Courtesy SKY & TELESCOPE

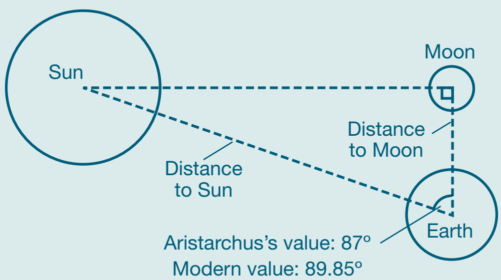
KEEP DIST

Cows can't jump over the moon, no one has ever touched a star, and according to the opening crawl of *Star Wars*, galaxies are "far, far away." But if rulers and tape measures don't work in the wider universe, how do astronomers gauge cosmic distances? How did we endow the night sky with a third dimension? And, given that space is expanding, what does the concept of distance mean anyway?

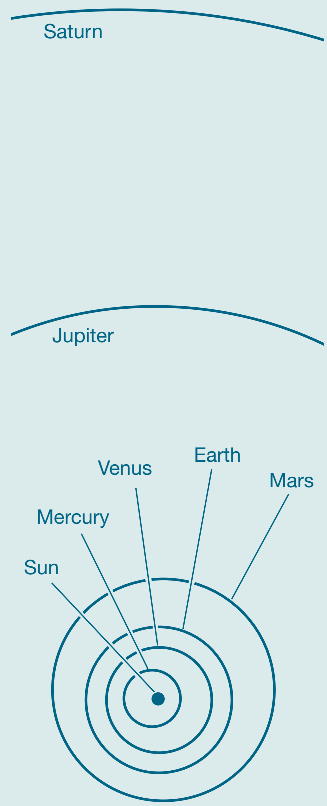
Many people struggle with these ideas. Separations of thousands or millions of light-years quickly lose their meaning when the method behind the measurement eludes you. So we've decided to tackle the matter head-on, starting in the solar system and expanding out to the farthest reaches of the cosmos. Buckle up for our crash course in cosmic surveying.

Step 1. The Solar System

Greek astronomer Aristarchus of Samos (3rd century BC) was one of the first to tackle the problem of taking a ruler to the universe: He determined the relative distances of the Sun and the Moon from Earth. Aristarchus tried to measure the angle between the Sun and the Moon on the sky at the exact moment of a half-moon (either first or last quarter). You might think the answer is obvious (90°), but that's only true if the Sun is at an infinite distance. Aristarchus arrived at a value of 87°, which told him the Sun is 19 times farther away than the Moon. Completely wrong — it's actually 390 times more distant, and the angle that Aristarchus was after is in fact 89.85° — but at least it was a start.



In the early 17th century, German astronomer Johannes Kepler derived his laws of planetary motion. His third law (the square of a planet's orbital period is proportional to the cube of its distance from the Sun) enabled him to calculate the relative sizes of all planetary orbits. It's simple: Jupiter's orbital period is 11.86 years, or 11.86 times the orbital period of Earth. Square this number ($11.86 \times 11.86 = 140.66$) and take the cube of the result ($\sqrt[3]{140.66} = 5.2$), and you arrive at the relative size of Jupiter's orbit compared to Earth's. However, absolute distances were still unknown — Kepler could draw a correct map of the solar system, but he didn't know the map's scale.

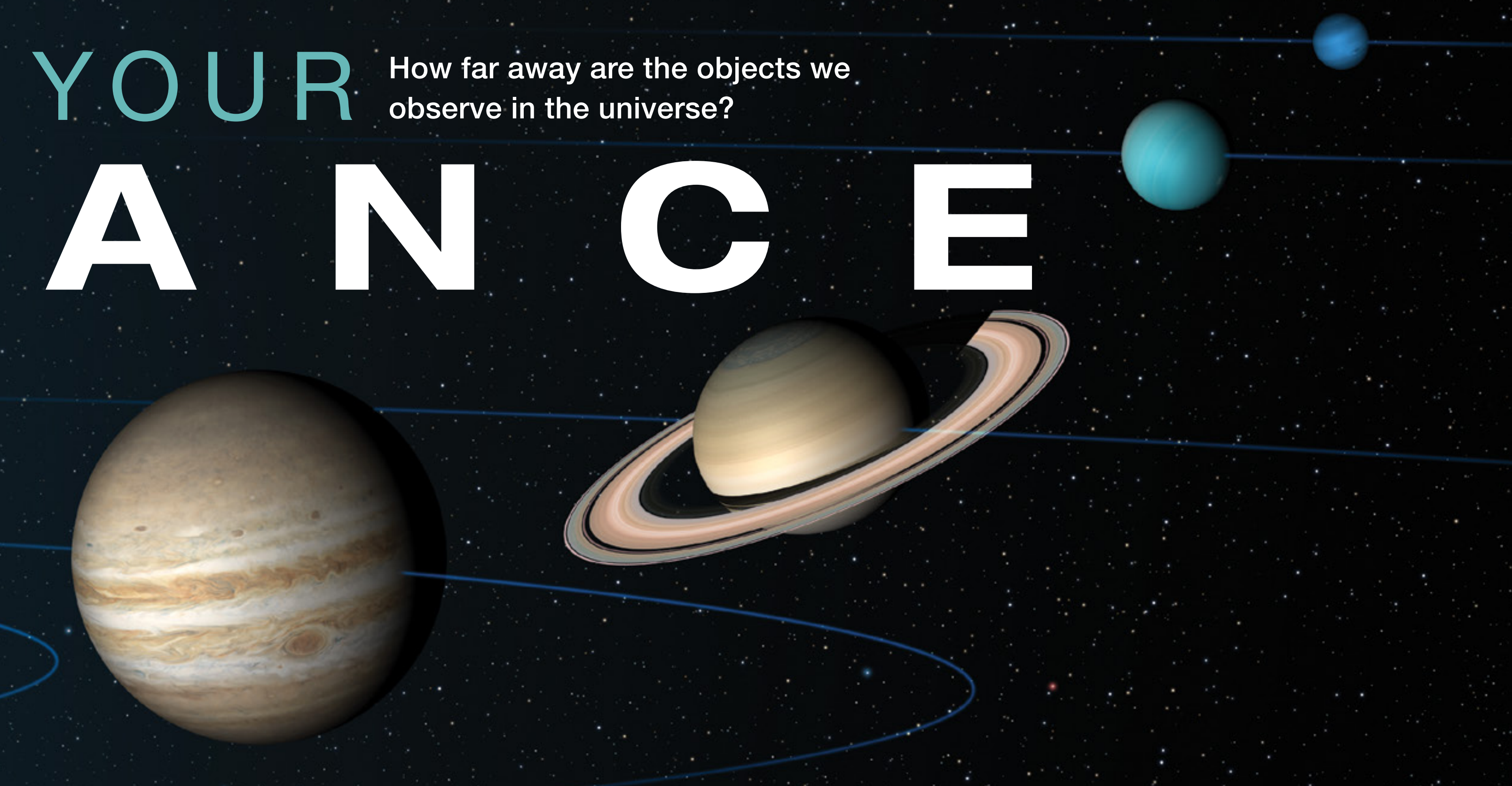


ALL ILLUSTRATIONS: CASEY REED; ALL DIAGRAMS: LEAH TISCIONE / S&T

YOUR

How far away are the objects we observe in the universe?

A N C E



Parallax came to the rescue in the late 17th century. You're probably familiar with the principle: First shut your left eye, then your right eye, and nearby objects appear to shift with respect to the background. The larger the shift, the closer the object is. Gian Domenico Cassini, Jean Picard, and Jean Richer measured the position of Mars among the stars at exactly the same time, but from different parts of the globe, in France and French Guiana. Their estimate of the distance of Mars was only 7% off. Later, timing measurements by observers watching Venus pass across the face of the Sun from different places on Earth, as well as parallax measurements of the near-Earth asteroid 433 Eros, gave even more reliable results (*S&T:* Jan. 2012, p. 70).

The most precise distance estimates in the solar system ping targets with radio waves, which travel at the speed of light. Send a powerful radar pulse to the Moon, Venus, or an asteroid; measure how long it takes before you receive the faint echo; and it's straightforward to calculate the distance, with a precision of less than an inch. The same can be done by pinging a spacecraft that's orbiting a remote planet.

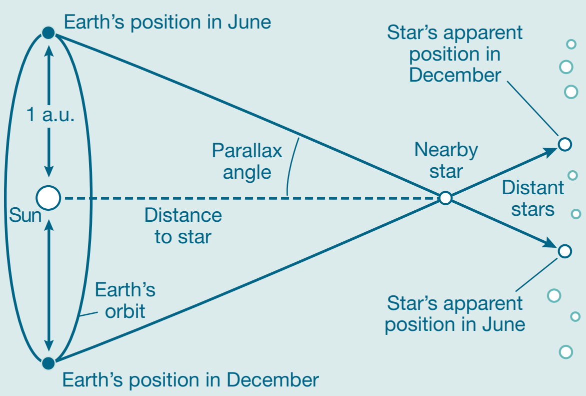
Some 2,300 years after Aristarchus, we've finally come to grips with the size and scale of the solar system. But what about the distances to the stars?

To Stars, Clusters, and Nebulae

Step 2. Stars, Clusters, and Nebulae

If each and every star in the universe had the same true luminosity as the Sun, gauging stars' distances would be easy: A star's apparent brightness would immediately tell you how distant it is, because a light source looks fainter the farther away it is. In fact, 17th-century Dutch astronomer Christiaan Huygens calculated the distance to Sirius (the brightest star in the night sky) by *assuming* it has the same luminosity as the Sun. Huygens concluded that Sirius had to be 27,664 times farther away than the Sun, corresponding to a distance of 0.437 light-year. "A bullet would spend almost seven hundred thousand years in its journey" between Earth and Sirius, Huygens wrote in his 1698 book *Cosmotheoros*. Parallax measurements (see next section) have since revealed that Sirius is actually 8.61 light-years away, implying that it is much more luminous than the Sun.

The most reliable way of gauging a star's distance is by measuring its *annual parallax*. The distance between France and French Guiana is too small a baseline to notice a shift in a star's position. But the diameter of Earth's orbit (300 million kilometers) is large enough. In 1838, German astronomer Friedrich Bessel was the first to accurately measure the position of a nearby star (61 Cygni) from two opposite points of our orbit around the Sun, half a year apart. Using current ground-based telescopes, the method works fine for stars out to a few hundred light-years. The ultra-precise European space telescope Gaia has measured parallaxes for more than a billion stars out to distances of thousands of light-years, although the accuracy rapidly diminishes with distance.



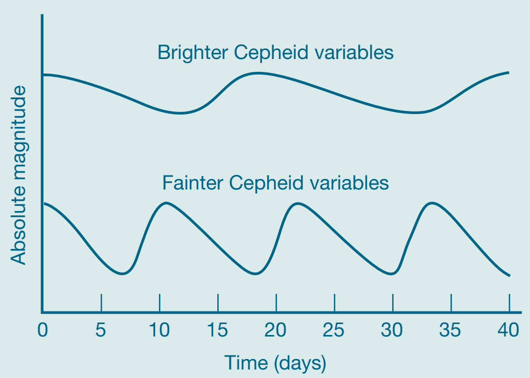
For a large collection of stars, like an open cluster or a globular cluster, astronomers can calculate a rough distance estimate by plotting each constituent star's color (or temperature) against its apparent brightness. Such a plot is called a *Hertzsprung-Russell diagram*. Astronomers know the relation between color and true luminosity for stars like the Sun that are fueled by hydrogen fusion in their cores. Comparing apparent brightness with true luminosity then yields the distance to the cluster. For gaseous nebulae, no such straightforward method exists — that's why distances to nebulae are notoriously uncertain, unless they contain stars for which distances can be derived. For instance, distance estimates for the Lagoon Nebula (M8) ranged from 4,000 to 6,000 light-years, until Gaia measurements helped confirm the lower value.

ECLIPSING BINARY SOURCE: NASA

To Galaxies

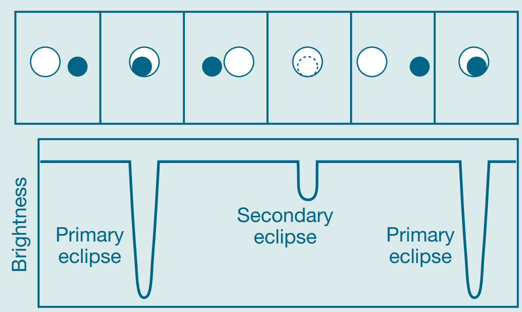
These methods and others have enabled us to chart various distances within our home galaxy. But things become more complicated — and less secure — when we reach beyond the Milky Way.

Certain variable stars, known as *Cepheids* (named after the prototype Delta Cephei), can be used as cosmic yardsticks. These stars show regular pulsations: They grow larger and smaller over time, with their energy output following suit. It turns out there's a relation between the peak luminosity and the pulsation period: The brightness variations are slower for more luminous stars and faster for the dimmer ones, as American astronomer Henrietta Leavitt discovered in the early 20th century (*S&T:* Dec. 2021, p. 12). By observing relatively nearby Cepheids, astronomers have calibrated this period-luminosity relationship. So if you see a distant Cepheid, just measure its pulsation period, use the Leavitt Law to find the star's true luminosity, compare it to its apparent brightness, and out rolls the distance.



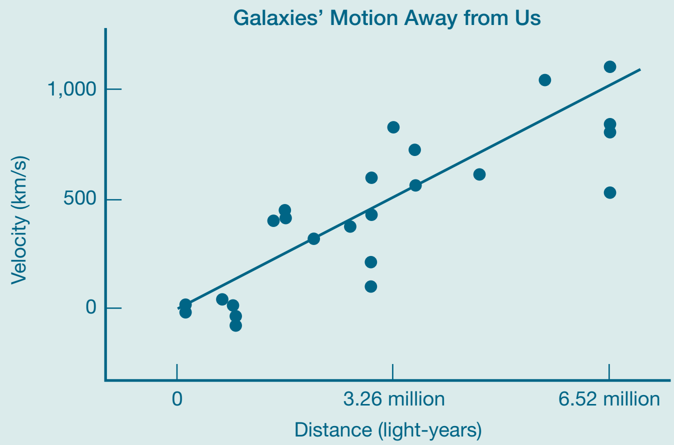
Another type of variable star for which individual distance estimates are possible is an *eclipsing binary*, in which two stars orbit a common center of gravity and mutually eclipse each other from our point of view. Although the stars are generally too close to each other to be observed separately, Doppler measurements reveal their orbital velocities: As one star approaches us, its light shifts to slightly shorter, bluer wavelengths, while the light from the receding star shifts to longer, redder ones. The result is a periodic doubling of the lines in the binary's spectrum. Combining this velocity info with how long it takes the binary to complete an orbit yields the true physical dimensions of the system. From precise eclipse timings — ingress, duration, and egress — you can then easily derive the radii of the two stars. Detailed spectroscopy tells you the *surface flux* of the stars, the amount of light emitted per unit area. If you know a star's radius and its surface flux, you can calculate its true luminosity. Finally, comparing the true luminosity to the observed apparent brightness gives you the distance.

Eclipsing binary stars



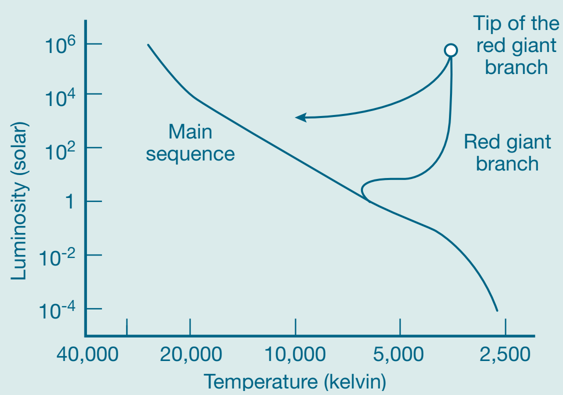
Step 3. Galaxies

Just looking at a remote galaxy doesn't reveal its distance. In fact, in the early 20th century many astronomers assumed that "spiral nebulae" were part of our Milky Way. Others correctly believed they were huge collections of stars similar to and way beyond the Milky Way. If so, rough guesstimates of their distances could be made by simply assuming that they all have the same size and luminosity as our home galaxy — just like Huygens assumed that other stars were similar to the Sun. In fact, after American cosmology pioneer Edwin Hubble established the true nature of galaxies by measuring distances to the nearest ones (see next section), he made similar assumptions about more distant galaxies — for instance, that the brightest star-forming region in any galaxy always emits more or less the same amount of light. That enabled him to conclude that a galaxy's distance is proportional to its observed recession velocity and helped him to discover that the universe is expanding.



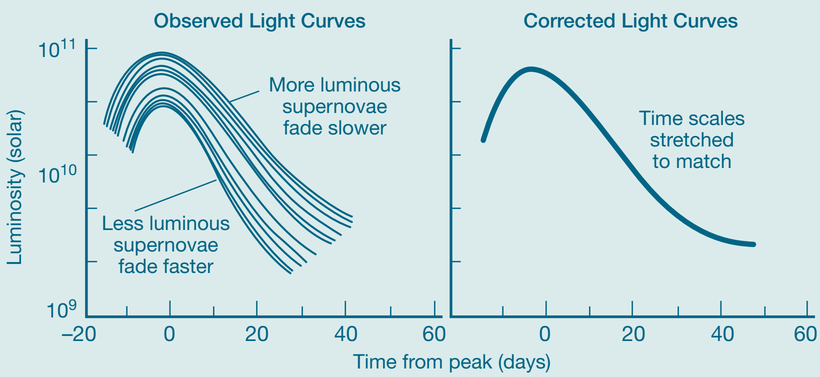
Today, to gauge a galaxy's distance, astronomers use *standard candles* — objects whose true luminosity is known. Extragalactic eclipsing-binary stars are generally too faint to study in much detail, but Cepheids are bright stars. In 1923, Hubble was the first to discover a Cepheid in the outer regions of the Andromeda "Nebula," enabling him to convincingly prove that the fuzzy spiral lies well outside our Milky Way Galaxy. (We now know it's 2½ million light-years away.) Using the Hubble Space Telescope, astronomers have studied Cepheids in galaxies tens of millions of light-years away. According to Adam Riess (Space Telescope Science Institute), the current best calibration of the Cepheid period-luminosity law comes from Gaia parallaxes and accurate Hubble photometry. "The result is a 1% accuracy in Cepheid distances," he says.

More recently, Wendy Freedman (University of Chicago) has pioneered the use of red giant stars as standard candles. Red giants are highly evolved stars that have used up the hydrogen fuel in their cores, converting it into helium. It turns out that red giants can only be so luminous: The star reaches a maximum value when the helium core becomes dense enough to generate a runaway thermonuclear explosion. So if you plot the Hertzsprung-Russell diagram for a large enough collection of red giant stars in a particular galaxy, the *tip of the red giant branch* (TRGB) is always located at the same true luminosity. "There are many advantages of the TRGB [method] over Cepheids," says Freedman. "In the future, I think that it will prove more accurate than the Cepheids."



HUBBLE DIAGRAM SOURCE: E. HUBBLE / *PROCEEDINGS OF THE NATIONAL ACADEMY OF SCIENCES* 1929; TRGB SOURCE: RICHARD POGGE; SNIA LIGHTCURVE SOURCES: C. R. NAVE / HYPERPHYSICS AND JOHN LUCEY / DURHAM UNIV.

Another useful standard candle is *Type Ia supernovae* — the catastrophic detonations of white dwarf stars. These stellar explosions can be seen over vast distances (they can rival their host galaxy's luminosity), and they always produce more or less the same amount of energy. Granted, some are more luminous than others, but astronomers can correct for that because fainter explosions fade more rapidly. All in all, it's a reliable method, and according to Riess, the calibration and accuracy of supernova Ia distances has only improved in recent years.



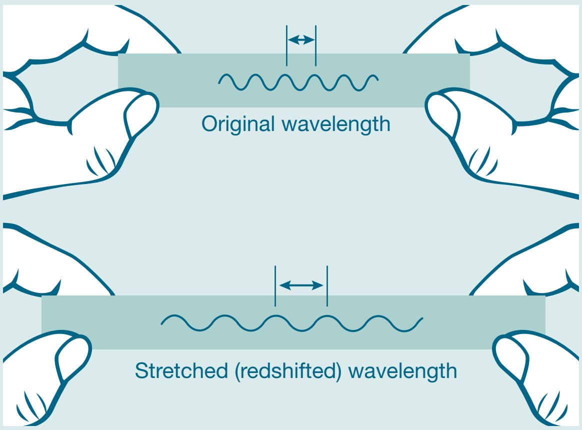
Finally, for a small number of galaxies a truly geometric distance estimate is possible. Small regions in the accretion disks around some supermassive black holes emit powerful *maser* emission (the microwave equivalent of laser light). Doppler measurements tell astronomers the line-of-sight velocities of these masers. High-resolution radio observations reveal the masers' minute motions in the plane of the sky. By combining real velocities and apparent motions, it's straightforward to derive the distance — a feat that has been successfully achieved for the active spiral galaxy M106, which turns out to be about 24 million light-years away.

So what about galaxies that are so remote that we can't discern individual stars? Here, we enter the mind-boggling world of the expanding universe, where the concept of distance starts to lose its mundane meaning.

To the Cosmos

Step 4. The Cosmos

As mentioned before, Edwin Hubble discovered the proportional relation between a galaxy's distance and its apparent recession velocity, the latter derived from the observed redward shift of the galaxy's light. The *cosmological redshift* (denoted by the letter *z*) is a reddening of the galaxy's light caused by the expansion of the universe stretching the light to longer, redder wavelengths: The longer the light waves travel through expanding space, the more they're stretched. Over the past few decades, astronomers have carefully calibrated the relationship, known as the Hubble-Lemaître Law. (Belgian cosmologist Fr. Georges Lemaître independently arrived at similar conclusions a couple of years before Hubble did.) As a result, the distance of a remote galaxy can in principle be deduced from its observed redshift alone.



There's a catch, however. The expansion of space pushes everything apart, but on top of that, galaxies are also moving *through* space. Depending on whether they're moving towards us or away from us, this motion will decrease or increase their redshift. The effect is especially important for relatively nearby galaxies, for which this additional Doppler shift can be a significant fraction of the cosmological redshift. Meanwhile, for very remote galaxies, the proportional Hubble-Lemaître Law doesn't hold, because space has not always expanded at the same rate. To disentangle all these effects, astronomers really need an independent way of measuring distances — you can't just rely on a simple redshift measurement to precisely know how far away a galaxy is.

Over time, astronomers have constructed an elaborate *cosmological distance ladder* to provide redshift-independent distance estimates of remote galaxies, based on the various methods described in the previous sections. Parallax and radar data within the solar system reveal the size of Earth's orbit, enabling annual parallax measurements of stars in the solar neighborhood. Precise Gaia parallaxes of Cepheids and red giants in our own Milky Way provide an accurate calibration of these distance indicators. Using the Leavitt Law and the TRGB method, astronomers can determine distances of galaxies out to many tens of millions of light-years. Type Ia supernova explosions in some of these galaxies then betray the true luminosity of these stellar detonations, making it possible to deduce the distances of other galaxies that also harbor exploding white dwarfs out to *billions* of light-years. In the late 1990s, such supernova-based distance estimates of extremely remote galaxies, combined with measurements of their redshifts, revealed the accelerating expansion of the universe. Cosmologists ascribe this uptick to a mysterious property of empty space known as dark energy (*S&T:* May 2018, p. 14).

And here is where our story takes a mind-bending turn:

What does distance even mean in the expanding universe? On scales of the solar system, we can understand it fairly easily. But for really remote galaxies, cosmic expansion makes the concept of distance quite tricky. In fact, many cosmologists protest that giving distances for anything farther than a couple billion light-years should be avoided.

Suppose you measure a galaxy's redshift to be $z = 1.5$, meaning that visible light emitted with a wavelength of 500 nanometers by the galaxy has been shifted by 1.5 × 500 = 750 nm to an observed infrared wavelength of 1250 nm. The Hubble-Lemaître Law tells you that the light has been traveling through expanding space for some 9.5 billion years. Intuitively, you'd conclude that the galaxy is 9.5 billion light-years away.

However, you can't simply convert the *light-travel time* into a distance. When the light was emitted 9.5 billion years ago, the universe was smaller, and the galaxy was a "mere" 5.8 billion light-years away. Because space is expanding, it took the light 9.5 billion years to reach Earth. But by the time the light finally arrives here, the galaxy's "true" (or *proper*) distance has increased to 14.6 billion light-years. (In the current cosmic moment, the latter is also equal to the *co-moving distance*, which puts everything on a grid that expands with the universe.)

There's also something called the *luminosity distance*. In a non-expanding universe, a galaxy's brightness decreases with the square of the distance: Three times farther away means nine times fainter. So you'd expect that our sample galaxy at 14.6 billion light-years is 100 times fainter than an identical galaxy at 1.46 billion light-years. But that's not how it works, explains cosmologist Ned Wright (University of California, Los Angeles). "Remote galaxies are incredibly faint," he says. "They are made fainter than the inverse square law by two factors of $1/(1 + z)$, one due to the redshift reducing the energy of photons, and the other due to the redshift reducing the photon arrival rate."

The result is that our remote galaxy at $z = 1.5$ is actually 625 times fainter than its closer twin, instead of just 100 times fainter. In a non-expanding universe, the remote galaxy would only be that faint if it were no less than 25 times farther away than the nearby one ($\sqrt{625} = 25$) — that is, at a distance of 25 × 1.46 = 36.5 billion light-years. This is the galaxy's luminosity distance.

And there's another reason why the most remote galaxies are so hard to observe. Not only are they much fainter than you would expect on the basis of their proper distance, they also are much larger on the sky than you'd think, spreading their light out and resulting in an extremely low *surface brightness*. The reason is that their perceived angular size is set at the time the light was emitted. So our sample galaxy at a proper distance of 14.6 billion light-years appears as faint as if it were 36.5 billion light-years away, but as large on the sky as it appeared 9.5 billion years ago, when its observed light was emitted at a distance of only 5.8 billion light-years. This is called the *angular size distance*.

Furthermore, all of these distances' values depend on cosmological parameters like the relative amounts of matter and dark energy in the universe and the universe's current expansion speed. Adjusting the parameters' values slightly shifts the values of the distances we calculate.

Both the luminosity distance and the angular size distance become pretty extreme for very high redshifts. A galaxy at a redshift of $z = 10$ has a light-travel-time distance of 13.3 billion years: We see the galaxy as it appeared 13.3 billion years ago, when the universe was just half a billion years old. Its proper distance is 31.4 billion light-years. However, the angular-size distance is just 2.9 billion light-years: On the sky, it appears about 10 times larger than you would expect on the basis of its current distance. Even more remarkably, the galaxy's luminosity distance is a whopping 345 billion light-years — it's 121 times fainter than you'd intuitively expect!

We've come quite a distance. Our crash course has brought us from the first thoughts about the scale of our solar system to mind-boggling concepts about remote galaxies in an ever-expanding universe. And we've only scratched the surface of the complicated topic of astronomical distance measurements, cosmic yardsticks, and universal expansion: It would take a whole book to describe each and every distance indicator and measurement technique. But after you've read this primer on cosmic surveying, your appreciation of the night sky will never be the same again. Thanks to centuries of scientific endeavor, the universe has gained depth.

■ Contributing Editor **GOVERT SCHILLING** is the author of *The Elephant in the Universe: Our Hundred-Year Search for Dark Matter* (Harvard University Press).