The End

Astrophysicists say that now they can finally tell us how the universe will expire--and it's not with a bang!

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For those who live in a city or near one, the night sky isn't much to look at--just a few scattered stars in a smoggy, washed-out expanse. In rural Maine, though, or North Dakota, or the desert Southwest, the view is quite different. Even without a telescope, you can see thousands of stars twinkling in shades of blue, red and yellow-white, with the broad Milky Way cutting a ghostly swath from one horizon to the other. No wonder our ancient ancestors peered up into the heavens with awe and reverence; it's easy to imagine gods and mythical heroes inhabiting such a luminous realm.

Yet for all the magnificence of the visible stars, astronomers know they are only the first shimmering veil in a cosmos vast beyond imagination. Armed with ever more powerful telescopes, these explorers of time and space have learned that the Milky Way is a huge, whirling pinwheel made of 100 billion or more stars; that tens of billions of other galaxies lie beyond its edges; and, most astonishing of all, that these galaxies are rushing headlong away from one another in the aftermath of an explosive cataclysm known as the Big Bang.

That event--the literal birth of time and space some 15 billion years ago--has been understood, at least in its broadest outlines, since the 1960s. But in more than a third of a century, the best minds in astronomy have failed to solve the mystery of what happens at the other end of time. Will the galaxies continue to fly apart forever, their glow fading until the cosmos is cold and dark? Or will the expansion slow to a halt, reverse direction and send the stars crashing back together in a final, apocalyptic Big Crunch? Despite decades of observations with the most powerful telescopes at their disposal, astronomers simply haven't been able to decide.

But thanks to a series of remarkable discoveries--the most recent just two weeks ago--the question may now have been settled once and for all. Scientists who were betting on a Big Crunch liked to quote Robert Frost: "Some say the world will end in fire,/ some say in ice./ From what I've tasted of desire/ I hold with those who favor fire." Those in the other camp preferred T.S. Eliot: "This is the way the world ends/ Not with a bang but a whimper." The verdict seems to be in: T.S. Eliot wins.

Why do we care? For one thing, this is a question that has haunted humans for as long as we have walked the earth. A definitive answer--if that is indeed what we have--will force philosophers and religious leaders to rethink their assumptions and beliefs about eternity and how the world will end. For scientists, meanwhile, there are certain details in these discoveries that have profound--and bizarre--implications. For example, the new observations bolster the theory of inflation: the notion that the universe when it was still smaller than an atom went through a period of turbocharged expansion, flying apart (in apparent, but not actual, contradiction of Albert Einstein's theories of relativity) faster than the speed of light.

An equally unsettling implication is that the universe is pervaded with a strange sort of "antigravity," a concept originally proposed by and later abandoned by Einstein as the greatest blunder of his life. This force, which has lately been dubbed "dark energy," isn't just keeping the expansion from slowing down, it's making the universe fly apart faster and faster all the time, like a rocket ship with the throttle wide open.

It gets stranger still. Not only does dark energy swamp ordinary gravity but an invisible substance known to scientists as "dark matter" also seems to outweigh the ordinary stuff of stars, planets and people by a factor of 10 to 1. "Not only are we not at the center of the universe," University of California, Santa Cruz, astrophysical theorist Joel Primack has commented, "we aren't even made of the same stuff the universe is."

These discoveries raise more questions than they answer. For example, just because scientists know dark matter is there doesn't mean they understand what it really is. Same goes for dark energy. "If you thought the universe was hard to comprehend before," says University of Chicago astrophysicist Michael Turner, "then you'd better take some smart pills, because it's only going to get worse."

ECHO OF THE BIG BANG

Things seemed a lot simpler back in 1965 when two astronomers at Bell Labs in Holmdel, N.J., provided a resounding confirmation of the Big Bang theory, at the time merely one of several ideas floating around on how the cosmos began. The discovery happened purely by accident: Arno Penzias and Robert Wilson were trying to get an annoying hiss out of a communications antenna, and after ruling out every other explanation--including the residue of bird droppings--they decided the hiss was coming from outer space.

Unbeknownst to the duo, physicists at nearby Princeton University were about to turn their antenna on the heavens to look for that same signal. Astronomers had known since the 1920s that the galaxies were flying apart. But theorists had belatedly realized a key implication: the whole cosmos must at one point have been much smaller and hotter. About 300,000 years after the instant of the Big Bang, the entire visible universe would have been a cloud of hot, incredibly dense gas, not much bigger than the Milky Way is now, glowing white hot like a blast furnace or the surface of a star. Because this cosmic glow had no place to go, it must still be there, albeit so attenuated that it took the form of feeble microwaves. Penzias and Wilson later won the Nobel Prize for the accidental discovery of this radio hiss from the dawn of time.

The discovery of the cosmic-microwave background radiation convinced scientists that the universe really had sprung from an initial Big Bang some 15 billion years ago. They immediately set out to learn more. For one thing, they began trying to probe this cosmic afterglow for subtle variations in intensity. It's clear through ordinary telescopes that matter isn't spread evenly throughout the modern universe. Galaxies tend to huddle relatively close to one another, dozens or even hundreds of them in clumps known as clusters and superclusters. In between, there is

essentially nothing at all.
That lumpiness, reasoned theorists, must have evolved from some original lumpiness in the primordial cloud of matter that gave rise to the background radiation. Slightly denser knots of matter within the cloud--forerunners of today's superclusters--should have been slightly hotter than average. So some scientists began looking for subtle hot spots.

FIRE OR ICE?

Others, meanwhile, attacked a different aspect of the problem. As the universe expands, the combined gravity from all the matter within it tends to slow that expansion, much as the earth's gravity tries to pull a rising rocket back to the ground. If the pull is strong enough, the expansion will stop and reverse itself; if not, the cosmos will go on getting bigger, literally forever. Which is it? One way to find out is to weigh the cosmos--to add up all the stars and all the galaxies, calculate their gravity and compare that with the expansion rate of the universe. If the cosmos is moving at escape velocity, no Big Crunch.

Trouble is, nobody could figure out how much matter there actually was. The stars and galaxies were easy; you could see them. But it was noted as early as the 1930s that something lurked out there besides the glowing stars and gases that astronomers could see. Galaxies in clusters were orbiting one another too fast; they should, by rights, be flying off into space like untethered children flung from a fast-twirling merry-go-round. Individual galaxies were spinning about their centers too quickly too; they should long since have flown apart. The only possibility: some form of invisible dark matter was holding things together, and while you could infer the mass of dark matter in and around galaxies, nobody knew if it also filled the dark voids of space, where its effects would not be detectable.

So astrophysicists tried another approach: determine whether the expansion was slowing down, and by how much. That's what Brian Schmidt, a young astronomer at the Mount Stromlo Observatory in Australia, set out to do in 1995. Along with a team of colleagues, he wanted to measure the cosmic slowdown, known formally as the "deceleration parameter." The idea was straightforward: look at the nearby universe and measure how fast it is expanding. Then do the same for the distant universe, whose light is just now reaching us, having been emitted when the cosmos was young. Then compare the two.

Schmidt's group and a rival team led by Saul Perlmutter, of Lawrence Berkeley Laboratory in California, used very similar techniques to make the measurements. They looked for a kind of explosion called a Type Ia supernova, occurring when an aging star destroys itself in a gigantic thermonuclear blast. Type Ia's are so bright that they can be seen all the way across the universe and are uniform enough to have their distance from Earth accurately calculated.

That's key: since the whole universe is expanding at a given rate at any one time, more distant galaxies are flying away from us faster than nearby ones. So Schmidt's and Perlmutter's teams simply measured the distance to these supernovas (deduced from their brightness) and their speed of recession (deduced by the reddening of their light, a phenomenon affecting all moving bodies, known to physicists as the Doppler shift). Combining these two pieces of information gave them the expansion rate, both now and in the past.

DARK ENERGY

By 1998 both teams knew something very weird was happening. The cosmic expansion should have been slowing down a lot or a little, depending on whether it contained a lot of matter or a little--an effect that should have shown up as distant supernovas, looking brighter than you would expect compared with closer ones. But, in fact, they were dimmer--as if the expansion was speeding up. "I kept running the numbers through the computer," recalls Adam Riess, a Space Telescope Science Institute astronomer analyzing the data from Schmidt's group, "and the answers made no sense. I was sure there was a bug in the program." Perlmutter's group, meanwhile, spent the better part of the year trying to figure out what could be producing its own crazy results.

In the end, both teams adopted Sherlock Holmes' attitude: once you have eliminated the impossible, whatever is left, no matter how improbable, has got to be true. The universe was indeed speeding up, suggesting that some sort of powerful antigravity force was at work, forcing the galaxies to fly apart even as ordinary gravity was trying to draw them together. "It helped a lot," says Riess, "that Saul's group was getting the same answer we were. When you have a strange result, you like to have company." Both groups announced their findings almost simultaneously, and the accelerating universe was named Discovery of the Year for 1998 by Science magazine.

For all its seeming strangeness, antigravity did have a history, one dating back to Einstein's 1916 theory of general relativity. The theory's equations suggest that the universe must be either expanding or contracting; it couldn't simply sit there. Yet the astronomers of the day, armed with relatively feeble telescopes, insisted that it was doing just that. Grumbling about having to mar the elegance of his beloved mathematics, Einstein added an extra term to the equations of relativity. Called the cosmological constant, it amounted to a force that opposed gravity and propped up the universe.

A decade later, though, Edwin Hubble discovered that the universe was expanding after all. Einstein immediately and with great relief discarded the cosmological constant, declaring it to be the biggest blunder of his life. (If he had stuck to his guns, he might have nabbed another Nobel.)

Even so, the idea of a cosmological constant wasn't entirely dead. The equations of quantum physics independently suggested that the seemingly empty vacuum of space should be seething with a form of energy that would act just like Einstein's disowned antigravity. Problem was, this force would have been so powerful that it would have blown the universe apart before atoms could form, let alone galaxies--which it clearly did not. "The value particle physicists predict for the cosmological constant," admits Chicago's Turner, "is the most embarrassing number in physics."

Aside from that detail, the Einstein connection made the idea of dark energy, or antigravity, seem somewhat less nutty when Schmidt and Perlmutter weighed in. Of course, some astrophysicists had lingering doubts. Maybe the observers didn't really have the supernovas' brightness right; perhaps the light from faraway stellar explosions was dimmed by some sort of dust. The unique properties of a cosmological constant, moreover, would make the universe slow down early on, then accelerate. That's because dark energy grows as a function of space. There wasn't much space in the young, small universe, so back then the braking force of gravity would have reigned supreme. More recently, the force of gravity fell off as the distance between galaxies grew and that same increase made for more dark energy. Nobody had probed deeply enough to find out what was really going on in the distant past.

Or rather, nobody had got enough data. Back in 1997, astronomers Mark Phillips of the Space Telescope Science Institute and Ron Gilliland of the Carnegie Institute of Washington had used the Hubble Space Telescope to spot a distant supernova designated SN 1997ff and, with the help of Peter Nugent, a Lawrence Berkeley astronomer on Perlmutter's team, had determined its speed of recession from Earth. Nugent couldn't figure out the distance, though: determining the brightness of a Type Ia calls for not just one but several measurements, spread over time.

On the rival team, Riess knew of the discovery, but he learned soon afterward that other Hubble photos had also caught the supernova, completely by chance. So one day last summer, he recalls, "I called Peter and began fishing around for information. I guess I wasn't especially cagey. He said almost right away, 'Are you asking about 1997ff?'"

Rather than try to scoop each other, the friendly rivals decided to cooperate--and soon realized they had stumbled onto something truly astonishing. The new supernova, some 50% closer to the beginning of the universe than any supernova known before, was far brighter than had been predicted. That neatly eliminated the idea of dust, since a more distant star should have been even more dust-dimmed than nearer ones. But the level of brightness also signaled that this supernova was shining when the expansion of the cosmos was still slowing down. "Usually," says Riess, "we see weird things and try to make our models of the universe fit. This time we put up a hoop for the observations to jump through in advance, and they did--which makes it a lot more convincing."

PROBING THE COSMIC FIREBALL

What makes it still more convincing is that an entirely different kind of observation--the long-standing search for lumpiness in the cosmic background radiation--now suggests independently that dark energy is real. The lumps themselves were first detected about a decade ago, thanks to the Cosmic Background Explorer satellite. At the time, astrophysicist and COBE spokesman George Smoot declared that "if you're religious, it's like seeing God."

But it was more like seeing God through dirty Coke-bottle glasses: the satellite saw lumps but couldn't determine much about them. In April, though, scientists offered up much sharper images from a balloon-borne experiment called BOOMERANG (Balloon Observations of Millimetric Extragalactic Radiation and Geophysics), which lofted instruments into the Antarctic stratosphere; from another named MAXIMA (Millimeter Anisotropy Experiment Imaging Array, which did the same over the U.S.); and from a microwave telescope on the ground at the South Pole, called DASI (Degree Angular Scale Interferometer).

All these measurements pretty much agreed with one another, confirming that the lumps scientists saw were real, not some malfunction in the telescopes. And two weeks ago, astronomers from the Sloan Digital Sky Survey confirmed that this primordial lumpiness has carried over into modern times. The five-year mission of the survey, to make a 3-D map of the cosmos, is far from complete, but scientists reported at the American Astronomical Society's spring meeting in Pasadena, Calif., that it is clearer than ever that galaxies cluster together into huge clumps that reflect conditions that existed soon after the Big Bang.

To the unaided eye, the images are meaningless. A statistical analysis, however, shows that the early lumps--actually patches of slightly warmer or cooler radiation--don't come at random but rather at certain fixed sizes. "It's as though you're studying dogs," says University of Pennsylvania astrophysicist Max Tegmark, "and you find out that they come in just three types: Labrador, toy poodle and Chihuahua."

That turns out to be enormously important. Knowing the characteristic sizes and also the temperatures, to a millionth of a degree, of these warm and cool regions gives theoretical physicists all sorts of information about the newborn cosmos. They were already pretty sure, from the equations of nuclear physics and from measurements of the relative amounts of hydrogen, helium and lithium in the universe, that protons, neutrons and electrons (the building blocks of every atom in the cosmos) add up to only about 5% of the so-called critical density--what it would take to bring the cosmic expansion essentially to a halt by means of gravity.

But when you add Tegmark's "dogs," plus the more esoteric equations of sub-nuclear physics, it turns out that an additional 30% of the needed matter most likely comes in the form of mysterious particles that have been identified only in theory, never directly observed--particles with quirky names like neutralino and axion. These are the mysterious dark matter, or most of it anyway. The cosmic background radiation itself began to shine when the universe was 300,000 years old, but the temperature fluctuations were set in place when it was just a split-second old. "It's pretty cool," says Tegmark, "to be able to look back that far."

THE FLAT UNIVERSE

The dogs also yield another key bit of information: they tell theorists how the universe is curved, in the Einsteinian sense. There's no way to convey this concept to a nonphysicist except by two-dimensional analogy (see How Does the Universe Curve? diagram). The surface of a sphere has what's called positive curvature; if you go far enough in one direction, you will never get to the edge but you will eventually return to your starting point. An infinitely large sheet of paper is flat and, because it is infinite, also edgeless. And a saddle that extends forever is considered edgeless and negatively curved. It also turns out that any triangle you draw on the paper has angles that add up to 180[degrees], but the sphere's angles are always greater than 180[degrees], and the saddle's always less.

Same goes for the universe, but with one more dimension. According to Einstein, the whole thing could be positively or negatively curved or flat (but don't try to imagine in what direction it might be curved; it's quite impossible to visualize). "What the new measurements tell us," says Turner, "is that the universe is in fact flat. Draw a triangle that reaches all the way across

the cosmos, and the angles will always add up to 180[degrees]."
According to Einstein, the universe's curvature is determined by the amount of matter and energy it contains. The universe we evidently live in could have been flattened purely by matter--but the new discoveries prove that ordinary matter and exotic particles add up to only about 35% of what you would need. Ergo, the extra curvature must come from some unseen energy--just about the amount, it turns out, suggested by the supernova observations. "I was highly dubious about dark energy based only on supernovas," says Princeton astrophysicist Edwin Turner (no relation to Michael, though the two often refer to each other as "my evil twin"). "This makes me take dark energy more seriously."

The flatness of the universe also means the theory of inflation has passed a key test. Originally conceived around 1980 (in the course of elementary-particle, not astronomical, research), the theory says the entire visible universe grew from a speck far smaller than a proton to a nugget the size of a grapefruit, almost instantaneously, when the whole thing was 0.000000000000000000000000000000000001 sec. old. This turbo-expansion was driven by something like dark energy but a whole lot stronger. What we call the universe, in short, came from almost nowhere in next to no time. Says M.I.T.'s Alan Guth, a pioneer of inflation theory: "I call the universe the ultimate free lunch." One of the consequences of inflation, predicted 20 years ago, was that the universe must be flat--as it now turns out to be.

If these observations continue to hold up, astrophysicists can be pretty sure they have assembled the full parts list for the cosmos at last: 5% ordinary matter, 35% exotic dark matter and about 60% dark energy. They also have a pretty good idea of the universe's future. All the matter put together doesn't have enough gravity to stop the expansion; beyond that, the antigravity effect of dark energy is actually speeding up the expansion. And because the amount of dark energy will grow as space gets bigger, its effect will only increase.

THE FATE OF THE COSMOS

That means that the 100 billion or so galaxies we can now see through our telescopes will zip out of range, one by one. Tens of billions of years from now, the Milky Way will be the only galaxy we're directly aware of (other nearby galaxies, including the Large Magellanic Cloud and the Andromeda galaxy, will have drifted into, and merged with, the Milky Way).

By then the sun will have shrunk to a white dwarf, giving little light and even less heat to whatever is left of Earth, and entered a long, lingering death that could last 100 trillion years--or a thousand times longer than the cosmos has existed to date. The same will happen to most other stars, although a few will end their lives as blazing supernovas. Finally, though, all that will be left in the cosmos will be black holes, the burnt-out cinders of stars and the dead husks of planets. The universe will be cold and black.

But that's not the end, according to University of Michigan astrophysicist Fred Adams. An expert on the fate of the cosmos and co-author with Greg Laughlin of The Five Ages of the Universe (Touchstone Books; 2000), Adams predicts that all this dead matter will eventually collapse into black holes. By the time the universe is 1 trillion trillion trillion trillion trillion trillion years old, the black holes themselves will disintegrate into stray particles, which will bind loosely to form individual "atoms" larger than the size of today's universe. Eventually, even these will decay, leaving a featureless, infinitely large void. And that will be that--unless, of course, whatever inconceivable event that launched the original Big Bang should recur, and the ultimate free lunch is served once more.

Astronomers and physicists are a cautious crew, and they insist that the mind-bending discoveries about dark matter, dark energy and the flatness of space-time must be confirmed before they are accepted without reservation. "We're really living dangerously," says Chicago's Turner. "We've got this absurd, wonderful picture of the universe, and now we've got to test it." There could be surprises to come: an Einstein-style cosmological constant, for example, is the leading candidate for dark energy, but it could in principle be something subtly different--a force that could even change directions someday, to reinforce rather than oppose gravity.

In any case, new tests of these bizarre ideas will not be too long in coming. Next week a satellite will launch from Cape Canaveral to make the most sensitive observations ever of the cosmic background radiation. Supernova watchers, meanwhile, are lobbying NASA for a dedicated telescope so they won't have to queue up for time on the badly oversubscribed Hubble. And lower-tech telescopes and microwave detectors, both on the ground and lofted into the air aboard balloons, will continue to refine their measurements.

If the latest results do hold up, some of the most important questions in cosmology--how old the universe is, what it's made of and how it will end--will have been answered, only about 70 years after they were first posed. By the time the final chapter of cosmic history is written--further in the future than our minds can grasp--humanity, and perhaps even biology, will long since have vanished. Yet it's conceivable that consciousness will survive, perhaps in the form of a disembodied digital intelligence. If so, then someone may still be around to note that the universe, once ablaze with the light of uncountable stars, has become an unimaginably vast, cold, dark and profoundly lonely place.