimal.

The fine-tuning problem was eventually solved by borrowing ideas from quantum field theory, a branch of physics dealing with fundamental particles and their interactions. During the Eighties and Nineties, most physicists were content with the Big Bang model and believed that a quantum mechanical process called *inflation* pushed the density of the early universe very close to its critical value in a brief period of runaway expansion. During inflation, the universe was dominated by a field of energy not unlike the dark energy being discussed today. In this scenario, the initial density of the universe was no longer relevant—inflation would drive any initial value towards the critical value in the blink of an eye.

At the turn of the millennium, however, this tidy theory began to fail. Large-scale surveys discovered distant supernovae by the dozen, allowing astronomers to determine how fast the universe was expanding billions of years ago. The cosmology *du jour* predicted that the universe was slowing down, but these and subsequent observations have shown that the expansion is actually speeding up!

To explain this result, Einstein's cosmological constant had to be brought back into the picture. This parameter corresponds to the energy density of a vacuum (the 'dark energy'), and just like the matter density the cosmological 'constant' evolves along with the universe.

The fine-tuning problem has therefore returned, in a different form. The initial density of vacuum energy had to be very close to zero at the Big Bang, or else an accelerating expansion would have driven apart all the matter before stars could form. Inflation can't solve the problem this time; technically speaking, the cosmological constant is itself one cause of inflation.

Once again, cosmologists find themselves debating the initial conditions of the universe. One common explanation, which has been used for decades to solve fine-tuning problems, is called the *anthropic principle*. In essence, this is the statement that we must live in a universe that can support life because we are here to observe it. This statement isn't very satisfying, however, since it doesn't offer any new insight into the nature of the universe.

In modern times, physicists such as Alexander Vilenkin (Tufts University) have begun to suggest that our universe is only one of many. They envision an eternally expanding field of fundamental energy, effervescent with an infinity of universes. Each one has a Big Bang of its own, popping into existence wherever quantum fluctuations cool the fundamental field sufficiently. If there are an infinite number of universes, then it is certainly much less surprising that some would be habitable. Our particular combination of cosmological parameters, however, remains a highly improbable event in its own right.

Advances in string theory and our understanding of higher dimensional spaces have made possible an even more astonishing solution to the coincidence problem. Quantum mechanical models have been proposed that allow the cosmological constant to decay from any initial value to almost zero. Such models, however, have two problems: first, the process typically requires trillions of years; and second, while the cosmological constant is large the density of matter in the universe drops to zero very quickly.

But what if the universe is much older than it appears? Professors Paul Steinhardt (Princeton University) and Neil Turok (Cambridge University) have come up with a novel solution that gives the cosmological constant time to decay to its required value. Resurrecting a ghost of the cyclical universe, they propose that our universe is one of two embedded in the eleven-dimensional space of string theory.

The two universes are linked with a spring-like attraction, and so pass through each other (moving along one of the higher dimensions) periodically. Every time they interact, enormous energies are released and both universes fill with hot plasma—a new Big Bang. There is no Big Crunch, as both universes are constantly expanding. A trillion years or so after one Big Bang, when the universe is practically empty, another Big Bang occurs and the stars and galaxies can form once more.

The underlying cosmological constant, however, is unaffected by this process and has all the time it needs to decay to a small value. Eventually stars and galaxies will have time to form, and the same will be true of every subsequent cycle. In this modern version of the old cyclical model, the coincidence is resolved because only a few cycles are required for the cosmological constant to decay. The number of star-producing cycles following the decay, however, is practically infinite.

Either way, it is clear that our perspective has changed. A single universe is no longer satisfying, given the most unlikely nature of our own. To explain our existence, it seems we must imagine others.

References:
Paul Steinhardt and Neil Turok, "Why the Cosmological Constant is Small and Positive", *Science* 4 May 2006, http://xxx.lanl.gov/astro-ph/0605173
Alexander Vilenkin, "The Vacuum Energy Crisis", *Science* 4 May 2006, http://xxx.lanl.gov/astro-ph/0605242

Articles from *Science* magazine are also available at
http://www.sciencemag.org/

[1]As the universe expands, its density decreases. The critical density is therefore actually a function of time, and had a much higher value in the early universe than it does today.