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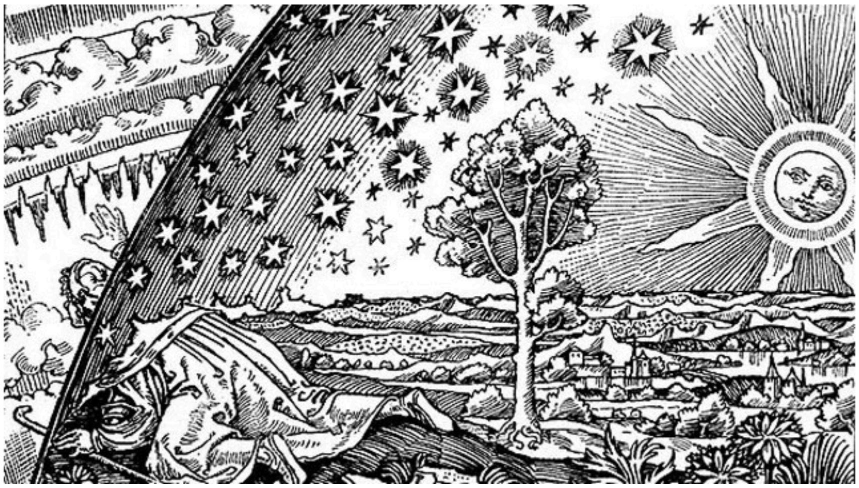
Up the Cosmic Distance Ladder

WHAT WE KNOW BY **LEE BILLINGS** / OCTOBER 19, 2009



THE DEVELOPMENT OF ASTRONOMY CAN BE SEEN AS A MILLENNIA-LONG QUEST TO MEASURE AND KNOW THE TRUE SCALE OF THE NATURAL WORLD.

One of the greatest difficulties when discussing the physical world is conveying its immense scale. While we can estimate the number of molecules contained in a single drop of water (roughly 1.5 sextillion, 1,500,000,000,000,000,000,000) or measure the distance light traverses in a single second (around 300 million meters), the values we obtain are so alien that we cannot intuitively comprehend them. For most people, the difference between one and 10 is far more palpable than the difference between a thousand billion and a thousand trillion. Against our Earth-bound frames of reference, sizes and distances grow too large or small, speeds and intervals too fast or slow, forces too strong or weak. Few disciplines illustrate this more clearly than astronomy, the oldest of the natural sciences.

Consider this: We live in a universe so large that light itself (and nothing goes faster) takes years to travel between stars, eons to travel between galaxies. All we see in the sky are essentially old photos of celestial objects as they were when their light first left to travel to Earth. When we look across space, we also look back in time.

The Sun is just a yellow dwarf star, and, like most stars visible in Earth's night sky, is contained in the Orion spur, a diminutive tendril of star-forming gas and dust sandwiched between the outskirts of two of the four massive spiral arms that make up our Milky Way galaxy. The Milky Way is roughly 100,000 light-years wide, a few thousand light-years thick, and filled with hundreds of billions of stars, each of which may have its own accompanying retinue of planets. Our closest major galactic neighbor, another spiral galaxy named Andromeda, lies 2.5 million light-years away—but it's getting closer by some 120 kilometers each second, all the time.

Some 3 billion years in the future, Andromeda may crash into the Milky Way, forming a single giant galaxy that will dominate all the other objects in our cluster of galaxies, which is known as the Local Group. We can observe billions and billions of galaxies further away, but even all this may be but an infinitesimal part of the larger universe, which seems to have sprung into existence 13.7 billion years ago. The universe is expanding, and even accelerating in its expansion, and may continue to do so forever.

Though this is just a cataloging of objects, distances, and sizes, the numbers involved lend the list a feeling of grandeur and raise questions in the curious mind: Just how is it that we know the distance from the Earth to the Sun, the other planets, and faraway stars? How do we know the architecture and future of our galaxy or the expansion rate of the universe? The short answer is that we know these things because of the cosmic distance ladder, a suite of interdependent methods to measure successively greater distances in the universe. Though most of the ladder was created in the 20th century, millennia of effort have contributed to its construction, and it is still being refined.

A dearth of records limit our knowledge of astronomy's earliest era, and ancient astronomers were themselves hindered by the absence of telescopes, but it is clear they took the first steps in establishing cosmic distances. Astronomy in antiquity blossomed with the Babylonians, but reached its zenith in Hellenistic Greece, where Eratosthenes of Cyrene calculated the circumference of the Earth, and Aristarchus of Samos proposed that the Earth revolved around the Sun. Based on Aristarchus' ideas, the Greek mathematician Archimedes wrote *The Sand Reckoner*, a work where he attempted to estimate the universe's size and how much sand would be required to fill it. Archimedes assumed the universe was a sphere, and his estimation of its diameter corresponds to a modern measurement of about one light-year. He thought it could hold about 1063 sand grains. Imperfect as it was, the astronomy of the Greeks would not be surpassed for more than a thousand years.

Planets

In 1543, Aristarchus' theory of heliocentrism was revived and expanded by the Polish astronomer Nicolaus Copernicus in Renaissance Europe. Then, building on the work of Copernicus, as well as the telescopic observations of Galileo Galilei and Tycho Brahe, the German astronomer Johannes Kepler devised his three eponymous laws of planetary motion. Kepler's third law established a clear relationship between the period of a planet's orbit and its distance from the Sun. By observing the motions of the planets from night to night, Kepler could estimate, for instance, that Mars was 1.5 times more distant from the Sun than Earth was, and that Jupiter was five times more distant still. But without the calibration of knowing precisely how far the Earth was from the Sun, such estimations were of limited use.

Today astronomers use radar beams to measure interplanetary distances, aiming powerful pulses at a planet or moon and waiting for the reflected "echo" to return. But before radar, such measurements were much more difficult. Astronomers relied on something called parallax. Extend your arm and look at your thumb first through your left eye, then your right. You'll notice your thumb's apparent position will change as you switch back and forth between eyes. This displacement is caused by the difference in perspective provided by two spatially separated viewpoints; the closer an object is to the two observation points, the greater that object's parallax. Using the principle of triangulation, an observer can calculate the distance to an object using the object's observed parallax and the known distance between the two observation points.

The Italian astronomer Giovanni Cassini, along with his colleague Jean Richer, performed the first measurement of interplanetary parallax in 1673. The planets were so distant that they only yielded clear parallax shifts when observers were located on far-flung portions of the globe. Cassini observed the position of Mars in the sky above Paris, France; Richer observed Mars' position above Cayenne in French Guiana. By calculating the difference between the two measurements, Cassini estimated the Earth–Mars distance to within 10 percent of its known modern value. Parallax measurements of other interplanetary distances soon followed. By knowing these, the Earth's distance from the Sun could finally be estimated with reasonable certainty.

Stars

Parallax worked well for interplanetary distance measurements because of the background of fixed stars, which allowed small shifts in planetary positions to be seen. But what was a boon for determining interplanetary distances was a bane for finding interstellar ones. No one knew anything of great certainty about interstellar distances, other than that they were large enough to make stars seem to hang immobile in the sky.

Soon, clever astronomers began attempting to measure stellar parallax by exploiting the Earth's motion around the Sun. If you measure the position of a nearby star in the sky in January, then when you measure that star's position again in June, the Earth's orbit around the Sun will have created a difference of hundreds of millions of kilometers between your two observations, enough to reveal a nearby star's parallax. The question became, which stars are nearby? Fortunately for 19th century astronomers, improved record keeping and telescopic observations revealed that stars aren't actually "fixed." In fact, several stars were eventually found that almost imperceptibly crept across the sky over timescales of months and years. These slight motions, it was hoped, indicated that those stars were relatively close to us.

Between 1832 and 1833, the Scottish astronomer Thomas Henderson measured the first reasonably accurate stellar parallax based on his observations of the Alpha Centauri star system. His calculations indicated Alpha Centauri was about 3.25 light-years away. (The modern estimate, using parallax, is 4.39 light-years.) But Henderson's uncertainty about the validity of his measurements caused him to delay publicizing his findings. Henderson finally published in 1838, two months after another astronomer, Friedrich Bessel, announced his own parallax measurement of a slightly more distant star, 61 Cygni. Today Bessel is remembered as the first to measure stellar parallax, and the technique is still the baseline for obtaining cosmic distances.

Slideshow

Far Out: A Space-Time Chronicle; Abrams; 2009; To see a slideshow of stunning objects at different distances and lyrical essays go to http://seedmagazine.com/slideshow/far_out/

Nebulae

The measurement of stellar parallax was just one part of astronomy's maturation during the middle of the 19th century; the outlines of additional rungs in the cosmic distance ladder were also taking shape. By this time, increasingly sensitive telescopes were discovering mysterious nebulae scattered among the stars in droves. Some of the nebulae looked like clouds, others looked like spirals. But what were they? Some astronomers thought they were planetary systems in various stages of formation or destruction; others thought they might even be island universes, huge accretions of stars reduced to faint smudges by their vast distance.

As the mystery of the nebulae deepened, the techniques that would eventually help solve it emerged. In 1814, the German optician Joseph von Frauenhofer fashioned a spectroscope (a telescope mated to a prism that can split starlight into its constituent colors) for viewing the Sun. He noticed, in looking at the Sun's spectrum, thin lines where colors were absent. These spectral shadows were shown to be caused by a luminous object's chemical composition and thus could be used to measure the material of the stars. By 1848, the French physicist Armand Fizeau proposed the dark lines could also be used to measure a star's motion by exploiting an effect first noticed by the Austrian physicist Christian Doppler. Doppler suggested that all waves, be they sound or light, would alter their wavelengths as their sources moved. Fizeau posited that shifts in stellar spectral lines toward the shorter, bluer wavelengths (blueshifts) indicated stellar motion toward the observer, and that shifts toward longer, redder wavelengths (redshifts) meant stellar motion away from an observer.

However, the key breakthrough that would help solve the nebulae mystery did not come until the first decade of the 20th century. While performing the menial task of counting stars on photographic plates for her employer, Edward Pickering, the American astronomer Henrietta Leavitt noticed something curious in the Small and Large Magellanic Clouds, two huge groupings of stars. In the Clouds, certain variable stars, stars that periodically brighten and dim, exhibited a cycle of brightening and dimming with metronomic regularity. More importantly, it appeared that the brighter these unique variable stars were, the longer the period of their cycle.

These stars were later named Cepheid variables, and their oscillatory behavior proved crucial to the cosmic distance ladder. By measuring the timing of a Cepheid's pulsation, its intrinsic luminosity can be inferred. Cepheids are standard candles, objects whose true luminosity we know. By comparing a standard candle's luminosity with its apparent brightness in the sky, its distance from Earth can be reliably estimated. Cepheids soon became key measures for distances in the Milky Way.

Galaxies

Beginning in 1912, the American astronomer Vesto Slipher began noting that nearly all the spiral nebulae he observed displayed redshifts—they all seemed to be moving away from the Earth at great speed. One notable exception was the first spiral nebulae he measured, which today we know as the Andromeda galaxy. Slipher's observations showed that Andromeda was heavily blueshifted, and he estimated that it was hurtling toward us at hundreds of kilometers per second. In the early 1920s another American astronomer, Edwin Hubble, used what was then the largest telescope on Earth, the 2.5-meter Hooker telescope, to study Cepheids in Andromeda. Hubble's data indicated that Andromeda was more than a million light-years away. At a stroke, our view of the universe transformed. Andromeda and the other spiral nebulae weren't planetary systems mid-formation in our own galaxy; they were each galaxies themselves, in a universe far more immense and spacious than most had dared to dream.

But even this was but a prelude to a greater discovery. Using the galactic redshifts collected by Slipher and others, in 1929 Hubble and his colleague Milton Humason found that a galaxy's redshift increased in proportion with the galaxy's distance from Earth. This observation is now known as Hubble's Law and is now used extensively to estimate distances to far-away galaxies. Hubble's Law showed conclusively that the universe was expanding. For decades, this remained the best observational evidence for the then-controversial big bang theory, which stated that the universe sprang into existence from an infinitesimal point billions of years ago. Today, we number galaxies in the hundreds of billions, but there may be innumerably more beyond where we can see, masked by space so vast that their galactic light has yet to reach us here.

The Universe

Beyond stellar parallax, which is useful only out to hundreds of light-years, or Cepheids, which can measure distances to nearby galaxies, additional techniques exist. Many of these also involve using celestial objects and phenomena as standard candles, linking their luminosity with some other aspect of their behavior, like rotation rate or size or color. The most notable additional technique uses exploding stars, particularly ones called Type Ia supernovae.

According to theory, a Type Ia supernova only occurs in a special kind of binary star system, where a giant star and a white dwarf star orbit one another. For the small, dense white dwarf, this is an all-you-can-eat buffet: It easily pulls gas off its larger, puffy companion, gradually building up layers of material on its surface. But once the growing white dwarf reaches a total mass about 1.4 times that of our Sun, it is doomed by its gluttony. At this point, like clockwork, the accumulated weight of all the extra material ignites a thermonuclear fusion reaction that engulfs the entire star. After a blinding flash of light, all that's left of the white dwarf is a slowly cooling, expanding shell of radioactive debris. By assuming that Type Ia's always detonate the same amount of material and release the same amount of energy regardless of where they're found in the universe, astronomers can estimate their intrinsic brightness and measure immense distances of hundreds of millions, even billions, of light-years.

In the late 1990s, two teams, the Supernova Cosmology Project and the High-z Supernova Search Team, were studying Type Ia supernovae to sharpen estimates of the universe's expansion rate. But instead of simply refining the established measurements, both teams independently discovered something astonishing: The supernovae they observed at the edge of the visible universe were dimmer, and thus further away, than they should have been according to Hubble's Law. It appeared that the universe was not only expanding, but also accelerating in its expansion. The rate of acceleration suggested that whatever powered it accounted for nearly 75 percent of the total energy in the entire universe. This strange force, now labeled dark energy, is one of the deepest mysteries in cosmology.

Much of the work that remains for pinning down interstellar, intergalactic, and extragalactic distances could hold great importance for our future. Gaia, a spacecraft launching in 2011 or 2012 that is designed to use parallax and other techniques to measure the motions of the Milky Way's stars, will construct a three-dimensional star map of the galaxy and potentially find hundreds of new extrasolar planets.

Fundamental refinements in parallax measurement will gradually trickle up the rungs of the cosmic distance ladder, sharpening distance estimations for standard candles in nearby galaxies and galactic clusters. With better measurements, we will finally know whether Andromeda, hurtling in our general direction at hundreds of kilometers per second, will eventually collide with our Milky Way in some 3 billion years.

Improved measurements of the universe's accelerating expansion could even help explain what exactly dark energy is and perhaps even forecast the ultimate fate of the entire universe. Will it accelerate in its expansion forever or could it perhaps slow or even reverse its course, eventually collapsing inward on itself in a "big crunch?" Could it then rise phoenix-like from the cosmic genesis of another big bang? The truth is, we don't really know—not yet—but the answers may be somewhere out there, hidden in the depths of the unbounded sky.