Origin of the Universe

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Cosmologists are closing in on the ultimate processes that created and shaped the universe

The universe is big in both space and time and, for much of humankind's history, was beyond the reach of our instruments and our minds. That changed dramatically in the 20th century. The advances were driven equally by powerful ideas—from Einstein's general relativity to modern theories of the elementary particles—and powerful instruments—from the 100- and 200-inch reflectors that George Ellery Hale built, which took us beyond our Milky Way galaxy, to the Hubble Space Telescope, which has taken us back to the birth of galaxies. Over the past 20 years the pace of progress has accelerated with the realization that dark matter is not made of ordinary atoms, the discovery of dark energy, and the dawning of bold ideas such as cosmic inflation and the multiverse. The universe of 100 years ago was simple: eternal, unchanging, consisting of a single galaxy, containing a few million visible stars. The picture today is more complete and much richer. The cosmos began 13.7 billion years ago with the big bang. A fraction of a second after the beginning, the universe was a hot, formless soup of the most elementary particles, quarks and leptons. As it expanded and cooled, layer on layer of structure developed: neutrons and protons, atomic nuclei, atoms, stars, galaxies, clusters of galaxies, and finally super clusters. The observable part of the universe is now inhabited by 100 billion galaxies, each containing 100 billion stars and probably a similar number of planets. Galaxies themselves are held together by the gravity of the mysterious dark matter. The universe continues to expand and indeed does so at an accelerating pace, driven by dark energy, an even more mysterious form of energy whose gravitational force repels rather than attracts. The overarching theme in our universe's story is the evolution from the simplicity of the quark soup to the complexity we see today in galaxies, stars, planets and life. These features emerged one by one over billions of years, guided by the basic laws of physics. In our journey back to the beginning of creation, cosmologists first travel through the well-established history of the universe back to the first microsecond; then to within 10–34 second of the beginning, for which ideas are well formed but the evidence is not yet firm; and finally to the earliest moments of creation, for which our ideas are still just speculation. Although the ultimate origin of the universe still lies beyond our grasp, we have tantalizing conjectures, including the notion of the multiverse, whereby the universe comprises an infinite number of disconnected subuniverses.

Expanding Universe

Using the 100-inch Hooker telescope on Mount Wilson in 1924, Edwin Hubble showed that fuzzy nebulae, studied and speculated about for several hundred years, were galaxies just like our own—thereby enlarging the known universe by 100 billion. A few years later he showed that galaxies are moving apart from one another in a regular pattern described by a mathematical relation now known as Hubble's law, according to which galaxies that are farther away are moving faster. It is Hubble's law, played back in time, that points to a big bang 13.7 billion years ago. Hubble's law found ready interpretation within general relativity: space itself is expanding, and galaxies are being carried along for the ride. Light, too, is being stretched, or redshifted—a process that saps its energy, so that the universe cools as it expands. Cosmic expansion provides the narrative for understanding how today's universe came to be. As cosmologists imagine rewinding the clock, the universe becomes denser, hotter, more extreme and simpler. In exploring the beginning, we also probe the inner workings of nature by taking advantage of an accelerator more powerful than any built on Earth—the big bang itself. By looking out into space with telescopes, astronomers peer back in time—and the larger the telescope, the farther back they peer. The light from distant galaxies reveals an earlier epoch, and the amount this light has redshifted indicates how much the universe has grown in the intervening years. The current record holder has a redshift of about eight, representing a time when the universe was one-ninth its present size and only a few hundred million years old. Telescopes such as the Hubble Space Telescope and the 10-meter Keck telescopes on Mauna Kea routinely take us back to the epoch when galaxies like ours were forming, a few billion years after the big bang. Light from even earlier times is so strongly redshifted that astronomers must look for it in the infrared and radio bands. Upcoming telescopes such as the James Webb Space Telescope, a 6.5-meter infrared telescope, and the Atacama Large Millimeter Array (ALMA), a network of 64 radio dishes in northern Chile, will take us back to the birth of the very first stars and galaxies. Computer simulations say those stars and galaxies emerged when the universe was about 100 million years old. Before then, the universe went through a time called the "dark ages," when it was almost pitch-black. Space was filled with a featureless gruel, five parts dark matter and one part hydrogen and helium, that thinned out as the universe expanded. Matter was slightly uneven in density, and gravity acted to amplify these density variations: denser regions expanded more slowly than less dense ones did. By 100 million years the densest regions did not merely expand more slowly but actually started to collapse. Such regions contained about one million solar masses of material each. They were the first gravitationally bound objects in the cosmos. Dark matter accounted for the bulk of their mass but was, as its name suggests, unable to emit or absorb light. So it remained in an extended cloud. Hydrogen and helium gas, on the other hand, emitted light, lost energy and became concentrated in the center of the cloud. Eventually it collapsed all the way down to stars. These first stars were much more massive than today's— hundreds of solar masses. They lived very short lives before exploding and leaving behind the first heavy elements. Over the next billion years or so the force of gravity assembled these million-solar-mass clouds into the first galaxies. Radiation from primordial hydrogen clouds, greatly redshifted by the expansion, should be detectable by giant arrays of radio antennas with a total collecting area of up to one square kilometer. When built, these arrays will watch as the first generation of stars and galaxies ionize the hydrogen and bring the dark ages to an end [see "The Dark Ages of the Universe," by Abraham Loeb; Scientific American, November 2006].

Faint Glow of a Hot Beginning

Beyond the dark ages is the glow of the hot big bang at redshift of 1,100. This radiation has been redshifted from visible light (a red-orange glow) beyond even the infrared to microwaves. What we see from that time is a wall of microwave radiation filling the sky—the cosmic microwave background radiation (CMB) discovered in 1964 by Arno Penzias and Robert Wilson. It provides a glimpse of the universe at the tender age of 380,000 years, the period when atoms formed. Before then, the universe was a nearly uniform soup of atomic nuclei, electrons and photons. As it cooled to a temperature of about 3,000 kelvins, the nuclei and electrons came together to form atoms. Photons ceased to scatter off electrons and streamed across space unhindered, revealing the universe at a simpler time before the existence of stars and galaxies. In 1992 NASA's Cosmic Background Explorer satellite discovered that the intensity of the CMB has slight variations—about 0.001 percent—reflecting a slight lumpiness in the distribution of matter. The degree of primordial lumpiness was enough to act as seeds for the galaxies and larger structures that would later emerge from the action of gravity. The pattern of these variations in the CMB across the sky also encodes basic properties of the universe, such as its overall density and composition, as well as hints about its earliest moments; the careful study of these variations has revealed much about the universe. As we roll a movie of the universe's evolution back from that point, we see the primordial plasma becoming ever hotter and denser. Prior to about 100,000 years, the energy density of radiation exceeded that of matter, which kept matter from clumping. Thus, this time marks the beginning of gravitational assembly of all the structure seen in the universe today. Still further back, when the universe was less than a second old, atomic nuclei had yet to form; only their constituent particles—namely, protons and neutrons— existed. Nuclei emerged when the universe was seconds old and the temperatures and densities were just right for nuclear reactions. This process of big bang nucleosynthesis produced only the lightest elements in the periodic table: a lot of helium (about 25 percent of the atoms in the universe by mass) and smaller amounts of lithium and the isotopes deuterium and helium 3. The rest of the plasma (about 75 percent) stayed i n the form of protons that would eventually become hydrogen atoms. All the rest of the elements in the periodic table formed billions of years later in stars and stellar explosions. Nucleosynthesis theory accurately predicts the abundances of elements and isotopes measured in the most primeval samples of the universe—namely, the oldest stars and high-redshift gas clouds. The abundance of deuterium, which is very sensitive to the density of atoms in the universe, plays a special role: its measured value implies that ordinary matter amounts to 4.5 ± 0.1 percent of the total energy density. (The remainder is dark matter and dark energy.) This estimate agrees precisely with the composition that has been gleaned from the analysis of the CMB. This correspondence is a great triumph. That these two very different measures, one based on nuclear physics when the universe was a second old and the other based on atomic physics when the universe was 380,000 years old, agree is a strong check not just on our model of how the cosmos evolved but on all of modern physics.

Answers in the Quark Soup

Earlier than a microsecond, even protons and neutrons could not exist and the universe was a soup of nature's basic building blocks: quarks, leptons, and the force carriers (photons, the W and Z bosons and gluons). We can be confident that the quark soup existed because experiments at particle accelerators have re-created similar conditions here on Earth today [see "The First Few Microseconds," by Michael Riordan and William A. Zajc; Scientific American, May 2006]. To explore this epoch, cosmologists rely not on bigger and better telescopes but on powerful ideas from particle physics. The development of the Standard Model of particle physics 30 years ago has led to bold speculations, including string theory, about how the seemingly disparate fundamental particles and forces are unified. As it turns out, these new ideas have implications for cosmology that are as important as the original idea of the hot big bang. They hint at deep and unexpected connections between the world of the very big and of the very small. Answers to three key questions—the nature of dark matter, the asymmetry between matter and antimatter, and the origin of the lumpy quark soup itself— are beginning to emerge. It now appears that the early quark soup phase was the birthplace of dark matter. The identity of dark matter remains unclear, but its existence is very well established. Our galaxy and every other galaxy as well as clusters of galaxies are held together by the gravity of unseen dark matter. Whatever the dark matter is, it must interact weakly with ordinary matter; otherwise it would have shown itself in other ways. Attempts to find a unifying framework for the forces and particles of nature have led to the prediction of stable or long-lived particles that might constitute dark matter. These particles would be present today as remnants of the quark soup phase and are predicted to interact very weakly with atoms. One candidate is the called the neutralino, the lightest of a putative new class of particles that are heavier counterparts of the known particles. The neutralino is thought to have a mass between 100 and 1,000 times that of the proton, just within the reach of experiments to be conducted by the Large Hadron Collider at CERN near Geneva. Physicists have also built ultrasensitive underground detectors, as well as satellite and balloon-borne varieties, to look for this particle or the by-products of its interactions. A second candidate is the axion, a superlightweight particle about a trillionth the mass of the electron. Its existence is hinted at by subtleties that the Standard Model predicts in the behavior of quarks. Efforts to detect it exploit the fact that in a very strong magnetic field, an axion can transform into a photon. Both neutralinos and axions have the important property that they are, in a specific technical sense, "cold." Although they formed under broiling hot conditions, they were slow-moving and thus easily clumped into galaxies. The early quark soup phase probably also holds the secret to why the universe today contains mostly matter rather than both matter and antimatter. Physicists think the universe originally had equal amounts of each, but at some point it developed a slight excess of matter—about one extra quark for every billion antiquarks. This imbalance ensured that enough quarks would survive annihilation with antiquarks as the universe expanded and cooled. More than 40 years ago accelerator experiments revealed that the laws of physics are ever so slightly biased in favor of matter, and in a still to be understood series of particle interactions very early on, this slight bias led to the creation of the quark excess. The quark soup itself is thought to have arisen at an extremely early time—perhaps 10–34 second after the big bang in a burst of cosmic expansion known as inflation. This burst, driven by the energy of a new field (roughly analogous to the electromagnetic field) called the inflaton, would explain such basic properties of the cosmos as its general uniformity and the lumpiness that seeded galaxies and other structures in the universe. As the inflaton field decayed away, it released its remaining energy into quarks and other particles, thus creating the heat of the big bang and the quark soup itself. Inflation leads to a profound connection between the quarks and the cosmos: quantum fluctuations in the inflaton field on the subatomic scale get blown up to astrophysical size by the rapid expansion and become the seeds for all the structure we see today. In other words, the pattern seen on the CMB sky is a giant image of the subatomic world. Observations of the CMB agree with this prediction, providing the strongest evidence that inflation or something like it occurred very early in the history of the universe.

Birth of the Universe

As cosmologists try to go even further to understand the beginning of the universe itself, our ideas become less firm. Einstein's general theory of relativity has provided the theoretical foundation for a century of progress in our understanding of the evolution of the universe. Yet it is inconsistent with the other pillar of contemporary physics, quantum theory , and the discipline's greatest challenge is to reconcile the two. Only with such a unified theory will we be able to address the very earliest moments of the universe, the so-called Planck era prior to about 10–43 second, when spacetime itself was taking shape. Tentative attempts at a unified theory have led to some remarkable speculations about our very beginnings. String theory, for example, predicts the existence of additional dimensions of space and possibly other universes floating in that larger space. What we call the big bang may have been the collision of our universe with another [see "The Myth of the Beginning of Time," by Gabriele Veneziano; Scientific American, May 2004]. The marriage of string theory with the concept of inflation has led perhaps to the boldest idea yet, that of a multiverse—namely, that the universe comprises an infinite number of disconnected pieces, each with its own local laws of physics [see "The String Theory Landscape," by Raphael Bousso and Joseph Polchinski; Scientific American, September 2004]. The multiverse concept, which is still in its infancy, turns on two key theoretical findings. First, the equations describing inflation strongly suggest that if inflation happened once, it should happen again and again, with an infinite number of inflationary regions created over time. Nothing can travel between these regions, so they have no effect on one another. Second, string theory suggests that these regions have different physical parameters, such as the number of spatial dimensions and the kinds of stable particles. The idea of the multiverse provides novel answers to two of the biggest questions in all of science: what happened before the big bang and why the laws of physics are as they are (Einstein's famous musing about "whether God had any choice" about the laws). The multiverse makes moot the question of before the big bang, because there were an infinite number of big bang beginnings, each triggered by its own burst of inflation. Likewise, Einstein's question is pushed aside: within the infinity of universes, all possibilities for the laws of physics have been tried, so there is no particular reason for the laws that govern our universe. Cosmologists have mixed feelings about the multiverse. If the disconnected subuniverses are truly incommunicado, we cannot hope to test their existence; they seem to lie beyond the realm of science. Part of me wants to scream, One universe at a time, please! On the other hand, the multiverse solves various conceptual problems. If correct, it will make Hubble's enlargement of the universe by a mere factor of 100 billion and Copernicus's banishment of Earth from the center of the universe in the 16th century seem like small advances in the understanding of our place in the cosmos. Modern cosmology has humbled us. We are made of protons, neutrons and electrons, which together account for only 4.5 percent of the universe, and we exist only because of subtle connections between the very small and the very large. Events guided by the microscopic laws of physics allowed matter to dominate over antimatter, generated the lumpiness that seeded galaxies, filled space with dark matter particles that provide the gravitational infrastructure, and ensured that dark matter could build galaxies before dark energy became significant and the expansion began to accelerate [see box above]. At the same time, cosmology by its very nature is arrogant. The idea that we can understand something as vast in both space and time as our universe is, on the face of it, preposterous. This strange mix of humility and arrogance has gotten us pretty far in the past century in advancing our understanding of the present universe and its origin. I am bullish on further progress in the coming years, and I firmly believe we are living in a golden age of cosmology.