Today in Astronomy 142: distances to the galaxies

- Standard candles and standard rulers.
- Henrietta Leavitt and the invention of standard candles.
- The extragalactic nature of the spiral nebulae and the Shapley-Curtis debate.
- The extragalactic distance scale, part 1.

The Small Magellanic Cloud, site of the discovery of the Cepheid period-luminosity relation. (Photograph by Weihao Wang (NRAO).)

Standard candles and standard rulers

There's only one direct distance measurement method for individual objects more than a few light-hours away – trig parallax – and it only works on objects within a few hundred parsecs, these days.

Thus astronomers have often sought standard candles or rulers to aid in distance determinations.

- **Standard candle**: an object with a well determined luminosity L known *a priori*, whose distance is therefore

  $r = \sqrt{L/4\pi f}$ (or equivalently $5\log\left(r/10\text{ pc}\right) = m - M$) .
- **Standard ruler**: an object with length d perpendicular to the line of sight is known *a priori*, whose distance is

  $$r = d/\sin\theta \cong d/\theta \quad .$$

Henrietta Leavitt and standard candles

Henrietta Swan Leavitt (AIP photo)

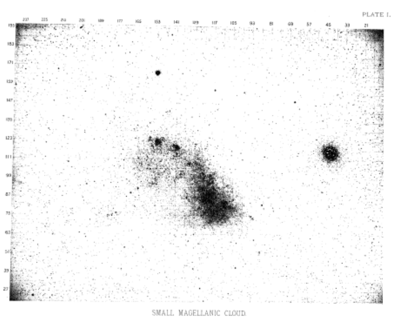
Today tens of thousands of Cepheid variable stars are known, a large fraction of which – about 2400 – were discovered by Henrietta Leavitt, perhaps the most illustrious of the women working as "computers" in Edward Pickering's group at Harvard College Observatory.

- 969 of them are in the Small Magellanic Cloud (Leavitt 1908), and therefore all about the same distance (~60 kpc).
- The photographic plates she used initially were taken at Harvard's 24-inch Bruce refractor in Arequipa, Peru.

Henrietta Leavitt and standard candles (continued)

- The Bruce telescope itself was built with a $50k donation to Harvard from Catherine W. Bruce of New York; the site in Peru was upgraded for it by another of Miss Bruce's bequests. (Pickering was a friend of Miss Bruce's.)
  - Leavitt never observed with it; women were not allowed to operate telescopes themselves, those days.
- Leavitt noted in the first few sets of Bruce photographic plates on the SMC and LMC that there were many variables among the brightest stars, and that the brighter variables had longer periods (Leavitt 1908).
  - She also noted that the light curves resemble those of "cluster variables," the stars we now call RR Lyrae variables; 47 Tuc was in all of her SMC plates.

Henrietta Leavitt and standard candles (continued)



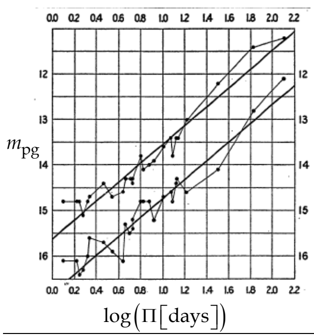
Negative of the SMC (left) and globular cluster 47 Tuc (right), printed from a Bruce Telescope plate by Henrietta Leavitt (Leavitt 1908).

Henrietta Leavitt and standard candles (continued)

- So Leavitt acquired lots more plates (~100) on the SMC, taken over a period of 16 years, from the Harvard archives, and worked out the light curves and periods of many of the variables.
- Choosing 25 with particularly good light curves and a large range of magnitudes, she determined their periods and showed that their magnitudes are proportional to the logarithm of the periods ("Pickering" 1912), concluding that

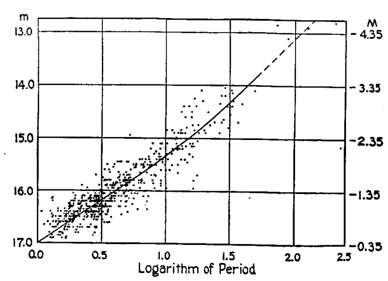
  Since the variables are probably at nearly the same distance from Earth, their periods are associated with their actual emission of light [*i.e.* luminosity], *as determined by their mass, density and surface brightness.*

Henrietta Leavitt and standard candles (continued)



Period-apparent magnitude relation for bright variables in the SMC ("Pickering" 1912). The upper (lower) curve represents each star's maximum (minimum) brightness. The linear fits have the same slope, 1 mag per 0.48 in the logarithm of period in days.

Henrietta Leavitt's SMC Cepheids



From Shapley 1961, *Galaxies* (Cambridge: Harvard. U. Press)

Henrietta Leavitt and standard candles (continued)

In modern terms, Leavitt's period-magnitude relation is

$$\overline{m_V} = -2.80\log\Pi + 17.42 \quad (\Pi \text{ in days}).$$

Since the absolute and apparent magnitudes differ only by the (constant) distance modulus, this represents a relation between period and absolute magnitude or luminosity. **Thus these variables with measured periods are standard candles**.

- Nowadays we know that the variables Leavitt found in the SMC and LMC are classical Cepheids, not cluster (RR Lyrae) variables. The $\Pi - L$ relation is calibrated from Cepheids in open clusters with distances measured by main-sequence fitting (Homeworks 5 and 8):

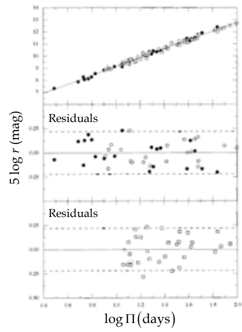
$$\overline{M_V} = -2.76\log\Pi + 1.354 \quad (\Pi \text{ in days}).$$

Henrietta Leavitt and standard candles (continued)

Modern value for the extinction-corrected distance modulus of classical Cepheids:

$$\mu_0 = (m-M)_0 = 5\log\left(\frac{r}{10\ \mathrm{pc}}\right)$$
$$= V + 3.65\log\Pi - 1.30(V-K)$$
$$+ (2.55 \pm 0.11) + 0.18A_V$$

On this scale, the distance to the SMC is $r = 63.2 \pm 0.7$ kpc (di Benedetto 1997).



Henrietta Leavitt and standard candles (continued)

As Leavitt's work enabled astronomers to measure distances outside the Milky Way, it counts as one of the most important discoveries in modern science.

- Edwin Hubble said many times that Leavitt deserved the Nobel Prize in Physics for the discovery of the period-luminosity relationship.
- In fact, a few years after Leavitt's untimely death (1921), a member of the Royal Swedish Academy of Sciences who wanted to nominate her, approached Harlow Shapley for information. Shapley informed the academician that she was dead (which disqualified her), but that anyway the most important result was the *interpretation* in terms of pulsations, which was his (Shapley's) work…

Cepheids and the 1918 size of the Galaxy

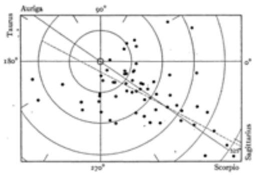

Shapley

Harlow Shapley recognized the importance of Leavitt's discovery of the period-luminosity relationship, and set about applying it as a standard candle in distance measurements of globular clusters. (See the lecture notes for 17 March.)

- He correctly identified Cepheid variability with pulsation (Shapley 1914), but couldn't know there were so many different kinds of pulsating stars. The regular variable stars in globular clusters (mostly RR Lyrae stars) are much less luminous than classical Cepheids.
- Nor did he know about interstellar extinction; in fact, he thought he had ruled it out (Shapley 1917) as an effect that would make the Galaxy look larger than it really is.

Cepheids and the 1918 size of the Galaxy

- Thus Shapley determined the *shape* of the globular-cluster distribution correctly, and found our offset from the center of the galaxy, but the Galaxy's diameter exceeded 100 kpc (Shapley 1918).
- By these measures the Magellanic Clouds were within the Milky Way, consistent with then-current ideas of them being unusually large Galactic stellar clusters.



Dots: cluster positions projected onto the plane of the Milky Way. Circles: radii in integer multiples of 10 kpc. From Shapley 1919.

Spiral nebulae

The Galactic diameter seemed so enormous to Shapley that he – and many others – began to think his work also ruled out the longstanding (Kant 1755) "island universe" description of the spiral nebulae, and that they are **not** distant objects similar in size to the Milky Way (Shapley 1919).

Spiral nebulae are what we now call spiral *galaxies*. At the time they knew the following about them:

- They come in the shapes and sizes we already know and love; some (the edge-on ones) bear an uncanny resemblance to the Milky Way.
- They were not resolved into individual stars.
- Like globular clusters, they "avoid" the Galactic plane: only observed at relatively high Galactic latitude.

Spiral nebulae (continued)

This was a time in which the sensitivity of astronomical observations was improving rapidly due to a new generation of ever-larger telescopes on good mountaintop sites, like George Ellery Hale's 60" (1908) and 100" (1917) reflectors on Mount Wilson, uphill from Pasadena, CA. Much attention turned to the faintest interesting objects, like spiral nebulae.

- "Flares" were observed in a few spiral nebulae (by, e.g., Pease, Curtis, the "computers") and as they were similar in brightness to novae, were suggested to be Galactic.
- Von Maanen reported observations of proper motion of the spiral arms of the big Sc galaxy M101. The corresponding rotation period was 10^5 years; if it were extragalactic the rotation speeds would be relativistic.

Spiral nebulae (continued)

- All but a few spiral nebulae – the ones with largest angular size – recede from the LSR at speeds much larger than typical of Galactic stars (Slipher, 1917).

The nature of the spiral nebulae thus seemed to Hale and the leadership of the US National Research Council to be a good topic for a debate that Hale conceived to liven up an annual meeting in April 1920.

- Hale, as director of Mt. Wilson, selected his bright young subordinate Shapley to represent the non-island-universe side of the debate.
- He wanted W.W. Campbell, director of Lick Observatory, to represent the island-universe side, but settled for Shapley's opposite number at Lick, Heber Curtis.

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The Shapley-Curtis debate

Shapley's main points in support of his assertion that spiral nebulae lie within our Galaxy:

- If the "flare stars" in spiral nebulae were novae, then their brightness is consistent with Galactic membership. (Use of novae as standard candles…)
- The observed proper motion of the arms of M 101, taken with relativity (no speed can exceed *c*), indicate that M 101 must lie within the Galaxy.
- If they lie within the Galaxy, the Galaxy can presumably influence them; Shapley postulated a hitherto unobserved force by which the Galactic plane repels the spiral nebulae, producing thereby the observed restriction to high Galactic latitude.

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The Shapley-Curtis debate (continued)


Curtis

Curtis' main points in claiming that the spiral nebulae are extra-Galactic, and in fact are island universes:

- The range of shapes of spirals looks like a population seen at different orientations ranging from face on to edge on, and the latter bear a strong resemblance to the Milky Way. (Standard argument.)
- That they aren't seen in the plane (suggesting extinction!), are essentially all receding, and have such large radial velocities, indicates that they comprise a different population from Galactic stars; there is thus no *a priori* reason for taking them to be Galactic members.
- To consider them to be extragalactic involves no assumption of hitherto unobserved physical forces.

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The Shapley-Curtis debate (continued)

The "debate" wasn't much of one, with each speaker giving a 40-minute talk (Shapley going first) and no rebuttal.

- Nobody envisioned this as huge at the time, least of all the speakers, who were both seeking job promotions and wanting most to make good impressions. (They got them.)
- But, as it sharpened the thinking of many other astronomers on scale of the Universe, it was a watershed.
  - Both Shapley and Curtis wrote up their arguments at great length for distribution (*Bull. NRC* **2**, 171, 1921).
  - This, and Curtis's later descriptions of a "set-to," gave non-attendees the impression that a titanic struggle had taken place, and the myth descended to the books.

See Hoskin 1976 for a less dramatic account.

Spiral nebulae are extragalactic

The real watershed event occurred a few years later, as Edwin Hubble (1925) detected pulsating variable stars in the disks of M 31 and M 33. Thereby he showed these nebulae to be ten times further away than the distance to the center of the Galaxy, derived in the same way by Shapley.

- With hindsight we know this distance was relatively too *small*, for the same reason that Shapley's distances were too large: the assumption that variables in globular clusters were the same as the classical Cepheids seen in M 31, M 33 and the Magellanic clouds.
- Regardless of precise distance, though, the results proved a large **ratio** for the M 31 or M33/Galactic center distances, far too large for them to lie within the Milky Way.

Spiral nebulae are extragalactic (continued)

What about the novae, M 101's rotation, high recession speeds, and Galactic plane avoidance?

- The "flares" in spirals turned out to be **supernovae**: a hitherto unsuspected class of astronomical object, but one that required no radically new physics for its explanation.
- Van Maanen's proper motion measurements were shown by Hubble and by van Maanen himself to be in error.
- Slipher's measurements held up, though: **the galaxies are nearly all receding from the Galaxy**, and are doing so at high speed. These results were used to great effect by Hubble in the late 1920s, as we will discuss next class.

Spiral nebulae are extragalactic (continued)

- With Trumpler's discovery of interstellar extinction, the reason that other galaxies are not seen in the plane of the Milky Way became obvious. This also unmasked problems in the Cepheid period-luminosity calibration.

Finally, Walter Baade (1944) resolved the bulge of M 31 into stars and showed that the bulge's HR diagram is very similar to the globular clusters.

- He identified thereby the distinction between Populations I and II, noting that this was also apparent in Oort's earlier distinction by random velocities.
- By 1954, he had shown that there were long-period Population II stars, now called W Virginis stars, with P-L relation parallel to the classical Cepheids but 1.5 magnitudes fainter.

The extragalactic distance scale, part 1 (distances less than about 30 Mpc)

Here are the first few rungs of the "ladder" by which distances to celestial objects are determined. Each rung uses the previous result, inheriting its uncertainty and adding its own.

1. Measure the AU, using radar reflection from Venus. It would be tempting to try to measure stellar distances by radar, but the reflected signal decreases with distance to the object according to $1/r^4$, so it turns out not to work for objects more than a few light-hours away.
2. Use trig parallax to determine the distances to the nearest stars, and an "absolute main sequence."
3. Use trig parallax to determine the distance to the nearest open clusters, checking to see that their main sequences match that of the trig-parallax stars.

The extragalactic distance scale, part 1 (distances less than about 30 Mpc), continued

4. With the open clusters as a calibration, use main-sequence fitting to determine the distances to open clusters that contain Cepheids, and thus the distance to the Cepheids themselves. This allows the measurement of luminosities for a sample of Cepheids, and thus a calibration of the Cepheid period-luminosity relation. Sound familiar?
5. Observe Cepheid periods and fluxes in galaxies, get their luminosities from their periods, and determine their distance (and that to their host galaxy) by using $r = \sqrt{L/4\pi f}$. This works until it is impossible to resolve Cepheids from nearby stars in the galaxy disks; the Hubble Space Telescope allows this technique to be extended from 3 Mpc (all you can get with ground-based measurements) to about 30 Mpc.