Lecciones en Astrofisica Avanzada (Semester 1 2024)

Mapping the Universe with Variable Stars (II)

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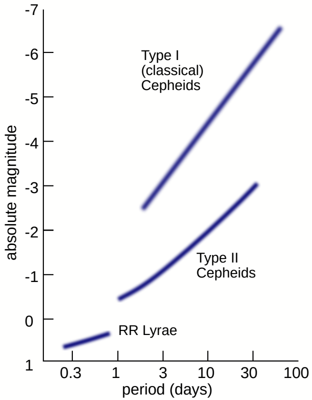
Period-Luminosity(-Metallicity) Relations for Cepheids and RR Lyrae

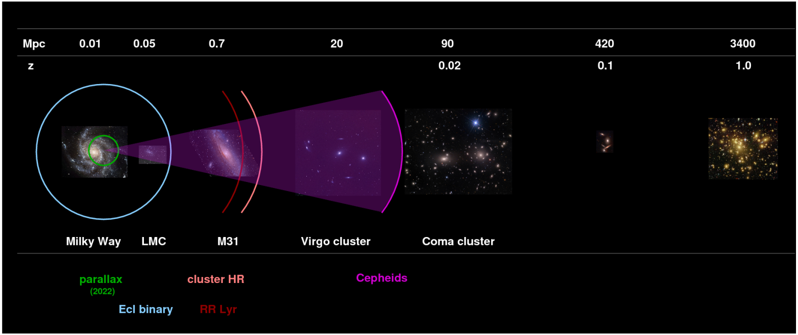
Period-luminosity relations are known for several types of pulsating variable stars: type I Cepheids, type II Cepheids, RR Lyrae variables, Mira variables, and other long-period variable stars.



The Period-Luminosity(-Metallicity) Relation

As Cepheids are more luminous than RR Lyrae, we can use them to measure distances farther into the depths of space.

In particular, Cepheids allow to measure the distance to the nearest galaxy cluster, the Virgo Cluster.



Pulsating Stars as Distance Estimators

The best-known relation between period and absolute magnitude is the direct proportionality law for **Classical Cepheid variables** (Henrietta Swan Leavitt (1908)).

foundation for scaling **galactic and extragalactic distances**

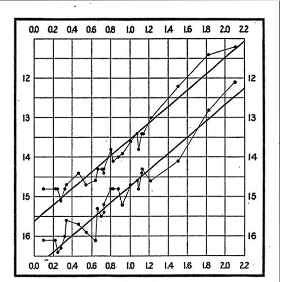
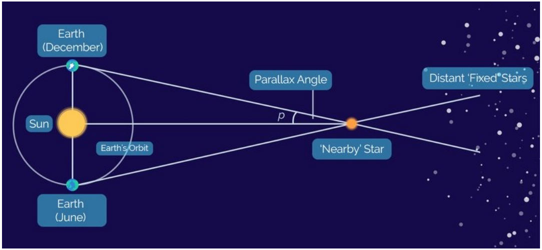


FIG. 2.

Plot from Leavitt's 1912 paper. The horizontal axis is the logarithm of the Cepheid's period, and the vertical axis is its apparent magnitude.

Parallax

As Earth revolves around the Sun, the direction in which we see a nearby star varies w.r.t distant stars as an effect of the change in viewpoint, leading to apparent movement of the star.



We define the parallax to be one half of the total change in direction.

$d = 1/p$
with parallax p in arc seconds, distance d in parsec.

1 parsec $= 3.086^{16}$ m $= 3.26156$ light years

Population I Cepheids:

Population I Cepheids are stars with relatively high metallicity (like our Sun) and thus are *second generation* stars, found in the disk of our galaxy. Classical Cepheids (also known as Population I Cepheids, type I Cepheids, or Delta Cepheid variables) undergo pulsations with very regular periods on the order of days to months.

The following relationship between a Population I Cepheid's period P and its mean absolute magnitude M_v was established from Hubble Space Telescope trigonometric parallaxes for 10 nearby Cepheids (Thomas et al. 2007, Benedict et al. 2002):

$$M_\mathrm{v} = (-2.43 \pm 0.12)\,(\log_{10} P - 1) - (4.05 \pm 0.02)$$

Period-Luminosity(-Metallicity) Relations for Cepheids and RR Lyrae

Population II Cepheids:

Population II Cepheids are stars found in globular clusters that are low-metallicity "first generation" stars. Type II Cepheids are fainter than their classical Cepheid counterparts for a given period by about 1.6 magnitudes (about 4 times less luminous).

Period-Luminosity Relations of Population II Cepheids (McNamara 1995):

$$P < 10 \text{ days: } M_v = -1.61 \log_{10} P - 0.05,$$
$$P > 10 \text{ days: } M_v = -4.17 \log_{10} P + 3.06$$

The steep slope for stars with $P > 10$ days may be due to an increase of mass with the period of pulsation.

Period-Luminosity(-Metallicity) Relations for Cepheids and RR Lyrae

RR Lyrae Stars:

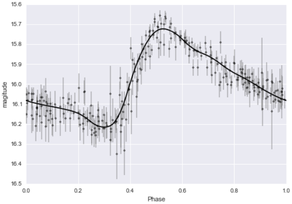
The PLZ relation is given as (e.g. Catelan et al. 2004, Sollima et al. 2006):

$$M_\lambda = \alpha_\lambda \log_{10}(P/P_{\mathrm{ref}}) + \beta_\lambda([\mathrm{Fe/H}] - [\mathrm{Fe/H}]_{\mathrm{ref}}) + M_{\mathrm{ref},\lambda} + \epsilon$$

where λ denotes the bandpass, P is the period of pulsation, M_{ref} is the absolute magnitude at a reference period and metallicity, and α, β describe the dependence of the absolute magnitude on period and metallicity. The variable ϵ is a standard normal random variable centered on 0 and with a standard deviation of the uncertainty in M_λ in order to model the intrinsic scatter in the absolute magnitude convolved with unaccounted measurement uncertainties.

Pulsating Stars as Distance Estimators

basic recipe for using variable stars to estimate distances:



- measure apparent mean brightness m
- measure period P

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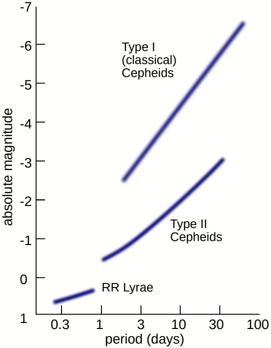

- measure apparent mean brightness m
- measure period P
- using period-luminosity relation, get absolute brightness M
- solve for distance using equation $d = 10^{(m-M+5)}/5$ parsec

  where 1 parsec $= 3.086^{16}$ m $= 3.26156$ light years

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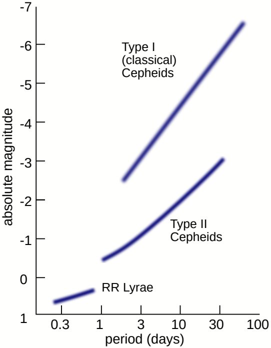

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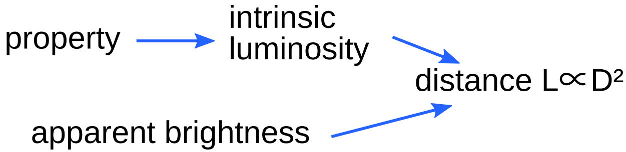
creating **3D maps** of structures in our Milky Way

Stellar Luminosities

review: reasons why measuring distances to stars is difficult

suppose all stars had the same luminosity, more distant ones would always look dimmer, allowing to infer the distance from the apparent magnitude

however: the **intrinsic luminosities** are not known and can differ



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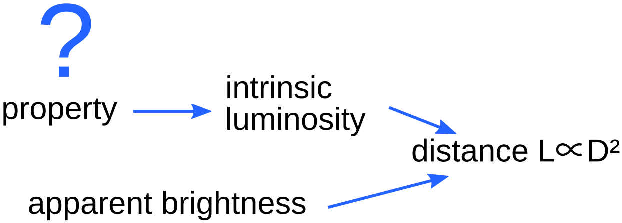


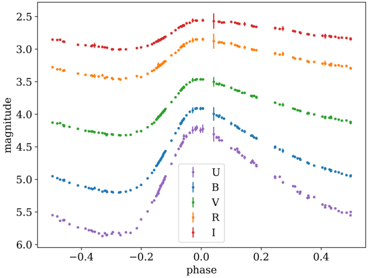
need to measure some property related to the intrinsic luminosity

Cepheids

Delta Cephei (δ Cep), **the prototype**:

Delta Cephei is a star in the constellation of Cepheus. Its variability was discovered in 1784 by the young English astronomer John Goodricke.

The star rises rather rapidly to maximum light and then falls more slowly to minimum light, taking a total of 5.4 days for one cycle.



Phase-folded UBVRI light curves of Delta Cephei showing magnitude versus pulsation phase. (Engle et al. 2014)

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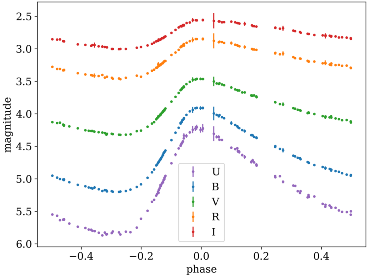

Phase-folded UBVRI light curves of Delta Cephei showing magnitude versus pulsation phase. (Engle et al. 2014)

Today this type is known as **classical Cepheids**.

Cepheids

Several hundred Cepheids are known in our Galaxy.

periods: 3 - 50 days
luminosities: 1000 - 10,000 $L_\odot$
$\delta L/L$: $\sim 10^{-2}$ - ~ 10
cause of variability: regular pulsations in the outer layers of the star

Polaris (α Ursae Minoris), the North Star, is a the closest Cepheid

its variability is changing:
for a long time varied by about 10% in visual luminosity with a period of just under 4 days recent measurements: δL is decreasing - some time in the future this star will no longer be a pulsating variable

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⇒ one more evidence that **stars evolve** and change in fundamental ways as they age, Cepheid is a stage in the life of a star

A Period-Luminosity Relation for Cepheids

The relation between period and luminosity was discovered in 1908 by Henrietta Leavitt, a staff member at the Harvard College Observatory.

While studying photographs of the Magellanic Clouds, she found over 1700 variable stars, including 20 Cepheids.
As they all are at approx. the same distance, she was able to compare their luminosities and periods, discovering a fundamental relationship between these characteristics leading to a much better way of estimating cosmic distances.

Henrietta Leavitt (1868-1921)

The Large Magellanic Cloud (so named because Magellan's crew were the first Europeans to record it) is a small, irregularly shaped galaxy near our own Milky Way.

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Leavitt's finding: the brighter-appearing Cepheids always have the longer periods of light variation.

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⇒ **conclusion:** period must be related to the luminosity

problem: distance to Magellanic Clouds unknown, so only $L \propto p$

calibration: measure the actual distances to a few nearby Cepheids in another way

(accomplished by finding cepheids associated in clusters with other stars whose distances could be estimated from their spectra)

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potential of the method immediately clear: distances to outer parts of the Milky Way!

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Astronomers, including Ejnar Hertzsprung and Harvard's Harlow Shapley, immediately saw the potential of the new technique; they and many others set to work exploring more distant reaches of space using Cepheids as standard candles.

In the 1920s, Edwin Hubble made one of the most significant astronomical discoveries of all time using Cepheids, when he observed them in nearby galaxies and discovered the **expansion of the universe**.

The most distant known variable stars are all Cepheids, with some about 60 million light-years away.

The Milky Way

Trying to understand the shape of the collection of stars we call our Galaxy is like trying to **map a forest from the inside**.

The Milky Way has been know since ancient times: the Greeks called it *galaxias kuklos*, or Milky Band. The Romans called it *Via Lactea* (road of milk); in China and Japan it was called the *River of Heaven*.

It was seen as a diffuse band of light crossing the night sky, but the nature of it was unknown.

credit: William Mathe

The Milky Way

Many Australian Aboriginal cultures tell of the Emu in the Sky: one of the few astronomies that focussed on the **dark spaces** instead of the bright stars.

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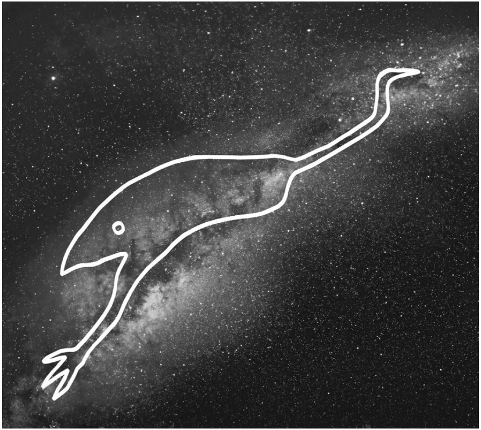

The Milky Way

Galileo was the first person to show that the **Milky Way was made of stars**.

I have observed the nature and the material of the Milky Way... The galaxy is, in fact, nothing but a collection of innumerable stars grouped together in clusters. Upon whatever part of it the telescope is directed, a vast crowd of stars is immediately presented to view. Many of them are rather large and quite bright, while the number of smaller ones is beyond calculation.

Galileo Galilei, The Starry Messenger (1610)

The Milky Way

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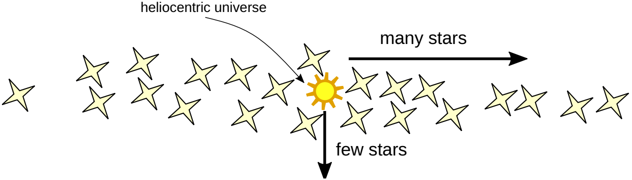
If the Universe was spherical, then numerous stars would lie in all directions. The fact that we see lots of stars only in some directions means the Universe is **anisotropic** - different in different directions.

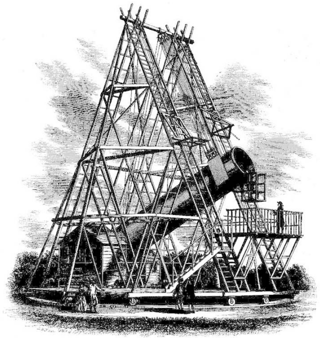


The Milky Way

In 1785, William and Caroline Herschel used star counts to determine the shape of the Milky Way.

They counted the number of stars in 683 directions in the sky: between 1 and 588 stars in the 15-arcmin eyepiece field of his Great Forty-Foot telescope.

He then assumed that stars filled the Galaxy boundary, outside which was emptiness. By counting the number of stars in each direction, he could work out the distance to this boundary.



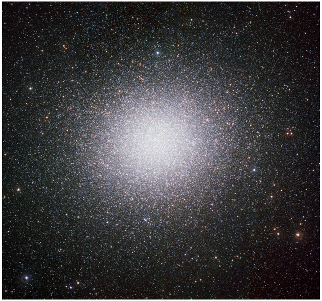
credit: Leisure Hour, Nov 2,1867

He deduced that the Milky Way is a **flattened thick disk**, with the Sun nearly at the center.

The Milky Way

In 1915, the young astronomer Harlow Shapley was studying globular clusters. He found that the **globulars are not evenly distributed in the sky**.
As seen from the Northern hemisphere, there are very few globulars in the summer sky, but many in the winter sky, towards Scorpio and Sagittarius.

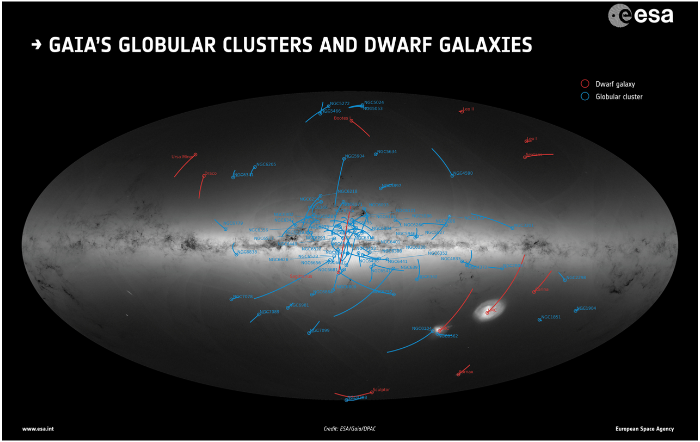
Globular clusters are clusters of stars, containing between 10,000 and a million stars. They are typically a few parsecs in size, and are densest in the centre, where there may be as many as 1,000,000 stars per cubic parsec.



The globular cluster ω Centauri, one of the largest in the Galaxy.

The Milky Way

The globular clusters form a great swarm concentrated in the sky towards the constellation of Sagittarius.



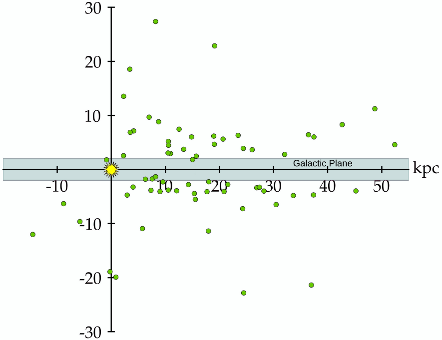
An all sky view of 75 globular clusters (blue) and 12 nearby dwarf galaxies (red) as viewed by ESA's Gaia satellite (2nd data release). Proper motion is indicated.

The Milky Way

How far away are the globular clusters?

Henrietta Leavitt had just published her period-luminosity relation for Cepheid variables; Shapley calibrated the relation using nearby variables, so he could use them as standard candles.

When Shapley plotted the 3D positions of the globular clusters, he found they were centred around a point about 16,000 parsecs away in Sagittarius.



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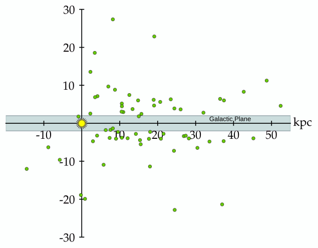
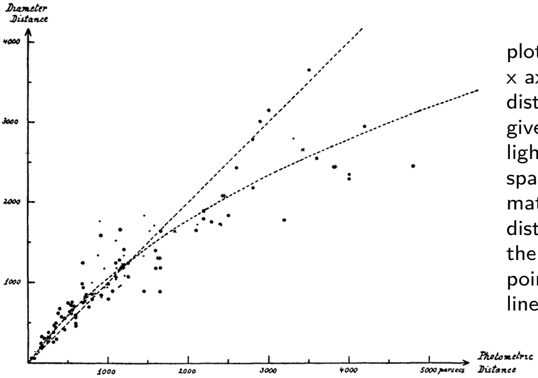


from the asymmetric distribution of globular clusters Shapley concluded: we live on the edge of the Milky Way

The Milky Way

Despite getting the right idea (the Sun is not at the center of the Milky Way), Shapley **overestimated** the Milky Way's size.

In 1930, Robert Trumpler finally came up with the crucial experiment. At the Lick Observatory, he estimated the distance of ∼100 open star clusters in **two ways**: once using their brightness and once using their size.



plot from Trumpler (1930): x axis gives the photometric distance to each cluster, y axis gives the diameter distance. If light travelled freely through space, unaffected by any material, then the two different distance estimates should yield the same result, and all the points should lie along a straight line of slope 1.

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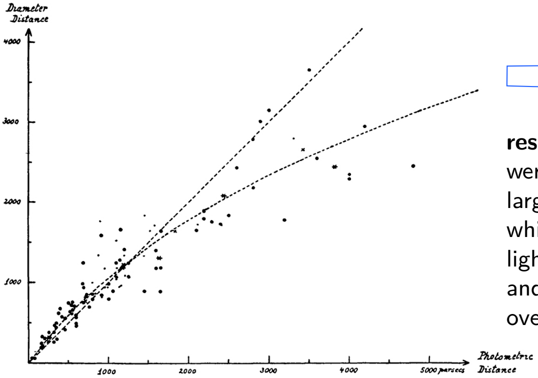
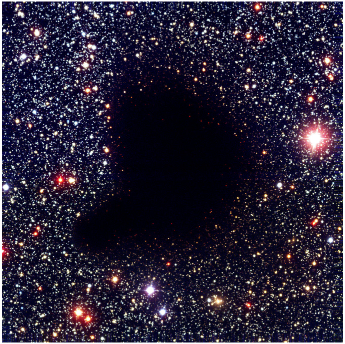


result: More distant clusters were seemingly systematically larger than nearby ones, which must mean that their light is being dimmed by dust and hence their distance overestimated.

The Milky Way

Trumpler concluded that the light from the clusters is **dimmed and reddened by dust** in the Galaxy.

The dark lanes in the Milky Way are thus explained as **dust clouds** hiding the light of stars beyond. The dust consists of tiny ($\sim$ few μm) particles of carbon and silicon.



The dark cloud Barnard 68, a likely future star formation site. Credit: ESO.

The Milky Way

While the size of our own Galaxy was being worked out, it was becoming clear that the **spiral nebulae**, which had been known for some time, were in fact other island universes - galaxies on their own.

> *The great spirals ... apparently lie outside our stellar system.*
>
> Edwin Hubble, 1917

The Milky Way

The **Great Debate** on the nature of spiral nebulae, also called the Shapley-Curtis Debate, was held on 26 April 1920 at the Smithsonian Museum of Natural History, between the astronomers Harlow Shapley and Heber Curtis.

Harlow Shapley
*Spiral nebulae are nearby objects **within** the Milky Way.*

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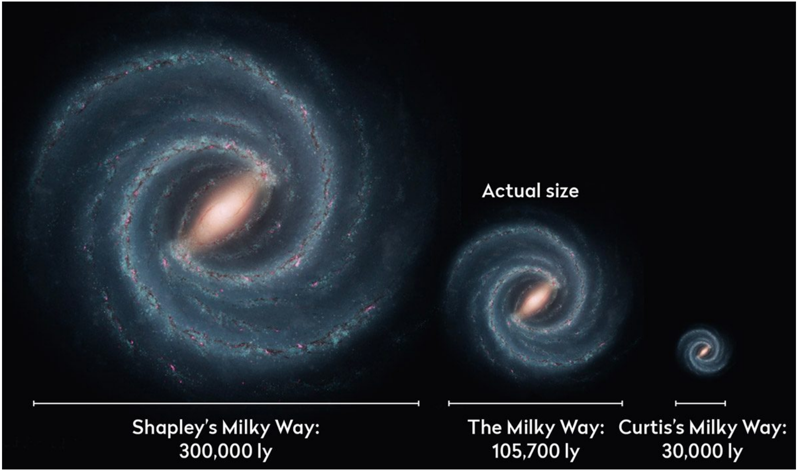
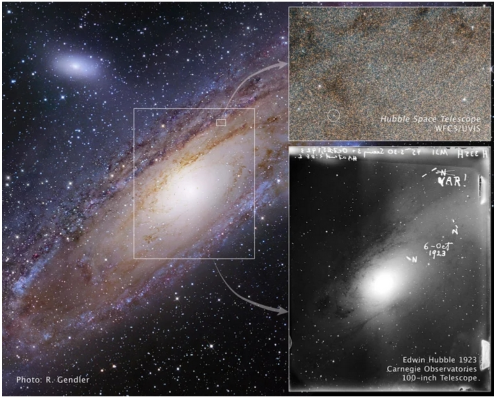
The Milky Way



observational evidence:

In 1923/1924, Edwin Hubble discovered Cepheids in the Andromeda Nebula. From this he determined the distance to the Andromeda Nebula which we call now the **Andromeda galaxy** to be a few million light-years and showed it is a separate star system outside of the Milky Way.

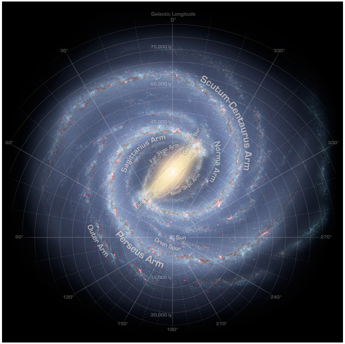


The Milky Way

today we know about the **structure of our Galaxy**:

- a bulge of old stars in the centre
- a disk of stars and gas
- a halo of globular clusters

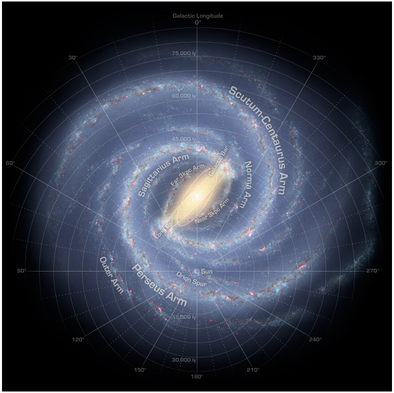
Seen from above, it would look like this:



The Milky Way

The Milky Way is about 25 kpc (75,000 light-years) in radius, with the Sun a little over halfway from the center.

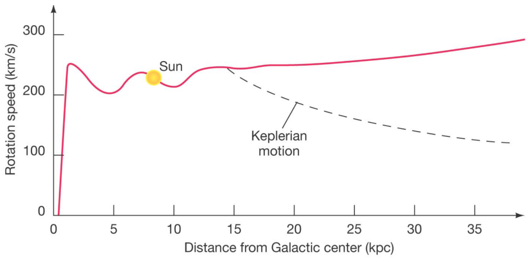
The **spiral arms** are embedded in the **disk**, which contains stars, open star clusters, and nearly all the galaxy's gas and dust. It is the site of most of the star formation in the Galaxy, so the disk is illuminated by bright blue massive stars.
Stars like the Sun lie within 500 pc above and below the central plane; the youngest stars lie within 50 pc.



The **bulge** is the dense cloud of stars that surrounds the centre of the galaxy. It has a radius of about 2 kpc and is slightly flattened.
The bulge contains little gas and dust and there is thus little star formation.

The Milky Way

The total number of stars in the Galaxy is about 200 billion; the total mass is about 1 trillion times the mass of the Sun (10^{12} solar masses).
By measuring the velocities of stars at different distances from the Galactic centre, we can derive the mass profile of the Galaxy. Instead of falling off, the rotation curve **increases** with distance from the center.



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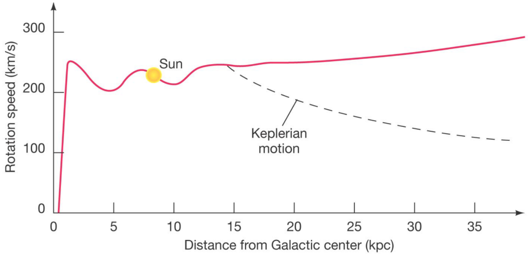
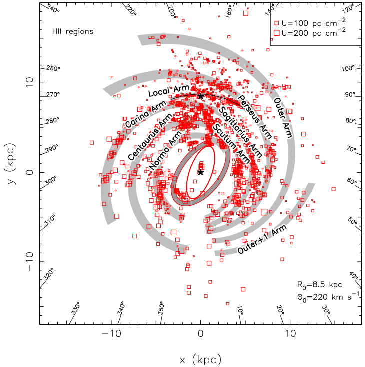


⇒ the mass of the Galaxy increases with distance from the center, the total mass is several times **larger than the visible mass** - **Dark Matter**

The Milky Way

How do we find the shape of the Galaxy from inside it?

We can try looking at the positions of **tracers**, such as young star clusters.



Spiral pattern of our Galaxy derived from H II nebulae around young stars; HII region distribution overlaid with a spiral arm model to indicate the identified arm segments. credit: Hou & Han (2014)

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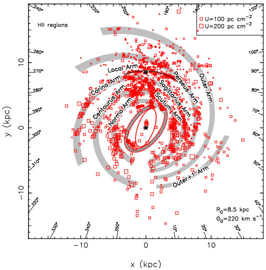
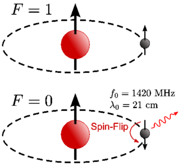


Hydrogen gas emits a photon with a wavelength of 21 cm (frequency 1420 MHz) when the spin of the electron flips over. This radiation can be seen at great distances, as radio waves are not absorbed by dust.



Cepheid Populations

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Cepheid Populations

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Using special red-sensitive photographic plates Dr. Baade discovered two populations of stars:

- redder, fainter "Type II" stars in globular clusters near Andromeda's center and in its outlying halo (like in the Milky Way)
- bluer, brighter "Type I" variable stars located in open clusters in Andromeda's disk (outer spiral arms).

⇨ two populations of Cepheids: Type I Cepheids more common in the disk of a galaxy and Type II Cepheids more common in the globular clusters

Cepheid Populations

From that it was further concluded that classical Cepheids and type II Cepheids follow different period-luminosity relationships. On average, the luminosity of type II Cepheids is less than classical Cepheids by about 1.5 magnitudes (but still brighter than RR Lyrae stars).

Baade's discovery led to a **twofold increase in the distance to M31**, and the extragalactic distance scale.

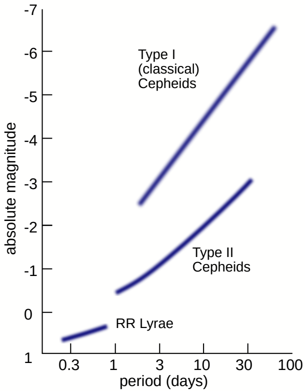
RR Lyrae stars, then known as Cluster Variables, were recognized fairly early as being a separate class of variable, due to their short periods.

The telescope that confirmed the scale of the cosmos: Mount Palomar's 200-inch Hale Telescope was completed in 1949.
credit: Mt. Wilson-Palomar Observatories

Period-Luminosity(-Metallicity) Relations for Cepheids and RR Lyrae

Nowadays, period-luminosity relations are known for several types of pulsating variable stars: type I Cepheids, type II Cepheids, RR Lyrae variables, Mira variables, and other long-period variable stars.

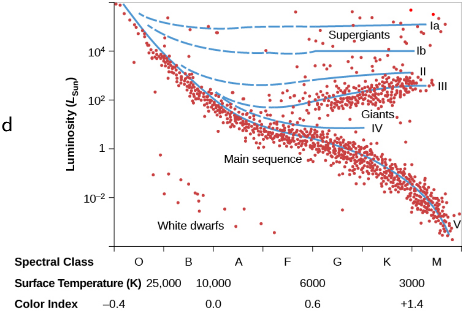
Reliable classification of variable stars makes it possible to chose the correct period-luminosity relation for a star.



Luminosity Classes - Distances from HR Diagrams

The most widely used system of star classification divides stars of a given spectral class into six categories called **luminosity classes**. These luminosity classes are denoted by Roman numbers as follows:

Ia: Brightest supergiants
Ib: Less luminous supergiants
II: Bright giants
III: Giants
IV: Subgiants (between giants and main-sequence stars)
V: Main-sequence stars



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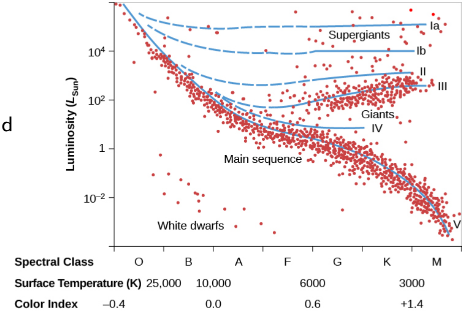


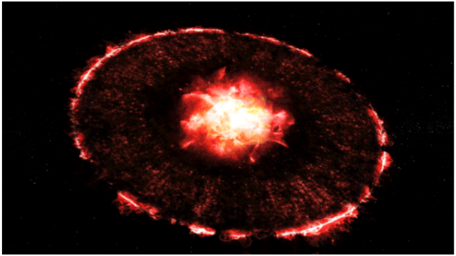
With both a star's spectral and luminosity classes determined from spectra, we can now read off the star's luminosity and thus determine the distance from the distance modulus.

Thermonuclear Supernovae - Typ Ia

A **Type Ia supernova** (read: "type one-A") is a supernova ocurring in binary systems in which one of the stars is a white dwarf. The other star can be anything from a giant star to an even smaller white dwarf.

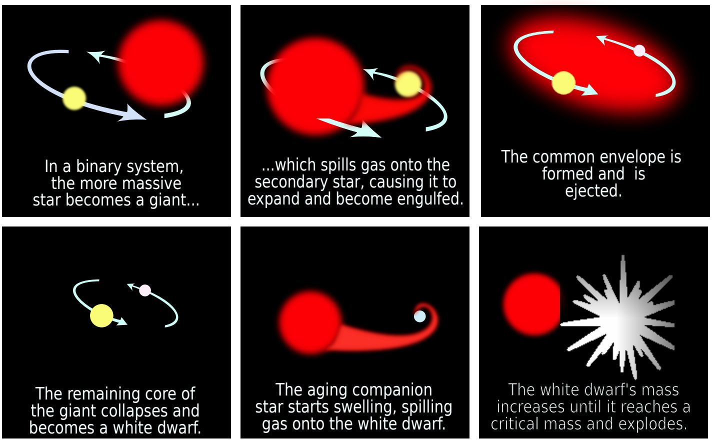
Physically, carbon-oxygen white dwarfs with a low rate of rotation are limited to below 1.44 $M_{\odot}$, the Chandrasekhar mass.

If a white dwarf accretes enough matter to push it over the Chandrasekhar limit, it will collapse as it cannot longer resist gravity, followed by an explosion.



An artist's illustration of cosmic dust in the blast waves from SN 1987A. (Image credit: NASA/SOFIA)

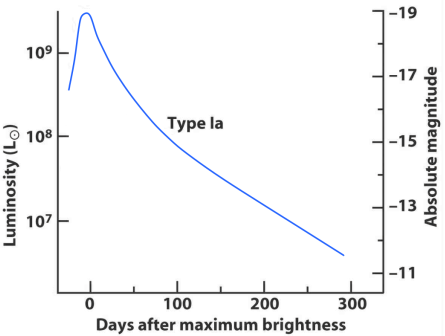
Thermonuclear Supernovae - Typ Ia



Thermonuclear Supernovae - Typ Ia

These supernovae - thermonuclear or Type Ia supernovae - have no hydrogen in their spectra at all.

They are so luminous that we can see them more than halfway across the universe. Because they all have very similar brightness, they are very important beacons for **measuring the distances*** to very distant galaxies.

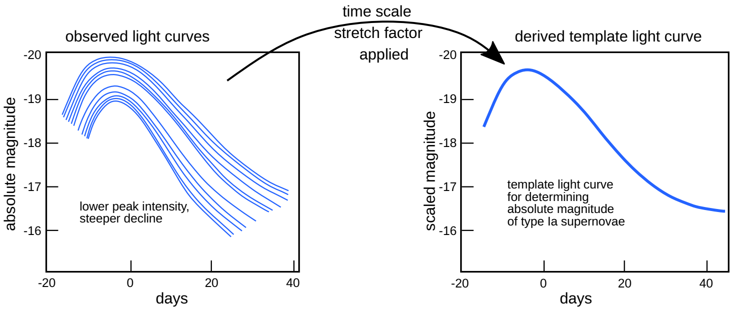


* more on this later on

Thermonuclear Supernovae - Typ Ia

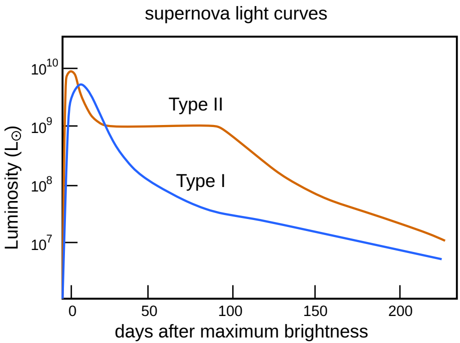
Type Ia supernova reach at maximum light an average maximum magnitude in the blue and visible wavelength bands of -19.3 with a typical spread of less than about 0.3 magnitudes.

The range of light curves differ in a systematic way: the peak brightnesses and their subsequent rate of decay are inversely proportional.



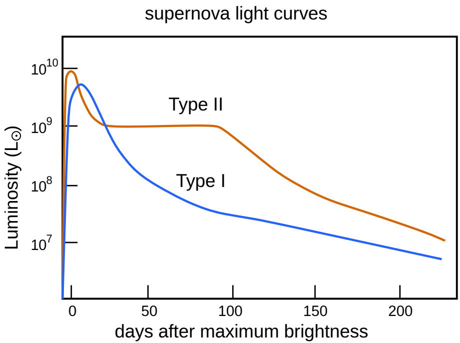
This illustration is based on Perlmutter (2023), a careful study of supernova Type Ia light curves which has led to approaches for standardizing them.

Type I and Type II Supernovae



Supernovae are classified as Type I if they have no H lines in their spectra. The light curves exhibit sharp maxima of about 10^{10} $L_\odot$ before fading gradually. They occur typically in elliptical galaxies, probably from Population II stars. The subclass Type Ia refers to those having a strong Si line (615 nm). They are Type Ib if they have strong He lines, and Ic if not.

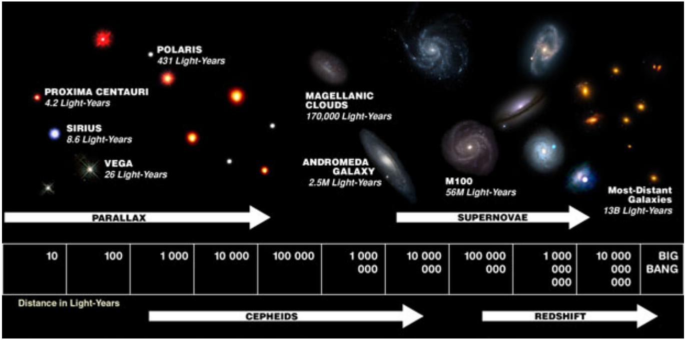
Type I and Type II Supernovae



Type II supernovae show strong H lines. Their light curves have less intense peaks, fading more sharply than Type I, and show a plateau. As not ocurring in elliptical galaxies, they are thought to be implosion-explosion events of a massive Population I type star in the spiral arm of galaxies.

The Distance Ladder

The cosmic distance ladder allows astronomers to confidently measure vast distances to stars and galaxies with overlapping techniques.



step 1: **Parallax**, stars up to a few tens of thousands of light-years

The method relies on watching nearby stars as they appear to move against the background of more distant stars, which look fixed. From this, a standard H-R diagram (with absolute magnitude and spectral class) can be made.

The Hipparcos and Gaia spacecraft map the Milky Way by measuring parallaxes.

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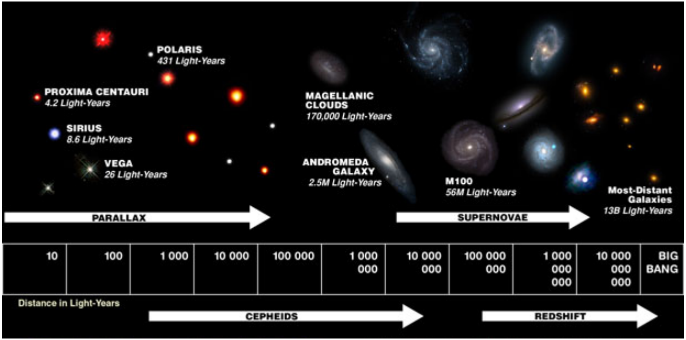

step 2: **Main Sequence Fitting**

A HR diagram with apparent magnitude and spectral class is made for a cluster (open or globular) of stars. Overlay with the standard H-R diagram from step 1 (with apparent magnitude and spectral class) to compare the apparent and absolute magnitudes of the main sequence (MS). This can be used to find the cluster distance from the distance modulus: $m - M = 5\log(d/10)$

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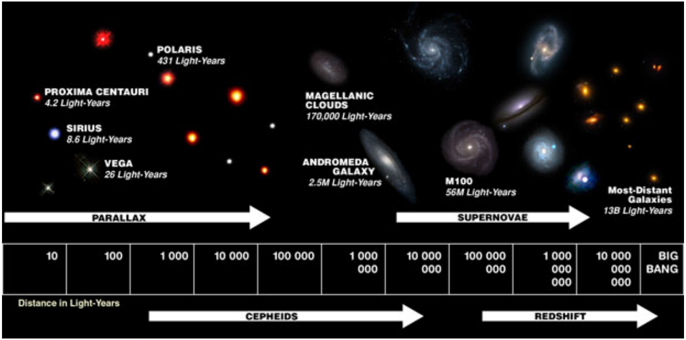

step 3: **Cepheids**

Some Cepheids are in clusters for which distance is known from Main Sequence Fitting. Thus, for stars in the cluster M is known. Use these Cepheids to calibrate the Period-Luminosity relation. Measure apparent magnitude m and pulsation period of Cepheids in other clusters or galaxies. Determine M from the Period-Luminosity relation and calculate the distance using the distance modulus.

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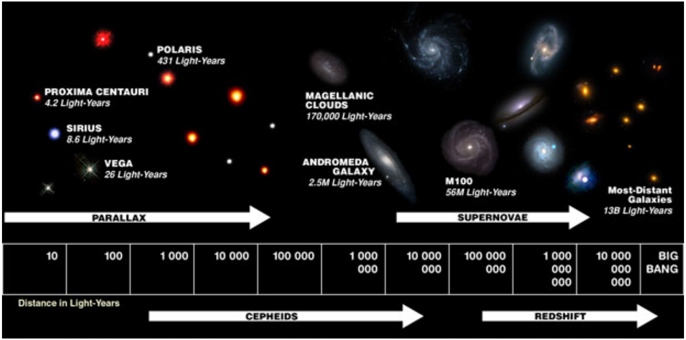

step 4: **Supernova**

In the same way as Cepheids, Supernovae (in particular type Ia) can be used as standard candles to determine distances to other galaxies Due to Supernova brightnesses, this is effective to several billion light years.

The Distance Ladder

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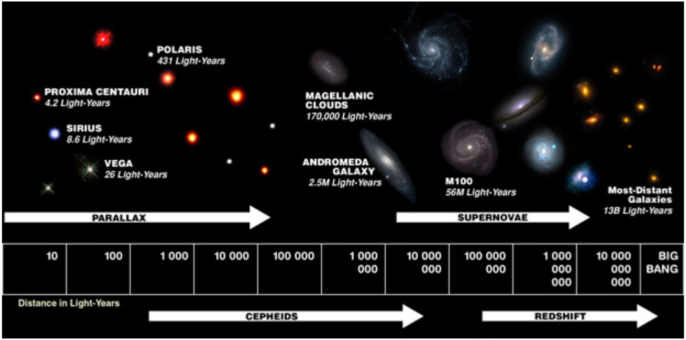

step 5: **Redshift**

Distant galaxies move away due to the expansion of the universe. We can measure this motion, which varies with distance: faster galaxies are more distant. Least-accurate method because it depends on a model of how the universe is expanding.

The Expansion of the Universe

In the 1980s, Saul Perlmutter at Lawrence Berkeley National Laboratory (LBNL) and his collaborators realized that they could use data about Type Ia supernovae (whose brightness is extremely consistent) to research the history of the expanding universe.
Over the course of a decade, Perlmutter's team collected enough data to look for a relationship between a supernova's brightness and distance.

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Over the course of a decade, Perlmutter's team collected enough data to look for a relationship between a supernova's brightness and distance.

The data revealed: all the supernovae all looked dimmer than they should for their distance.

They spent more than six months checking every aspect of the graph, looking for some aspect of the analysis that might be wrong.

The Expansion of the Universe

In fact, the data showed the **universe was expanding ever more quickly**.

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A dramatic implication: For the data to work with Einstein's theory of general relativity, about 70 percent of the universe's energy must be from some unknown source: **Dark Energy**.

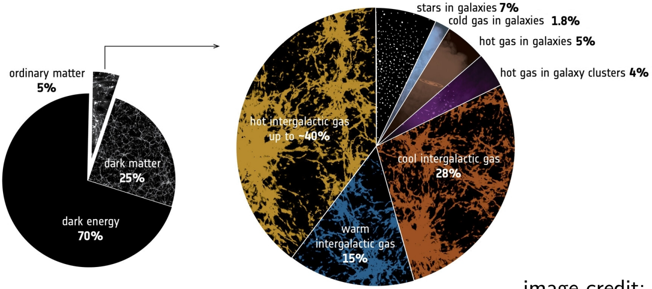

image credit: ESA

In 2011, Perlmutter, Brian Schmidt, and Adam Riess received the **Nobel Prize** in physics for the discovery.

The Expansion of the Universe

Data of the Southern Sky taken from the Dark Energy Camera in Chile is helping scientists in their understanding of what dark energy is and how it influences the expansion of the universe.

Outlook

observations modern space- and ground-based observatories enable us to understand the Milky Way and other galaxies in more detail