



Cepheid Calibration

Fritz Benedict

One of the sterling accomplishments of the *Hubble Space Telescope* has been its measurement of the “Hubble constant.” Named after Edwin Hubble, who in 1929 discovered that the universe is expanding, the Hubble constant characterizes the present-day expansion rate of the universe and is required to determine its age. In practice, measurement of the Hubble constant is extraordinarily difficult—Edwin Hubble’s initial estimate was off by about 600%. During most of the last century, astronomers could not agree to within about a factor of two. *Hubble Space Telescope* observations in the late 1990s narrowed the range of uncertainty to about 10%. Today, one of astronomy’s greatest challenges is to reduce the uncertainty to about 5%.

The quest for a precise estimate of the universe’s expansion rate is not just an academic exercise. Knowing its exact value can help astronomers distinguish between different theories for “dark energy,” a mysterious pressure that counteracts gravity and pushes galaxies apart at an accelerating rate. Two separate teams of astronomers discovered dark energy in 1998, using *Hubble* and ground-based observatories to make careful measurements of the brightness of distant exploding stars. This was one of the most surprising and profound discoveries of the 20th century. In an odd twist, pursuing this discovery has astronomers pointing *Hubble* at some bright, *nearby* stars.

As a class, Cepheid variables are the most useful stars in the sky. They are named for their archetype, δ Cephei, the fourth brightest star in the constellation Cepheus—although the most familiar Cepheid variable is the North Star. Cepheids vary in brightness, with periods from a few days to about two months. They moved to center stage in astronomy in 1908, when Henrietta Leavitt discovered a mathematical relationship between their period and their intrinsic brightness. Since then, astronomers have employed Cepheids as “standard candles” for measuring cosmic distances.



Present among the thousands of stars seen by *Hubble* in this close-up of our neighboring galaxy, the Large Magellanic Cloud, are a few whose brightness varies rhythmically over a period of days to weeks. These variable stars provide an important key to unlocking the correct scale of the universe, as this article explains.

The apparent brightness of a light source varies inversely as the square of its distance. In other words, if the distance between an observer and a light source is doubled, the light source will appear four times as faint to the observer. Astronomers can use this inverse square law to estimate distances. The difficulty lies in making the first step: finding a good standard candle—a class of sources that vary in apparent brightness only due to changes in distance.

For years after Leavitt's discovery, astronomers could only use Cepheids as *uncalibrated* standard candles, because no Cepheid had been assigned an accurate distance until fairly recently. Even so, Cepheids were immediately useful for measuring *relative* distance. For example, in the early 1920s, when Edwin Hubble discovered Cepheids in the Andromeda nebula that were about 100 times fainter than their counterparts in the Small Magellanic Clouds, he could infer that they were 10 times farther away—and far beyond the most generous estimates of the limits of our Milky Way galaxy at that time. That result ended the debate about whether the Milky Way constituted the entire universe, or was just one of many galaxies. Henceforth, the proper title for Andromeda was “galaxy,” not “nebula.”

Because Cepheids are such good standard candles—the stars are bright and Leavitt's relation is quite exact—astronomers strive to calibrate them to the highest possible accuracy, and to investigate any possible sources of error when using them to measure distances.

The absolute calibration of Cepheids calls for triangulating the distances to as many nearby Cepheids as possible. Astronomical triangulation involves observing a star at different times of the year, and measuring its displacement relative to more distant stars. Its apparent position changes because we view it at different angles as Earth moves around the Sun. The apparent displacement of a star when viewed from opposite sides of Earth's orbit is its “annual parallax.” When a star is 1 parsec (3.26 light-years) away, its annual parallax is 1 arc second. (One arc second is roughly the diameter of a dime, viewed from a distance of two miles.)

With its superb resolving power, *Hubble* can resolve individual stars in distant galaxies. In the magnificent spiral galaxy NGC 3370, 98 million light-years away, individual Cepheid variable stars were identified and studied.





Henrietta Leavitt: Timeless Contributions

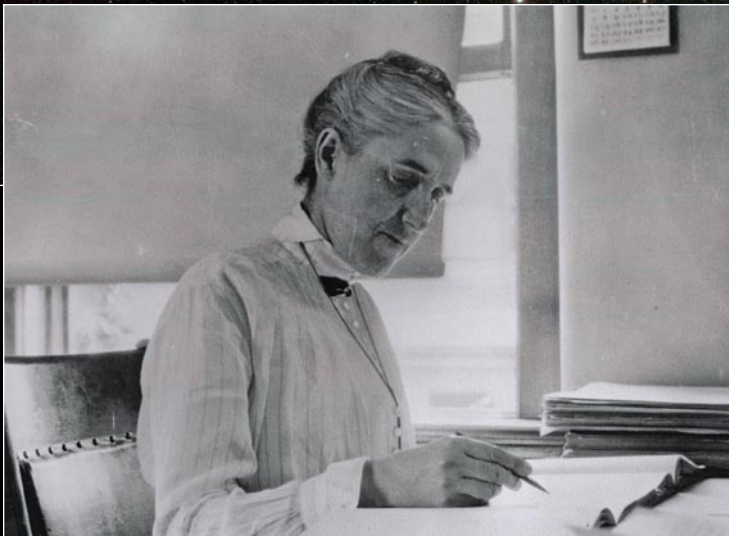
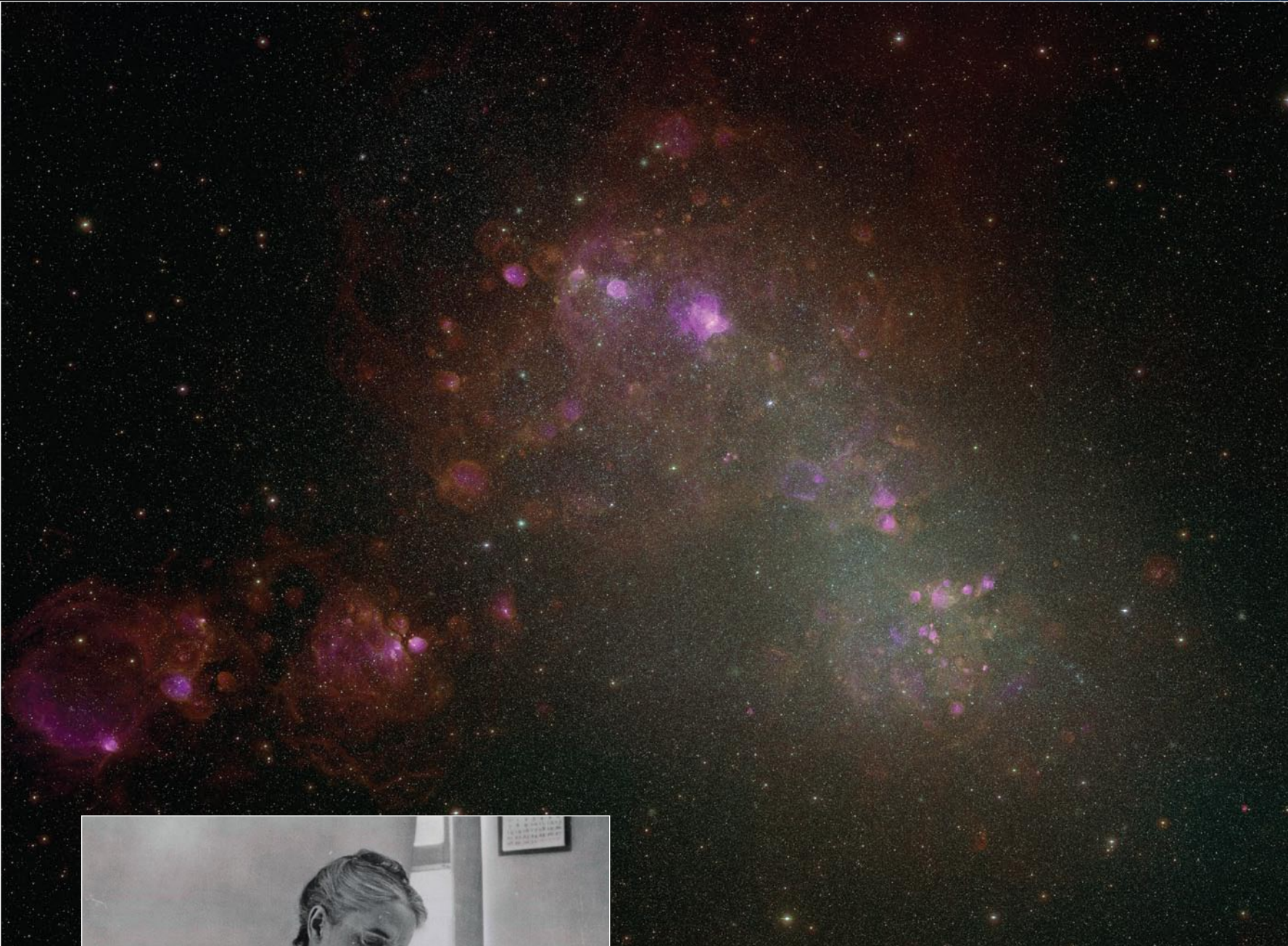
Sometimes a great advance in science is achieved through selfless work performed by a modest person not striving for recognition on the stage of history. Such was the contribution of Henrietta Leavitt, one of many female “computers” working at the Harvard College Observatory for small hourly wages. Her years of patiently studying astronomical photographs—from 1893 until her death in 1921—culminated in finding the missing link for measuring cosmic distance: the period-luminosity relation of Cepheid variable stars.

Leavitt's job at the observatory was to measure the brightness of stars on photographic plates from Harvard's telescopes in Massachusetts and abroad. Her product was a record of results comprising the identity of each star based on its position, and the star's brightness on the date of the observation, which she determined by comparing the star's tiny photographic image with those of other stars. She performed this exacting task year after year in pursuit of various projects for Edward Pickering, the observatory director.

Leavitt was asked to take special note of any stars that varied in brightness, which a small fraction do, although the various reasons for such fluctuations were not known at the time. Until she began finding them on plates from Peru of the Small Magellanic Cloud, all variable stars were at unknown distances, beyond the reach of triangulation. Even though the distance to the Small Magellanic Cloud was also unknown, it could be assumed that all the variable stars found there were at approximately the *same* distance. In that case, all these stars had the same (unknown) ratio of apparent brightness to true brightness. Therefore, observed ratios of apparent brightness between the stars could be interpreted as ratios of *true* brightness, independent of the observer.

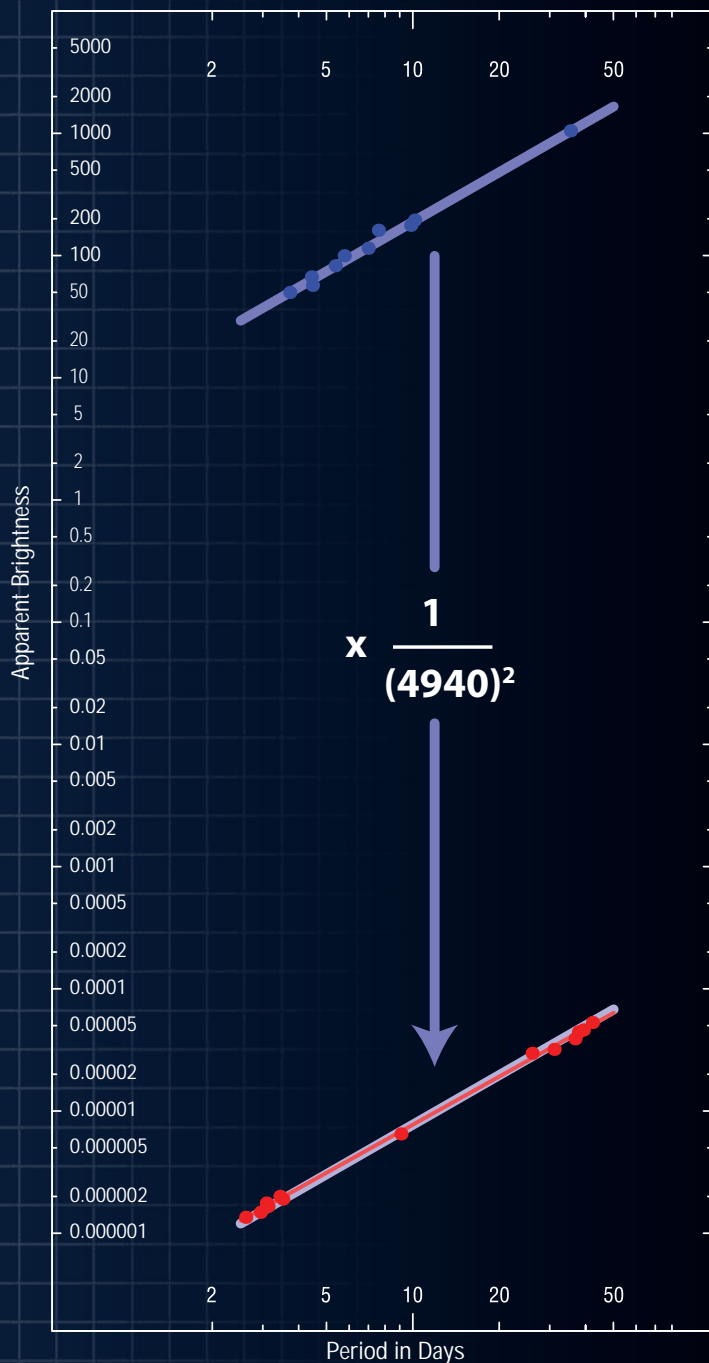
At the end of her report in the *Annals of the Astronomical Observatory of Harvard College*, Leavitt wrote of 16 particular stars, “It is worthy of notice that in Table VI the brighter variables have the longer periods.” These were the Cepheid variable stars, and she had found that the brighter the Cepheid, the longer the period of its variation. What a discovery! Astronomers have relied on it ever since to measure distances to remote galaxies.

Once the distance to a few nearby Cepheids was measured by parallax—making the relationship between period and intrinsic brightness absolute—astronomers began using it as a technique for estimating true astronomical distances. This continues today, probing ever deeper into the universe as larger and larger telescopes find Cepheid variable stars in increasingly remote galaxies. Without Cepheids, the history of astronomy would be very different, and legendary names like “Hubble” might be far less well known today.



△ The Small Magellanic Cloud is an irregularly-shaped galactic neighbor of our Milky Way galaxy. Careful study over time of hundreds of individual stars in this system led Henrietta Leavitt to discover some whose variability could be related mathematically to their brightness. (Photo credit: F. Winkler/Middlebury College, the MCELS Team, and NOAO/AURA/NSF.)

◁ Henrietta Leavitt (Photo credit: Harvard College Observatory.)



Hubble measured the distances to 10 nearby Cepheid variable stars. Using the distances, astronomers could correct the apparent brightness of these stars to the values that would be observed if they all were located at the standard distance of 10 parsecs (blue dots). The best fit to the corrected data is the new calibration of the Cepheid standard candle, the best mathematical estimate of the relationship between period and intrinsic brightness (upper blue line).

Using the infrared camera on *Hubble*, astronomers measured the apparent brightness and periods of 13 Cepheids in the Large Magellanic Cloud (red dots) and obtained a best fit to the data (red line). In this case, the Cepheids are all at about the same, large distance from the observer. When the Cepheid calibration curve is displaced downward by a reduction in brightness by a factor of 24.4 million, it almost exactly coincides with the data from the Large Magellanic Cloud. Therefore, the Cloud is the square root of that factor, or 4,940 times farther away than the standard distance of 10 parsecs, or 49,400 parsecs distant.

The Fine Guidance Sensors on *Hubble* are the most accurate instruments available to astronomers for measuring the annual parallax of stars, induced by the yearly motion of Earth around the Sun. *Hubble* has three of these powerful instruments. Two are needed to stabilize the pointing of the telescope during regular operations, but the third is available to astronomers. With this instrument, observers can measure the positions of stars in its wide field of view with an accuracy exceeding 0.001 arc second, or the size of a dime seen from a distance of about 2,000 miles.

Before *Hubble*, very few nearby Cepheids had been assigned good distances. Now, *Hubble* has triangulated the distances to 10 nearby Cepheids with an accuracy better than 10%.

Combined with another recent *Hubble* result—a small correction of the intrinsic brightness for a Cepheid's chemical composition—these new distance measurements have significantly improved the calibration of Cepheids as standard candles.

The new Cepheid calibration was checked on two galaxies with distances well known by other means, because of special circumstances. The first test was the Large Magellanic Cloud. (The Large and Small Magellanic Clouds are dwarf galaxies orbiting the Milky Way.) The second was the galaxy NGC 4258, at 100 times greater distance. In both cases, the two independent distance estimates agreed to 2–3%.

Today, after a century of key contributions to science, Henrietta Leavitt's Cepheid variable stars remain on the forefront of astronomical research. They are the main link between the bedrock—measuring distances by geometric triangulation—and other techniques for estimating cosmological distances to investigate the extent and structure of the universe itself. Indeed, a key reason for building the *Hubble Space Telescope* originally was to measure Cepheid variable stars in galaxies at distances of tens of millions of parsecs, which it achieved with outstanding success—laying the groundwork for today's understanding of the age of the universe and the mysterious dark energy. There can be no remaining doubt that Cepheids in distant galaxies can be used with confidence to yield precise distances.



Fritz Benedict is a member of the *Hubble* Astrometry Science Team. His scientific interests have centered on high precision parallaxes and the astrometric detection of low-mass companions to stars. He looks forward to working with data from the *Space Interferometry Mission*, looking for the astrometric signatures of Earth-sized planets around nearby stars. Fritz sails a Catalina 22 on Lake Travis outside Austin, Texas, walks his dog, reads science fiction, and maintains a home with Ann, his wife of 39 years.