

# GOING THE DISTANCE

*Without knowledge of cosmic distances,  
the secrets of the universe would remain locked.*

**by Marcia Bartusiak**

Consider the vexation in not knowing with certainty whether you are three-foot-tall or six-foot-tall, or that the distance from Chicago to Los Angeles is 1,000 miles or 2,000 miles. Buying a new pair of slacks or planning this summer's roadtrip would be a guaranteed headache. But believe it or not, astronomers are regularly saddled with such uncertainty when it comes to nailing down some of the most fundamental cosmological parameters.

In the closing decades of the 20th century, astronomers were stalled. The Hubble Constant — a simultaneous measure of the universe's expansion rate, and key to its age and ultimate dimensions — persistently varied by a factor of two among different collaborations. To cosmologists, not knowing such a fundamental feature of the cosmos was, and still is, terribly frustrating.



Through no inherent fault or lack of ingenuity amongst its ranks, astronomy is steeped in a rich tradition of uncertainty when it comes to determining distances to stars, nebulae, and galaxies. Still, despite the difficulty, astronomers have continually devised many clever ways to adequately determine distance, and the good news is that they keep getting better and better.

“Twenty years ago there were huge problems,” says R. Brent Tully of the University of Hawaii. “We didn’t have confidence in our distance measurements to close-by objects such as the Andromeda Galaxy. But now there seems to be a falling-into-place.” New detectors, more powerful computers, and new distance markers — coupled with the use of the Hubble Space Telescope (HST) and powerful ground-based observatories — are at last allowing astronomers to conduct precise surveys. “The revolution came about because we now have the technology to implement ideas that were so difficult in the past,” adds Saul Perlmutter of the Lawrence Berkeley National Laboratory in California. In the process, long-held notions about the dynamics of the universe have been completely overturned.

### BABY STEPS

Astronomical distance measurements outside of the solar system got a serious boost in 1838 when the German astronomer and mathematician Friedrich Wilhelm Bessel successfully measured the distance to the nearby star 61 Cygni (see “Constructing the Distance Ladder,” page 28).

Measurements beyond the Milky Way Galaxy became possible in the early 1900s thanks to the work of astronomers like Henrietta Swan Leavitt. While working at the Harvard College Observatory, Leavitt discovered a fascinating property of Cepheids — variable stars that regularly pulsate in size and luminosity over periods of just a few days. She noticed that the period of the pulsation correlates closely with the Cepheid’s brightness: the longer the period, the brighter the star.

With a calibrated Cepheid period-luminosity relation, astronomers finally possessed the means to figure out a star’s intrinsic luminosity, and ultimately its distance. Cepheid stars could be treated as “standard candles” — well-understood and reliable brightness indicators.



An object’s brightness decreases with the square of its distance. So, by knowing a Cepheid’s intrinsic luminosity, derived from the pulsation period, astronomers are able to determine how far away the star is by seeing how much it appears to have dimmed. Moreover, astronomers have been treated to a bonus. As Cepheids are 10,000 times brighter than the sun, they can be spotted at great distances.

### SURVEYING THE EXPANSE (CEPHEID VARIABLES)

It was observations of Cepheids in M31, the Pinwheel Galaxy in Triangulum (M33), and NGC 6822 that

**Top: 2.5 million light-years and closing: Cepheids in the arms of Andromeda reveal the proximity of our near neighbor.** B. J. Mochejska/FLWO/MDM  
**Left: Henrietta Swan Leavitt (1868–1921).** HCO  
**Right: Cosmic couple Wendy Freedman and Barry Madore carry the Cepheid torch.** Raleigh Souther

allowed American astronomer Edwin Hubble to discover the universe in 1923. He conclusively proved that these “spiral nebulae” don’t reside within the borders of the Milky Way Galaxy. But, rather, they are distant galaxies, comprised of billions of stars, lying millions of light-years away.

Hubble also noticed a pattern in his growing catalog of extragalactic dis-

tance measurements: The more distant the galaxy, the more its light shifted toward the red end of the spectrum. He concluded that the light waves were getting stretched (redshifted) because the universe is expanding. The farther away the galaxy, the greater its recession velocity.

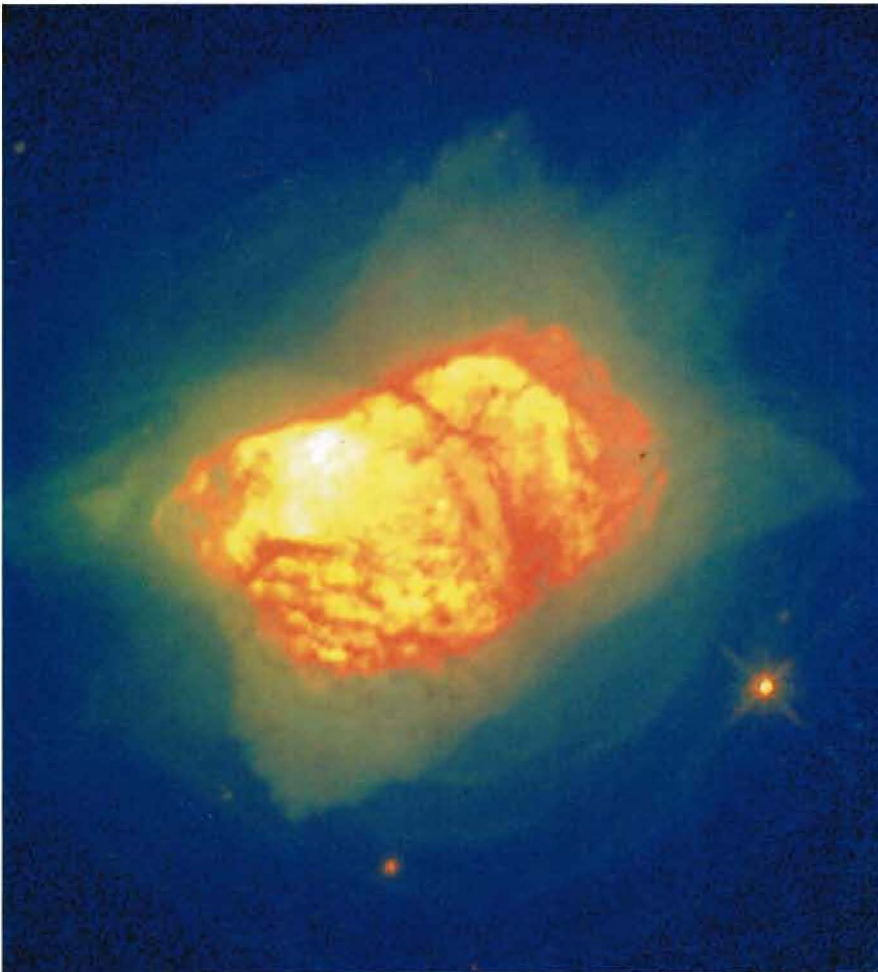


Hubble calculated an expansion rate for the universe (Hubble Constant) of 500 kilometers per second per megaparsec (one parsec is equivalent to 3.26 light-years, and the prefix “mega” means million), but eventually a better understanding of the different types of Cepheid variables brought the rate down to between 50 and 100.

Shifting that expansion rate into reverse, astronomers can extrapolate back to a time when all matter occupied the same space — the moment of the Big Bang. A Hubble Constant ranging from 100 to 50 translates into a universe from 10 to 20 billion years old, respectively. This uncertainty persisted for several decades. What’s more, each camp — those defending a low Hubble Constant and those fighting for a higher value — fiercely argued that their methods were better calibrated and thus more precise.

**Left: Multiple distance indicators may lie waiting in remote galaxies such as M51.** ING/WHT

**Below: Planetary nebulae, like the Milky Way’s NGC 7027, are seen out to the Virgo Cluster.** NASA/HST



## STEP BY STEP

Settling the disagreement over the Hubble Constant became a high priority in the closing decades of the twentieth century. So much so, in fact, that a chief design constraint for the HST was that its aperture be large enough to significantly extend the Cepheid-based distance scale — all the way out to the Virgo Cluster some 50 million light-years away. The 2.4-meter HST mirror allows astronomers to resolve Cepheids ten times farther than ground-based telescopes. Since 1993, members of the Hubble Key Project, led by Wendy Freedman of the Carnegie Observatories, as well as other users of HST, have discovered hundreds of new Cepheids in more than two dozen galaxies. As a result, the Key Project now calculates a Hubble Constant of 72 kilometers per second per megaparsec, give or take 10 percent — just about in the middle of the previously disputed range.

It was important to find Cepheids in galaxies beyond our Local Group and out to Virgo. Cepheid distance measurements are the workhorse of the cosmological distance determination business. In fact, astronomers use Cepheid-determined distances to calibrate further distance measurements, forming what’s known as the Cosmological Distance Ladder (see “Constructing the Distance Ladder,” page 28). To everyone’s delight (and relief), these various markers are agreeing with one another fairly well out to the Virgo Cluster. “It’s nice to see that happen,” says Freedman. “The distance ladder isn’t so shaky anymore.”

## COUNTING HEADSTONES (PLANETARY NEBULAE)

Planetary nebulae — luminous death shrouds of low-mass stars like the sun — form an additional rung on the distance ladder. As these low-mass stars evolve from their hydrogen-burning phase and on to the red giant phase, they eventually shed their outer layers of gas into interstellar space, leaving behind an incredibly dense and hot white dwarf core. The sloughed gas subsequently absorbs ultraviolet radiation from the hot stellar remnant and largely re-emits it at a few choice wavelengths, especially a strong green line formed by twice-ionized oxygen atoms. This makes planetary nebulae out to the Virgo Cluster easy to spot with ground-based telescopes.

Planetary nebulae are valuable distance indicators because they are found not only in spirals but also in elliptical galaxies, which don't contain Cepheids. Thus, they can bridge distance scales based solely on one type of galaxy or the other, notes Robin Ciardullo of Pennsylvania State University, who, along with George Jacoby of the Kitt Peak National Observatory, largely pioneered this technique.

In the late 1980s, Jacoby and Ciardullo used planetary nebulae to measure a distance to the Virgo Cluster. Others, who gauge distances based on the surface brightness of elliptical galaxies, a technique introduced by University of Hawaii astronomer John Tonry, seem to agree. "Despite the fact that our techniques have nothing in common, we get the same answer," notes Ciardullo. Follow-up investigations by the Hubble Cepheid team also match their findings within 10 percent.

### **BRIGHTER, FASTER, FARTHER?**

(TULLY-FISHER RELATION)

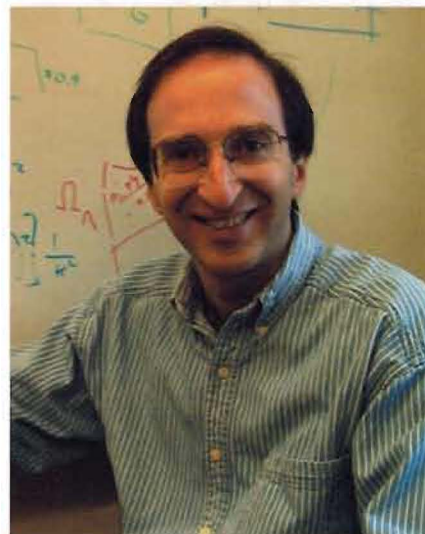
Continuing up the ladder, previous methods are used to calibrate tech-

niques, such as the Tully-Fisher relation, which allows astronomers to measure distances even greater than that of the Virgo Cluster. In the mid-1970s, astronomers R. Brent Tully, now with the University of Hawaii, and J. Richard Fisher of the National Radio Astronomy Observatory, discovered a link between a spiral galaxy's luminosity and its rotation rate.

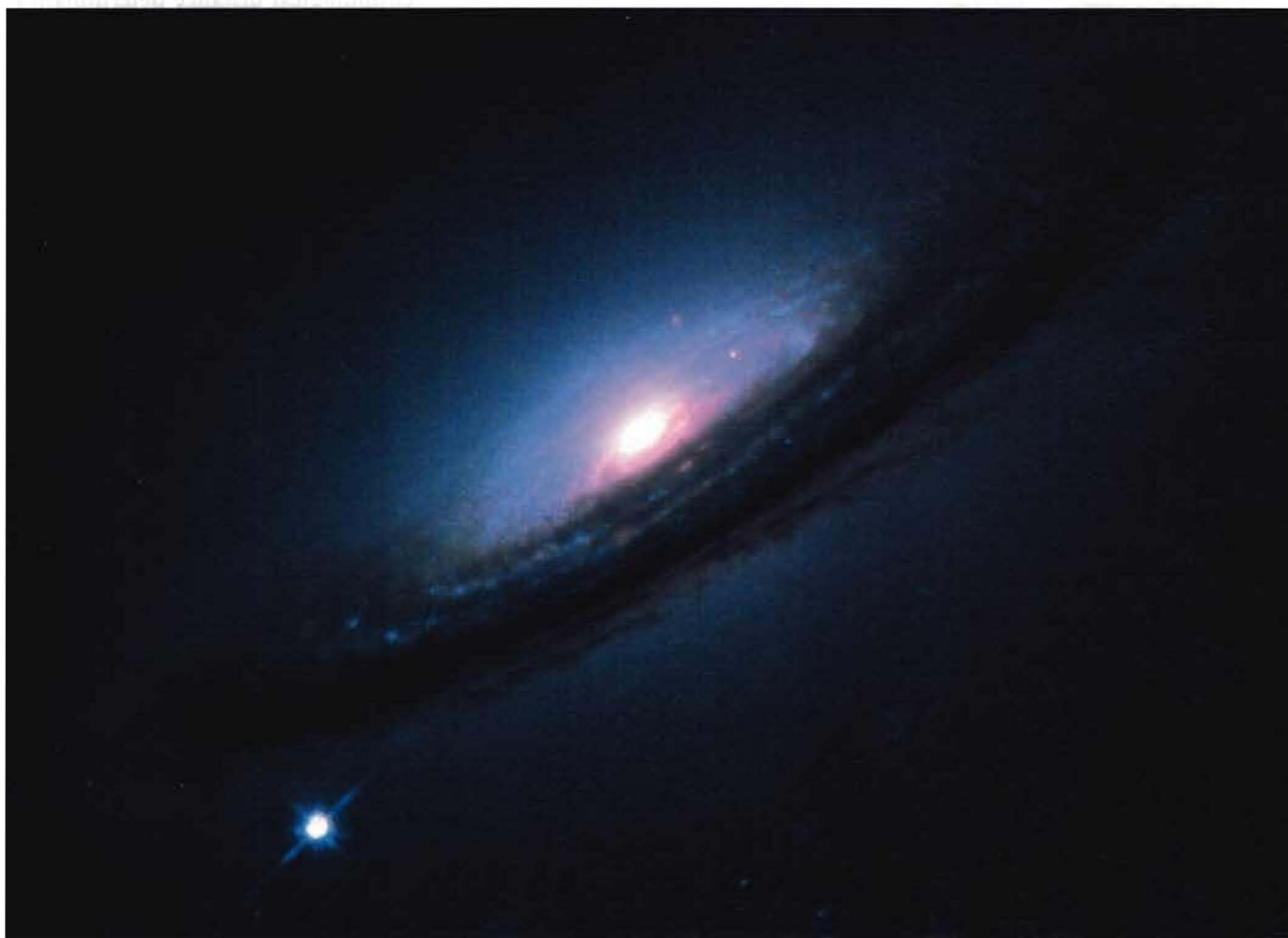
Bright spiral galaxies, having more mass, rotate faster than dimmer spirals. By determining a galaxy's rotation rate — one way is to measure hydrogen emissions with radio telescopes — astronomers are able to peg its intrinsic luminosity and ultimately use it as a standard candle.

The Tully-Fisher relation is valuable because it's so handy. With other methods, such as planetary nebulae or Cepheids, astronomers must hunt for specific objects that may or may not be

found. The most recognizable galaxy type in the cosmos — the ubiquitous spiral — can be found anywhere they look. The method does have larger margins of uncertainty, but it serves as a useful double-check. Tully and his colleagues have analyzed nearly a thousand galaxies in this way, out to about one hundred million light-years.



**Right: Supernova sleuth Saul Perlmutter waited ten years for his team to finally hit pay dirt. LBNL**  
**Below: Modern supernovae searches routinely uncover dozens of blasts, like SN1994D (lower left of image), each year. NASA/HST/High-Z SN Search**



## SUPER-STANDARD CANDLES

(TYPE IA SUPERNOVAE)

In the last five years, perhaps the most exciting development in cosmic distance measurements has been the use of Type Ia supernovae as standard candles. “This is a revolutionary old method,” quips Perlmutter. Walter Baade first suggested in 1927 that supernovae (what he then called “Hauptnovae” or chief novae) would be useful distance markers, but it took many years for astronomers to recognize that there were different kinds of supernovae with differing brightnesses.

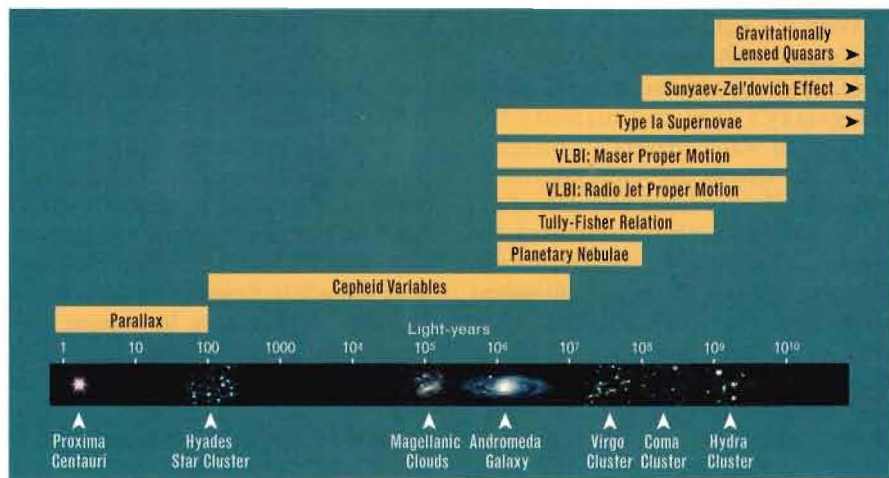
Massive stars blow up as brilliant supernovae (known as “Type II” explosions) when they run out of fuel. Still, there are other ways for stars to go supernova. White dwarf stars, objects as tiny as Earth yet as massive as the sun, often reside in binary star systems and are known to steal gas from their stellar companions.

As a white dwarf pilfers mass, it gets compressed under the weight of the added material. If squeezed down far enough — or to the point that the total mass of the white dwarf reaches about 1.4 times the mass of the sun — a runaway thermonuclear explosion ensues and the entire star is consumed in about a second.

Perhaps most exciting to cosmologists, however, is that such explosions (called Type Ia supernovae) yield a similar peak brightness, allowing them to be calibrated as standard candles. And they are so bright — up to 10 times brighter than Type II supernovae — that they can be seen all the way to the edge of the visible universe.

Perlmutter started working on this approach a decade ago, in part to prove that supernovae could be reliably spotted and in appreciable numbers. He and his colleagues formed the Supernova Cosmology Project and by the mid-1990s were finding batches of supernovae with every observing session, convincing major observatories that it was worthwhile to schedule telescope time to examine these objects as distance markers.

Meanwhile, another international group of astronomers, known as the High-Z Supernova Search Team, had long been focusing on understanding the mechanisms of these explosions. “We complemented each other,” notes University of California — Berkeley astronomer Alex Filippenko, who has worked on both teams.



The rival teams observe many fields on the celestial sky once or twice a year, right after a new moon when the sky is darkest, using telescopes in Chile and Hawaii. Three weeks later, they examine the same fields to detect changes. Type Ia supernovae are extremely rare, but by examining hundreds of thousands of galaxies at a time, a dozen or so supernovae are usually sighted in any one session. They then follow up with a variety of ground-based telescopes to examine the candidates in more detail.

In 1997, preliminary results indicated that some of these supernovae, a few billion light-years distant, appeared fainter than expected. They thought that perhaps supernovae in the past were less luminous because of differing chemical compositions. But, since the spectra of the distant supernovae did not differ from stellar explosions nearby, the supernova hunters concluded that it's more likely the universe was expanding more slowly in the past and is now accelerating. This would make the supernovae more distant (and dimmer) than expected.

The recent discovery of the most distant Type Ia supernova ever observed, by Adam Reiss of the Space Telescope Science Institute and Peter Nugent at the Lawrence Berkeley National Laboratory (see *AstroNews* July 2001, page 20), corroborates the finding of an accelerating universe. It now seems highly probable that the universe is dominated by a yet-unknown form of dark energy, which usurps the gravitational attraction between matter in the universe to speed up the cosmic expansion.

Upon initially hearing the news, Tully had confidence in the accelerated expansion hypothesis, mainly because

the new finding settles some old disputes. Previously, when distance measurements suggested a high Hubble Constant, problems arose. That's because a large Hubble Constant implies that the universe is fairly young, generally 10 billion years or less.

But certain stars in the Milky Way Galaxy have been found to be far older than 10 billion years. With an added dark energy to gradually boost expansion over time, the universe suddenly becomes older. “There is no longer a conflict,” says Tully. “Everything works much better.”

Nonetheless, astronomers like Perlmutter are still proceeding with caution. “What will help,” he says, “is going out into space to measure thousands of supernovae each year.” And the SNAP (Supernova/Acceleration Probe) satellite is on the drawing board to do just that.

With SNAP, astronomers will be able to measure the universe's expansion at various epochs to see how it has changed over time, and determine what's causing the current acceleration.

## AVOIDING THE LADDER ALTOGETHER

(VLBI)

Astronomers over the last decade have also been developing and enhancing new techniques that will allow them to skip the distance ladder altogether, to take distance measurements of faraway objects directly.

Using the Very Long Baseline Array (VLBA) — a set of ten radio telescopes situated around the world from Hawaii to the Virgin Islands — astronomer James Moran of the Harvard-Smithsonian Center for Astrophysics and his colleagues recently made a direct distance measurement to the spiral galaxy NGC 4258 (M106).

With the radio telescopes acting as one giant dish, thousands of miles wide, they were able to tightly focus on the galaxy's core and measure the velocity of water masers — compact molecular clouds that emit an intense radio signal — swirling in a disk of gas at the galaxy's center. Comparing the masers' intrinsic speed (inferred from Doppler shift of the maser emission) with how fast they appear to be moving as seen from Earth yielded a distance. (Imagine a boat, racing across the far horizon at a known speed. Seeing how much more slowly the boat appears to move from shore gives one a

means of determining its distance with a bit of geometry.) In this way, M106 was found to be nearly 24 million light-years away.

“[M106] was the miracle source,” says Moran. “There was perfect placement of the masers within the disk.” Astronomers using HST to measure Cepheids in M106 initially came up with a slightly longer distance, about 26 million light-years, but recent corrections to the HST data bring them closer to the maser-based distance. “We

like to look upon the masers as giving the fundamentally correct answer, as it's based on simple geometry,” says Moran.

**Deep in the dusty core of M106, swirling masers act as cosmic beacons.** NASA/HST



## CONSTRUCTING THE DISTANCE LADDER: LOCAL DISTANCE MEASUREMENTS

Measuring astronomical distances has never been a one-shot deal. Observers have proceeded slowly, step by step, along a distance ladder. Nearby objects, with well-known properties, are used to calibrate brighter objects that can be used as distance indicators farther out. They in turn are used to calibrate other indicators to even greater distances. One error in that chain affects the accuracy of all the steps that follow. “There's always a weak point,” says University of Hawaii astronomer R. Brent Tully. “We charge after the weak point of the moment, settle it, and then something else steps in.”

The first (and most reliable) step is trigonometric parallax, which depends solely on geometry and the radius of Earth's orbit, which is very well known. The concept is easily demonstrated by holding a finger six inches from your eyes. Looking at your finger first with one eye, then the other, it appears to shift against the background. You'll notice that the shift lessens as your finger moves farther away.

Earth shifts every six months some 186 million miles from one side of its orbit to the other. At each extreme, astronomers get a slightly different line of sight to a nearby star, as seen against the distant background stars. This “parallax shift” allows observers to triangulate and measure the distance to the star (see diagram).

Modern parallax measurements are useful out to several hundred light-years for individual stars. Friedrich Wilhelm Bessel was the first to carry out such a stellar parallax measurement in 1838 from his observatory in Königsberg, Prussia (now Kaliningrad, Russia). He measured the shift for the star 61 Cygni, obtaining a distance of 10.4 light-years (very close to today's accepted value of 11.4 light-years).

Before 1989, only a few dozen stars had parallax measurements with 5 percent error or less. It was then that the European Space Agency's Hipparcos satellite began a four-year mission to measure the shift for more than 7,000 stars to 5 percent accu-

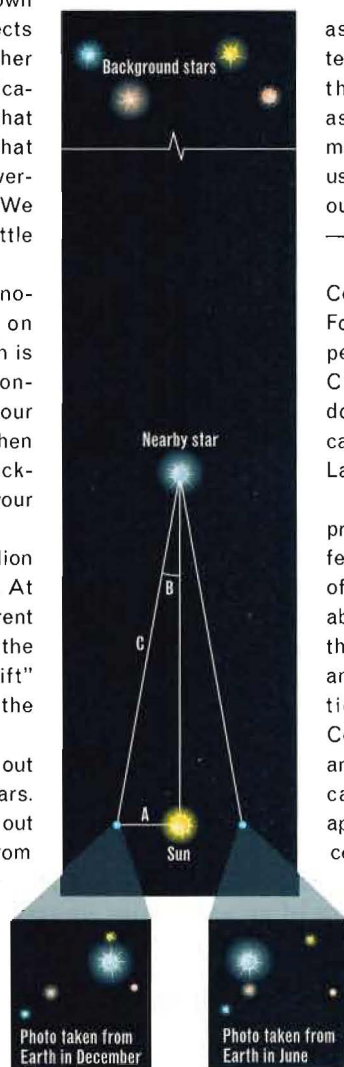
racy. With lesser accuracy, it pegged the parallaxes and brightness of more than a million stars in the Milky Way.

For stars beyond the reach of parallax, astronomers turn to other techniques. Star clusters, for example, offer a good collection of stars at the same distance. By studying clusters, astronomers can gain a handle on the absolute magnitude of a certain spectral type. They can then use that class of stars as a standard candle farther out. This can be done out to the Magellanic Clouds — about 150,000 light-years.

The premiere standard candles are the Cepheids, supergiant stars that regularly pulsate. For a century, astronomers have known that the period of the pulsation is directly related to the Cepheid's intrinsic luminosity. But a valuable double-check on that relationship was recently carried out by Caltech graduate student Benjamin Lane and his collaborators.

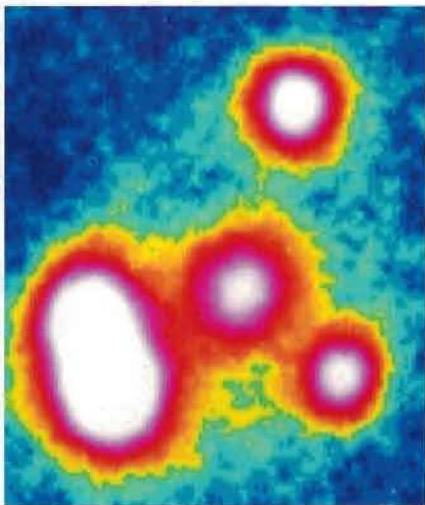
The Palomar Testbed Interferometer is comprised of two 16-inch telescopes, separated by 360 feet, that conspire to generate the resolving power of one giant telescope. The twin instruments were able to resolve the disk of Zeta Geminorum, one of the brightest Cepheids in the northern sky. Lane and his team could then observe the star's pulsation and measure the change in its diameter. Comparing this modulation with the corresponding angular change on the sky, the astronomers could calculate the distance directly, which came to approximately 1,100 light-years (give or take 15 percent). With improvements, they hope to better the accuracy to within a few percent. Lane's work serves as a valuable calibration on the luminosity of Cepheids farther out, independent of Leavitt's period-luminosity law.

Other variable stars are useful in a similar way. Yellow RR Lyrae stars, for example, have very short periods (less than a day) and seem to have the same absolute magnitude. Spotting an RR Lyrae thus gives you a handle on the distance required to reach its level of dimness. — M.B.



## KEEPING THINGS PROPER (QUASAR JETS)

Along a similar vein, radio jets shooting out from the cores of active galaxies may reveal their distances. Roughly ten percent of quasars and active galaxies have active jets, so there's a good supply of sources for this technique. More importantly, they can be measured to distances far beyond those currently reached by Cepheids or supernovae. Following jet motions with radio telescopes, observers compare apparent motion to actual motion, based on Doppler shift and magnetic field measurements.



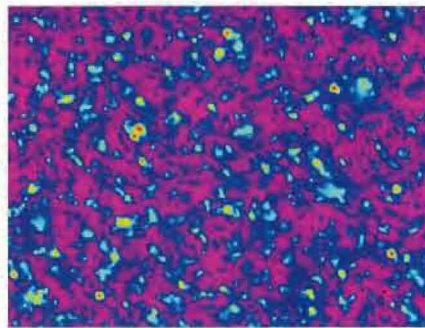
Dan Homan and John Wardle of Brandeis University conducted such a test on the quasar 3C 279. The movement of any one feature in the jet is on the order of a few milliarcseconds on the sky. "That's about the height of a fairly tall person on the moon as seen from Earth," notes Homan. But, as with the masers, radio astronomers can detect such subtle motions with the VLBA. With this direct tape measure, Homan and Wardle arrived at a distance to 3C 279 of about 6 billion light-years. The Hubble Constant they calculate from this information is consistent with an accelerating universe deduced from the supernovae findings.

## COSMIC SPECTACLES (GRAVITATIONAL LENSING)

Another direct-measurement technique that shows great promise is gravitational lensing. Light from a distant source, such as a brilliant quasar, can often be deflected and split by the gravitational field of an intervening object, such as a galaxy or cluster of galaxies. In other words, the galaxy acts

as a lens. As a result, multiple images of the quasar are detected by observers. With the light beams taking different paths around the galaxy, each traverses a different distance in its journey to Earth. If the distant source briefly flares, each image will reveal it at different times, the first flare arriving along the beam with the shortest path, followed by the longer paths. By modeling the size and mass of the gravitational lens, astronomers can determine its distance directly.

Astronomers have timed such flare delays in several lensed quasars, but it has taken months and even years to



**Left: A nearby galaxy, lying seven billion light-years in front of PG1115+080, creates multiple images of the quasar.** NOAJ/Subaru

**Above: Simulated galaxy clusters (red clumps) modify existing temperature differences in the microwave background.** J. Burwell/U. Pen/U. Seljak

monitor the changes in the multiple images. Princeton astrophysicist Edwin Turner and his associates, for example, monitored the flaring of the double quasar 0957+561 for more than a year. One image dropped in brightness by about 15 percent; 417 days later, its twin image diminished in the same way. From this, they calculated a Hubble Constant of 64 kilometers per second per megaparsec.

Recently, astronomers George Chartas of Penn State and Marshall Bautz of MIT noted a dramatic fluctuation in a lensed quasar over just a few hours in x rays, using the Chandra X-Ray Observatory. More sightings like this open up the possibility of using this technique with better efficiency.

## NEW KID ON THE BLOCK? (SUNYAEV-ZEL'DOVICH EFFECT)

There is renewed interest in a technique based on the Sunyaev-Zel'dovich effect, named after the Russian physicists Rashid Sunyaev and Yakov Zel'dovich, who first discussed it some 30 years ago. They pointed out that the

cosmic microwave background, the remnant radiation released shortly after the Big Bang, can be scattered by intervening matter, such as huge clusters of galaxies.

At low radio frequencies, the temperature of the microwave background near the cluster appears lower. At higher frequencies, the background appears brighter, because the hot electrons in the cluster scatter the microwave photons and boost their energy. By studying background changes, along with the cluster's x-ray properties, one can assess the thickness of the cluster and, hence, its overall size. Comparing actual size with the cluster's apparent size on the sky, the cluster's distance can be determined.

John Carlstrom at the University of Chicago and several colleagues have been studying clusters in this manner with both x-ray space telescopes and millimeter radio arrays in California. So far, they've determined distances to some 17 clusters, out to several billion light-years. "For now, the Sunyaev-Zel'dovich effect is more like an independent check rather than leading the way, but I think that its future looks very, very good," says Carlstrom.

## BRINGING IT HOME

Astronomers have never claimed immunity from Murphy's Law. As remote distance measurements are agreeing nicely, one of the primary rungs of the distance ladder has recently been plagued with problems. "The biggest uncertainties are in our own backyard," warns Freedman.

For unknown reasons, the distance to the Large Magellanic Cloud, stubbornly varies among different indicators. Parallax measurements of Cepheids yield a distance of about 180,000 light-years, while other methods, like the use of RR Lyrae stars (see "Constructing the Distance Ladder," page 28) and eclipsing binaries, suggest shorter distances, from 140,000 to 150,000 light-years.

"No distance measurement technique is completely fail-safe," says Filippenko. "But the hope is that together we can be consistent." **A**

*Marcia Bartusiak is a member of Astronomy's editorial advisory board. Her latest book is Einstein's Unfinished Symphony: Listening to the Sounds of Space-Time (Joseph Henry Press, 2000).*