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EDUCATION ARTICLE

Cosmic Evolution

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Abstract Just as biological evolution is the heart of modern biology, cosmic evolution is the heart of modern cosmology. For instructors to be confident in teaching science, it is helpful for them to appreciate the current understanding of the composition and development of the universe, especially the revolutionary changes that have taken place in our understanding over the last two decades. Biological evolution requires the products of cosmic evolution—the elements of which life is composed were formed in the cores of stars—and the two areas of science are thus crucially, and even inspiringly, connected.

Keywords Cosmic evolution · Big Bang · Stars · Universe · Atom · Earth

Both biological evolution and cosmic evolution have become hot-button issues in the past 20 years; it is nevertheless vitally important that teachers not steer away from either of them in order to avoid controversy in the classroom. To omit these vital subjects would leave students ignorant of some of the most important advances in science in the past century.

The past two decades have witnessed a revolution in our understanding of the makeup and evolution of the universe on its largest scales, and the result has been to alter our picture of the future in dramatic new ways, with results that also impact upon our understanding of our place in the cosmos, the possible existence of life elsewhere in the universe, and the development and evolution of life on our planet.

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First and foremost, however, there is one issue that needs to be emphasized. The Big Bang *really* happened. Like biological evolution, there is no controversy here, no doubt. The expansion of the universe is a fact. Three observational pillars: the observed almost exactly thermal "cosmic background" radiation (CBR) coming from the Big Bang with a temperature of almost three degrees Kelvin, precisely that predicted for an expanding universe that has been cooling for 13.7 billion years, an age that is completely consistent with the age of our galaxy as determined by modeling the evolution of the stars within it on computers; the observed "Hubble expansion," in which distant galaxies are observed to be, on average, moving away from us, with a velocity proportional to distance—a clear signature of an expanding universe; and the observed cosmic abundance of the light elements hydrogen, deuterium, helium, and lithium, which differ by almost ten orders of magnitude but nevertheless are all consistently explained by the application of well-known nuclear physics to the behavior of a hot dense universe at a time of about one second into the Big Bang. (For detailed teaching activities and tools, the reader is referred to a list provided at the end of this article.) The detailed theoretical models of exotic physics of the very early universe may be speculative, and there are several key features of our expanding universe we may not yet understand, including the composition of the dominant form of matter in the universe, but the general empirical underpinning of the Big Bang is essentially unassailable at this point.

The very beginning of our universe, the moment of the Big Bang, is still shrouded in mystery, although exciting new ideas are being developed on this subject. One thing has remained a constant, however. We know that, in the beginning, there were no atoms, or Eves.

Shortly after the moment of the Big Bang, when our universe spawned from an infinitesimal speck smaller than the size of a single atom and well before it cooled to the point where even atomic nuclei began to form, all evidence currently points to a period of remarkably rapid expansion, called “inflation,” in which the size of our universe increased by at least 28 orders of magnitude in less than a millionth of a billionth of a billionth of a second (Guth 1998).

For only in this way can we understand why our currently observable universe, which otherwise would have been much larger than the distance a light ray could have traveled since the Big Bang, is so remarkably uniform. Had the universe inflated in this fashion, however, the original size of our currently observable universe would have been much smaller, so small that different regions within our universe could have been in causal contact and come into thermal equilibrium, explaining the fact that the temperature of our universe is remarkably isotropic, with different regions having a uniform temperature at better than one part in 10,000.

This is not the only reason that we now expect inflation occurred, however. In the first place, our theories of fundamental physics suggest that it is quite likely that, as the universe cooled, the configuration of fundamental particles and fields altered several times as a result of what physicists call “phase transitions.” These are similar in spirit to the transitions that occur in matter when it is cooled, as when, for example, water condenses from gas to liquid or freezes from liquid to solid. In the case of the early universe, however, during the transition from one state to the other, a period of exponential expansion of space can occur as energy is briefly trapped in space before being released as the transition completes.

More important than this theoretical argument, however, is the fact that one can predict that, during inflation, quantum mechanical fluctuations in matter and radiation get converted into fluctuations in the density of matter on large scales that get frozen in and re-emerge millions or billions of years later to collapse into all the structures we see today: clusters of galaxies, galaxies, and stars. In the past decade, we have been able to probe directly for these small fluctuations by observing the so-called cosmic microwave background radiation, a direct signal coming from a time when the universe was about 300,000 years old, the time when it had cooled enough for protons to capture electrons to form neutral hydrogen, the dominant form of ordinary matter. Once this occurs, the universe, which formerly had involved a dense charged plasma, becomes transparent to electromagnetic radiation, and the light from that time can travel for billions of years unimpeded, making its way to microwave receivers here on earth. By observing the radiation coming from this time, we can measure extremely small temperature fluctuations across the sky, and these directly reflect the small primordial fluctuations in matter and radiation that would later collapse to form observed large-scale structures (Weinberg 1993; Krauss 2001). (This observation was recently awarded the Nobel Prize in Physics.) And lo and behold, the spectrum of fluctuations that is predicted to arise from the simplest models of inflationary behavior in the early universe agrees spot on with that which is observed.

The cosmic microwave background (CMB) provides another remarkable result that is not only consistent with the idea of inflation, but is also highly suggestive that the universe itself could have arisen from nothing via quantum mechanical fluctuations in empty space. By observing the angular size of hot spots and cold spots in the CMB, we can actually directly determine the geometry of the universe, i.e., whether it is open, closed, or flat. The idea is relatively simple in principle, though it has taken precision measurements of the CMB in recent years to implement. The largest regions that can have collapsed significantly due to local gravitational attraction at early times are those that are the size of the horizon—the distance across which light can have traveled over the time available since the Big Bang. This provides a “ruler” we can use to determine the geometry of the universe by observing how “big” such regions appear to our measuring apparatus here on earth. If light travels in straight lines (i.e., a flat universe), such regions should appear to be about one degree across today. If light were to bend outward as it goes back toward the source (open universe), such regions would appear to be smaller than a degree, and if light were to converge as it goes back to the source (closed universe), such regions would appear to be bigger than a degree across.

Careful measurements have now established definitively that the universe appears to be flat, to a precision of one percent. This is particularly exciting, not just because a flat universe represents a relatively generic prediction of inflation, but also because a flat universe has zero total gravitational energy. If our universe were to arise, literally, from nothing, by some quantum mechanical phenomenon, then we would expect the total energy to be zero at that time. If the local total gravitational energy is conserved as the universe expands, it would still remain zero today. Living in such a universe suggests indeed that this particularly attractive possibility can be a reality (Krauss and Turner 2004).

Moving forward in time, when the universe was between one second and five minutes old, as the temperature fell below about ten billion degrees, another modern signature of the Big Bang was established. By this time, protons and neutrons had cooled sufficiently so that the nuclear reactions between them began to proceed in a single direction, toward the buildup of heavier nuclei. First, protons and neutrons combined to form the nucleus of heavy hydrogen, deuterium. Then deuterium nuclei collide with protons and neutrons and rarely build up to form helium-3, a light isotope of helium, and then helium-4, the standard stable isotope. Because of the lack of any stable isotope with mass number five, collisions of helium with protons or neutrons are not effective at building up heavier elements, and so, while a small amount of lithium is produced, essentially no elements beyond atomic number three are produced in the early moments of the Big Bang. Nevertheless, measurements of nuclear reaction rates in the laboratory allow us to predict, given an initial abundance of protons and neutrons, how much hydrogen, deuterium, helium, and lithium should have been produced in the Big Bang. And once again, the predictions, which vary over ten orders of magnitude, from 25 percent elemental abundance of helium, to a few parts in 10^5 of deuterium, to a few parts in 10^{10} lithium, agree remarkably well, within uncertainties, with observations. This agreement allows us to essentially pin down the abundance of protons and neutrons in the universe, a fact that will prove to be important shortly.

Following the emergence of light elements in the first few minutes of the Big Bang, nothing much of significance happens as the universe continues to cool and expand. Ultimately, almost 400,000 years later, the universe has cooled to about 3,000 degrees Kelvin. At this temperature, for the first time, neutral atoms form as hydrogen nuclei (protons) capture electrons to form the dominant atom in the universe, hydrogen, leaving the signatures in the CMB described earlier.

While hydrogen, helium, and lithium appeared in the Big Bang, all of the elements that are necessary for our own existence and survival, carbon, nitrogen, oxygen, iron, etc., did not come into existence for literally billions of years, as the small fluctuations in the density of gas on large scales began to collapse under their own gravitational attraction to form galaxies and stars. Stars began to form as gas clouds collapsed to the point where their own density is great enough so the light emitted by the colliding gas particles cannot escape the system, and the gas heats up, producing a pressure that fights against gravity. Eventually, gravity wins out over pressure as the gas collapses to the point where the core of the nascent star reaches a temperature in excess of ten million degrees. At this temperature, nuclear reactions begin to take place, generating huge amounts of energy that can produce pressures that can balance gravity for a period of billions of years, a million times longer than would otherwise be possible.

In the cores of stars, nuclear reactions that mimicked those in the first moments of the Big Bang expansion take place, converting hydrogen to helium. But once the hydrogen fuel is exhausted, the star contracts further, heating up to millions of degrees, and helium nuclei fuse to form carbon and so on, through neon, oxygen, and silicon. Eventually, silicon nuclei fuse to form iron, and there the process stops because iron cannot fuse with other nuclei to release energy. At this point, in a single second, the core of a supermassive star can collapse until all the nuclei in all the atoms are touching, forming essentially one huge atomic nucleus, what we call a "neutron star." At this point, the inter-nuclear forces are so great that the collapse abruptly halts, producing a huge shock wave that propagates to the outer layers of the star, blowing them into space in a massive supernova explosion. In the process, all of the heavy elements produced during the star's lifetime are released into the cosmos.

In this way, every atom that would ultimately form Earth, and your body, was processed. Stars died so that you could be born. Atoms in your left hand may have emerged from a different star than your right hand, but either way, you are a star child, made of star dust. The starting point of biological evolution thus occurred long before the first amino acids arose in interstellar space.

Carl Sagan once gave as the first line in a recipe for making a apple pie: First, invent the universe. On a less grand scale, one can truly say that in order to get organic materials to form the building blocks of life here on Earth, the elements that form these materials have to exist beforehand. Carbon, nitrogen, and oxygen, among the key elements crucial for the existence of life on our planet, evolved, if you wish, in the dense cores of stars, governed by the laws of physics, just as diverse life on earth evolved by the laws of chemistry combined with natural selection. There is nothing I know about the universe that is more poetic. You are connected to the cosmos in a direct and real way.

As stars and galaxies formed, all the cosmic structures we now observe in the universe today were built over the course of billions of years forming a cosmic web whose features we are only now beginning to be able to discern with our large telescopes. Our own galaxy has evolved considerably—200 million stars have exploded since it was formed, many of which exploded before our own sun formed 4.57 billion years ago, and small satellite galaxies have been captured, much as our own galaxy and the neighboring Andromeda galaxy will collide and merge five billion years from now.

I should pause briefly and discuss the age of the universe and the age of the earth, as these two facts about nature are also the subject of frequent attacks against science in schools. We know the age of the universe using a myriad of different techniques. The simplest argument comes from the observed expansion of the universe. If we take the observed expansion rate and work backwards using known laws of physics, we find that everything we see was once located at a single point some 13.7 billion years ago. At the same time, we can build stars on computers in order to try and model stellar evolution, including the evolution of our own sun, and we find we get agreement with what we see in the galaxy, in terms of the observed distribution of stars of different brightnesses and colors if the galaxy is about 12 billion years old. This makes sense, since it would have taken about a billion years or so for the diffuse gas expanding as part of the Big Bang to collapse into galaxies. How do we know this? Quite simply observations of the CMB tell us that primordial anisotropies in matter and radiation were initially very, very small. In order for gravity to cause slightly overdense regions to collapse sufficiently to form galaxies and clusters of galaxies, we calculate the minimum time necessary to have been close to a billion years or so.

On Earth, all observations point to a history that extends billions, not millions or thousands, of years back. (See the companion piece in this issue by Robert M. Hazen, "How old is Earth, and how do we know?") This is completely consistent with observations of our sun, whose evolution can be carefully worked out using known laws of physics. Based on comparing predictions of the sun's surface temperature, radius, and density gradients with observations, we come up with the estimate I gave earlier, about 4.57 billion years old. This number is independently and accurately determined by radiometric dating of the ages of the most primitive meteorites measured in the solar system.

As Richard Dawkins has said, for anyone to claim Earth, the sun, or the universe is thousands of years old, not billions of years old, is like claiming the distance across the United States is several inches across, not thousands of miles. The claim flies so strongly in the face of everything we know to be true about the universe as to be ridiculous.

Even as we learn about the past history of our universe, our vision of its future has evolved considerably. We have learned that our own galaxy, and indeed all galaxies, are dominated by some, as of yet unknown, form of matter that doesn't emit light like stars or hot gas. We expect that this "dark matter" is made from a new type of elementary particle not found on earth because the calculations of the production of light elements in the early universe tell us that there are simply not enough protons and neutrons in the universe to account for all of this material, by almost a factor of ten. But far stranger is the fact that we have discovered that the expansion of the universe appears to be accelerating over time, as if the universe is dominated by a form of cosmic anti-gravity. This is only possible if the dominant form of energy in the universe resides not in matter, but in empty space! Moreover, measurements from the cosmic microwave background suggest that there must be at least three times as much energy in empty space as can be accounted for all the matter around galaxies, including dark matter. If we accept this inference, then we can calculate, using Einstein's equation of general relativity, how fast the universe should be accelerating, and this acceleration agrees precisely with what we observe to be the case (Krauss 1999).

Thus, we are left with a strange universe, two to four percent of which is made up of everything we can see and 96% or so of which is made up of mysterious dark matter and dark energy. We appear to be cosmically insignificant on a scale we never before envisaged. You could get rid of us, our planet, our solar system, the sun, all the stars in our galaxy, and all the visible galaxies in the universe, and the universe would be largely the same. We appear to be no more than a bit of cosmic pollution in a universe full of dark matter and dark energy.

The discovery of dark energy has forced scientists to consider another strange possibility. Because we have no fundamental understanding of why empty space should have the energy it appears to possess, some scientists have pointed out that if the amount of energy space possessed was vastly different, in particular, vastly more, then galaxies would not have formed, and then stars would not have formed, and ultimately astronomers would not have formed. So the universe may be the way it is simply because we are here to observe it.

While this statement may appear to have religious connotations, it doesn't. Rather, it suggests natural selection working on a truly cosmic scale. If there are many universes, we would expect to find ourselves existing only in those in which the laws of nature are compatible with our existence, just as it is not surprising to find that bees can detect the colors of certain flowers. There is no design at work here. Simply, if the bees couldn't detect the colors, they couldn't get the nectar they need to survive. Similarly, if the energy of empty space were vastly different, we wouldn't have evolved in the first place. Our existence in our universe could therefore merely be a selection effect, turning evolution into a cosmic phenomenon and not merely a biological and terrestrial one.

We don't know if this selection effect will ultimately explain the value of the energy of empty space or whether some fundamental physical reason will be discovered for why the universe has to have the properties it is observed to have. But either way, if the energy of empty space remains, the future will be vastly different than we had otherwise imagined before its discovery. The longer we wait, the less of the universe we will see, as distant galaxies eventually recede away from us faster than the speed of light. In the far future, the visible universe will be cold, dark, and essentially empty.

This miserable ultimate fate, combined with our own cosmic insignificance, may depress you, but it shouldn't.

Here we are on this small planet, orbiting an unassuming star at the edge of a rather average galaxy. Yet while we have never left our own solar system, with the consciousness that four billion years of evolution has managed to endow us, we have been able to trace the story of the Big Bang back to its earliest moments and can predict the future billions of years forward. Rather than be depressed, we need to enjoy our brief moment in the sun, to make the most of our brains and our consciousness, and to make our life meaningful on our own terms.

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