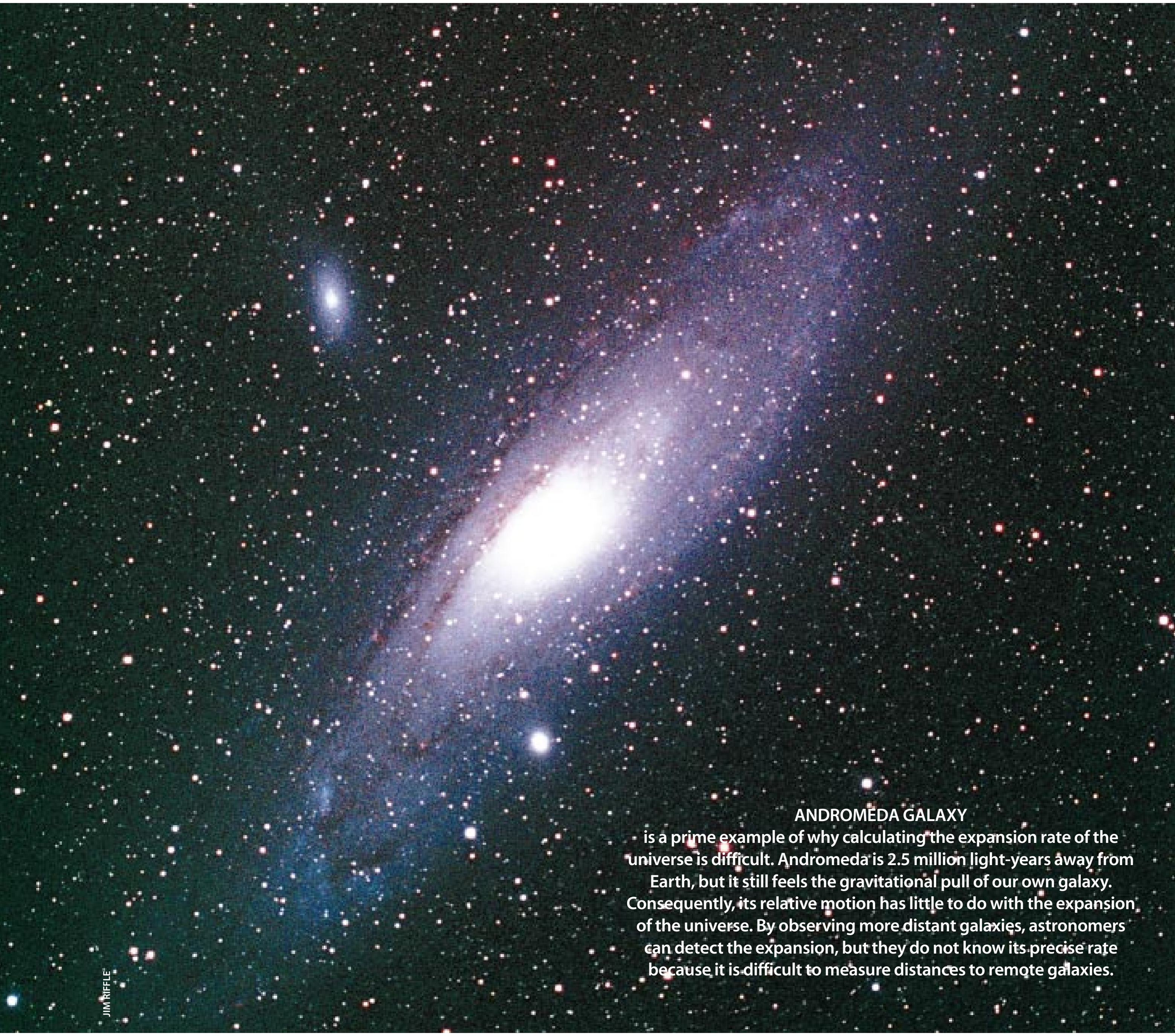
The Expansion Rate and Size of the Universe

by Wendy L. Freedman



ANDROMEDA GALAXY is a prime example of why calculating the expansion rate of the universe is difficult. Andromeda is 2.5 million light-years away from Earth, but it still feels the gravitational pull of our own galaxy. Consequently, its relative motion has little to do with the expansion of the universe. By observing more distant galaxies, astronomers can detect the expansion, but they do not know its precise rate because it is difficult to measure distances to remote galaxies.

JIM RIFFLE

Our Milky Way and all other galaxies are moving away from one another as a result of the big bang, the fiery birth of the universe. As we near the end of the millennium, it is interesting to reflect that during the 20th century, cosmologists discovered this expansion, detected the microwave background radiation from the original explosion, deduced the origin of chemical elements in the universe and mapped the large-scale structure and motion of galaxies. Despite these advances, elementary questions remain. When did the colossal expansion begin? Will the universe expand forever, or will gravity eventually halt its expansion and cause it to collapse back on itself?

The age, evolution and fate of the universe depend on just how fast it is expanding. By measuring the size of the universe using a variety of new techniques, astronomers have recently improved estimates of the expansion rate

For decades, cosmologists have attempted to answer such questions by measuring the universe's size-scale and expansion-rate. To accomplish this task, astronomers must determine both how fast galaxies are moving and how far away they are. Techniques for measuring the velocities of galaxies are well established, but estimating the distances to galaxies has proved far more difficult. During the past decade, several independent groups of astronomers have developed better methods for measuring the distances to galaxies, leading to completely new estimates of the expansion rate. Recently the superb resolution of the Hubble Space Telescope has extended and strengthened the calibration of the extragalactic distance scale, leading to new estimates of the expansion rate.

At present, several lines of evidence point toward a high expansion rate, implying that the universe is relatively young, perhaps only 10 billion years old. The evidence also suggests that the expansion of the universe may continue indefinitely. Still, many astronomers and cosmologists do not yet consider the evidence definitive. We actively debate the merits of our techniques.

An accurate measurement of the expansion rate is essential not only for determining the age of the universe and its fate but also for constraining theories of cosmology and models of galaxy formation. Furthermore, the expansion rate is important for estimating fundamental quantities, from the density of the lightest elements (such as hydrogen and helium) to the amount of nonluminous matter in galaxies, as well as clusters of galaxies. Because we need accurate distance measurements to calculate the luminosity, mass and size of astronomical objects, the issue of the cosmological distance scale, or the expansion rate, affects the entire field of extragalactic astronomy.

Astronomers began measuring the expansion rate of the universe some 70 years ago. In 1929 the eminent astronomer Edwin P. Hubble of the Carnegie Institution's observatories made the remarkable observation that the velocity of a galaxy's recession is proportional to its distance. His observations provided the first evidence that the entire universe is expanding.

The Hubble Constant

Hubble was the first to determine the expansion rate. Later this quantity became known as the Hubble constant: the recession velocity of the galaxy divided by its distance. A very rough estimate of the Hubble constant is 100 kilometers per second per megaparsec. (Astronomers commonly represent distances in terms of megaparsecs, where one megaparsec is the distance light travels in 3.26 million years.) Thus, a typical galaxy at a distance of 50 megaparsecs moves away at about 5,000 kilometers (3,000 miles) per second. A galaxy at 500 megaparsecs therefore moves at about 50,000 kilometers per second, or more than 100 million miles per hour!

For seven decades, astronomers have hotly debated the precise value of the expansion rate. Hubble originally obtained a value of 500 kilometers per second per megaparsec (km/s/Mpc). After Hubble's death in 1953, his protégé Allan R. Sandage, also at Carnegie, continued to map the expansion of the universe. As Sandage and others made more accurate and extensive observations, they revised Hubble's original value downward into the range of 50 to 100 km/s/Mpc, thereby indicating a universe far older and larger than suggested by the earliest measurements.

During the past two decades, new estimates of the Hubble constant have continued to fall within this same range, but preferentially toward the two extremes. Notably, Sandage and his longtime collaborator Gustav A. Tammann of the University of Basel have argued for a value of 50 km/s/Mpc, whereas the late Gérard de Vaucouleurs of the University of Texas advocated a value of 100 km/s/Mpc. The controversy has created an unsatisfactory situation in which scientists have been free to choose any value of the Hubble constant between the two extremes.

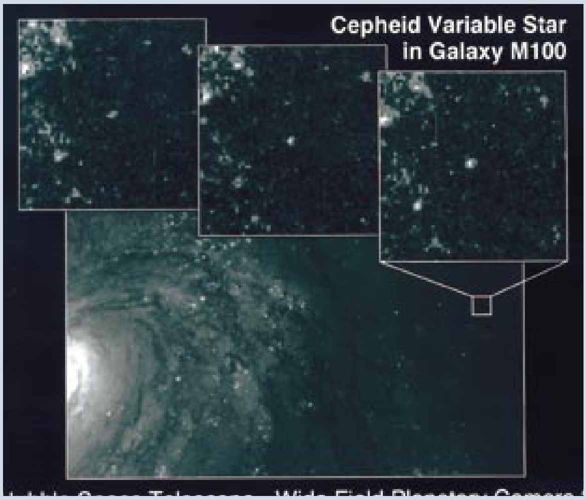
In principle, determining the Hubble constant is simple, requiring only a measurement of velocity and distance. Measuring a galaxy's velocity is straightforward: Astronomers disperse light from a galaxy and record its spectrum. A galaxy's spectrum has discrete spectral lines, which occur at characteristic wavelengths caused by emission or absorption of elements in the gas and stars making up the galaxy. For a galaxy receding from Earth, these spectral lines shift to longer wavelengths by an amount proportional to the velocity—an effect known as redshift.

If the measurement of the Hubble constant is so simple in principle, then why has it remained one of the outstanding problems in cosmology for almost 70 years? In practice, measuring the Hubble constant is extraordinarily difficult, primarily for two reasons. First, although we can measure their velocities accurately, galaxies interact gravitationally with their neighbors. In so doing, their velocities become perturbed, inducing "peculiar" motions that are superimposed onto the general expansion of the universe. Second, establishing an accurate distance scale has turned out to be

Why Cepheid Variables Pulsate

Several times more massive than the sun, a Cepheid variable is a relatively young star whose luminosity changes in a periodic way: a Cepheid brightens and then dims more slowly over a period of a few days to months. It pulsates because the force of gravity acting on the atmosphere of the star is not quite balanced by the pressure of the hot gases from the interior of the star.

The imbalance occurs because of changes in the atmosphere of a Cepheid. An important ingredient in the atmosphere is singly ionized helium (that is, helium atoms that have lost a single electron). As radiation flows out of the interior of a Cepheid, singly ionized helium in the atmosphere absorbs and scatters radiation, and it may become doubly ionized (that is, each helium atom releases a second electron). Consequently, the atmosphere becomes more opaque, making it difficult for radiation to escape from the atmosphere. This interaction between radiation and matter generates a pressure that forcefully pushes out the atmosphere of the star. As a result, the Cepheid variable increases in size and in brightness.



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CEPHEID VARIABLE in the galaxy M100 is shown here at three different times in its light cycle (*top*). As seen from left to right, the star brightens.

Yet as the atmosphere expands, it also cools, and at lower temperatures the helium returns to its singly ionized state. Hence, the atmosphere allows radiation to pass through more freely, and the pressure on the atmosphere decreases. Eventually, the atmosphere collapses back to its initial size, and the Cepheid returns to its original brightness. The cycle then repeats.

—*W.L.F.*

much more difficult than anticipated. Consequently, an accurate measure of the Hubble constant requires us not only to establish an accurate extragalactic distance scale but also to do this already difficult task at distances great enough that peculiar motions of galaxies are small compared with the overall expansion, or Hubble flow. To determine the distance to a galaxy, astronomers must choose from a variety of complicated methods. Each has its advantages, but none is perfect.

Measuring Distances to Galaxies

Astronomers can most accurately measure distances to nearby galaxies by monitoring a type of star commonly known as a Cepheid variable. Over time, the star changes in brightness in a periodic and distinctive way. During the first part of the cycle, its luminosity increases very rapidly, whereas during the remainder of the cycle, the luminosity of the Cepheid decreases slowly. On average, Cepheid variables are about 10,000 times brighter than the sun.

Remarkably, the distance to a Cepheid can be calculated from its period (the length of its cycle) and its average apparent brightness (its luminosity as observed from Earth). In 1908 Henrietta S. Leavitt of Harvard College Observatory discovered that the period of a Cepheid correlates closely with its brightness. She found that the longer the period, the brighter the star. This relation arises from the fact that a Cepheid's brightness is proportional to its surface area. Large, bright Cepheids pulsate over a long period just as, for example, large bells resonate at a low frequency (or longer period).

By observing a Cepheid's variations in luminosity over time, astronomers can obtain its period and average apparent luminosity, thereby calculating its absolute luminosity (that is, the apparent brightness the star would have if it were a standard distance of 10 parsecs away). Furthermore, they know that the apparent luminosity decreases as the distance it travels increases—because the apparent luminosity falls off in proportion to the square of the distance to an object. Therefore, we can compute the distance to the Cepheid from the ratio of its absolute brightness to its apparent brightness.

During the 1920s, Hubble used Cepheid variables to establish that other galaxies existed far beyond the Milky Way. By measuring apparent brightnesses and periods of faint, starlike images that he discovered on photographs of objects such as the Andromeda Nebula (also known as M31), the Triangulum Nebula (M33) and NGC 6882, he could show that these objects were located more than several hundred thousand light-years from the sun, well outside the Milky Way. From the 1930s to the 1960s, Hubble, Sandage and others struggled to find Cepheids in nearby galaxies. They succeeded in measuring the distances to about a dozen galaxies. About half these galaxies are useful for the derivation of the Hubble constant.

One of the difficulties with the Cepheid method is that dust between stars diminishes apparent luminosity. Dust particles absorb, scatter and redden light from all types of stars. Another complication is that it is hard to establish how Cepheids of different chemical element abundances differ in brightness. The effects of both dust and element abundances are most severe for blue and ultraviolet light. Astronomers must either observe Cepheids at infrared wavelengths, where the effects are less significant, or observe them at many different optical wavelengths so that they can assess the effects and correct for them.

During the 1980s, my collaborator (and husband) Barry F. Madore of the California Institute of Technology and I remeasured the distances to the nearest galaxies using charge-coupled devices (CCDs) and the large reflecting telescopes at many sites, including Mauna Kea in Hawaii, Las Campanas in Chile and Mount Palomar in California. As a result, we determined the distances to nearby galaxies with much greater accuracy than has been done before.

These new CCD observations proved critical to correct for the effects of dust and to improve previous photographic photometry. In some cases, we revised distances to nearby galaxies downward by a factor of two. Were it feasible, we would use Cepheids directly to measure distances associated with the universe's expansion. Unfortunately, so far we cannot detect Cepheids in galaxies sufficiently far away so that we know they are part of a "pure" Hubble expansion of the universe.

Nevertheless, astronomers have developed several other methods for measuring relative distances between galaxies on vast scales, well beyond Cepheid range. Because we must use the Cepheid distance scale to calibrate these techniques, they are considered secondary distance indicators.

During the past decade, astronomers have made great strides developing techniques to measure such relative distances. These methods include observing and measuring a special category of supernovae: catastrophic explosions signaling the death of certain low-mass stars. Sandage and his collaborators are now determining the Hubble constant by studying such supernovae based on the calibration of Cepheids. Other secondary distance-determining methods include measuring the brightnesses and rotations of velocities of entire spiral galaxies, the fluctuations (or graininess) in the light of elliptical galaxies, and the analysis and measurement of the expansion properties of another category of younger, more massive supernovae. The key to measuring the Hubble constant using these techniques is to determine the distance to selected galaxies using Cepheids; their distances can, in turn, be used to calibrate the relative extragalactic distance scale by applying secondary methods.

Yet scientists have not reached a consensus about which, if any, secondary indicators are reliable. As the saying goes, "the devil is in the details." Astronomers disagree on how to apply these methods, whether they should be adjusted for various effects that might bias the results, and what the true uncertainties are. Differences in the choice of secondary methods lie at the root of most current debates about the Hubble constant.

Establishing a Distance Scale

One technique for measuring great distances, the Tully-Fisher relation, relies on a correlation between a galaxy's brightness and its rotation rate. High-luminosity galaxies typically have more mass than low-luminosity galaxies, and so bright galaxies rotate slower than dim galaxies. Several groups have tested the Tully-Fisher method and shown that the relation does not appear to depend on environment; it remains the same in the dense and outer parts of rich clusters and for relatively isolated galaxies. The Tully-Fisher relation can be used to estimate distances as far away as 300 million light-years. A disadvantage is that astronomers lack a detailed theoretical understanding of the Tully-Fisher relation.

COURTESY OF HARVARD UNIVERSITY ARCHIVES

HENRIETTA S. LEAVITT of Harvard College Observatory found, in 1908, a correlation between the period of a Cepheid variable and its absolute brightness. This correlation allows astronomers to measure distances to the nearest galaxies.

Another distance indicator that has great potential is a particular kind of supernova known as type Ia. Type Ia supernovae, astronomers believe, occur in double-star systems in which one of the stars is a very dense object known as a white dwarf. When a companion star transfers its mass to a white dwarf, it triggers an explosion. Because supernovae release tremendous amounts of radiation, astronomers should be able to see supernovae as far away as five billion light-years—that is, a distance spanning a radius of half the visible universe.

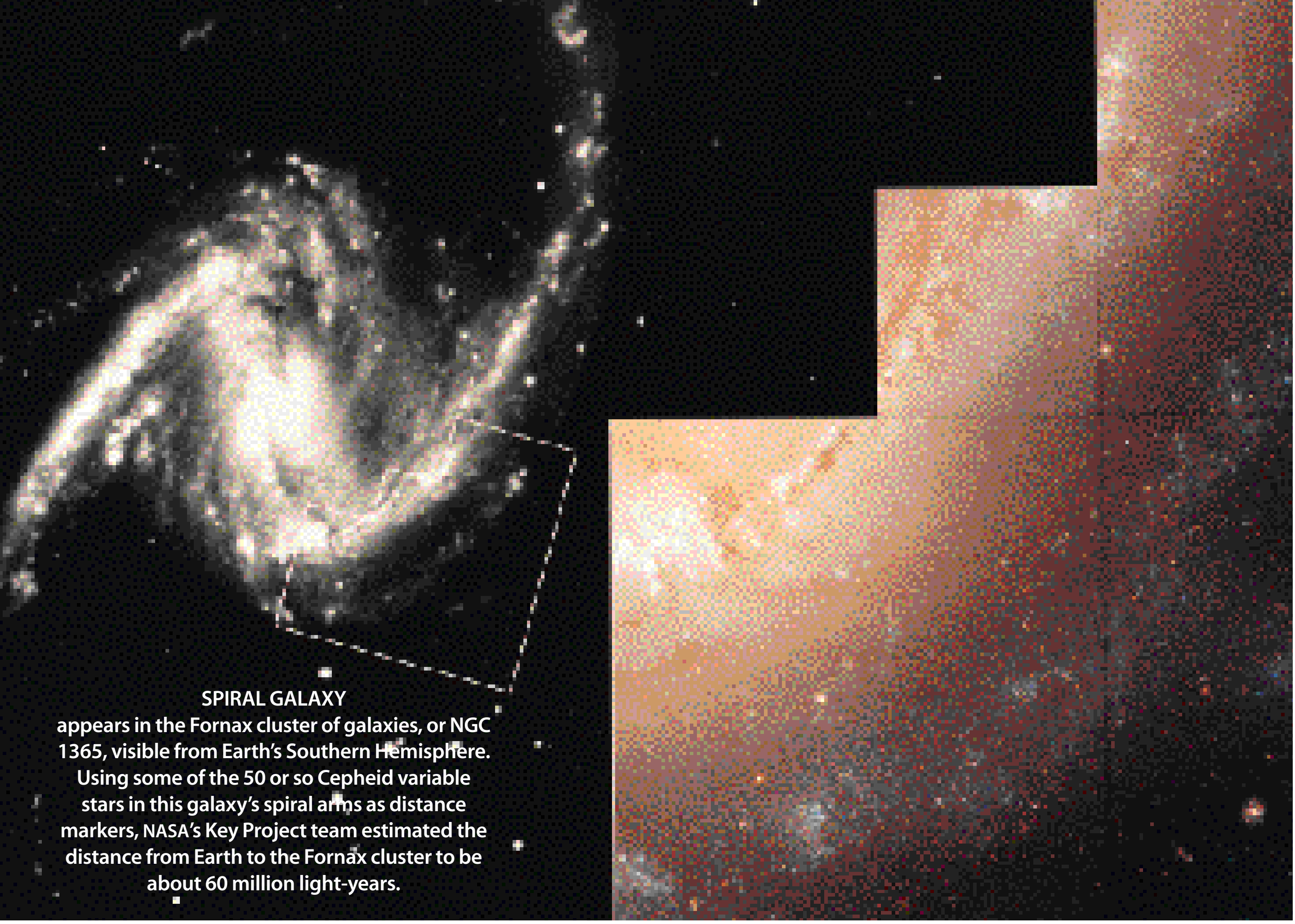
Type Ia supernovae make good distance indicators because, at the peak of their brightness, they all produce roughly the same amount of light. Using this information, astronomers can infer their distance.

If supernovae are also observed in galaxies for which Cepheid distances can be measured, then the brightnesses of supernovae can be used to infer distances. In practice, however, the brightnesses of supernovae are not all the same; there is a range of brightnesses that must be taken into account. A difficulty is that supernovae are very rare events, so the chance of seeing one nearby is very small. Unfortunately, a current limitation of this method is that about half of all supernovae observed in galaxies close enough to have Cepheid distances were observed decades ago, and these measurements are of low quality.

An interesting method, developed by John L. Tonry of the Massachusetts Institute of Technology and his colleagues, exploits the fact that nearby galaxies appear grainy, whereas remote galaxies are more uniform in their surface-brightness distribution. The graininess decreases with distance because the task of resolving individual stars becomes increasingly difficult. Hence, the distance to a galaxy can be gauged by how much the apparent brightness of the galaxy fluctuates over its surface. This method cannot currently extend as far as the Tully-Fisher relation or supernovae, but it and other methods offer an important, independent way to test and compare relative distances. These comparisons yield excellent agreement, representing one of the most important advancements in recent years.

For decades, astronomers have recognized that the solution to the impasse on the extragalactic distance scale would require observations made at very high spatial resolution. The Hubble telescope can now resolve Cepheids at distances 10 times farther (and therefore in a volume 1,000 times larger) than we can do from the ground. A primary motivation for building an orbiting optical telescope was to enable the discovery of Cepheids in remoter galaxies and to measure accurately the Hubble constant.

More than a decade ago several colleagues and I were awarded time on the Hubble telescope to undertake this project. This program involves 26 astronomers, led by me, Jeremy R. Mould of Mount Stromlo and Siding Springs Observatory, and Robert C. Kennicutt of Steward Obser-



SPIRAL GALAXY
appears in the Fornax cluster of galaxies, or NGC 1365, visible from Earth's Southern Hemisphere. Using some of the 50 or so Cepheid variable stars in this galaxy's spiral arms as distance markers, NASA's Key Project team estimated the distance from Earth to the Fornax cluster to be about 60 million light-years.

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vatory. Our effort involves measuring Cepheid distances to about 20 galaxies, enough to calibrate a wide range of secondary distance methods. We aim to compare and contrast results from many techniques and to assess the true uncertainties in the measurement of the Hubble constant.

Though still incomplete, new Cepheid distances to a dozen galaxies have been measured as part of this project. Preliminary results yield a value of the Hubble constant of about 70 km/s/Mpc with an uncertainty of about 15 percent. This value is based on a number of methods, including the Tully-Fisher relation, type Ia supernovae, type II supernovae, surface-brightness fluctuations, and Cepheid measurements to galaxies in the nearby Virgo and Fornax clusters.

Sandage and his collaborators have reported a value of 59 km/s/Mpc, based on type Ia supernovae. Other groups (including our own) have found a value in the middle 60 range, based on the same type Ia supernovae. Nevertheless, these current disagreements are much smaller than the earlier discrepancies of a factor of two, which have existed until now. This progress is encouraging.

Two other methods for determining the Hubble constant spark considerable interest because they do not involve the Cepheid distance scale and can be used to measure distances on vast cosmological scales. The first of these alternative methods relies on an effect called gravitational lensing: if light from some distant source travels near a galaxy on its way to Earth, the light can be deflected, as a result of gravity, according to Einstein's general theory of relativity. The light may take many different paths around the galaxy, some shorter, some longer, and consequently arrives at Earth at different times. If the brightness of the source varies in some distinctive way, the signal will be seen first in the light that takes the shortest path and will be observed again, some time later, in the light that traverses the longest path. The difference in the arrival times reveals the difference in length between the two light paths. By applying a theoretical model of the mass distribution of the galaxy, astronomers can calculate a value for the Hubble constant.

The second method uses a phenomenon known as the Sunyaev-Zel'dovich (SZ) effect. When photons from the microwave background travel through galaxy clusters, they can gain energy as they scatter off the hot plasma (x-ray) electrons found in the clusters. The net result of the scattering is a decrease in the microwave background toward the position of the cluster. By comparing the microwave and x-ray distributions, a distance to the cluster can be inferred. To determine the distance, however, astronomers must also know the average density of the electrons, as well as their distribution and temperature, and have an accurate measure of the decrement in the temperature of the microwave background. By calculating the distance to the cluster and measuring its recessional velocity, astronomers can then obtain the Hubble constant.

The SZ method and the gravitational-lensing technique are promising. Yet, to date, few objects are available with the required characteristics. Hence, these methods have not yet been tested rigorously. Fortunately, impressive progress is being made in both these areas with large, new surveys. Current applications of these methods result in values of the Hubble constant in the range of 40 to 80 km/s/Mpc.

The debate continues regarding the best method for determining distances to remote galaxies. Consequently, astronomers hold many conflicting opinions about what the best current estimate is for the Hubble constant.

How Old Is the Universe?

The value of the Hubble constant has many implications for the age, evolution and fate of the universe. A low value for the Hubble constant implies an old age for the universe, whereas a high value suggests a young age. For example, a value of 100 km/s/Mpc indicates the universe is about 6.5 to 8.5 billion years old (depending on the amount of matter in the universe and the corresponding deceleration caused by that matter). A value of 50 km/s/Mpc suggests, however, an age of 13 to 16.5 billion years.

And what of the ultimate fate of the universe? If the average density of matter in the universe is low, as current observations indicate, the standard cosmological model predicts that the universe will expand forever.

Nevertheless, theory and observations suggest that the universe contains more mass than what can be attributed to luminous matter. A very active area of cosmological research is the search for this additional "dark" matter in the universe. To answer the question about the fate of the universe unambiguously, cosmologists require not only a knowledge of the Hubble constant and the average mass density of the universe but also an independent measure of the age of the universe. These three quantities are needed to specify uniquely the geometry and the evolution of the universe.

The value of the Hubble constant has many implications for the fate of the universe.

If the Hubble constant turns out to be high, it would have profound implications for our understanding of the evolution of galaxies and the universe. A Hubble constant of 70 km/s/Mpc yields an age estimate of nine to 12 billion years (allowing for uncertainty in the value of the average density of the universe). A high-density universe corresponds to an age of about nine billion years. A low-density universe corresponds to an age of about 12 billion years for this same value of the Hubble constant.

These estimates are all shorter than what theoretical models suggest for the age of old stellar systems known as globular clusters. Globular clusters are believed to be among the first objects to form in our galaxy, and their age is estimated to be between 13 and 17 billion years. Obviously, the ages of the globular clusters cannot be older than the age of the universe itself.

Age estimates for globular clusters are often cited as a reason to prefer a low value for the Hubble constant and therefore an older age of the universe. Some astronomers argue, however, that the theoretical models of globular clusters on which these estimates depend may not be complete and may be based on inaccurate assumptions. For instance, the models rely on knowing precise ratios of certain elements in globular clusters, particularly oxygen and iron. Moreover, accurate ages require accurate measures of luminosities of globular cluster stars, which in turn require accurate measurements of the distances to the globular clusters.

Recent measurements from the Hipparcos satellite suggest that the distances to globular clusters might have to be increased slightly. The resulting effect of this change, if confirmed, would be to lower the globular cluster ages, perhaps to 11 or 12 billion years. Given the current uncertainties in the measurements of both the Hubble constant and the models and distances for globular clusters, these new results may indicate that no serious discrepancy exists between the age of the universe, based on expansion, and the age of globular clusters.

In any case, these subtle inconsistencies highlight the importance of accurate distance measurements, not only for studying galaxies and determining the Hubble constant but also for understanding globular clusters and their ages.

A high value for the Hubble constant raises another potentially serious problem: it disagrees with standard theories of how galaxies are formed and distributed in space. For example, the theories predict how much time is required for large-scale clustering, which has been observed in the distribution of galaxies, to occur. If the Hubble constant is large (that is, the universe is young), the models cannot reproduce the observed distribution of galaxies.

Scientists are excited about results in the next decade. The recently installed NICMOS infrared camera on the Hubble telescope will allow us to refine the Cepheid distances measured so far. Large, ground-based telescope surveys will increase the number of galaxies for which we can measure relative distances beyond the reach of Cepheids.

Promising space missions loom on the horizon, such as the National Aeronautics and Space Administration's Microwave Anisotropy Probe (MAP) and the European Space Agency's Planck Surveyor. These two experiments will permit detailed mapping of small fluctuations in the cosmic microwave background. If current cosmological theories prove correct, these measurements will robustly determine the density of matter in the universe and independently constrain the Hubble constant.

Although the history of science suggests that ours is not the last generation to wrestle with these questions, the next decade promises much excitement. There are many reasons to be optimistic that the current disagreement over values of the cosmological parameters governing the evolution of the universe will soon be resolved.

The Author

WENDY L. FREEDMAN is a staff member at the Carnegie Institution's observatories in Pasadena, Calif. Born in Toronto, she received a Ph.D. in astronomy and astrophysics from the University of Toronto in 1984 and, in 1987, became the first woman to join Carnegie's scientific staff. In 1994 she received the Marc Aaronson Prize for her contributions to the study of extragalactic distance and stellar populations of galaxies. A co-leader of the Hubble Space Telescope Key Project to measure the Hubble constant, she is also a member of the National Research Council's Committee on Astronomy and Astrophysics, the executive board of the Center for Particle Astrophysics and the National Aeronautics and Space Administration's scientific oversight committee planning the Next Generation Space Telescope. Beyond astronomy, her main interest is her family: husband Barry, daughter Rachael and son Daniel. This article updates a version that appeared in *Scientific American* in November 1992.