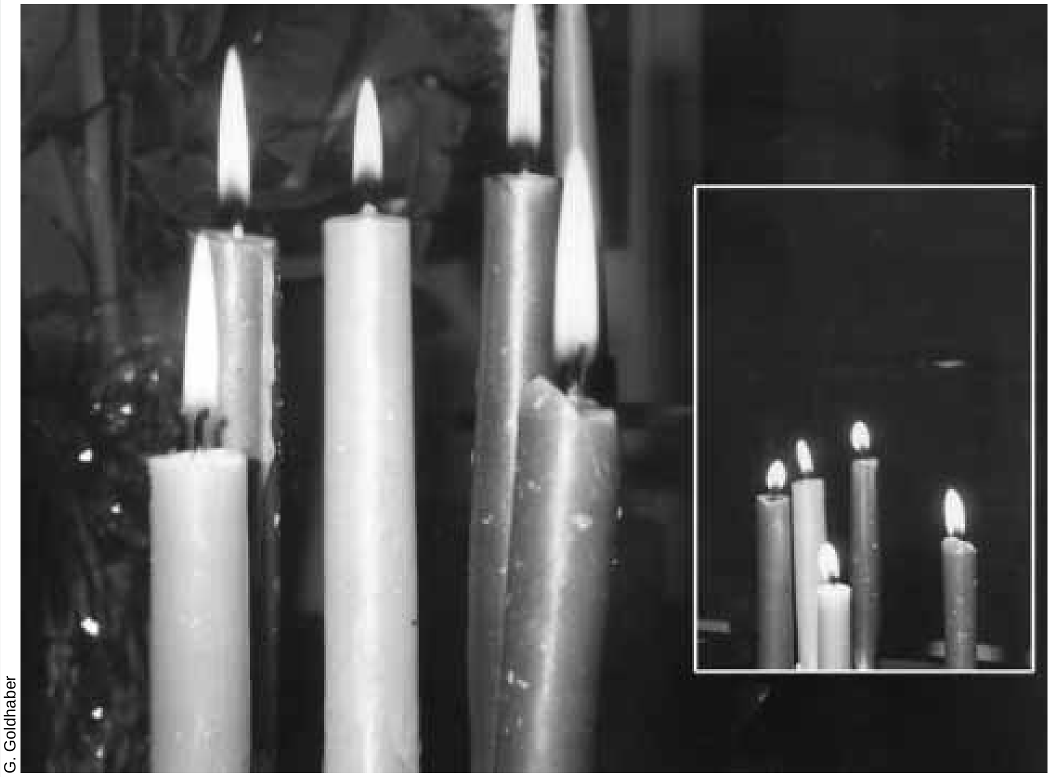
The Fate of the Universe

ONE OF THE FUNDAMENTAL PROBLEMS in astrophysics and cosmology concerns the ultimate fate of the Universe. Will it go on expanding, as it has been doing ever since the Big Bang? Or will the gravitational pull of the objects in it eventually halt the expansion so that it either comes to rest or begins a contraction that ends in a Big Crunch?

One promising approach to finding an answer is to measure the rate at which galaxies and other cosmological objects are slowing down over time. Around eight years ago, a group of astrophysicists at the Lawrence Berkeley National Laboratory (LBNL), in collaboration with groups in Australia and England, decided to measure this "deceleration rate" through the study of very distant supernovae. This group, known as the Supernova Cosmology Project and headed by Saul Perlmutter, is affiliated with LBNL's Institute for Nuclear and Particle Astrophysics and UC Berkeley's Center for Particle Astrophysics. We now have data from more than 45 distant supernovae (or exploding stars) and have completed a pilot study on the first seven. Soon we can begin to resolve the question of the fate of the Universe.

When we talk about the Universe's expansion, we must be careful not to think of it as analogous to a bomb exploding outwards from a single central point. It is better to imagine space itself expanding between every two points in the Universe, like the space between two dots on the surface of a balloon being blown up. In opposition to this expansion, however, there is another factor at work—the gravitational pull of all the matter in the Universe,

by GERSON GOLDHABER AND JUDITH GOLDHABER



G. Goldhaber

"Standard candles" illustrating the brightness versus inverse square of the distance law. The inset shows the candles at three times the distance to the nearby candle image.

With their discovery of the most distant supernovae ever observed, an international scientific team led by researchers from Lawrence Berkeley National Laboratory hope to learn the ultimate fate of our Universe.

which acts like a brake on the expansion and leads to a deceleration. We know that this deceleration must exist, but we do not know how large it is, or how effective it may be in counterbalancing the expansion.

In the face of this uncertainty, several alternative scenarios for the history and fate of the Universe have been proposed. The first, known as the "negative curvature" or open universe, is one in which the density of matter (and thus the gravitational force) is too small to overcome the initial velocity of the expansion. Such a universe is infinite, one that would continue to expand forever. The second scenario, known as the "positive curvature" or closed universe, is a finite universe—one in which the density of matter is great enough to cause the expansion to come to a halt, reverse direction, and contract towards a final Big Crunch. Finally, in the flat universe, the density is high enough to stop the expansion, but not to bring about a contraction. Such a universe (also considered an infinite universe) would slow down its expansion at such a rate that it would come to rest only after an infinite amount of time.

TYPE IA SUPERNOVAE AS STANDARD CANDLES

What can supernovae tell us about the fate of the Universe? Their usefulness comes about through a rather interesting feature that certain types of supernovae (known as Type Ia) share. They are all of virtually identical intrinsic brightness, and, because of this, we can tell how far away they are.

Readers may be surprised to learn that astronomers still have difficulty measuring distances in the Universe, but they do. A bright object may appear closer to us than a dim one; on the other hand, it may simply be intrinsically brighter. A calculation based on the "redshift"—

the degree to which the spectral lines of light from an object are shifted towards the red end of the spectrum—can provide an estimate within about 20 percent accuracy, but that's not good enough for many cosmological puzzles. What has been needed is an object of known and intense brightness to use as a unit of measure—a "standard candle." Fortunately, there is good reason to believe that Type Ia supernovae (the brightest of all the different types of supernovae) can, with some additional detailed measurements, function as calibrated standard candles.

The Supernova Cosmology Project data were taken at the Isaac Newton and William Herschel Telescopes at the Spanish Observatorio del Roque de las Muchachos; the Kitt Peak National Observatory telescopes; the Keck 10-meter telescopes; the Chilean Cerro Tololo Inter-American Observatory 4-meter telescope, and the Hubble Space Telescope.

WHY DO TYPE IA SUPERNOVAE BEHAVE AS STANDARD CANDLES?

There is a Type Ia supernova going off somewhere in the Universe every few seconds. These supernovae begin with a kind of star known as a white dwarf—stars of about the mass of our sun that have gone through a nuclear aging process. First, through fusion, they have converted most of their hydrogen and helium to carbon and oxygen. Then, through a collapse caused by gravitational force, electrons have been stripped from the carbon and oxygen atoms, resulting in the formation of what is called a "degenerate electron gas," in which their nuclei are embedded. A typical white dwarf has a mass close to the mass of our sun, but a radius comparable to that of the Earth.

In order for a white dwarf to end its life as a supernova, it must be part of a binary system with another star—a common occurrence in the heavens. Under these conditions the white dwarf, with its powerful gravitational pull, accretes matter from its large, gaseous companion, and continues to grow ever more massive. When it reaches a critical mass of 1.4 solar masses, the gravitational force overcomes the electron-gas pressure, which occurs due to the quantum mechanical rule that more than two electrons cannot be squeezed into the same space. The star collapses within seconds, and explodes in a Type Ia supernova. These supernovae therefore behave as standard candles; because they all have about the same mass at the time they collapse, they all have about the same intrinsic brightness.

The heat generated in the collapse of the white dwarf leads to fusion of the carbon and oxygen nuclei, and within seconds, the energy released by these fusion reactions causes a rebound. The newly created material is ejected with velocities of about 10,000 to 30,000 kilometers per second. The fusion process continues through a number of steps, ending in a large mass of the radioactive isotope nickel-56, which begins to decay (with a half life of about six days) into its daughter isotope cobalt-56. The cobalt-56, in its turn, decays with a half life of about 77 days to iron-56, which is stable. The ionization produced by these radioactive isotopes yields light that reaches our instruments; their slow decay permits us to observe and study the supernova for about two months. The light intensity reaches a maximum value after about 15 days and then begins to fade.

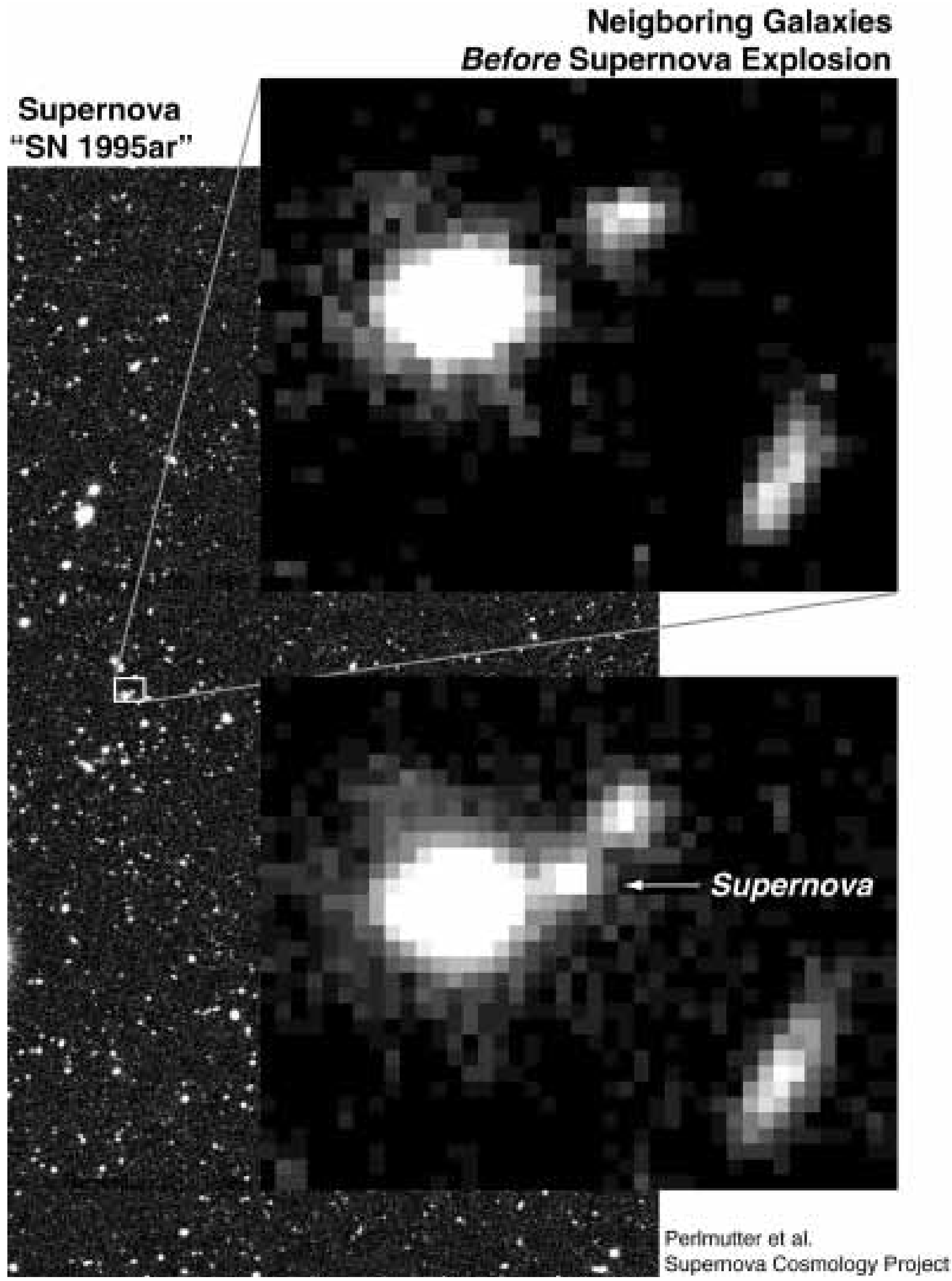
FINDING SUPERNOVAE

All the supernovae we see in distant galaxies occurred billions of years ago (typically 4 to 8 billion). By the time their light reaches us, they have long since disappeared—all their mass having dispersed through space in an ever-expanding sphere. Several times a year, in the week just after the new moon, members of our group visit one of several cooperating observatories (in Arizona, Canary Islands, Chile, and elsewhere) and take a series of 10-minute exposures of the night sky with a very sensitive CCD (charge-coupled device) camera mounted on a telescope. We use a powerful telescope (about 4 meters in aperture) and aim it at a region of the sky not too thickly sprinkled with nearby stars from our own galaxy—we are trying to peer out beyond our own cosmological neighborhood into the vastness of the Universe beyond, almost two thirds of the way to its edge. Typically, in two nights we may make about 50 such exposures, observing a total of about 4 square degrees. Each "snapshot" is repeated again some 30 minutes later to give ample exposure time for the most distant galaxies and also to permit us to identify transient phenomena like asteroids or cosmic rays.

Three weeks later, just before the new moon, we go back to the same telescope and take another series of images of the exact same region. We then compare the first set of images (the reference images) with the second set (optimistically called the "discovery images"). When a supernova explodes, it can be as bright or even much brighter than all the rest of the stars in its galaxy combined. Thus a supernova that appeared in the three weeks between the two sets of images reveals itself as a bright spot that shows up clearly when the discovery image is compared with the reference image (see figure on the right). Nearly all the supernovae we find are Type Ia (even though only about 20 percent of the supernovae in the nearby region of the Universe are), since we are looking out into the very distant regions, where dimmer supernovae cannot be detected.

We have described this process as if it were done with visual scanning (as indeed it could be and was some years ago for nearby supernovae), but we actually use computers for almost every step. The CCD images are sent back to Berkeley from the telescope over the Internet, and our computer programs subtract one image from another and flag likely candidates the very same night.

These candidates must then be scrutinized and analyzed further, because several phenomena—a cosmic ray passing through the telescope, a nearby asteroid, a "hot pixel" in the CCD camera—can mimic the bright light of a supernova. We have developed reliable methods of identifying and discarding these three types of impostors; however, a fourth type—an Active Galactic Nucleus (AGN) is harder to identify, and must be eliminated at a later stage through spectroscopy.

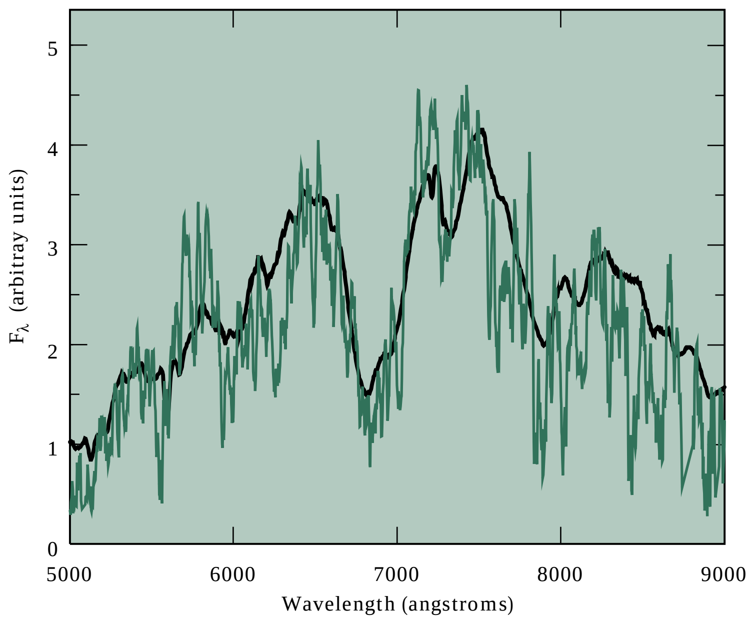


An image of a supernova, SN1995ar, discovered by the Supernova Cosmology Project at a redshift of z = 0.46. Both images were taken using a red filter on the Cerro Tololo, Chile, Inter-American Observatory 4-meter telescope. The Supernova Cosmology Project now has members at Berkeley, California; Cambridge, England; Stockholm, Sweden; Paris, France; Garching, Germany; Batavia, Illinois; Baltimore, Maryland; Sydney and Mt. Stromlo, Australia; and La Silla, Chile.

ANALYZING THE DATA

Once we think we have found a supernova, a much more detailed analysis begins. For this analysis, we use two approaches, spectroscopy and photometry.

Spectroscopy has two important functions in our experiment. First, it permits us to recognize candidates



The spectrum of the most distant clearly identified Type Ia supernova, at a redshift of z = 0.83, SN1997bp. The green curve is the spectrum measured at the 10-meter Keck telescope of the California Association for Research in Astronomy in Hawaii. The black curve is the spectrum of a nearby supernova (SN 1989B), for comparison, with its spectrum shifted to the red by multiplying its wavelength scale by a factor of 1+z = 1.83.

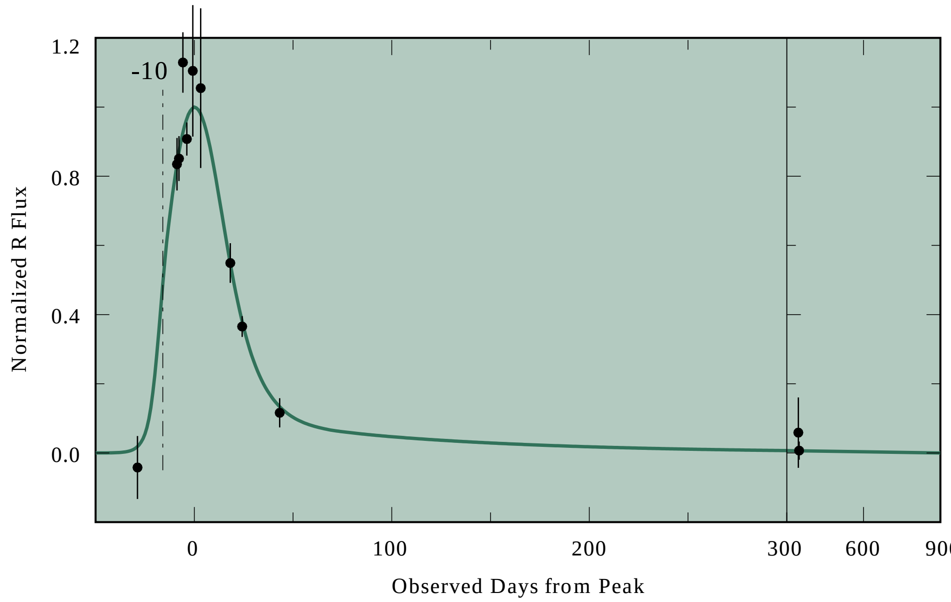
that are clearly identified as Type Ia supernovae and those that are really not (AGNs and supernovae of other types). We do this by identifying the characteristic line spectrum associated with elements between hydrogen and iron in the material ejected from the supernova. Because of the explosive expansion of this material, the spectral lines are characteristically very broad. This so-called "Doppler broadening" comes about because different parts of the ejecta have widely different projected velocities.

Spectroscopy also allows us to calculate the recession velocity—how fast the galaxy containing the supernova was receding from us at the time of the event. In order to find the recession velocity, we observe the degree to which the supernova's spectral lines are shifted towards the red end of the spectrum. As Hubble discovered in 1929, the more pronounced this redshift (which means greater velocity relative to the observer), the more distant the galaxy.

However, terms like "recession velocity"—though adequate for discussing the motion of nearby stars and galaxies—do not describe with sufficient precision what happens to light over immense distances. For this, we must turn to the terminology of General Relativity, in which redshift is expressed not as due to a Doppler shift from a receding object but rather as an increase in the wavelength of light as it traverses space, which is expanding. Cosmologists use the following rule: take the distance between two points at some early time, and multiply it by a scale factor that increases with time. In relativistic terms, then, the redshift equals the difference between the present-day scale factor (a_o) and the smaller scale factor at the earlier time when the supernova occurred (a_s), divided by the scale factor a_s. For simplicity in this article, however, we will continue to use the term "recession velocity"—the language of the Doppler shift for a receding galaxy.

In parallel with the spectroscopic analysis, we also follow up each supernova discovery by obtaining additional images at other telescopes around the world. This allows us to measure the supernova's light curve, the plotted graph of its brightness over time. Typically, the light rises to a peak a few days after it is first observed, and then dims in a slow curve over a period of about two months. It has been established from studies of nearby Type Ia supernovae that this curve is very nearly the same for all. A final image is taken a year later, when the supernova's light has essentially disappeared. This gives us a good measurement of the brightness of the galaxy without the supernova, and—through subtraction—allows us to calculate the peak brightness of our now-vanished supernova.

With the measurement of spectrum and light curve, the observational part of our experiment for a particular supernova is complete, and we are now in a position to calculate the deceleration rate. Clearly, if this rate is large (that is, the expansion is rapidly slowing down) the galaxy containing the supernova will be



Light curve for the supernova SN1995ar discovered by the Supernova Cosmology Project. The points are the measured values. Most of the follow-up points were taken at the Wisconsin-Indiana-Yale National Optical Astronomy Observatory in Arizona. The curve is a standard template in the supernova rest system, fitted to the data. The template curve has been expanded along the time axis by a factor 1+z = 1.46 to take into account the relativistic time dilation due to the expansion of the Universe.

closer to us than it would have been in a universe in which the deceleration rate is small. We are speaking here in general, qualitative terms; however, an equation based on General Relativity directly relates deceleration rate to the three quantities that we have determined—the intrinsic brightness of Type Ia supernovae (based on measurements from known nearby supernovae), their apparent brightness (based on our own measurements of the light curves), and the recession velocity (as indicated by our measurements of the redshift).

OMEGA & LAMBDA

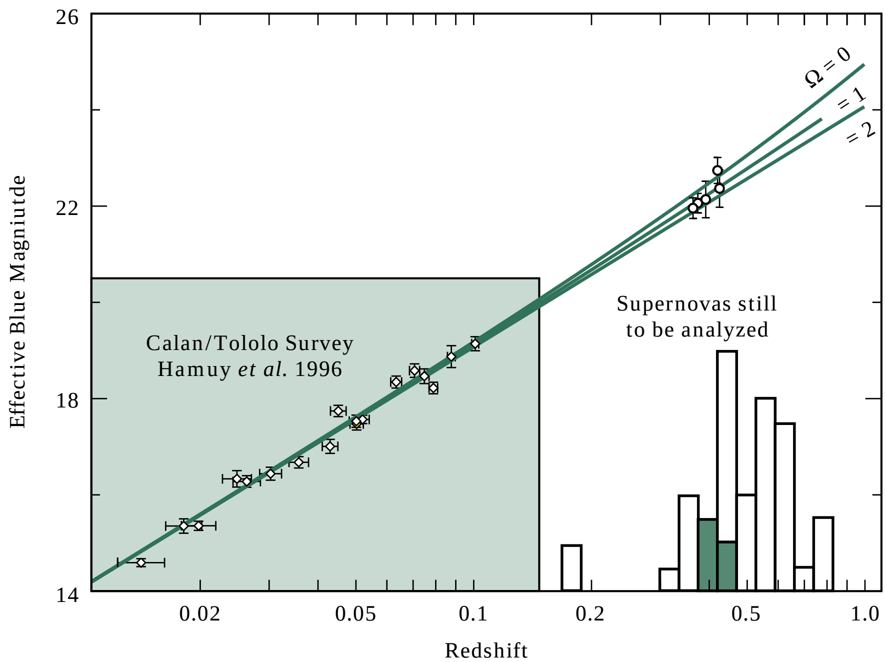
Cosmological theories about the fate of the Universe frequently refer to a quantity known as omega (Ω), which is related to the deceleration rate and to two other quantities, matter density and vacuum energy density.

By matter density we mean the mass of all the matter—visible and dark—in a given region of the Universe, divided by the volume of that region (assuming that for a sufficiently large region, the Universe can be considered uniform). Obviously, matter density, because it is the source of gravity, is directly related to the deceleration rate. The higher the density, the greater the deceleration. Omega is the ratio of matter density to a "critical" density, at which the pull of gravity becomes strong enough to yield just enough deceleration to stop the expansion of the Universe. Thus, if the value of omega is less than 1, the negative curvature case is most likely, and the Universe will continue expanding forever. If it is exactly 1, the flat universe case looks like the winner (refer to Alan Guth's article on page 14 in this issue); if it's greater than 1, we're headed for the Big Crunch.

When Einstein introduced his General Theory of Relativity in 1916, the Universe was assumed to be static. To understand such a static universe, Einstein had to introduce a repulsive force to compensate for gravitational attraction. He called the origin of this force "the cosmological constant" lambda (Λ).

Later, when Hubble discovered that the Universe is actually expanding, Einstein called the cosmological constant his greatest mistake. However, we dare not agree with this assessment without further examination. Since Λ is consistent with General Relativity, the existence and value of Λ must be regarded as experimental questions. Recently, certain cosmologists have appropriated the cosmological constant and proposed that it may be related to the energy density of the vacuum—a concept also dear to the heart of particle physicists. If the cosmological constant exists, it will affect the rate of deceleration; indeed, if its value is large enough, it could even result in a universe whose expansion is accelerating rather than decelerating.

To include Λ in our picture, (we now define omega total (Ω_T) which



High redshift supernovae from the Supernova Cosmology Project compared with low redshift supernovae from the Calan-Tololo Survey on a graph of magnitude versus redshift distribution. Magnitude is a logarithmic measure of brightness, and brightness decreases toward larger numbers.The points near z = 0.5 are the supernovae used in the first determination of the mass density of the Universe, with three comparison values of this mass density, Ω_M, shown as three solid curves for the case $\Omega_\Lambda = 0$. The redshift distribution of the supernovae still to be analyzed is shown as white bars.

is omega for matter density (Ω_M) plus omega for vacuum energy density, or omega due to the cosmological constant (Ω_Λ). For the remainder of this article, we shall use the unmodified term Ω to mean Ω_T.

Before the work described in this article, estimates of Ω, based on a variety of experiments, ranged from 0.1 to 1.5. At the beginning of our experiment, we limited ourselves to measuring Ω_M. As the experiment evolved, however, we realized that we could expand it in such a way as to obtain both Ω_M and Ω_Λ. As it turns out, the redshift is related in different ways to matter density and vacuum energy density, so if we divide our Type Ia supernovae into two groups—those with a very large redshift and those with a significantly smaller one—we hope to be able to measure each component separately.

RESULTS & CONCLUSIONS

So where do we stand? And where is the Universe heading? In mid-1997, data from more than 45 supernovae were in various stages of analysis in our group. Moreover, it should be pointed out that ours is no longer the only group collecting such data. Beginning about 1995, Brian Schmidt and co-workers from Australia, Chile, the University of Washington, Harvard, and Berkeley began a similar search, known as the High-*z* Supernova team.

As of this writing, the Supernova Cosmology Project has completed its first analysis of 7 supernovae, and we are working on the analysis of 15 discovered more recently, which should be completed soon. For an additional 25 Type Ia supernovae observed in 1997, another year must pass before we can take the final images of the galaxy after the supernova has died out. Finally, we hope to measure 100 more supernovae over the next few years, with emphasis on very distant ones (with redshifts approaching 1, as compared to our current typical redshift of 0.5).

Although the number of supernovae is still too small to support reliable conclusions about the fate of the Universe, we have analyzed the data by making certain assumptions. For example, if we assume that $\Omega_\Lambda = 0$ (that is, that there is no repulsive force at work in the Universe) we can calculate a value for Ω_M equal to 0.9±0.6. On the other hand, if we make the assumption of a flat universe in which $\Omega = 1$, we obtain a value for Ω_Λ of 0.06±0.3, and Ω_M is given by $1 - \Omega_\Lambda$. Of course, the statistical and systematic error of 0.3 is large enough to move the value of Ω_M clear over to the other side of 1, so our present results still overlap all three possible scenarios for the Universe!

However, some interesting conclusions can already be drawn from the data. The visible part of the Universe is believed to correspond to a very small value of $\Omega_M \simeq 0.01$, and baryonic matter (that is, matter that is made up of protons and neutrons) perhaps to only 0.1. Thus for the value of Ω_M we obtained, there must be an enormous quantity of dark matter of as yet unknown composition.

And the envelope, please? We will all just have to wait and see.