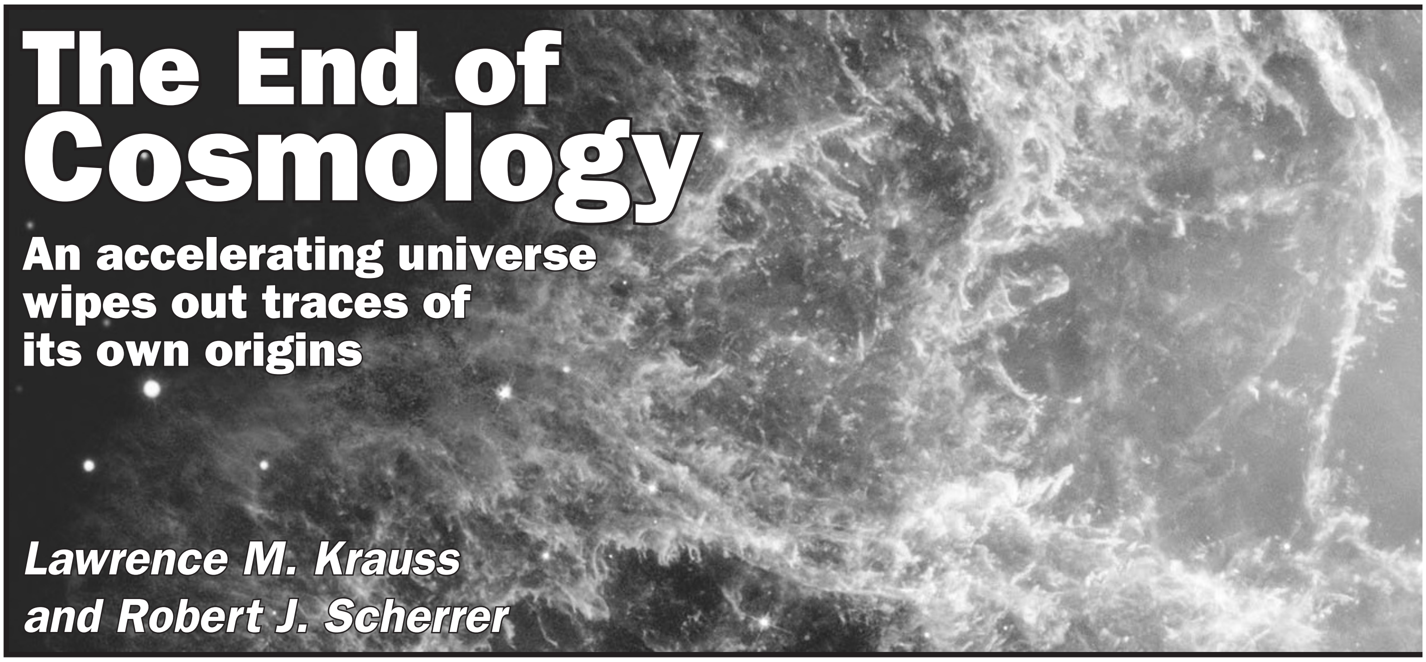


The End of Cosmology

An accelerating universe wipes out traces of its own origins

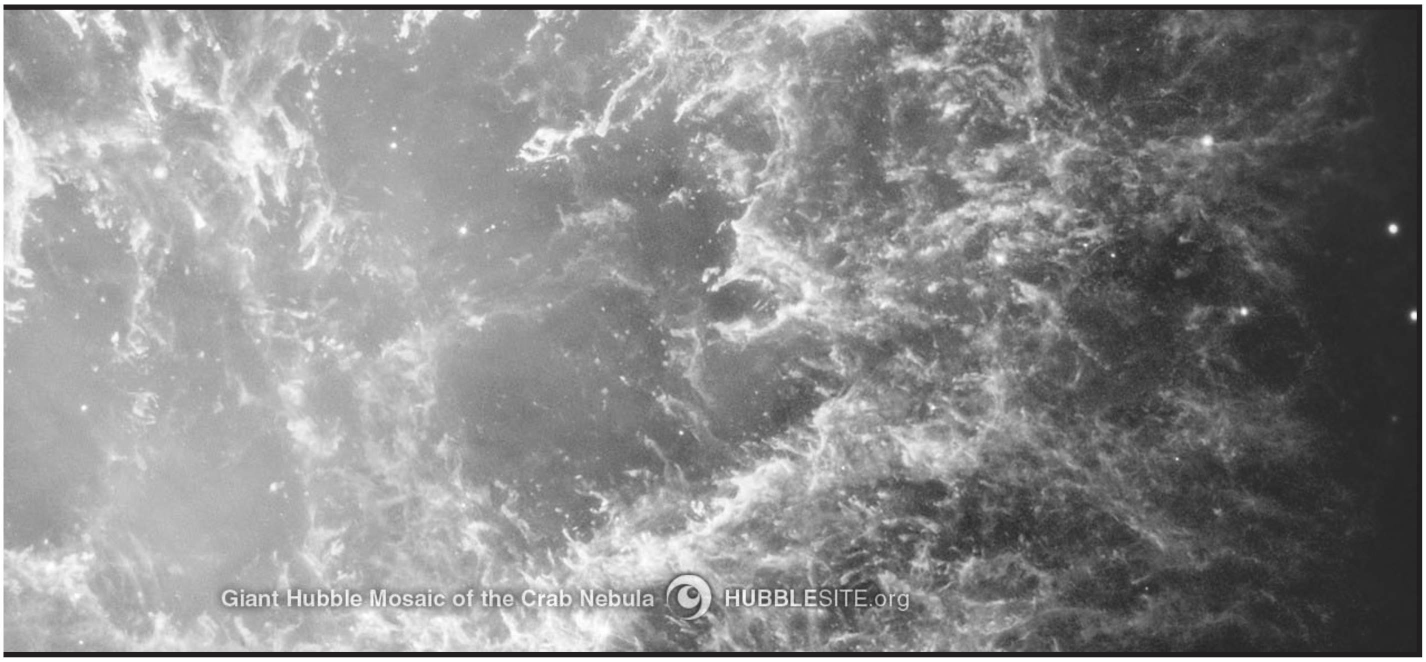
Lawrence M. Krauss and Robert J. Scherrer

One hundred years ago a *Scientific American* article about the history and large-scale structure of the universe would have been almost completely wrong. In 1908 scientists thought our galaxy constituted the entire universe. They considered it an "island universe," an isolated cluster of stars surrounded by an infinite void. We now know that our galaxy is one of more than 400 billion galaxies in the observable universe. In 1908 the scientific consensus was that the universe was static and eternal. The beginning of the universe in a fiery big bang was not even remotely suspected. The synthesis of elements in the first few moments of the big bang and inside the cores of stars was not understood. The expansion of space and its possible curvature in response to matter was not dreamed of. Recognition of the fact that all of space is bathed in radiation, providing a ghostly image of the cool afterglow of creation, would have to await the development of modern technologies designed not to explore eternity but to allow humans to phone home.

> ***The ultimate future of the observable universe is to collapse into a black hole.***

It is hard to think of an area of intellectual inquiry that has changed more in the past century than cosmology, and the shift has transformed how we view the world. But must science in the future always reflect more empirical knowledge than existed in the past? Our recent work suggests that on cosmic timescales, the answer is no. We may be living in the only epoch in the history of the universe when scientists can achieve an accurate understanding of the true nature of the universe.

A dramatic discovery almost a decade ago motivated our study. Two different groups of astronomers traced the expansion of the universe over the past five billion years and found that it appears to be speeding up. The source of this cosmic antigravity is thought to be some new form of "dark energy" associated with empty space. Some theorists, including one of us (Krauss), had actually anticipated this new result based on indirect measurements, but in physics it is direct observations that count. The acceleration of the universe implies that empty space contains almost three times as much energy as all the cosmic structures we observe today: galaxies, clusters and superclusters of galaxies. Ironically, Albert Einstein first postulated such a form of energy to keep the universe static. He called it the cosmological constant [see "Cosmological



Antigravity," by Lawrence M. Krauss; *Scientific American*, January 1999].

Dark energy will have an enormous impact on the future of the universe. With cosmologist Glenn Starkman of Case Western Reserve University, Krauss explored the implications for the fate of life in a universe with a cosmological constant. The prognosis: not good. Such a universe becomes a very inhospitable place. The cosmological constant produces a fixed "event horizon," an imaginary surface beyond which no matter or radiation can reach us. The universe comes to resemble an inside-out black hole, with matter and radiation trapped outside the horizon rather than inside it. This finding means that the observable universe contains only a finite amount of information, so information processing (and life) cannot endure forever [see "The Fate of Life in the Universe," by Lawrence M. Krauss and Glenn D. Starkman; *Scientific American*, November 1999].

Long before this information limit becomes a problem, all the expanding matter in the universe will be driven outside the event horizon. This process has been studied by Abraham Loeb and Kentaro Nagamine, both then at Harvard University, who found that our so-called Local Group of galaxies (the Milky Way, Andromeda and a host of orbiting dwarf galaxies) will collapse into a single enormous supercluster of stars. All the other galaxies will disappear into the oblivion beyond the event horizon. This process takes about 100 billion years, which may seem long but is fairly short compared to the wilderness of eternity.

Collapsing Pillars

What will astronomers of the far future, living in this supercluster, conclude about the history of the universe? To think about this question, recall the pillars on which our current understanding of the big bang is based.

The first is Einstein's general theory of relativity. For nearly 300 years Newton's theory of universal gravitation served as the basis for almost all of astronomy. Newton's theory does an excellent job of predicting the motions of objects on scales from the terrestrial to the galactic, but it is completely incapable of dealing with infinitely large collections of matter. General relativity overcomes this limitation. Shortly after Einstein published the theory in 1916, Dutch physicist Willem de Sitter solved the equations of general relativity for a simplified universe incorporating Einstein's cosmological constant. De Sitter's work appeared to reproduce the prevailing view of the universe at the time: an island galaxy embedded in a largely empty, static void.

Cosmologists soon realized that the stasis was a misinterpretation. In fact, the de Sitter universe is eternally expanding. As Belgian physicist Georges Lemaître later made clear, Einstein's equations predict that an infinite, homogeneous, static universe is impossible. The universe has to expand or contract. From this realization, the big bang theory, as it would later be called, was born.

The next pillar came in the 1920s, when astronomers detected the expansion of the universe. The first person to provide observational evidence for expansion was American astronomer Vesto Slipher, who used the spectra of stars to measure the velocities of nearby galaxies. Waves of light from a star moving toward Earth are compressed, shortening the wavelength and making the light bluer. Light waves from an object moving away from us are stretched, making the wavelength longer and the light redder. By measuring the lengthening or compression of the light waves from distant galaxies, Slipher was able to determine whether they were moving toward us or away from us and at what speed. (At the time, astronomers were not even sure whether the fuzzy patches of light that we call "galaxies" were actually independent bodies of stars or simply gas clouds inside our own galaxy.) Slipher found that almost all these galaxies were moving away from us. We seemed to be sitting at the center of a runaway expansion.

The person who is generally credited for discovering the expansion of the universe is not Slipher but American astronomer Edwin Hubble. (When was the last time you read about the Slipher Space Telescope?) Hubble determined not just the velocities of nearby galaxies but also their distances. His measurements led to two conclusions that justify his fame. First, Hubble showed that galaxies were so far away that they really were independent collections of stars, just like our own galaxy. Second, he discovered a simple relation between the distance to galaxies and their velocities. The velocity was directly proportional to its distance from us: a galaxy twice as far away as another was moving twice as fast. This relation between distance and velocity is exactly what happens when the universe is expanding. Hubble's measurements have since been refined, most recently by the observations of distant supernovae, which led to the discovery of dark energy.

The third pillar is the faint glow of the cosmic microwave background, discovered serendipitously in 1965 by Bell Labs physicists Arno Penzias and Robert Wilson as they tracked down sources of radio interference. This radiation was quickly recognized to be a relic left over from the early stages of the expansion of the universe. It indicates that the universe began hot and dense and has since cooled and thinned out.

The final observational pillar of the big bang is that the hot, dense early universe was a perfect location for nuclear fusion. When the temperature of the universe was one billion to 10 billion kelvins, lighter nuclei could fuse into heavier nuclei, a process known as big bang nucleosynthesis. This process can occur for only a few minutes as the universe expands and cools, so fusion was limited to the lightest elements. Most of the helium in the universe was produced then, as was deuterium, or heavy hydrogen. The measured abundances of helium and deuterium match the predictions of big bang nucleosynthesis, providing further evidence for the theory as well as an accurate estimate of the abundance of protons and neutrons in the universe.

Dark Skies

What will the scientists of the future see as they peer into the skies 100 billion years from now? Without telescopes, they will see pretty much what we see today: the stars of our galaxy. The largest and brightest stars will have burned up their nuclear fuel, but plenty of smaller stars will still light up the night sky. The big difference will occur when these future scientists build telescopes capable of detecting galaxies outside our own. They won't see any! The nearby galaxies will have merged with the Milky Way to form one large galaxy, and essentially all the other galaxies will be long gone, having escaped beyond the event horizon.

The disappearance of distant galaxies is not immediate but gradual. The redshift of these galaxies becomes infinitely large as they approach the horizon. Krauss and Starkman calculated that this redshift will exceed 5,000 for all galaxies by 100 billion years, rising to an unfathomable 10^{53} by 10 trillion years – at which time even the highest-energy cosmic rays will have redshifted so much that their wavelength will be larger than the horizon size. These objects will then be truly and completely invisible to us.

As a result, Hubble's crucial discovery of the expanding universe will become irreproducible. All the expanding matter in the universe will have visually disappeared beyond the horizon, and everything remaining will be part of a gravitationally bound cluster of stars. For these future astronomers, the observable universe will closely resemble the "island universe" of 1908: a single enormous collection of stars, static and eternal, surrounded by empty space.

> ***In all chaos there is a cosmos, in all disorder a secret order.***
>
> Carl Jung

Our own experience demonstrates that even when we have data, the correct cosmological model is not so obvious. For example, from the 1940s to the mid-1960s, with the edifice of observational cosmology resting only on Hubble's discovery of the expanding universe, some astrophysicists resurrected the idea of an eternal universe: the steady-state universe, in which matter is created as the universe expands, so that the universe as a whole does not really change with time. This idea proved to be an intellectual dead end, but it does demonstrate the kind of mistaken notion that can develop in the absence of adequate observational data.

Where else might astronomers of the future search for evidence of the big bang? Would the cosmic microwave background allow them to probe the dynamics of the universe? Alas, no. As the universe expands, the wavelengths of the background radiation stretch and the radiation becomes more diffuse. When the universe is 100 billion years old, the peak wavelengths of the microwave radiation will be on the scale of meters, corresponding to radio waves instead of microwaves. The intensity of the radiation will be diluted by a factor of one trillion and might never be seen.

Even further into the future, the cosmic background will become truly unobservable. The space between stars in our galaxy is filled with an ionized gas of electrons. Low-frequency radio waves cannot penetrate such a gas; they are absorbed or reflected. A similar effect is the reason that AM radio stations can be picked up far from their cities of origin at night; the radio waves reflect off the ionosphere and back down to the ground. The interstellar medium can be thought of as one big ionosphere filling the galaxy. Any radio waves with frequencies below about one kilohertz (a wavelength of greater than 300 kilometers) cannot penetrate into our galaxy. Radio astronomy below one kilohertz is forever impossible inside our galaxy. When the universe is about 25 times its present age, the microwave background will be stretched beyond this wavelength and become undetectable to the residents of the galaxy. Even before then, the subtle patterns in this background radiation, which have provided so much useful information to today's cosmologists, will become too muted to study.

Burning Up

Would observations of the abundances of chemical elements lead cosmologists of the distant future to a knowledge of the big bang? Once again, the answer is likely to be no. The problem is that our ability to probe big bang nucleosynthesis hinges on the fact that the abundances of deuterium and helium have not evolved very much since they were produced 14 billion years ago. Helium produced in the early universe, for example, makes up about 24 percent of the total matter. Although stars produce helium in the course of their fusion reactions, they have increased this abundance by no more than a few percent. Astronomers Fred Adams and Gregory Laughlin of the University of Michigan at Ann Arbor have suggested that this fraction could increase to as much as 60 percent after many generations of stars. An observer in the distant future would find the primordial helium swamped by the helium produced in later generations of stars.

Currently the cleanest probe of big bang nucleosynthesis is the abundance of deuterium. Our best measurements of the primordial deuterium abundance come from observations of hydrogen clouds backlit by quasars, extremely distant and bright beacons thought to be powered by black holes. In the far future of the universe, however, both these hydrogen clouds and quasars will have passed beyond the event horizon and will be forever lost to view. Only galactic deuterium might be observable. But stars destroy deuterium, and little will survive. Even if astronomers of the future observe deuterium, they might not ascribe it to the big bang. Nuclear reactions involving high-energy cosmic rays, which have been studied today as a possible source of at least some of the observed deuterium, might seem more plausible.

Although the observational abundance of light elements will not provide any direct evidence for a fiery big bang, it will nonetheless make one aspect of future cosmology different from the illusory cosmology of a century ago. Astronomers and physicists who develop an understanding of nuclear physics will correctly conclude that stars burn nuclear fuel. If they then conclude (incorrectly) that all the helium they observe was produced in earlier generations of stars, they will be able to place an upper limit on the age of the universe. These scientists will thus correctly infer that their galactic universe is not eternal but has a finite age. Yet the origin of the matter they observe will remain shrouded in mystery.

What about the idea with which we began this article, namely that Einstein's theory of relativity predicts an expanding universe and therefore a big bang? The denizens of the far future of the universe should be able to discover the theory of general relativity from precision measurements of gravity in their own solar system. Using this theory to infer a big bang, however, rests on observations about the large-scale structure of the universe. Einstein's theory predicts an expanding universe only if the universe is homogeneous. The universe that our descendants survey will be anything but homogeneous. It will consist of an island of stars embedded in a vast emptiness. It will, in fact, resemble de Sitter's island universe. The ultimate future of the observable universe is to collapse into a black hole, precisely what will in fact occur to our galaxy in the distant future.

A theologian is like a blind man in a dark room searching for a black cat which isn't there - and finding it!

H.L. Mencken

Alone in the Void

Is there no way at all for our descendants to perceive an expanding universe? One telltale effect of acceleration would indeed remain within our observational horizon, at least according to our current understanding of general relativity. Just as the event horizon of a black hole emits radiation, so, too, does our cosmological event horizon. Yet the temperature associated with this radiation is unmeasurably small, about 10-30 kelvin. Even if astronomers were able to detect it, they would probably attribute it to some other, far larger local source of noise.

Ambitious future observers might also send out probes that escape the supergalaxy and could serve as reference points for detecting a possible cosmic expansion. Whether it would occur to them to do so seems unlikely, but in any event it would take billions of years at the very least for the probe to reach the point where the expansion noticeably affected its velocity, and the probe would need the energy output comparable to that of a star to communicate back to its builders from such a great distance. That the science-funding agencies of the future would support such a shot-in-the-dark is unlikely, at least if our own experience is any guide.

"I hope you love birds too. It is economical. It saves going to heaven."

Emily Dickinson

Thus, observers of the future are likely to predict that the universe ultimately ends with a localized big crunch, rather than the eternal expansion that the cosmological constant produces. Instead of a whimper, their limited universe will end with a bang.

We are led inexorably to a very strange conclusion. The window during which intelligent observers can deduce the true nature of our expanding universe might be very short indeed. Some civilizations might hold on to deep historical archives, and this very article might appear in one – if it can survive billions of years of wars, supernovae, black holes and countless other perils. Whether they will believe it is another question. Civilizations that lack such archives might be doomed to remain forever ignorant of the big bang.

Why is the present universe so special? Many researchers have tried to argue that the existence of life provides a selection effect that might explain the coincidences associated with the present time [see "The Anthropic Principle" by George Gale; *Scientific American*, December 1981]. We take different lessons from our work.

First, this would quite likely not be the first time that information about the universe would be lost because of an accelerating expansion. If a period of inflation occurred in the very early universe, then the rapid expansion during this era drove away almost all details of the preexisting matter and energy out of what is now our observable universe. Indeed, one of the original motivations for inflationary models was to rid the universe of pesky cosmological objects such as magnetic monopoles that may once have existed in profusion.

More important, although we are certainly fortunate to live at a time when the observational pillars of the big bang are all detectable, we can easily envisage that other fundamental aspects of the universe are unobservable today. What have we already lost? Rather than being self-satisfied, we should feel humble. Perhaps someday we will find that our current careful and apparently complete understanding of the universe is seriously wanting.

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