Newly Refined Hubble Constant Narrows Possible Explanations for Dark Energy

Taken from:
*Hubble 2009: Science Year in Review*


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Newly Refined Hubble Constant Narrows Possible Explanations for Dark Energy

Nearly a century ago, when considering the cosmological implications of his monumental theory of General Relativity (GR), Albert Einstein realized that his equations needed a small adjustment. It was the widely held view of astronomers in 1917 that although planets, stars, and assemblies of stars all move with respect to each other, the universe as a whole is static—neither contracting nor expanding. Einstein’s original formulation of GR did not permit such a stable universe. However, the famous physicist found that the addition of a constant term to his equations produced one. This “cosmological constant” had the effect of a repulsive force that kept the universe from collapsing under its own weight, like a house of cards.

In 1929, astronomer Edwin Hubble found a relationship between the galaxy distances he could measure and the velocities of those same galaxies determined by others. In short, virtually all galaxies were found to be receding, and the further away a galaxy is located from us, the faster it recedes. More specifically, galaxy distance is proportional to velocity. This relationship between velocity and distance—now called the Hubble constant, or $H_0$—meant the universe was expanding, not static. No additional mathematical help was needed to shore it up from collapse. Einstein then referred to the cosmological constant as his “biggest blunder.”

In 1998, two research teams used multiple (mostly ground-based) telescopes to look deep into space—and hence far back in time—in order to measure the rate at which the universe’s expansion slows down under the relentless pull of gravity. In effect, they were searching for the change of the Hubble constant with cosmic time. The key question they were trying to answer—one which had been on the forefront of astrophysics for decades—was whether gravity is ultimately strong enough to halt the expansion. If so, the universe would ultimately fall back upon itself in a “big crunch.” If not, the expansion would continue forever.

The majestic spiral galaxy NGC 3370 is important because its close proximity to Earth enables Hubble to resolve and study its individual stars, and also because it fairly recently hosted a Type Ia supernova. This makes it a useful galaxy for calibrating the cosmic distance scale.
One team was led by Adam Riess (Space Telescope Science Institute and the Johns Hopkins University) and Brian Schmidt (Mount Stromlo Observatory). The other was led by Saul Perlmutter (Lawrence Berkeley National Laboratory). Both studies came to the same stunning conclusion.

Independently, these two research teams discovered that the universe is not slowing, but actually is in the process of accelerating. This unexpected condition was attributed to an unknown repulsive force they named “dark energy.” Dark energy seems to behave like Einstein’s cosmological constant due to the presence of energy in “empty” space, but further observations were needed to see if it truly remained stable over time.

Using the Hubble Constant to Characterize Dark Energy

One of the major reasons for launching the Hubble Space Telescope in 1990 was to more accurately measure the Hubble constant, an essential ingredient in determining the age, size, and fate of the universe. Until the launch of the Hubble telescope, the range of measured values for the expansion rate spanned from 50 to 100 kilometers per second per megaparsec—an unacceptably large factor of two. (A megaparsec is the unit of distance commonly used to measure the distance between galaxies. It equals one million parsecs or 3.26 million light-years.) By 2001, the team for the Hubble Space Telescope Key Project on the Extragalactic Distance Scale had refined the value of the Hubble constant to 72 ± 8.

In 2003, Riess and his team used the Advanced Camera for Surveys on Hubble to probe dark energy and acceleration to greater distances and more ancient epochs in the universe’s history than had been possible in 1998. What Riess and colleagues found was that earlier than about five billion years ago, the universe was doing what had originally been expected—it was decelerating under the influence of gravity. However, at five billion years ago, the expansion underwent a transition from deceleration to the acceleration observed in the more local universe and reported in 1998.
The repulsive force of dark energy and the attractive force of gravity were each present on both sides of the transition. In the earlier times gravity, particularly the gravity of dark matter, which accounts for most of the universe’s mass, was the stronger of the two—it was “winning the battle” against dark energy. However, as space continued to expand, the gravitational tug of diluted dark matter became weaker than the push of dark energy. Since the transition period five billion years ago, the universe has been speeding up—dark energy is now dominating the contest between these two forces.

Scientists know with some certainty that nearly three-quarters of the energy density of the local universe is in the form of dark energy. However, they do not know what it is. In 2009, to better characterize dark energy, Riess and his SH0ES (Supernova H0 for the Equation of State) Team used Hubble to refine the value of the universe’s expansion rate to an accuracy of 4.5 percent. The new value is 74.2 kilometers per second per megaparsec, with an error margin of ± 3.6. This means that for every additional million parsecs a galaxy is from Earth, it is on average receding 74 kilometers per second faster. This new, more accurate value of the Hubble constant was combined with 2008 data from NASA’s Wilkinson Microwave Anisotropy Probe (WMAP) that measured the distant, early universe based on fluctuations in the cosmic microwave background, to test and constrain the properties of dark energy.

This pie chart shows the mass-energy composition of the universe today. It appears that dark energy density does not decrease with time, so it now dominates the universe even though it was a tiny contributor 13.7 billion years ago, when the universe was born.
The refined Hubble constant continues to imply—now with three times as much confidence than before—that dark energy may really be the steady push on the universe that Einstein imagined, rather than something more ephemeral. By tracing the expansion history of the universe between today and when the universe was only approximately 380,000 years old, the Riess team was able to place limits on the nature of the dark energy that is causing the expansion to speed up.

Two independent teams of astronomers set out to measure the change in the universe’s expansion rate to determine if the universe was rapidly or slowly decelerating. What they both found instead is that the universe is currently accelerating. Additional Hubble data acquired subsequent to the original studies indicates that the universe was in fact decelerating before it began accelerating.

The discovery of dark energy, the refinement of the Hubble constant, and the implications of that refined value for dark energy are tremendously important to the astrophysics of the new millennium. It is critical, however, to realize that these discoveries rely on observational evidence which is extremely challenging to gather and interpret accurately—in particular, how we measure cosmic distances.
Cosmic Tug Of War

What astronomers know today about the expansion-rate history of the universe is illustrated in this figure. The gravitational force from matter, including dark matter, is depicted as a stretched rubber band—the force is inward and has the effect of slowing the expansion. Dark energy, on the other hand, is rendered as a compressed spring—it pushes outward and exerts a repulsive force, accelerating the expansion. Whether deceleration or acceleration occurs depends on the difference, or net force—attractive (inward) or repulsive (outward).

The main body of the figure shows four “time slices” over history using the stretched rubber band and compressed spring graphics to characterize the relative strengths of these two opposing forces. In the earliest time slice (lowest in the figure) more than five billion years ago, the universe was smaller and more dense than it is today; gravity from matter opposed dark energy and was actually the stronger force. The net force was attractive, as indicated by the two inward-directed arrows, and the universe was expanding but slowing down. Approximately five billion years ago, a transition occurred at which the two forces were equal and cancelled each other out. The net force was zero, as indicated by the lack of arrows. At this point in time, the universe was expanding, but at a constant velocity. In the upper two time slices—the lower representing the present universe and the upper portraying its future—dark energy dominates the tug of war, exceeding the reduced gravitational force in a less-dense universe. As indicated by the outward-directed net force arrows, this repulsive force accelerates the expansion of the universe.

The Hubble data analyzed by the SHOES Team is consistent with—but does not yet prove—the idea that dark energy is constant over cosmic time. Gravity’s influence, however, is steadily declining.
Measuring Distance Using Standard Candles, and Strengthening the Cosmic Distance Ladder

Astronomers can use simple geometry to triangulate the distances to the nearest stars by studying how they shift against background stars as the Earth orbits the Sun. But to gauge deeper distances, scientists depend on finding so-called “standard candles”—stars or other objects whose intrinsic luminosities are known and thus their distances can be derived from their apparent brightnesses.

Among the most reliable of these candles is a special class of pulsating stars called Cepheid variables. Cepheids brighten and dim in a predictable pattern over a period of days to weeks, like slowly winking lights on a Christmas tree. The more luminous they are, the longer their cycles. Through their regular, slow winking, such stars in a galaxy broadcast their luminosities and hence, their distances. As critical as they are, Cepheids by themselves cannot take us to the most remote distances in mapping out the complete history of universal expansion—they are simply not bright enough.

Therefore astronomers must step outward by means of a “distance ladder,” a tool that links together progressively longer-range distance indicators by using each rung of the ladder to calibrate the next. The nearby Cepheids are first calibrated, and then used to calibrate brighter standard candles in more distant galaxies. Unfortunately, the luminous, more useful candle sources are rare and difficult to find in sufficient numbers. Many astronomers currently use a kind of exploding star known as a Type Ia supernova, brilliant enough to be seen across up to two-thirds of the observable universe. Type Ia supernovas all explode with nearly the same amount of energy and therefore have almost the same intrinsic luminosity (the small differences in luminosity can be calculated by detailed examination of their “light curves”—the rapid rise and then slow fall-off of the observed light). Thus, these supernovas are reliable distance indicators for more distant measurements as long as their “rung of the ladder” is calibrated against the others.
Riess’s 2009 study used Hubble’s Near Infrared Camera and Multi-Object Spectrometer (NICMOS) and the Advanced Camera for Surveys (ACS) to observe more than 100 Cepheid variables in a nearby cosmic mile marker, the galaxy NGC 4258—also known as Messier 106 in Ursa Major. The SH0ES team also used NICMOS and ACS to observe 150 Cepheid variable stars across six galaxies that had hosted well-observed Type Ia supernovas. These included the galaxies NGC 3370 (see on page 120) and NGC 3021.

Hubble measurements have simplified the cosmic “distance ladder,” which is needed to calculate a more precise value for the universe’s expansion rate. At select host galaxies, Cepheid variable stars—known as indispensable distance indicators—are cross-calibrated to Type Ia supernovas in the same host galaxy. The new technique reduced the distance ladder to three “rungs”: (1) The distance to galaxy NGC 4258 is measured using straightforward geometry and Kepler’s laws; (2) Cepheids in six more distant galaxies are used to calibrate the luminosity of Type Ia supernovas; (3) The Hubble constant is measured by observing a brighter milepost marker, Type Ia supernovas, in more distant galaxies hundreds of millions of light-years away.
In galaxy NGC 4258, astronomers have also found clouds emitting radio waves at a frequency characteristic of water vapor circling the center of the galaxy. By tracking the speeds and motion across the sky of these clouds with high-resolution radio observations, they determined the distance of this galaxy to an unusually high accuracy of 3%. Knowing this distance allowed Riess and his team to calibrate the Cepheids, which they then used to determine the true luminosities of Type Ia supernovas in the other six galaxies.

Once the Type Ia supernova luminosities are calibrated via Cepheids in this way, they greatly extend the accuracy and utility of the cosmic distance ladder, as well as permit a significantly more accurate value of the Hubble constant to be obtained.

In 2009, the Riess team was able to measure the Hubble constant, $H_0$, to an accuracy 2.5 times greater than the previous 2001 Hubble result. In addition to the use of NGC 4258 as the “anchor galaxy,” astronomers needed Hubble’s powerful infrared capabilities with NICMOS for the study. Infrared light is key because it penetrates intervening dust that might interfere with the precise measurement of a Cepheid. This helped the team obtain more accurate measurements of the Cepheids’ true brightnesses, free from the obscuration that occurs from the dust.

Using Hubble as the only telescope for Cepheid observations was absolutely essential to the SH0ES team’s success. This eliminated the inevitable “systematic errors” that arise when data from different telescopes are taken and analyzed together. With Hubble, the team was able to sidestep some of the shakiest rungs along the previous distance ladder involving uncertainties in the behavior of Cepheids. At the current time, Hubble Space Telescope is the sole facility that can observe supernova explosions deeply enough and accurately enough to chart the early days of dark energy.
Spiral galaxy NGC 3021 was one of several host galaxies of recent Type Ia supernovas used to refine the measurement of the universe’s expansion rate. Hubble made precise measurements of Cepheid variable stars in the galaxy, highlighted by green circles in the four inset boxes. The Cepheids are used to calibrate an even brighter milepost marker that can be used over greater distances, a Type Ia supernova (SN1995a), which is circled in red.
The Challenge Ahead

In the 400 years since Galileo turned his telescope to the sky, there have been just a few instances where observational astronomy challenged fundamental physics. The discovery that the universe is accelerating has handed this generation just such a challenge. It is both a shocking surprise and an exciting opportunity for theoretical and observational scientists alike.

The SH0ES team has made a more precise and accurate measure of the Hubble constant; which, together with the WMAP measurements in the early universe, has yielded a measurement of dark energy consistent with Einstein’s cosmological constant. Eventually, Riess envisions the Hubble constant being refined to a value with an error of no more than one percent, to put even tighter constraints on solutions to dark energy.

*Spiral galaxy NGC 4258, also known as M106, played a key role in refining the expansion rate of the universe to a new level of precision. Ground-based radio observations of the galaxy led to a highly accurate geometric determination of its distance. This, coupled with the fact that Hubble resolved and studied some of its individual Cepheid variable stars, enabled calibration of the “Cepheid rung” of the cosmic distance “ladder,” a crucial part of the overall process. (Photo credit: B. Slotnick, J. Slotnick, and A. Block/NOAO/AURA/NSF)*
Further Reading


Dr. Adam G. Riess is a professor of astronomy and physics at The Johns Hopkins University and a senior scientist at the Space Telescope Science Institute, both in Baltimore, Maryland. His research involves cosmological measurements and analysis. In 1998, he led a group study that provided the first direct and published evidence that the expansion of the universe was accelerating and filled with “dark energy.” Beginning in 2002, Dr. Riess led the team to find 25 of the most distant supernovas known with the Hubble Space Telescope. This work culminated in the highly significant first detection of the preceding decelerating epoch of the universe, helped to confirm the current acceleration, and began to characterize the time-dependent nature of dark energy. Dr. Riess has been awarded the Warner, Shaw, Gruber, and Sackler prizes for academic achievement, is the recipient of a MacArthur Fellowship, and was elected to the National Academy of Sciences in 2009. Dr. Riess earned his Ph.D. in Astrophysics from Harvard University.