Gravitational-lensing measurements push Hubble-constant discrepancy past 5σ

If the tension can't be attributed to systematic errors, it could be a sign of new cosmological physics.

Little is known about what dark matter and dark energy, the dominant components of the universe, really are. But the standard model of Big Bang cosmology, known as ΛCDM, incorporates how they outwardly behave. Dark energy, the model presumes, takes the form of a cosmological constant Λ, a constant energy density per unit volume of vacuum. Dark matter, meanwhile, is nonrelativistic (or cold; the CDM stands for "cold dark matter"), and it interacts with itself and with ordinary matter only via gravity and possibly the weak force.

With just a handful of free parameters, ΛCDM is appealing in its simplicity, and it generally agrees well with observations of the universe. But an exception is emerging in the Hubble constant H_0, the universe's present rate of expansion.

For ΛCDM to predict a value for H_0, its free parameters must be constrained—for example, by a map of the cosmic microwave background (CMB), a picture of the spatial structure of the early universe. From 2009 to 2013, the *Planck* observatory measured the CMB with great resolution and precision; its map, combined with ΛCDM, yields an H_0 of 67.4 ± 0.5 km/s/Mpc.[1] The structure of the early universe can also be inferred from the distribution of galaxies today (see the article by Will Percival, PHYSICS TODAY, December 2017, page 32); that approach gives the same prediction for H_0, albeit with wider error bars.

But H_0 can also be calculated directly from the distances to various astronomical objects and the velocities at which they're apparently receding from Earth. (See the article by Mario Livio and Adam Riess, PHYSICS TODAY, October 2013, page 41.) And direct measurements disagree with the ΛCDM value. The SH0ES (Supernova, H_0, for the Equation of State of Dark Energy) collaboration has been honing in on an H_0 measurement using so-called standard candles: type Ia supernovae and Cepheid variable stars, whose luminosities are known. The team's latest H_0 value, 74.0 ± 1.4 km/s/Mpc, differs from the ΛCDM value by 4.4 standard deviations.[2]

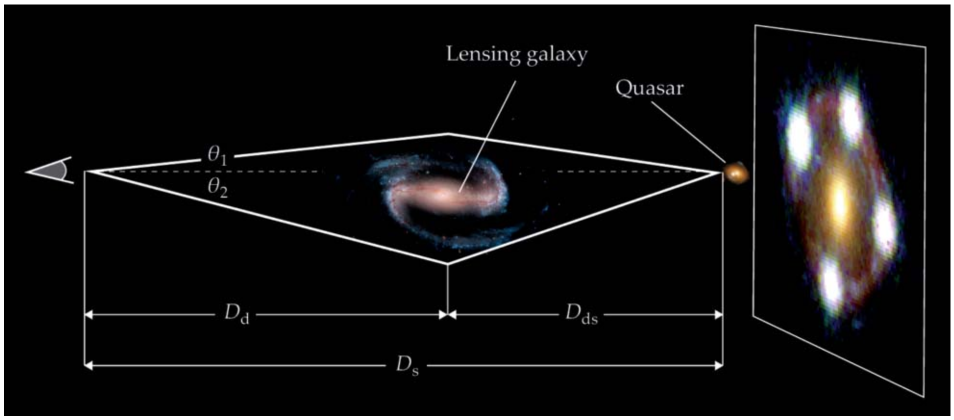

FIGURE 1. STRONG GRAVITATIONAL LENSING by a foreground galaxy can cause a quasar to appear as several distinct images. Observing the relative time delays among those images provides information about the combination of distances between Earth, the lensing galaxy, and the quasar. Given that the angles θ_1 and θ_2 are small, the difference in path lengths shown here is proportional to $D_d D_s/D_{ds}$; the difference in light travel time, which includes the effects of general relativity and the universe's expansion, is proportional to that same value. (Image by Freddie Pagani.)

A difference of that magnitude, although unlikely to arise by chance alone, could still be due to some unappreciated systematic uncertainty in SH0ES's methodology. That explanation, however, is starting to look much less likely in light of new work from the H0LiCOW (H_0 Lenses in COSMOGRAIL's Wellspring) collaboration, led by Sherry Suyu, which uses gravitationally lensed quasars to independently measure H_0. In 2017 the collaboration published a first result based on three lensed quasars (reference 3; see also PHYSICS TODAY, April 2017, page 24). The current work, with key contributions by Kenneth Wong and Geoff Chen, extends the analysis to six quasars.[4] The result, $73.3 + 1.7 - 1.8$ km/s/Mpc, agrees well with the SH0ES value. Combining the SH0ES and H0LiCOW measurements gives an H_0 of 73.8 ± 1.1 km/s/Mpc, which is 5.3σ different from the ΛCDM prediction.

Lensing measurements

The theoretical basis for H0LiCOW's method, called time-delay cosmography, dates back to a 1964 paper[5] by Norwegian astrophysicist Sjur Refsdal. But not until decades later did telescopes have the capability to implement it. When a quasar or other distant, luminous object lies directly in line with a massive foreground galaxy, its light can be so strongly bent that it appears to Earth-based observers as multiple images. Because the light in each image traverses a path of a different length and a different gravitational potential, as shown in figure 1, any fluctuation in the quasar's intensity shows up in the lensed images at different times.

Refsdal's insight was that measuring those time differences (which are on the order of weeks) and the images' angular deflections (on the order of arcseconds) provides crucial information about the absolute distances to the quasar and the foreground galaxy. The measurement doesn't directly yield D_d (the distance from Earth to the galaxy), D_s (the distance from Earth to the quasar), or D_{ds} (the distance from the galaxy to the quasar), but it does constrain their combination, which is enough information to calculate H_0 from the objects' known redshifts.

Earth-based telescopes suffice to resolve the lensed images and monitor their time delays. For years, the COSMOGRAIL (Cosmological Monitoring of Gravitational Lenses) collaboration has employed 1- to 2-m telescopes around the world to keep an eye on dozens of confirmed lensed quasars; some of the recorded light curves are shown in figure 2.

Measuring the time delays is just one piece of the puzzle. Another crucial ingredient in the H_0 calculation is the lensing galaxy's mass distribution, which is needed to calculate the deflection angles (which can't be directly measured, because the quasar's true position on the sky is unseen) and the gravitational effects on the light travel time for each image. The mass distribution isn't observable, but it can be modeled from the precise positions and shapes of the lensed images. An effective model requires high-resolution images from the *Hubble Space Telescope*.

It also requires some good judgement. The choice of when to stop adjusting the mass-distribution model requires a subjective assessment of how well the model agrees with the observed data. The H0LiCOW researchers worried that their decisions might be influenced, even subconsciously, by the value of H_0 they were hoping to get. So they developed a technique of blind data analysis, whereby they could work on the model and test it against the data without ever seeing the distance or H_0 values it would yield. They agreed beforehand that once they settled on a mass distribution that looked good, there was no going back: They'd publish whatever results it yielded with no further modifications.

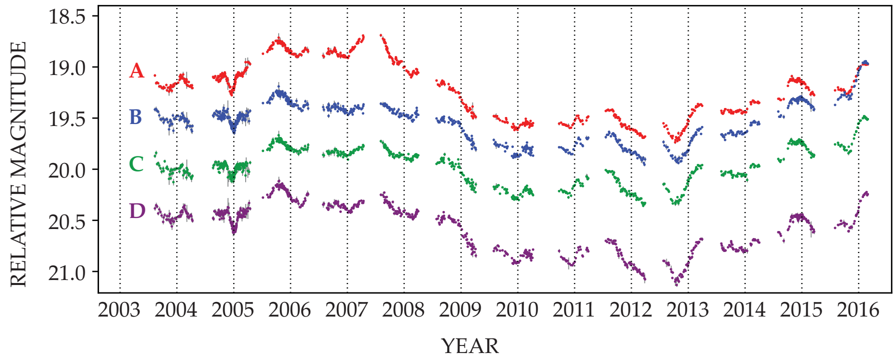

FIGURE 2. LIGHT CURVES from the four lensed images of the quasar shown in figure 1, collected over 13 years by five telescopes from the COSMOGRAIL (Cosmological Monitoring of Gravitational Lenses) collaboration. Fluctuations in the quasar's intensity appear first in images A and C, then in image B, and finally, about two weeks later, in image D. (Adapted from ref. 3.)

"Because our analysis was blind, we could have gotten any result," says Wong. "So it was a bit surprising to find that we were within 1σ of SH0ES."

Off the distance ladder

SH0ES, meanwhile, has been tackling its own challenges in precisely determining H_0. Type Ia supernovae, which are luminous enough to be seen at great distances, are extremely effective tools for measuring relative cosmic distances: Their peak luminosities are nearly all the same, so supernovae that appear dimmer must be farther away. From the slight curve in the relationship between their distances and velocities (inferred from their redshifts) came the Nobel-winning discovery that the expansion of the universe is accelerating (see PHYSICS TODAY, December 2011, page 14). That determination, however, was made without knowing the absolute distance to any of the supernovae under study, so it didn't yield a precise value of the present-day expansion rate H_0.

To convert the relative distances into absolute ones, astronomers use a hierarchy of measurements called the cosmic distance ladder (see the article by Daniel Holz, Scott Hughes, and Bernard Schutz, PHYSICS TODAY, December 2018, page 34). The distances to nearby objects, within a thousand parsecs or so, can be accurately measured using the geometric method of parallax. But supernovae of any type are rare events, and there hasn't been one close enough to Earth for many hundreds of years. Cepheid variable stars can bridge that gap. They're both numerous enough to be well represented near Earth and bright enough to be visible at the same distances as the nearest supernovae. As discovered by Henrietta Leavitt a century ago, Cepheids' luminosities are related to their pulsation periods, so their relative distances can be inferred from their apparent brightness.

SH0ES has been shoring up the links between parallax, Cepheids, and supernovae, and other groups have checked and rechecked them. But there remained the possibility that some aspect of the underlying physics—of supernova evolution, Cepheid pulsation, or the telescopes used to observe them—wasn't understood as well as astronomers thought it was.

It's important, therefore, that H0LiCOW and SH0ES get the same answer from independent methods. SH0ES's measurement has nothing to do with gravitational lensing or modeling of galaxy mass distributions, and H0LiCOW's has nothing to do with the mechanisms of Cepheids or supernovae. If SH0ES's result is marred by a systematic error, H0LiCOW's analysis would have to coincidentally include a different error of almost exactly the same magnitude and sign.

Discovery?

In high-energy physics, a signal with statistical significance of 5σ is the threshold for claiming discovery of a new particle or effect. (See, for example, PHYSICS TODAY, September 2012, page 12, and August 2019, page 14.) The statistical meaning of a 5σ result is the same in all contexts: Assuming a Gaussian distribution of measurement fluctuations, there's a 1 in 3.5 million chance that the result could arise by statistical fluctuations alone, in the absence of any underlying effect.

But cosmologists so far have been reluctant to declare that the tension in H_0 measurements must be a sign of physics beyond the ΛCDM model, in part because it's not at all clear what that physics would be. There aren't many ways the ΛCDM model could be modified that would both close the H_0 gap and maintain the model's agreement with all other measurements. Some of the possibilities theorists are exploring include dark radiation (relativistic dark particles, such as sterile neutrinos, whose wavelengths get stretched as the universe expands), non-Newtonian modifications to gravity, or a dark energy that's not constant. But there's no specific evidence, yet, of any of them, and a complete theoretical picture remains elusive.

The H0LiCOW researchers are working on adding more quasars to their analysis, with the goal of reducing their measurement uncertainty below 1%, or 0.7 km/s/Mpc. If their H_0 value remains unchanged, such a measurement would be 5σ different from the ΛCDM on its own, independent of SH0ES or any other result.

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References

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3. V. Bonvin et al., *Mon. Not. R. Astron. Soc.* **465**, 4914 (2017).
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Rare nuclear transition provides evidence for stellar explosion mechanism

With its higher-than-expected propensity to capture electrons, neon could drive some stars' thermonuclear death.

When the core of a massive star runs out of nuclear fuel, it collapses under its own gravity to form a neutron star or a black hole and sheds its outer layers in a supernova. (See, for example, the article by Hans Bethe, PHYSICS TODAY, September 1990, page 24.) However, for smaller stars in the 7- to 11-solar-mass range, gravitational collapse may not be the only possible route to a supernova. Those stars are abundant in our galaxy, but the final phase of their evolution is unclear. Some may undergo gravitational collapse like massive stars. But if nuclear reactions in a star's core generate sufficient energy to counter collapse, its life may also end in a thermonuclear

FIGURE 1.OLIVER KIRSEBOM, KNEELING AT COMPUTER, AND COLLEAGUES designed an experiment at the University of Jyväskylä accelerator laboratory in Finland to measure how frequently radioactive fluorine-20 emitted electrons and decayed to ground-state neon-20. The photo was taken at 1444 m depth in the underground laboratory. (Image courtesy of Oliver Kirsebom.)