Climbing the Cosmic Distance Ladder “in” a WorldWide Telescope

#LeavittLaw

gallery presentation by Joao Alves (U. Vienna & Radcliffe) Alyssa Goodman (Harvard & Radcliffe)

Cepheid Variable Star V1 in M31

Hubble Space Telescope • WFC3/UVIS

NASA, ESA, and the Hubble Heritage Team (STScI/AURA)
Astronomer Henrietta Swan Leavitt died on this day in 1921. Her groundbreaking work at the Harvard Observatory helped establish some of our fundamental understandings of the universe.
#LeavittLaw

How Henrietta Leavitt’s insight took the measure of the Universe

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A sense of scale
(WorldWide Telescope tour)
"our nebula...is of the third form; that is: A very extensive, branching, compound Congeries of many millions of stars."

(assumes star evenly distributed in space)
The Kapteyn Universe (Kapteyn Astronomical Institute)

(uses photographs to perform star counts, derives distances statistically, neglects dust extinction. Vertical structure of the Galaxy correct)
Orthocorona: AC 948 Aug 1, 1900
just off edge

AC 3836 Aug 17, 1903
9.5 9.7

AC 1595 July 1, 1901
eff. too short

AM 1287 May 28, 1902
9.4 9.6

AM 1051 Sept 7, 1901
9.4 9.6

AM 1237 May 2, 1902
9.4 9.6

AM 1251 May 15, 1902
9.5 9.7

AM 1270 May 26, 1902
9.4 9.6
The variables appear to fall into three or four distinct groups. The majority of the light curves have a striking resemblance, in form, to those of cluster variables. As a rule, they are faint during the greater part of the time, the maxima being very brief, while the increase of light usually does not occupy more than from one-sixth to one-tenth of the entire period. It is worthy of notice that in Table VI the brighter variables have the longer periods. It is also noticeable that those having the longest periods appear to be as regular in their variations as those which pass through their changes in a day or two. This is especially striking in the case of No. 821, which has a period of 127 days, as 89 observations with 45 returns of maximum give an average deviation from the light curve of only six hundredths of a magnitude. Six of the sixteen variables are brighter at maximum than the fourteenth magnitude, and have periods longer than eight days. It will be noticed that this proportion is much greater here than in Table II. The number which have been measured up to the present time is 59, and of these the brighter stars were first selected for discussion, as the material for them was more abundant. A few of the fainter variables, selected at random, were then studied, but no attempt has yet been made to determine periods for the remainder. While, therefore, the light curves thus far obtained have characteristics to which the majority of the variables will probably be found to conform, no inference can be drawn with regard to the prevalence of any particular type, until many more of the periods have been determined.
Cepheid stars are variable.
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Cepheids pulsation period is related to their intrinsic brightness #LeavittLaw.

Leavitt & Pickering 1912
Cepheids pulsation period is related to their intrinsic brightness #LeavittLaw.

Leavitt & Pickering 1912
Comparing intrinsic brightness to apparent brightness gives distance, just like looking at a faraway light bulb.
Once a cepheid’s distance is be known by TWO methods (e.g. parallax and intrinsic-apparent brightness comparison), a “ladder” is established, where Cepheids can give distance just from #LeavittLaw (period → distance).
Cepheids pulsation period is related to their intrinsic brightness #LeavittLaw.

Measuring periods accurately is much easier than measuring brightness accurately.
Cepheid stars are variable.

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Measuring periods accurately is much easier than measuring brightness accurately.

Distances for the MOST distant Cepheids (in other galaxies) are tied to another method (e.g. redshifts + #HubbleLaw), to add more rungs to the ladder.
What happened?

Fig. 16.8 The Kapteyn Universe (Kapteyn Astronomical Institute)

Shapley 1918

*Figure from de Sitter’s book ‘Kosmos’, published in 1934 and credited to Jan H. Oort (see P. van der Kruit book on Kapteyn).*
HOW MANY UNIVERSES ARE THERE?

This evening two California astronomers will discuss the Size of the Universe, and present their views as to whether or not there is only one or several universes, before the National Academy of Sciences, which is now in session in Washington.

In this public meeting, Dr. Harlow Shapley of the Mt. Wilson Solar Observatory, will discuss recently secured evidence pointing to the dimensions of our galaxy of stars, known popularly as the Milky Way, which he believes to be ten times greater than is held in the older theories concerning the dimensions and compositions of the Milky Way. In other words, he claims that it takes light about three hundred thousands of years to cross from one side to the other of the space occupied by the 3,000,000,000 stars of which our sun is the nearest one. He holds the spiral nebulae, those clam-shell-like cloudy luminous objects seen by great telescopes, to be inside our system.

Doctor Shapley's views will be followed by the discussion of Doctor Eber D. Curtis of the Lick Observatory, who will defend the older view that our Milky Way is approximately of the dimensions suggested by Newcomb, about 30,000 light-years in diameter, with the spiral nebulae regarded as very probably individual galaxies of "island universes", like ours. Thus there may be a million other universes each having 3,000,000,000 stars. Inhabitants of these numerous universes would see our Milky Way as a spiral nebula. The lecture on these two learned astronomers will be followed by a general discussion of the auditors present who are interested in the development of this new field in scientific research.
What happened?

Hubble 1925
What happened?

*Cepheids in a mid-distance galaxy, Hubble, using Leavitt*
Distances for the MOST distant Cepheids (in other galaxies) are tied to another method (e.g. redshifts + #HubbleLaw), to add more rungs to the ladder.

- **faraway galaxies using redshift**  
  (Hubble 1929)

- **Cepheids in mid-distance galaxies**  
  (Hubble 1925, using Leavitt)

- **Cepheids in nearby galaxies**  
  (Leavitt 1908, 1912)

- **Milky Way Cepheids nearby**  
  (statistical parallax, Hertzsprung 1913)

- **Sun (geometry)**
faraway galaxies using redshift (Hubble)
Cepheids in mid-distance galaxies (Hubble, using Leavitt)
Milky Way Cepheids nearby (parallax, Hertzsprung)

Nearby star distances measured via "parallax."
Cepheids in nearby galaxies (Leavitt)

OGLE Survey 21st Century SMC Cepheids

Leavitt's Law with modern data
Cepheids in nearby galaxies
(Leavitt)

Henrietta Leavitt's 25 SMC Cepheids

Leavitt's Law

Cepheids in a nearby galaxy
Earth-Sun distance calculated since ancient times from geometry.
The “Simple” Cosmic Distance Ladder

faraway galaxies using redshift
(Hubble 1929)

Cepheids in mid-distance galaxies
(Hubble 1925, using Leavitt)

Cepheids in nearby galaxies
(Leavitt 1908, 1912)

Milky Way Cepheids nearby
(statistical parallax, Hertzsprung 1913)

Sun (geometry)
A sense of scale

(WorldWide Telescope tour)
extra slides (not shown)
Three Steps to Measuring the Expansion Rate of the Universe

1. Cepheids: Used as standard candles to measure distances within the Milky Way and nearby galaxies.
2. Cepheids and Type Ia supernovae: Used to measure distances to distant galaxies, where the Cepheids are used to determine the distance to the supernovae.
3. Distant galaxies in the expanding Universe: Used to study the overall expansion of the universe.

Galaxies hosting Cepheids and Type Ia supernovae

Distance

0 - 10 k ly
100 Million - 1 Billion Light-years

Light redshifted (stretched) by expansion of space
A fully modern “distance ladder”

<table>
<thead>
<tr>
<th>Entfernung (Distance)</th>
<th>Leavitt’s Cepheids in the SMC</th>
</tr>
</thead>
<tbody>
<tr>
<td>~ 15 000 000 000 Ly</td>
<td>Kosmologische Ausdehnung</td>
</tr>
<tr>
<td>~ 10 000 000 000 Ly</td>
<td>Supernovae Typ Ia</td>
</tr>
<tr>
<td>~ 1 000 000 000 Ly</td>
<td>Veränderliche Cepheiden</td>
</tr>
<tr>
<td>~ 150 000 Ly</td>
<td>Veränderliche RR Lyrae</td>
</tr>
<tr>
<td>~ 1500 Ly</td>
<td>Stellare Parallaxe</td>
</tr>
<tr>
<td>~ 0.008 Ly</td>
<td>Parallaxe des Erddurchmessers</td>
</tr>
<tr>
<td>12 700 km</td>
<td>Erde</td>
</tr>
</tbody>
</table>

(courtesy ESO Supernova center)
A fully modern “distance ladder”

Use of Cepheids as distance indicators today

- ~ 15 000 000 000 Ly
- ~ 10 000 000 000 Ly
- ~ 100 000 000 Ly
- ~ 1500 Ly
- ~ 0.008 Ly
- 12 700 km

(courtesy ESO Supernova center)
Fig. 1. The Sequence of Nebular Types.

The diagram is a schematic representation of the sequences of classification. A few nebulae of mixed types are found between the two sequences of spirals. The transition stage, S0, is more or less hypothetical. The transition between E7 and SB, is smooth and continuous. Between E7 and Sa, no nebulae are definitely recognized.

“Hubble’s Tuning Fork Diagram”
The Shapley-Curtis Debate at the Smithsonian Natural History Museum, 1920
Boyden station - Arequipa, Peru
Extra background links


Phil Plait on distances: https://www.youtube.com/watch?v=CWMh61yutjU


DASCH project: http://dasch.rc.fas.harvard.edu
The LMC in WWT
SOME HELPFUL BORROWED SLIDES FROM https://www.harding.edu/lmurray/
LAMBERT E. MURRAY
Note on This Distance Scale

- When Cepheid variables were first utilized, there were no Cepheid variables close enough to measure their distance using direct parallax measurements.
- Distances to the Cepheid variables in our own galaxy were determined using statistical techniques, and were dependent upon these theoretical calculations.
- This situation recently changed with the Hipparcos satellite, and we were able to get a more accurate measure of this important “standard candle”. It turns out that the Cepheid variable stars are actually brighter than was initially guessed using the statistical arguments. As a result, we now know that objects are actually about 10% farther away than we previously had thought, i.e., the universe is about 10% larger than we thought.
Hubble’s Measurement for M31

- Making use of a Cepheid variable star he observed in M31 (a spiral-shaped nebula), Hubble concluded that this nebula was 2.2 million light years beyond the Milky Way, thus establishing the existence of “island universes”, or what we today call galaxies.

- Today we recognize M31 as the Andromeda Galaxy, the only object not part of the Milky Way that can be seen with the naked eye from the Earth’s northern hemisphere.
Shapley Uses RR Lyra Variables to Determine our Place in the Milky Way

- Shapley made use of RR Lyra variable stars found in many globular clusters to determine the distances to these clusters.

- RR Lyra variables, like the Cepheid variables also have a period – luminosity relationship.

- By measuring the distances to, and the relative locations of the globular clusters, Shapley determined that these clusters were spherically distributed about a point not centered on the Earth.

- He made the correct assumption that these clusters are clustered around the center of the galaxy.
Shapley’s Conclusions

- Shapley correctly concluded that the sun lay about 2/3 of the way out from the center of the galactic disk.

- Shapley’s distance measurements, however, were wrong, for like many early astronomers, he was unaware of the importance of the Interstellar Medium (or ISM) and the dimming produced by the interstellar dust.

- This same mistake had earlier convinced William Herschel that the earth was at the center of the galaxy. He had argued that the center of the galaxy should have more stars. But when he counted the stars is the Milky Way he found that there were about as many stars is one direction as the other. He did not know about the obscuring gas and dust in the center of our field of view.
Determining Distances to Galaxies

- Cepheid variable stars can be used to measure the distances to galaxies that are within about 60 Mpc (200 million ly).
- Beyond that other standard candles must be used – these all depend upon knowing (or at least having some estimate of) the absolute magnitude of the standard candle.
- Other standard candles which are used.
  - Red and Blue Supergiants (out to about 250 Mpc or 800 million ly)
  - Bright Globular clusters (out to 400 Mpc)
  - Bright HII regions (out to 900 Mpc)
  - Supernova explosions (beyond 900 Mpc)
The Tully-Fisher Relation

- Yet another standard candle is the line width of the 21-cm hydrogen emission line.
- The Tully-Fisher relation indicates that the broader the emission line, the brighter the galaxy. Thus the width of the emission line can be used to determine the absolute magnitude of a distant galaxy.
- The reason this works is that the line width is determined by the Doppler shift – red shifted on the receding side and blue shifted on the approaching side of the galaxy. The larger the shift (the wider the line) the faster the rotation of the galaxy, the more mass contained in the galaxy, thus the more stars – giving rise to a brighter galaxy.
The Hubble Law

- As early as 1914, Slipher, working at the Lowell Observatory had observed that a large number of spiral galaxies that he had been studying exhibited a red shift in their spectra – indicating that most of these galaxies were moving away from us.

- During the 1920’s Edwin Hubble determined the distances to a number of these galaxies using Cepheid variable stars and noticed a correlation between the distance to the galaxies and the observed red–shift of the spectrum.

- He found that the farther away a galaxy was, the greater the red-shift.
FIGURE 1

Velocity-Distance Relation among Extra-Galactic Nebulae.
Velocity-Distance Relation among Extra-Galactic Nebulae.

Radial velocities, corrected for solar motion, are plotted against distances estimated from involved stars and mean luminosities of nebulae in a cluster. The black discs and full line represent the solution for solar motion using the nebulae individually; the circles and broken line represent the solution combining the nebulae into groups; the cross represents the mean velocity corresponding to the mean distance of 22 nebulae whose distances could not be estimated individually.