In accord on the birth of the universe, cosmologists are inching toward a consensus on its ultimate fate.

"Cosmology is the field of science that is the least secure and the most exciting; you have a great deal of controversy because the data are so few."

—Allan R. Sandage, Hale Observatories

The birth of the universe, and its death, are questions spawned by the 20th century. They result from the discovery barely a half century ago that the universe is expanding. Indeed, less than two decades ago, astronomers and cosmologists still debated, bitterly at times, whether the expanding universe had ever had a beginning or whether, conversely, it had existed eternally.

The striking resolution of that confrontation—with a discrete beginning, the big bang, emerging over the concept of a steady state universe—is one of the epic tales of science. Its climax was the unexpected discovery, announced in 1965, of the existence in the universe of a pervasive background of radiation left behind by the primordial explosion that spawned the universe. That radiation provided dramatic evidence that the universe had indeed begun with an initial explosion of unimaginable force. And it provided cosmologists with basic information about the early universe that has enabled them to construct second-by-second and minute-by-minute models of its earliest events.

With their almost universal agreement that the universe had a beginning, cosmologists are now free to ask how it will end. Yet, what once seemed a simpler question than that of birth—whether the universe will expand forever, driven outward by the force of that first cosmic explosion, or will eventually collapse upon itself, pulled inward by the gravity of its own mass—now appears an issue destined to remain unresolved, perhaps, until the next century.
Light’s Doppler effect

The big bang theory of the universe originated with Georges Lemaître of Belgium, and got its name from George Gamow, a Russian-born U.S. physicist of puckish wit. But the threads of that theory go back to Albert Einstein. In his general theory of relativity, Einstein described space and time as interlinked in a four-dimensional, geometric model. He also envisioned space as static, and he produced a mathematical model of a static universe.

But a Russian mathematician, Alexander A. Friedman, in reviewing Einstein’s calculations, found that Einstein’s static universe model had depended on the incorporation of a constant in the calculations; without the change introduced into the computations by the constant, Friedman found in 1922, the mathematics could as readily, and more convincingly, describe a dynamic universe—one that could be either expanding or contracting.

As Friedman was recalculating the Einstein model, V.M. Slipher was uncovering evidence that supported Friedman’s concept of a dynamic universe and laying the base for answers to the critical question—expanding or contracting—left hanging by the composite Einstein-Friedman model.

Slipher was studying the light spectra of a group of nebulae thought to lie in the Milky Way galaxy; he found the spectra to be shifted toward the red. The red shift is light’s Doppler effect: When an object moves away from an observer, the wavelengths of the light received from it are lengthened and its spectral lines are shifted toward the red end of the spectrum; if the object is moving toward the observer, the wavelengths are shortened and the spectral lines are shifted toward the blue. The greater the shift, the faster the object is moving. Slipher found that the distant nebulae he was studying were all moving away from the earth at apparent speeds, computed from the amount of red shift, of up to 1,800 kilometers a second.

At the same time that Slipher was doing his red shift work at Lowell Observatory, Edwin P. Hubble at Mount Wilson Observatory was resolving Cepheid variable stars (see “The Extragalactic Ferment” in this Mosaic) in Andromeda and two other bodies in the vicinity of the Milky Way galaxy. By 1923 he was able to show that what appeared to be nebulae were, in fact, other galaxies.

Hubble went on to the study of more distant galaxies, determining their distance by using the brightest of the objects he could resolve within them as what later came to be called cosmic “standard candles” (see “The Extragalactic Ferment” in this Mosaic). By 1929 he was able to assemble the two phenomena—red shift and distance—and perceive a curious cosmic regularity: Slipher’s red shifts appeared to be roughly proportional to the remoteness of Hubble’s galaxies.

The next, inevitable jump Hubble would make only with the utmost caution: The coincidence, he offered, could be construed as proving the expansion of the universe. And, with Milton L. Humason, he undertook a major study to test the notion that more distant galaxies would show greater red shifts.

Lemaître, meanwhile, had published his first paper on the cataclysmic origin of an expanding universe in an obscure Belgian journal in 1927. It remained un­ noted until George McVittie, then a student of Sir Arthur Eddington, called Eddington’s attention to it in 1930. Lemaître had envisioned the universe beginning as a “primeval atom,” a mass of highly compressed and extremely hot matter. As this material expanded, it thinned, cooled and formed the stars and galaxies seen today. There followed considerable correspondence between Eddington and Hubble, and by the end of 1930 the expanding universe was an accepted fact: It began as Lemaître had proposed; it was expanding as Hubble had discovered.

The big bang is us

The concept of an expanding universe is difficult for many to grasp. “It’s anti-intuitive and against all experience,” says P. J. E. Peebles of Princeton University. The universe has no center and no edge. The big bang occurred not in the universe; it was and is the universe. So, for any observer at any point in the universe, all galaxies in all directions appear to be moving away from him. But it is not that the galaxies are escaping; it is that the universe is expanding.

The most common analogy is that of a balloon. If tiny paper spots are attached to the balloon and the balloon is filled with air, the distance from each spot to any other spot will increase in every direction as the balloon expands. Viewed from any single spot, all other spots are moving away from it. Dennis W. Sciama, who is of Oxford University and is visiting Mt. Holyoke College in Massachusetts, offers another analogy: The galaxies are like molecules within a crystal lattice; the lattice itself is expanding.

The Hubble constant

The discovery of the expanding universe marked a major turning point in cosmology. Hubble, in 1929, also introduced the concept that was to become known as the “Hubble relation” between a galaxy’s speed and distance. By means of the extragalactic standard candles, he calculated the distances to 18 galaxies, compared these with their red shift velocities and concluded that the speed at which the galaxies are receding is proportional to their distance. He followed this two years later with new supporting evidence, and in 1936 recomputed the constant of proportionality to be 530 kilometers per second per megaparsec (a parsec equals 3.26 light-years). This value of the constant implied that a galaxy one megaparsec from earth would be receding at 530 kilometers per second, a galaxy two megaparsecs away would be receding at 1,060 kilometers per second and so on.

By using the Hubble relation, and working backward in time, the time of the big bang can also be estimated. But this would be only an upper limit on the age of the universe; the Hubble constant does not reflect any acceleration or deceleration in the universe’s expansion. Unfortunately, the reciprocal of Hubble’s original constant gave an age to the universe of only 1.8 billion years. Rocks on earth were then already known to be as old as 3.0 billion years. Obviously, the universe could not be younger than the earth.

As astronomers have refined their estimates of distance and means of determining red shift velocities, a number of them have revised the Hubble constant. Its value, nonetheless, is still somewhat uncertain. One often-used figure is 75 kilometers per second per megaparsec. Another is 50 kilometers per second per megaparsec, first established by Allan Sandage of Hale Observatories and Gustav A. Tammann of Basel University, using the 5-meter (200-inch) Hale telescope on Palomar Mountain. Sandage’s Hubble constant gives the universe an age of 18.8 billion years.

Not with a bang...?

Gamow, too, made major contributions to the concept of an expanding universe throughout the nineteen-forties. These included the description of the big bang, advanced in 1946 with Ralph
All doubt gone. The ability of the five-meter Palomar Mountain telescope to resolve into stars Galaxy NGC 147, in the Milky Way's local group, adds a dimension not available to the century's early cosmologists.
Alpher and Robert Herman. But there were major problems with Gamow's ideas and the notion of an expanding universe. For one, there was the then-known discrepancy between the Hubble age of the universe and the age of the earth. And theorists found difficulty in explaining the conditions that might exist in the kind of primordial explosion Gamow described.

These difficulties led Herman Bondi, Thomas Gold (now at Cornell University) and Fred Hoyle (then of Cambridge University) to propose the steady state theory in 1948. They envisioned a universe that had had no beginning and would have no end, one that would always appear to be the same. It was an expanding universe, but one in which hydrogen was continuously created to form galaxies to replace those galaxies that had receded beyond view.

Despite the realization by many observational astronomers that there was evidence that galaxies—though certainly not stars—were all of the same apparent age, that the oldest stars in one were no older or younger than the oldest stars in another, the notion drew many adherents. The nineteen-fifties saw a great debate: big bang versus steady state. Like the competing version of the universe it sought to model, however, the steady state theory had a finite life. The first nail to be driven into its coffin was forged in 1955, when Sir Martin Ryle and Peter Scheuer of Cambridge University reported a count of radio sources.

Steady state theory predicted specifically how many radio sources of a given range of intensities should be observable from earth. Ryle and Scheuer found, however, that there were more faint sources than the steady state theory could account for. This suggested evolution of galaxies, and of the universe, which the steady state model could not accommodate.

Steady state suffered another blow in 1966 when Sciamma, then at Cambridge University, and Martin J. Rees, also of Cambridge, compared quasars of large red shifts with quasars of small red shifts. They found too many distant quasars to fit steady state; their work was confirmed and refined by Hale's Maarten Schmidt.

The inference was not unchallenged, however. Some cosmologists argued—as a few continue to argue—that the red shifts of quasars are not cosmological, but might be gravitational or even geriatric in origin. The death blow to steady state and the triumph of big bang came, however, with the unexpected detection of the universe's pervasive background radiation, a finding Sciamma calls "absolutely the most important discovery in cosmology since the expansion of the universe was discovered."

The cosmic background radiation not only provided dramatic evidence against the steady state theory; it allowed cosmologists to model more explicitly the conditions present at the time of the big bang. It also gave them a precise tool with which to explore cosmological theories by direct observation. And the tale of its discovery is almost as fascinating as the insights derived from its presence.

**Three degrees Kelvin**

In 1964, Arno A. Penzias and Robert W. Wilson of Bell Telephone Laboratories set out to measure the intensity of radio waves emitted in the Milky Way far outside of the galactic plane. They began their probing, says Penzias, at 7.35 centimeters, a short wavelength at which galactic radio noise was expected to be slight. They found, instead, considerable noise that appeared to be independent of direction and varied neither with the time of day nor the season. The microwaves filled the sky.

Penzias and Wilson set the noise at an equivalent temperature between 2.5 and 4.5 degrees Kelvin (above absolute zero).

(Radio astronomers often describe the intensity of radio signals in terms of an equivalent temperature. Any object with a temperature above absolute zero will emit radio waves because of the thermal motion of its electrons. The intensity of noise inside a box with opaque walls depends upon only one thing—the temperature of the box's walls. When radio astronomers talk of radio noise in terms of an equivalent temperature of black-body radiation, they mean the intensity of the radiation equal to the radio noise found inside a black box, the opaque walls of which are at that temperature.)

Though the Bell Labs researchers had determined the radio noise's intensity, they still could not, by the end of 1964, account for the signals' origin. They had even investigated the possibility that the signals represented excessive heat in their horn antenna, caused by pigeon droppings.

Penzias and Wilson did not know it at the time, but the existence of such pervasive radio noise as they had detected had been predicted. As early as 1948, Alpher and Herman had suggested that the big bang would have left a cosmic radiation background whose temperature would be 5.0 degrees Kelvin. Similar predictions were made in 1964 by Ya. B. Zeldovich in the Soviet Union and Hoyle and R. J. Tayler in Great Britain.

At Princeton, in 1964, Robert H. Dicke also predicted the existence of residual cosmic radiation from the big bang, and Peebles estimated that the radiation would be at about 10.0 degrees Kelvin. Dicke proposed to P. G. Roll and David T. Wilkinson that they search for the microwave background. The two men were readying their equipment when Penzias called Dicke early in 1965, having heard about the 10.0-degree-Kelvin prediction from a friend. Roll and Wilkinson confirmed the Bell Labs findings; the background became a fact.

The value of the cosmic background radiation is now set at 2.76 degrees Kelvin. (Cosmologists continue to round off to 3.0 degrees Kelvin to designate it.) Big bang models require initial high density and temperatures about 10^12 degrees Kelvin. The 3.0-degree-Kelvin radiation represents residual electromagnetic energy that once was in thermal equilibrium, a condition in which the amount of energy gained exactly balances the energy that is lost to the surrounding environment.

As the story unfolds, the cosmic radiation was released early in the universe, while the basic material of the universe was being forged. Its photons were emitted long before the stars or galaxies blazed to life, long before dust grains formed, long, even, before protons and electrons combined to make the universe's most pervasive material: neutral hydrogen.

The photons of background radiation being detected from earth today have traveled through space enormous distances since they were first emitted, cooling, as the universe expanded, to their present equivalent temperature. Their wavelengths—like the wavelengths of light—have been lengthened by the expansion of the universe; the cosmic background radiation thus shows a characteristic red shift.

**The last full measure**

When an object is heated, it gives off radiation spanning the entire electromagnetic spectrum. The intensity of each wavelength depends on the temperature of the body. In the waning weeks of the 19th century, Max Planck, in Germany, unveiled a formula that predicts the intensity of each wavelength at any tem-
perature. Plotted on a graph, this intensity versus wavelength forms a distinctive curve.

If the universe's observed background radiation is of big bang origin, it must fit this Planck curve. And, since the initial Penzias-Wilson discovery, measurements of the background have fitted the curve.

This, for all but a few diehards, confirmed the big bang. Nevertheless, it was not conclusive; all the measurements had been in the longer wavelength end of the curve. They could conceivably represent radiation produced by conditions other than the big bang.

Experiments covering the shorter wavelength segment were needed to clinch the argument. But these wavelengths are blocked from terrestrial observation by the earth's atmosphere; it was necessary to get instruments above the atmosphere.

Several attempts to obtain short wavelength measurements by rocket and balloon flights proved inconclusive. Then, in 1976, Paul L. Richards and his colleagues at the University of California at Berkeley obtained short wavelength readings during a flight out of the National Balloon Facility in Texas. They found the background radiation to fit closely the Planck curve in those wavelengths as well. Similar results have been obtained by a group at Queen Mary College in London.

This work confirms the 3.0-degree-Kelvin background radiation and fits it to the pattern predicted for a remnant of a universe that began very hot and very dense. 'That's the death blow to the steady state theory, which says that at any time in the past the density must be the same as it is today,' Sciama says. "Even the staunchest steady state defenders have said they can't account for the 3.0-degree-Kelvin background radiation in the steady state theory."

"The 3.0-degree-Kelvin radiation gives us a handle on the universe much deeper than we've ever had before," Wilkinson says. "The photons are coming from matter at extremely high red shift, further back in time and space than the quasars or galaxies."

**The uneven background**

In 1967, Wilkinson and Bruce Partridge, now at Haverford College, showed the 3.0-degree-Kelvin background radiation to be extremely isotropic—uniform in all directions—to at least one part in 1,000. (George F. Smoot, Marc V. Gorenstein and Richard A. Muller of the University of California's Lawrence Berkeley Laboratory reported new data in 1977 that shows the background radiation is isotropic to one part in 3,000.)

But even apparent isotropy has to have its limits, and Peebles pointed out in 1967 that some anisotropy—or unevenness—should be detectable in the cosmic background radiation. It would be caused by: (1) the clumping of matter into the clusters of galaxies, and (2) the movement of earth and Milky Way through space. While it would be impossible to detect the Milky Way's absolute motion—Einstein's general theory of relativity precludes the measurement of absolute motion—it should be possible to determine the earth's motion relative to the universe's background radiation.

In 1969, an experiment reported by Stanford University graduate student Edward A. Conklin, now at Forth, Inc., appeared to record the earth's relative velocity. Two years later, a Princeton graduate student, Paul Henry, now at Bell Labs, reported similar data. Other work, by Wilkinson and Brian E. Corey of the Massachusetts Institute of Technology and by Smoot, Gorenstein and Muller, has further confirmed Conklin's and Henry's findings.

Both groups used essentially identical instruments to search for anisotropy in the cosmic radiation. Corey and Wilkinson flew theirs during a ten-hour, high-altitude balloon flight from the National Balloon Facility in May 1975. The Lawrence Berkeley group made its measurements from a National Aeronautics and Space Administration U-2 research aircraft during eight flights, at an altitude of 20 kilometers, between December 1976 and May 1977.

Corey and Wilkinson report finding a relative velocity for the Milky Way of 330 kilometers per second. Smoot, Gorenstein and Muller report a velocity of 390 kilometers per second, ±60 kilometers per second, slightly less than the uncertainty (±80) given by Corey and Wilkinson. The Milky Way, it has been found, is moving rapidly in the direction of the constellation Hydra.

"The velocity seems large, if, indeed, that is what we are measuring," Wilkinson says. "I'm not sure it is. Only part of the sky has been scanned, and it could be that what we are observing is some anisotropy of the universe."

What Wilkinson suggests is that the data may reflect two effects: the relative velocity of the Milky Way and a slight anisotropy in the background radiation.

"That would say that in the initial big bang, everything didn't blow out spherically, that there was some direction to it," he says. "Then one would have to look for a reason: Why did it blow out faster in one direction?"
The Still-Veiled Instant

Though cosmologists generally agree now that it all began with the big bang, the details of that event, the step-by-step process that produced the universe, remain a matter of debate. Steven Weinberg of Harvard University, a theoretical physicist, synthesized the latest thinking about the early universe last year in his book *The First Three Minutes*.

Weinberg began his account, however, not at the big bang, but about one-hundredth of a second into the universe’s existence, when the temperature had already dropped to $10^{11}$ degrees Kelvin. Subatomic particles called pi mesons would have dominated at the very beginning, and physicists simply don’t know enough about their behavior to carry the scenario back to the instant the universe began. As a consequence, many intriguing questions remain about the creation of the universe, including, says Peebles, the almost metaphysical question: “What was the universe like one-thousandth of a second before the big bang?”

Nonetheless, there is greater agreement today about how the universe began than on how it will end. Edwin Hubble established that the universe is expanding. The question is whether it will expand forever. The general theory of relativity allows either an “open” universe, in which expansion is forever, or a “closed” universe, in which ultimately the force of gravity reverses the expansion and all matter collapses back to a central point—the “big crunch,” as an article in *Scientific American* once called it.

Open or closed? “That’s just been a much tougher nut to crack than anyone thought,” says Kip S. Thorne of the California Institute of Technology. “It’s a very open issue, and I don’t see any hope of solving it in the next decade.”

The Crucial Matter

The key to whether the universe is open or closed lies in the amount of matter that exists. Cosmologists often express this in terms of a “critical density,” expressed in terms of so much mass per cubic centimeter. If the average density of the universe is less than the critical density, the universe is open; it will expand forever, though at a slowing rate as time passes. If the average density is greater, the universe is closed; it will collapse under the influence of its own gravity at some time in the future. One problem, however, is that to determine the critical density with the necessary precision, one must know the universe’s Hubble age, which is not known precisely. If the Hubble age is 18.8 billion years, as Sandage estimates, the critical density is about $2 \times 10^{-29}$ grams per cubic centimeter.

“That’s a number as important as 3.0 degrees Kelvin,” Wilkinson says. “It tells us something about the end, just as 3.0 degrees Kelvin tells us something about the beginning.”

There are a number of ways to determine whether the universe contains enough matter to close it, how close it comes to the critical density. These include: (1) measuring the rate of deceleration of the cosmic expansion; (2) determining the total mass; and (3) ascertaining the relative abundance of deuterium.
and helium. These have been done, to one degree or another, and the results suggest an open universe. The data, however, are far from overwhelmingly persuasive.

One method of measuring deceleration involves plotting the speed of recession of close and distant galaxies. This reveals by how much the universe’s rate of deceleration has declined over time. Hubble’s law says velocity is proportional to distance, so determining deceleration requires determining the distances of galaxies.

The distance to galaxies is estimated by measurement of their brightness or magnitude. If galaxies blazed forever at the same intensity, determining the distance to faraway galaxies would be easy. But galaxies long have been assumed to dim as they age; corrections for galactic evolution must be made in computing the distances of distant galaxies.

In 1975, James E. Gunn of Caltech and Beatrice M. Tinsley, now of Yale University but then at the University of Texas, used the latest models of stellar evolution to correct the magnitude of distant galaxies. When they had made their computations, their data suggested that the universe is accelerating, not decelerating.

Since gravity must have slowed the universe’s expansion to some degree since the big bang, what accounts for the apparent acceleration found by Gunn and Tinsley? Jeremiah Ostriker and S. D. Tremaine of Princeton have suggested one possible explanation: that larger galaxies evolve not only through the evolution of their own stars, but also because they “eat” smaller galaxies. (See “The Extragalactic Ferment” in this Mosaic.) The Milky Way, for example, is apparently in the process of swallowing the galaxy known as the Large Magellanic Cloud, which may already be gravitationally bound to it.

A cannibalistic galaxy would get not only nourishment from its neighbor; it would get a facelift as well. With its fuel supply recharged, such a galaxy should look somewhat to significantly younger and brighter than its age would ordinarily dictate, confusing any scale based on red shift and magnitude.

No one has yet determined how or to what extent this galactic cannibalism affects the brightness of galaxies, if indeed the phenomenon actually occurs. So, red shift magnitude computations are currently in eclipse as a means of measuring the universe’s deceleration. “This method is now believed not to have the charm or the potential we thought it did ten years ago,” says Sandage. “The outcome depends too much on the correction for the evolutionary process.”

A deceleration quotient

Cosmologists often express the universe’s deceleration with a dimensionless number called the deceleration parameter, written $q_0$.

In the standard model, if $q_0$ is greater than 0.5, the deceleration is rapid enough to close the universe; if $q_0$ is less than 0.5, the universe is open.

Sandage proposes that the deceleration parameter can be determined by measurements made in the local supercluster, the thousands of galaxies, including the Milky Way, that center around the Virgo cluster. This method would avoid the problems of galactic evolution that arise with magnitude-red shift comparisons. “We’re in the area of local mass,” he says. “If we can’t get an effect in the lumpy, local part, there surely won’t be any on the global scale.”

Sandage says the deceleration parameter can be determined by comparing the kinetic energy of galaxies in the local supercluster with the strength of the supercluster’s gravitational field. The local supercluster becomes, in effect, a laboratory from which findings can be extrapolated to the rest of the universe. If $q_0$ is high, it should be detected, because the density contrast or “lumpiness” of the local supercluster would impart a random motion to the galaxies’ Hubble flow. Sandage finds none.

“We don’t see any motion other than that imparted by the big bang,” he says. “The energy in the gravitational field of the local supercluster is low compared to..."
its kinetic energy. The local supercluster does not perturb the Hubble flow. Therefore, gravity is not effective in controlling the motions. Hence, \(q_0\) is small.”

Indeed, Sandage places \(q_0\), somewhere between .05 and .1. But the precision represented by the number is far too slight to offer a definitive answer.

Weighed and found open

Late in 1974, J. Richard Gott III of Princeton (then at Caltech), along with Gunn, David N. Schramm of the University of Chicago (then at the University of Texas) and Beatrice Tinsley, reported their efforts to measure the average density of the universe. Their technique consisted of counting the galaxies in a given volume of space, multiplying this by the mass of the galaxies and dividing by the volume selected.

“Weighing” the galaxies involved observing the gravitational motions of pairs and clusters of galaxies. Newtonian mechanics were then used to determine their combined mass. This technique provided not only the mass of the galaxies’ visible elements, but all nonvisible mass contained within a cluster, including black holes and intergalactic dust and gas, as well. Gott, Gunn, Schramm and Tinsley concluded from the average density that the universe contains only about six percent of the mass needed to close it.

Deuterium abundance

Further evidence for an open universe comes from studies of the relative abundance of deuterium—a heavy form of hydrogen—and helium. Conventional physics contends that all deuterium—which is destroyed in stars—originated in the big bang; the deuterium abundance was set within the first few minutes, when the temperature of the primordial fireball had dropped to 10⁹ degrees Kelvin. This was the time of nucleosynthesis, when helium formed.

The amount of deuterium that remained after nucleosynthesis depends upon the density of the big bang. The more dense the matter, the more collisions that would occur and the more deuterium that would be destroyed as helium was created. An accurate knowledge of the original abundance of deuterium would establish the density of the big bang.

The first calculation of the cosmic deuterium abundance, based on the density inferences of the 3.0-degree-Kelvin radiation background, was made in 1966 by Peebles. The next year, Robert Wagoner of Stanford, William Fowler of Caltech and Hoyle produced a more refined prediction. Measurements of the relative abundance of deuterium in nearby interstellar space were obtained in 1973 by Donald G. York and John B. Rogerson Jr. of Princeton, using an ultraviolet spectrometer aboard the earth-orbiting satellite Copernicus. After allowing for the deuterium destroyed in stellar nuclear reactions, York and Rogerson calculated an average density for the present universe of 4 x 10⁻³¹ gram per cubic centimeter, or roughly ten percent of the mass needed to close the universe.

The significance of the Copernicus findings rests on the assumption that all deuterium was made within minutes after the big bang. But some theorists challenge that assumption, suggesting that deuterium might be produced by such phenomena as supernovas, cosmic rays and quasars. If this is true, it would reduce the relative abundance of primordial deuterium and increase the density of the big bang.

The missing mass

Thus far, the evidence suggests that the universe contains too little mass to reverse its expansion. If the universe is closed, there must exist extensive amounts of undetected matter. This has prompted the search for what is called the universe’s “missing mass.” And, indeed, some work now suggests that the mass of the universe may be far larger than that indicated by the deceleration parameter studies and the relative cosmic abundance of deuterium.

There is a cosmological principle which holds that, on the large scale, matter is uniformly distributed throughout the universe. On the small scale, this is not true. Stars form galaxies, galaxies cluster together and galaxy clusters clump into superclusters. Peebles, Edward J. Groth, Michael Seldner and Raymond M. Soneira of Princeton and Marc Davis of Harvard showed in 1977 that the cosmic clustering of galaxies follows a simple and regular pattern, a finding that may relate to both the big bang and the universe’s fate.

The group worked with a sky survey compiled by C. Donald Shane and Carl A. Wirtanen of Lick Observatory. The survey contains some one million galaxies that are brighter than 19th magnitude. The map the Princeton team produced provides graphic evidence that the clustering of distant galaxies and the clustering of nearby galaxies is statistically the same and occurs in a hierarchical way: galaxies bunched in clusters, clusters, in turn, bunched in superclusters.

Next, the group set out to model a universe that would match the one observed. One conclusion they reached is that the clustering results because the curvature of space is not totally smooth, and this lumpiness even existed at the time of the big bang.

“In this theory,” Peebles says, “space is curved; where there is matter, it is curved a little more. There is an analogy I like: The curvature breaks up like a slightly dried-out apple. If you stand back, the surface is a nice, smooth curve. But if you look closely, it’s slightly wrinkled. That is what space looked like near the big bang. That presumably tells us something about the nature of the big bang, and it’s a clue for people who make theories of the big bang to work on.”

The model also predicts that if the universe contains only the mass that has been detected so far, small, dense clusters of galaxies would have formed, but not the giant superclusters. “That is telling us that we need, not a closed universe, necessarily, but a denser universe; denser by a factor of maybe ten times that credited to it,” Peebles says.

Heavy halos

One place the missing mass might be concentrated, Peebles suggests, is in halos surrounding galaxies.

Last year, Dennis J. Hegyi and Garth L. Gerber of the University of Michigan reported finding a luminous halo in the giant spiral galaxy NGC 4565, extending out 34 kiloparsecs from 4565’s galactic plane. If this halo is produced by stars rather than by hot, tenuous gas, it could add significant mass to the galaxy. And the assumption is that other galaxies possess similar halos.

Also last year, Stephen Murray, William Forman, Christine Jones and Ricardo Giacconi of the Harvard-Smithsonian Center for Astrophysics reported that X-ray emissions observed in three superclusters of galaxies implied that the superclusters contained five to ten times as much mass in the form of hot gas as exists in the galaxies’ stars. They based their conclusion on an analysis of data from the satellite Uhuru. They suggested that the gas, which has a temperature of 10⁸ degrees Kelvin, may be hydrogen and helium remnants of the big bang.

That might still not be enough mass, however, to close the universe. Gunn, for
instance, points out that, while heavy galactic halos probably do contain ten times the mass visible in the galaxies, that is a far cry from the 100 times the visible mass that is necessary to produce a closed universe. And the method he and his colleagues—Gott, Schramm and Tinsley—used to determine mass precludes, he says, any such vast amount of undetected mass.

More recently, observations by the Small Astronomy Satellite and the High-Energy Astronomical Observatory (see "Catchers of the Sky" in this Mosaic) indicate considerable additional mass in the gases among the galaxies in galaxy clusters—particularly in clusters Coma, Virgo and Abell.

In galaxy cluster Virgo-A, for instance, HEAO found X-ray emissions indicating otherwise invisible gas of the equivalent of $10^{12}$ solar masses in among the cluster's galaxies—30 times the mass in the cluster's visible bodies.

If that is typical of all clusters, says X-ray astronomer Herbert Friedman of the Naval Research Laboratory, it could add up to enough mass to close the universe.

That's a big "if," however, and still doesn't seem to be the missing mass discovery that will close the universe.

The mass of the neutrino

Ultimately, the existence of enough missing mass to produce a closed universe may rest with the elusive neutrino. Neutrinos became free particles in the first few seconds of the big bang, when its temperature was 10^10 degrees Kelvin. They permeate the universe, and because they are subject to the same red shift phenomenon as the 3.0-degree-Kelvin background radiation, there should exist a neutrino background for which an equivalent temperature of about 2.0 degrees Kelvin has been predicted.

Conventional physics holds that neutrinos are massless. But in recent years a number of particle physicists have theorized that the neutrino may have a slight rest mass, on the order of 10^{-5} that of the electron. If they do have this rest mass, they could be the dominant form of mass in the universe, because there are so many of them. Unfortunately, the interaction of neutrinos with matter is extraordinarily weak, and no one has yet found a way to detect them on a cosmic scale (see "Stellar Ontogeny...to Ashes" in this Mosaic).

And so the question remains: Is the universe destined to expand forever?

**But what if...?**

There are those who appear almost ready to close the book on the closed universe, as it has been closed on the steady state.

Caltech's James Gunn, for instance, believes the failure of anyone so far to come up with a place to look for enough missing mass to close the universe is pretty conclusive. "There's still reason to doubt," he observes, "but you have to weasel a lot to close the universe."

And Robert Jastrow, director of the Institute for Space Studies of the Goddard Space Flight Center, believing that the evidence is strong for an open universe, finds that the closing of that question opens another for astronomers and physicists, one with which they will be less comfortable:

If the universe indeed is open, as it seems to him to be, and will go on expanding eternally, which seems to follow, then, he holds, it must have had a beginning. This would not be the comfortably cyclic beginning of a closed-but-open universe that expanded, then contracted and then expanded again and again, oscillating endlessly under the impetus of a succession of big bangs tens of billions of years apart. It would be a finite, one-time-only beginning, one about which such metaphysical questions as first-cause and uncaused-cause must be raised. And they can be raised eternally, fruitlessly, because, as Jastrow notes, the evidence by which they must be answered was destroyed in the same big bang that enabled them to be raised.

"Science cannot bear the thought," Jastrow says, "that there is an important natural phenomenon that it cannot hope to explain even with unlimited time and money." That is the kind of thought, he notes, that frustrates scientists; it makes them ill-tempered.

They—and all of us—may be more comfortable with Sandage's more contemporary view: that we don't yet have enough information even to ask the questions intelligently.

"My personal view is that we don't have enough data to argue the question," Sandage says. "The problem is interesting, because it forces people to work. It will certainly be debated for a long time, and it will stimulate new observations that can't but help."