How Do We Know It Is That Far?

Dr. Billy Teets
Vanderbilt University Dyer Observatory
Osher Lifelong Learning Institute
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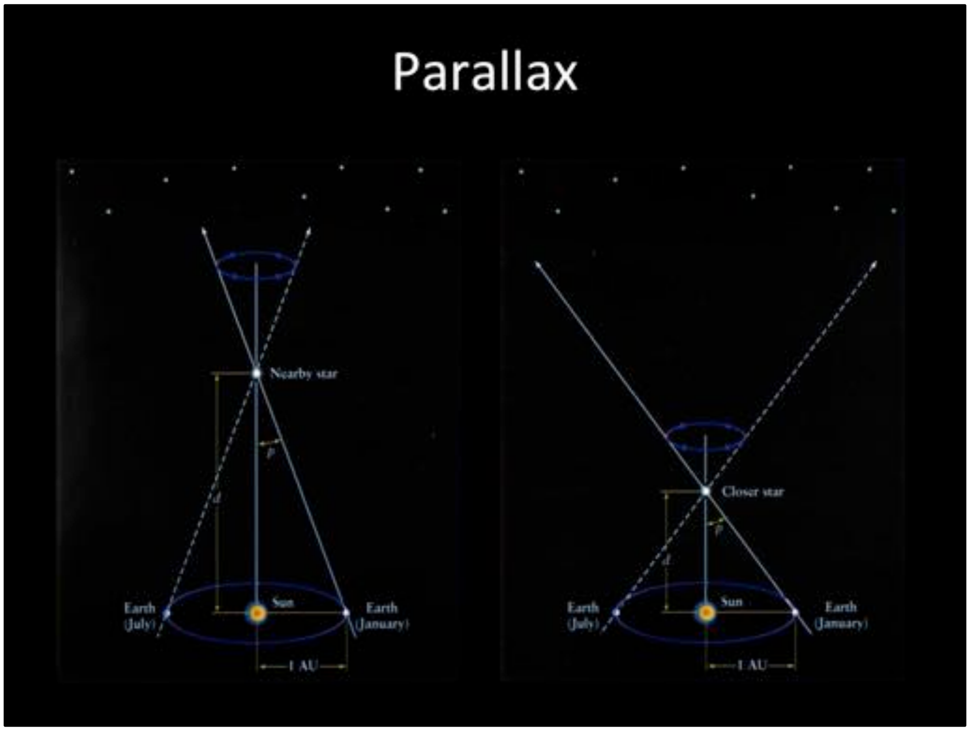
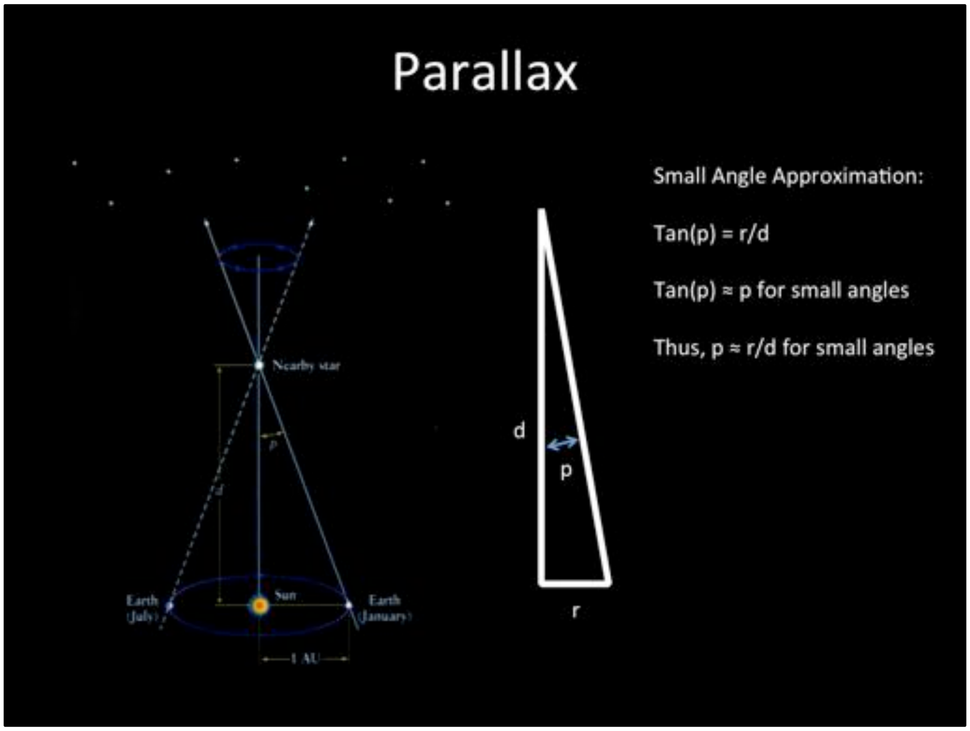
Outline – The Cosmic Distance Ladder

- Distances to the Closer Stars
- Main Sequence Fitting
- Cepheid & RR Lyrae Variables
- Type Ia Supernovae
- Galactic Redshift



Parallax

Two diagrams showing how parallax works for a nearby star (left side) and an even closer star (right side). At the bottom of the diagrams we have the Earth orbiting the Sun. At the top of the diagrams are numerous background stars that are very far away. As Earth orbits the Sun the nearby star will appear to shift back and forth among the background stars (the solid and dashed lines represent Earth's line of sight and where we would see the nearby star). The angle that the star appears to move is denoted by P, the distance between the Earth and Sun is known as an Astronomical Unit (AU), and the distance to the star is denoted by d. Note that the closer the star is to us (right side) the greater the apparent shift in position against the background stars.



Parallax

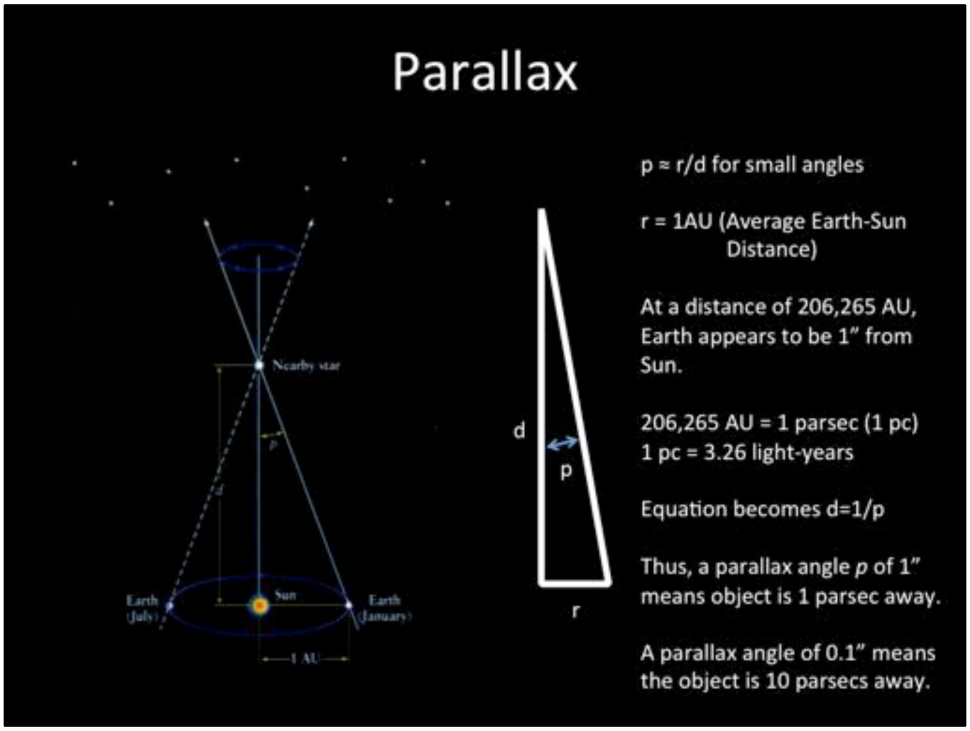
Small Angle Approximation:

Tan(p) = r/d

Tan(p) ≈ p for small angles

Thus, p ≈ r/d for small angles

The trigonometric relationship between r, d, and p. Due to us working with very small angles, we can use the small angle approximation of p = r/d (if we use appropriate units).



Parallax

$p \approx r/d$ for small angles

r = 1AU (Average Earth-Sun Distance)

At a distance of 206,265 AU, Earth appears to be 1″ from Sun.

206,265 AU = 1 parsec (1 pc)
1 pc = 3.26 light-years

Equation becomes d=1/p

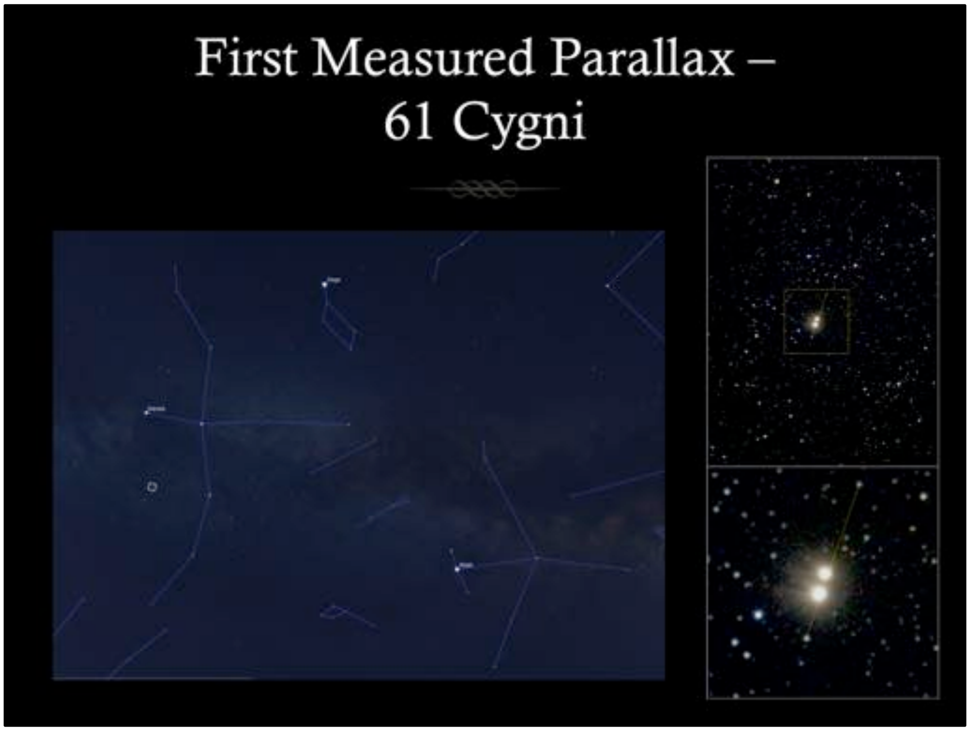
Thus, a parallax angle *p* of 1″ means object is 1 parsec away.

A parallax angle of 0.1″ means the object is 10 parsecs away.

Since r is 1AU, we can plug that into our equation to simplify it to p=1/d or d = 1/p (the second is more useful since we are trying to find the distance to the star). Since we are working with arcseconds and AU, we should try to use a more convenient unit for d. Since we are at 1AU from the Sun, a star that is 206,265 AU from us will appear to shift 1 arc-second against the background stars. We now use the convenient unit of 1 parsec = 206,265 AU.

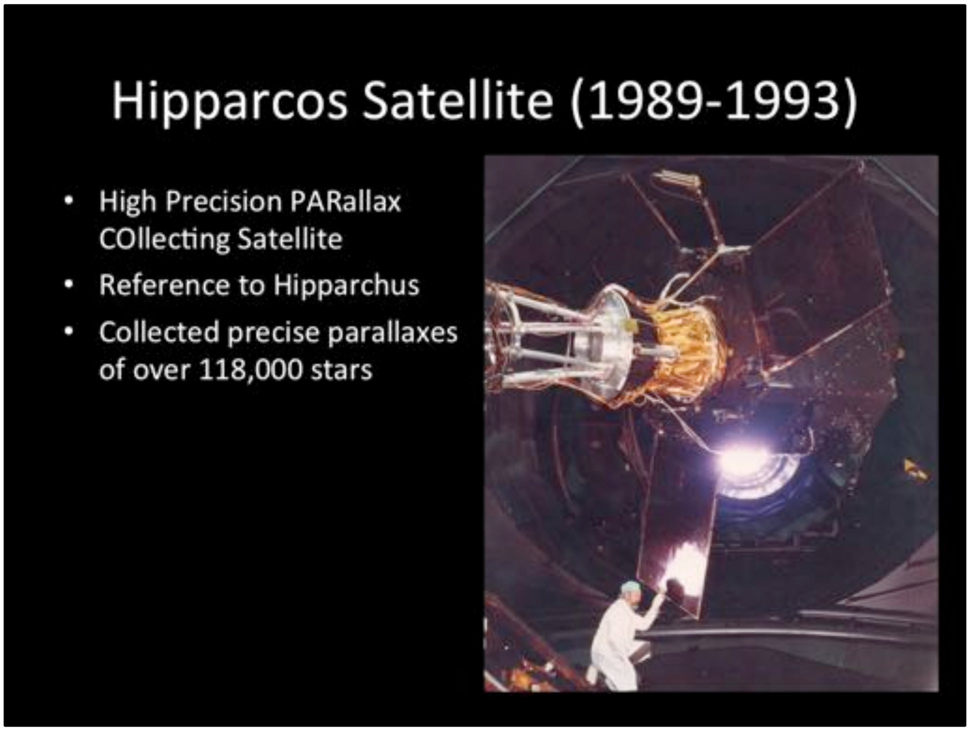
Therefore, if a star has a parallax of 1 arc-second (written as 1”), then that means it will be one parsec from us: d = 1/p becomes d=1/1=1 parsec.
If a star has a parallax of .1 arc-second, then that means it will be 10 parsecs from us: d = 1/p becomes d=1/.1=10 parsecs.
If a star has a parallax of .001 arc-second, then that means it will be 1000 parsecs from us: d = 1/p becomes d=1/.001=1000 parsecs.

By the way, a parsec is 3.26 light-years.



First Measured Parallax – 61 Cygni

The first star to have a parallax measured was 61 Cygni (Friedrich Bessel – 1838). This star also has a high proper motion. Each year one can observe (telescopically) that it has moved against the background stars.

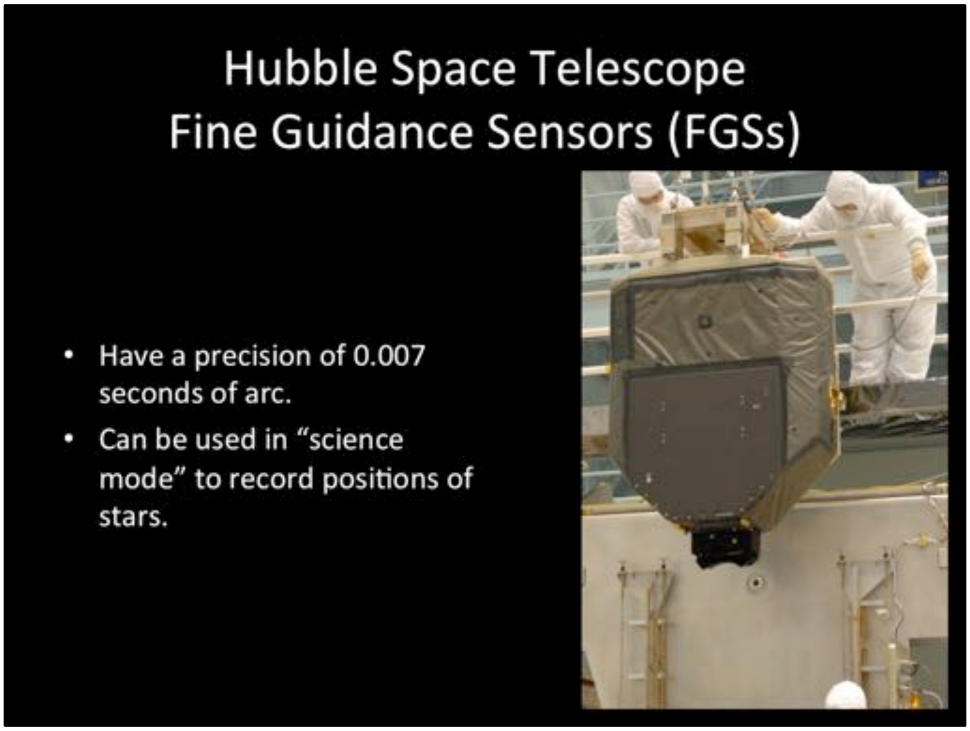


Hipparcos Satellite (1989-1993)

- High Precision PARallax COllecting Satellite
- Reference to Hipparchus
- Collected precise parallaxes of over 118,000 stars

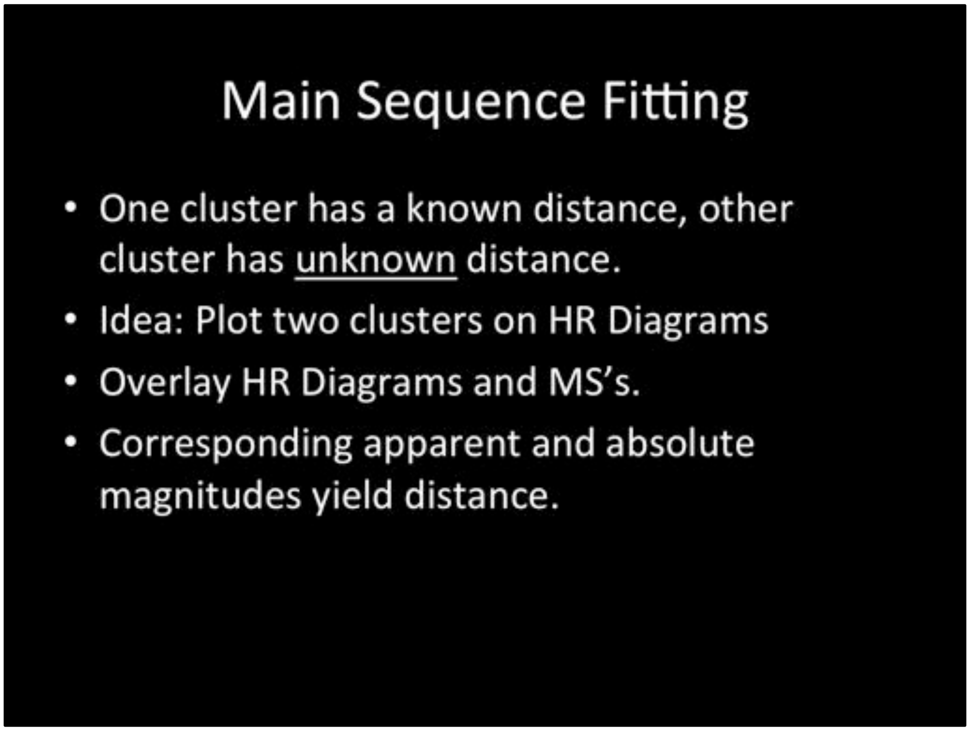
Hipparchus was an ancient Greek astronomer who is noted for having devised a magnitude system to denote the brightness of stars.

The GAIA mission is the successor to Hipparcos and will measure, among other things, the precise parallaxes for over 1 billion stars.



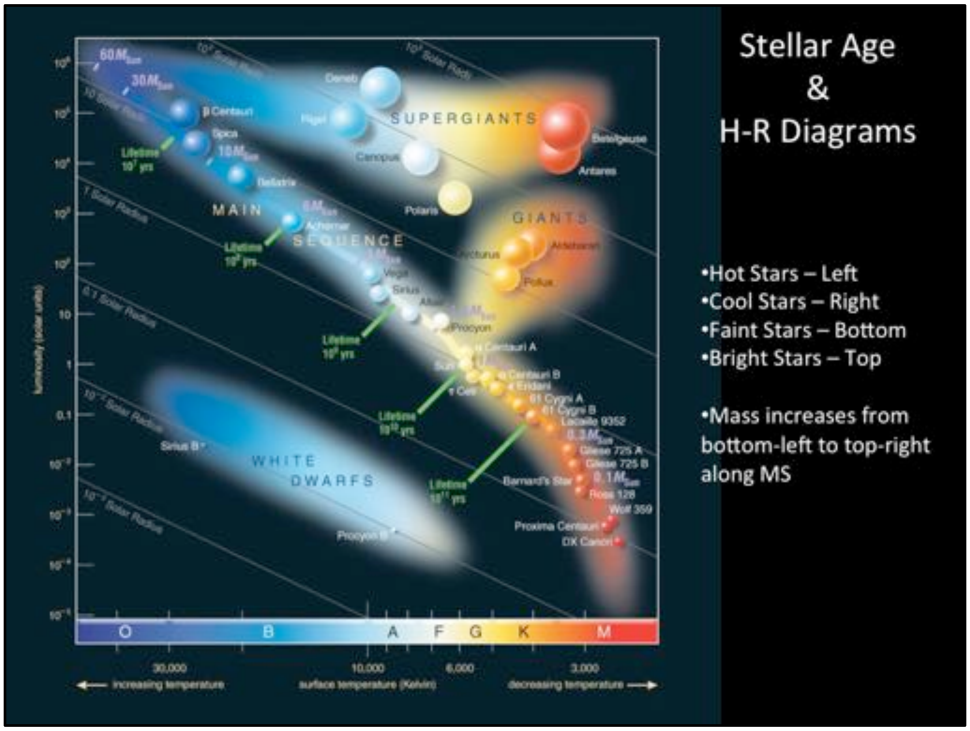
Hubble Space Telescope
Fine Guidance Sensors (FGSs)

- Have a precision of 0.007 seconds of arc.
- Can be used in "science mode" to record positions of stars.



Main Sequence Fitting

- One cluster has a known distance, other cluster has unknown distance.
- Idea: Plot two clusters on HR Diagrams
- Overlay HR Diagrams and MS’s.
- Corresponding apparent and absolute magnitudes yield distance.



Stellar Age & H-R Diagrams

- Hot Stars – Left
- Cool Stars – Right
- Faint Stars – Bottom
- Bright Stars – Top

- Mass increases from bottom-left to top-right along MS

A Hertzsprung-Russell diagram is a plot of star luminosity (how bright the star actually is) versus temperature. Placing a star on the HR Diagram allows one to know much more about the star, including its diameter, mass, evolutionary stage, etc.

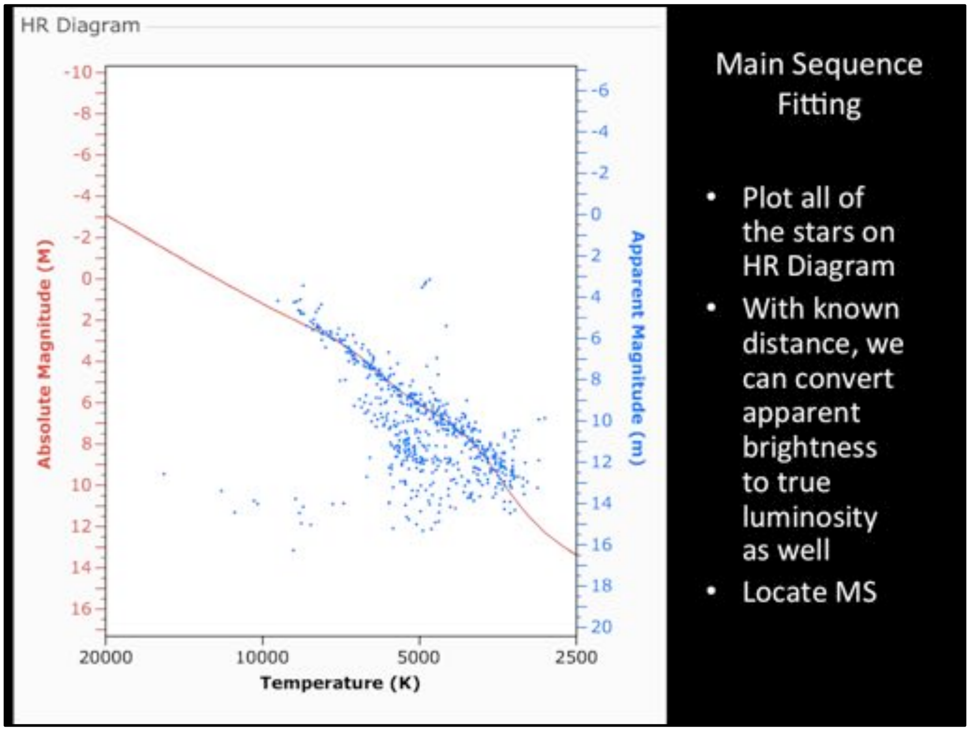
The central band of stars that run from top-left to bottom-right is known as the Main Sequence. Roughly 90% of stars would fall on this band because stars spend 90% of their life on the main sequence as they fuse hydrogen into helium in their cores (our Sun is doing this right now). Once a star begins to run out of core hydrogen, it will swell up and move off of the main sequence to become a red giant or a red supergiant star.

Main Sequence Fitting

- Analogy: Box of assorted light bulbs
- Bulbs have various wattages (luminosities)
- One illuminated bulb from unknown distance does not tell you bulb wattage.
- Turn on all bulbs – then you can tell which bulb is which.

Main Sequence Fitting

- First, find nearby cluster distance (e.g., Hyades)

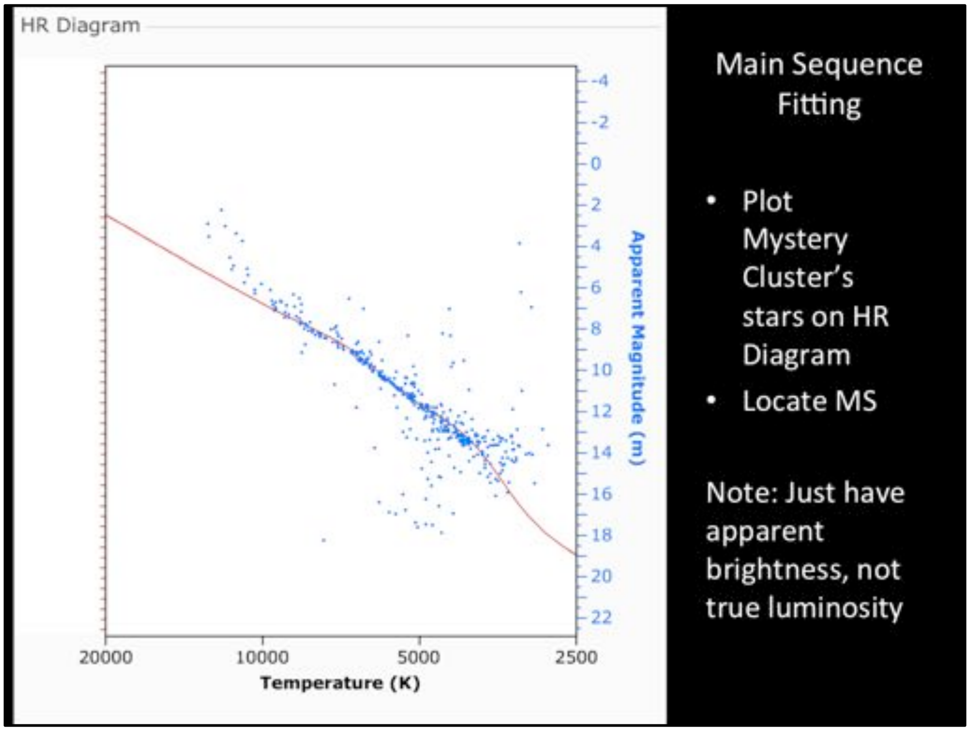


Main Sequence Fitting

- Plot all of the stars on HR Diagram
- With known distance, we can convert apparent brightness to true luminosity as well
- Locate MS

Main Sequence Fitting

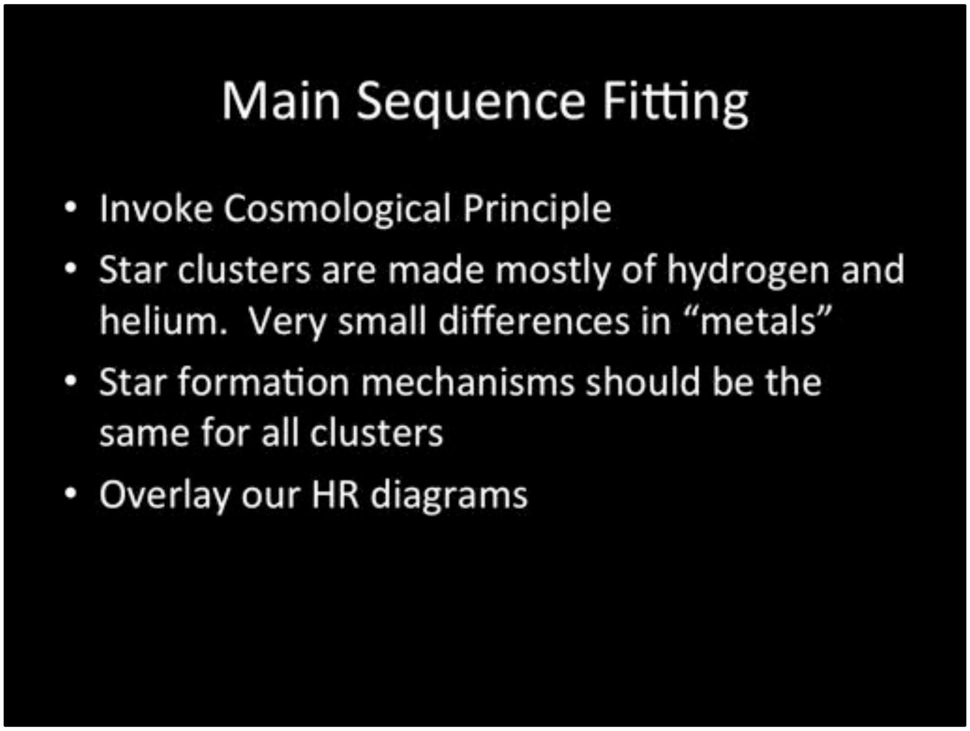
- Next, locate a “Mystery Cluster” (e.g., Pleiades) of unknown distance



Main Sequence Fitting

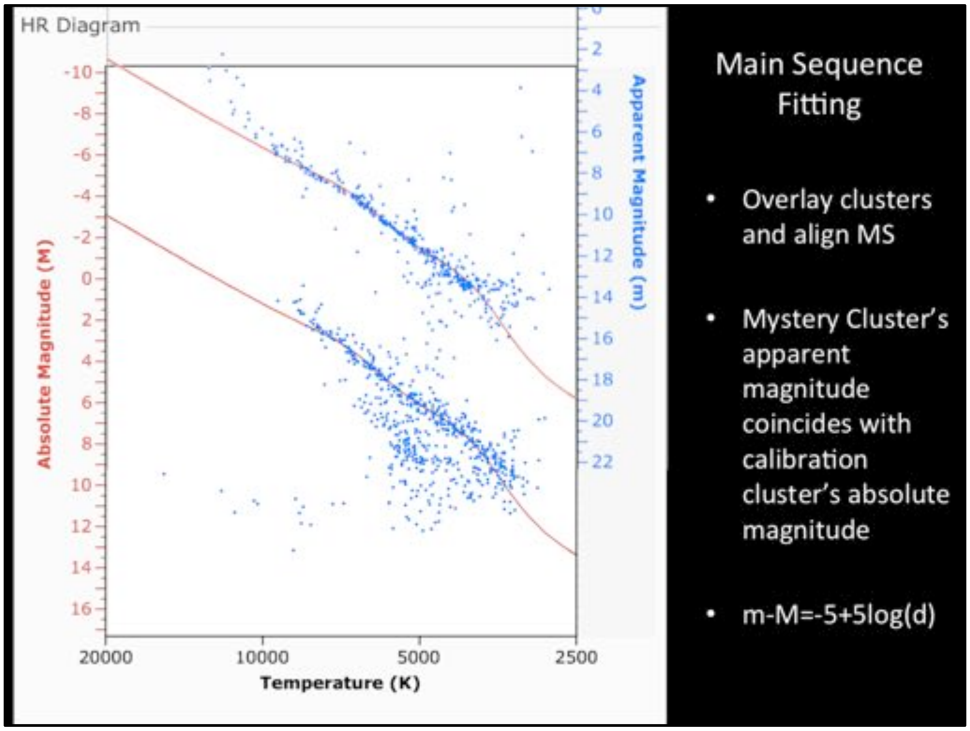
- Plot Mystery Cluster's stars on HR Diagram
- Locate MS

Note: Just have apparent brightness, not true luminosity



Main Sequence Fitting

- Invoke Cosmological Principle
- Star clusters are made mostly of hydrogen and helium. Very small differences in "metals"
- Star formation mechanisms should be the same for all clusters
- Overlay our HR diagrams

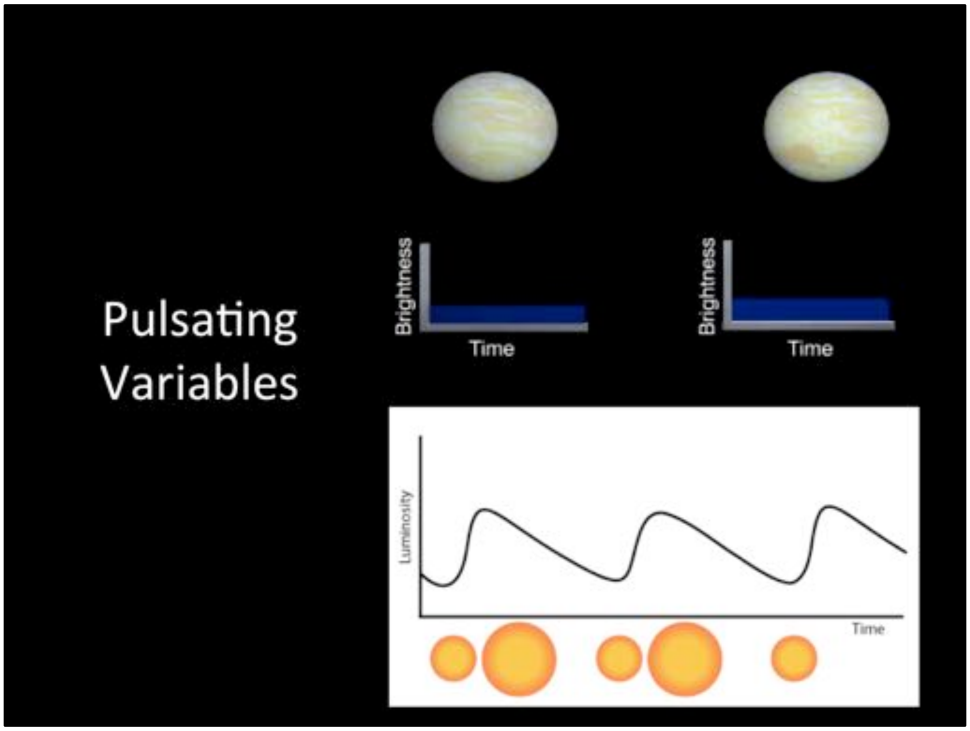


Main Sequence Fitting

- Overlay clusters and align MS
- Mystery Cluster's apparent magnitude coincides with calibration cluster's absolute magnitude
- m-M=-5+5log(d)

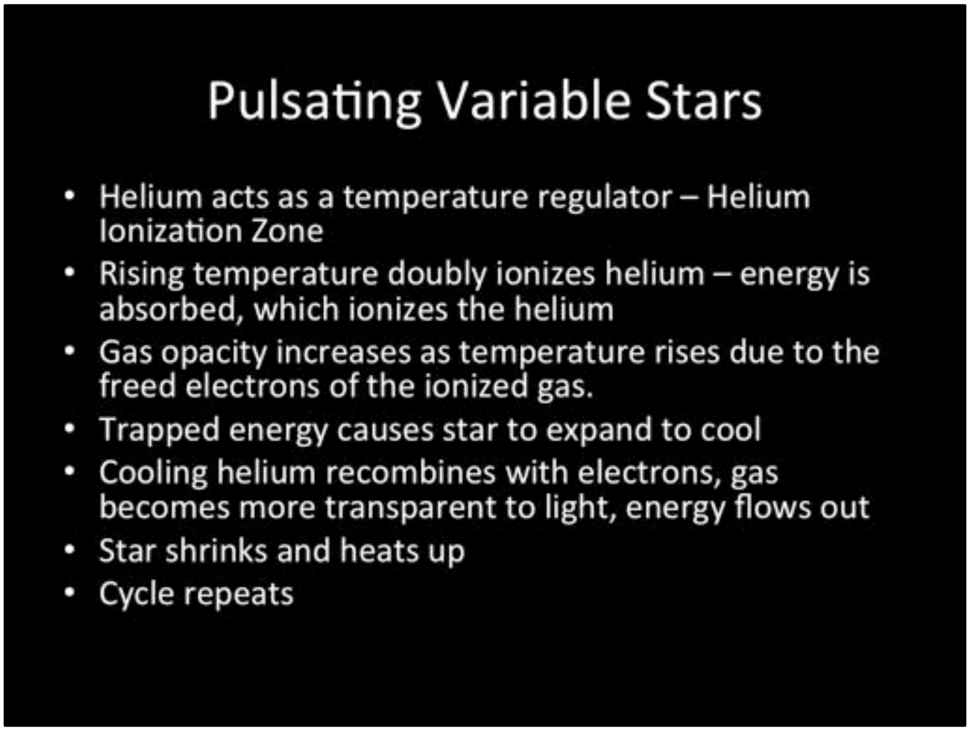
On this presentation slide, you would move the two HR Diagrams (one has absolute magnitude and the other has apparent magnitude) up/down so that the two main sequences overlap as well as possible. The result is the absolute magnitude scale on the left is now aligned correctly to apparent magnitude scale on the right. In essence the cluster of unknown distance (for which we only had apparent magnitudes/ apparent brightnesses of the stars) now has a corresponding absolute magnitude scale (true luminosity). Since we have apparent brightness values and true luminosity values for each of the stars in the cluster of unknown distance we can now calculate the distances of the stars.

Note: absolute magnitude (true luminosity) is denoted by "M" and apparent magnitude (how bright the stars appear in our sky) is denoted by "m." The final equation on this slide is known as distance modulus, and it relates these two variables to distance.



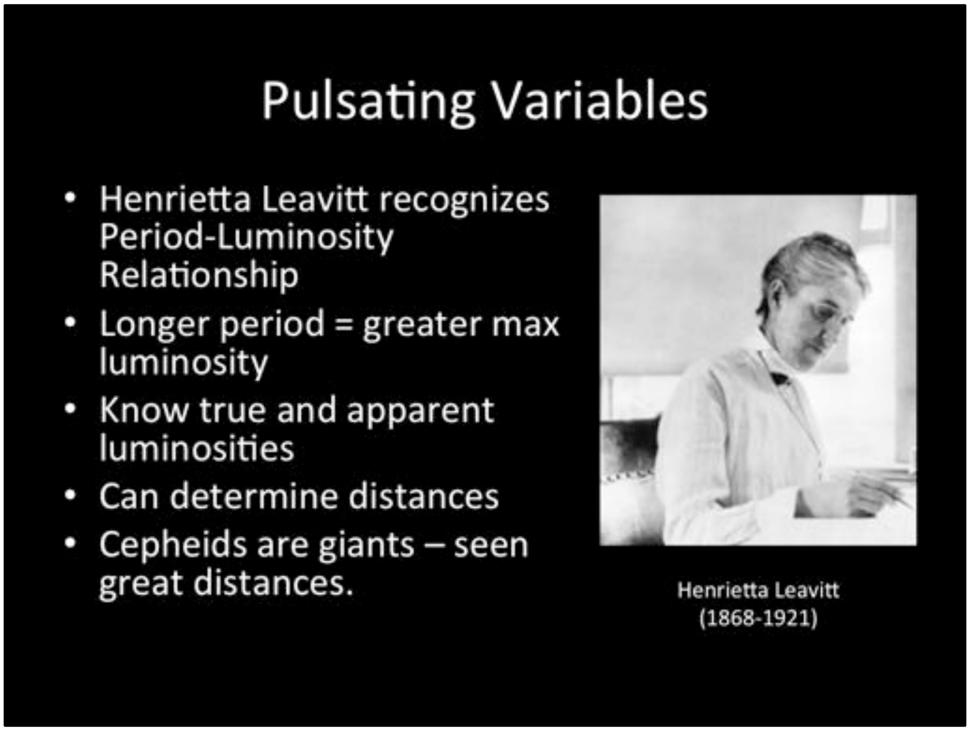
Pulsating Variables

There are many types of variable stars, but there are a few types that physically pulsate and change brightness as a result. Cepheid variables and RR Lyrae variables are examples. When the star is at its largest, it is also at its highest luminosity.



Pulsating Variable Stars

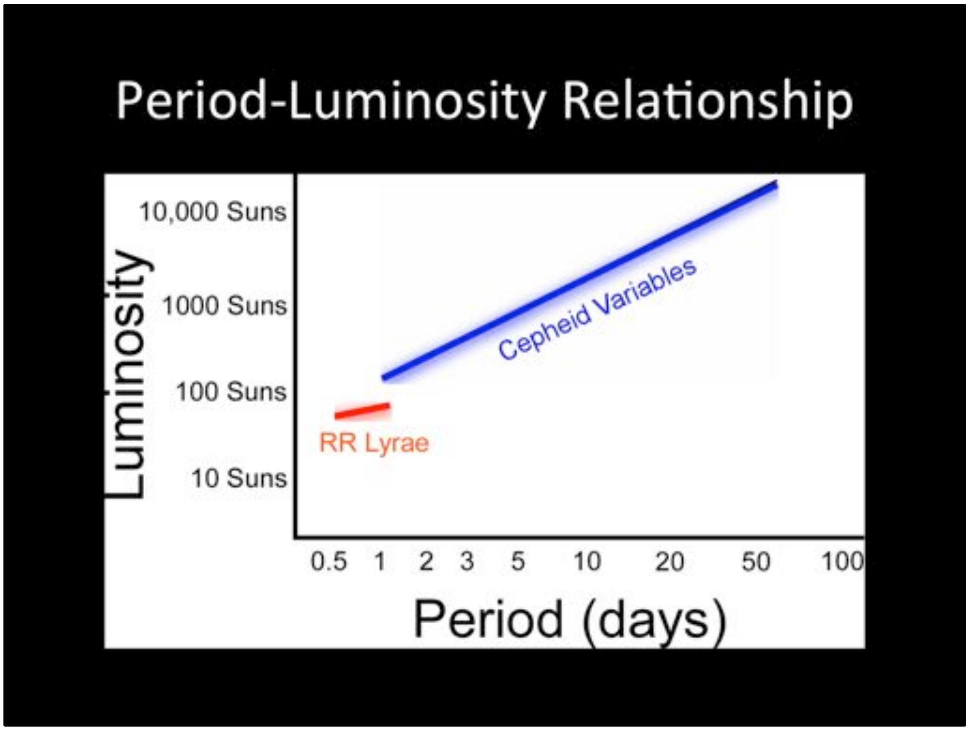
- Helium acts as a temperature regulator – Helium Ionization Zone
- Rising temperature doubly ionizes helium – energy is absorbed, which ionizes the helium
- Gas opacity increases as temperature rises due to the freed electrons of the ionized gas.
- Trapped energy causes star to expand to cool
- Cooling helium recombines with electrons, gas becomes more transparent to light, energy flows out
- Star shrinks and heats up
- Cycle repeats



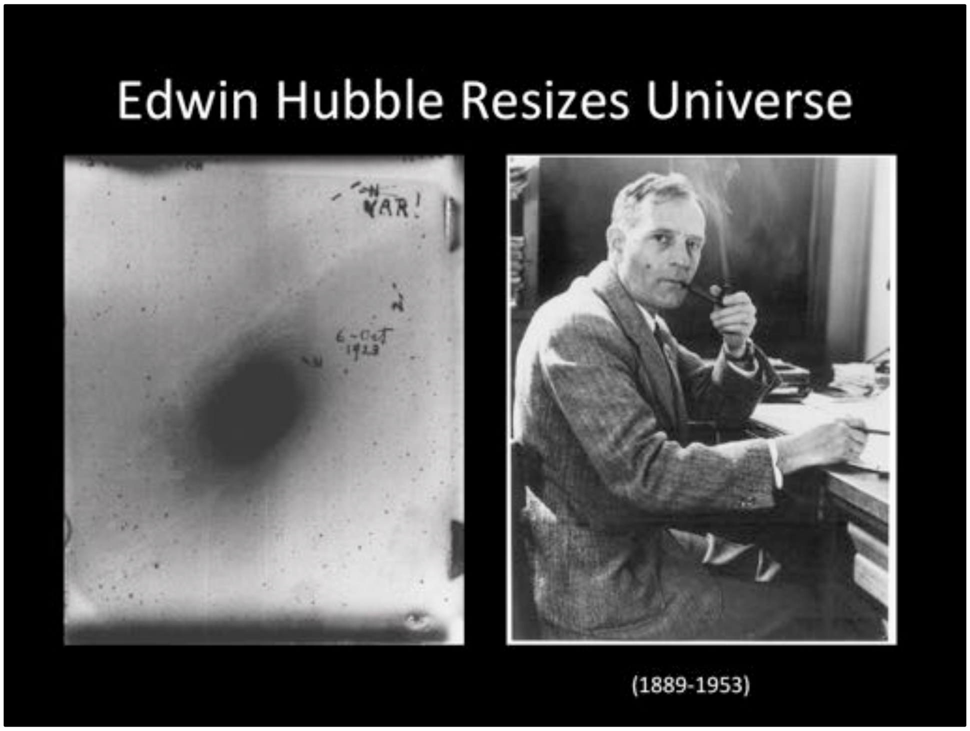
Pulsating Variables

- Henrietta Leavitt recognizes Period-Luminosity Relationship
- Longer period = greater max luminosity
- Know true and apparent luminosities
- Can determine distances
- Cepheids are giants – seen great distances.

Henrietta Leavitt
(1868-1921)



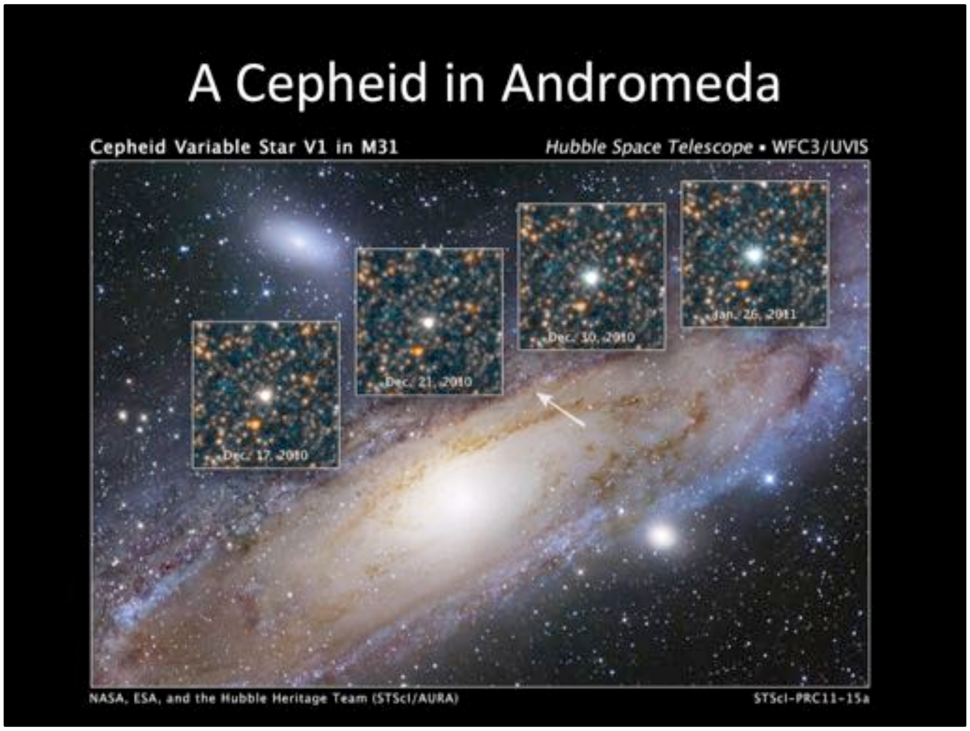
Period-Luminosity Relationship



Edwin Hubble Resizes Universe

(1889-1953)

Edwin Hubble used Cepheid variables to determine the distances of some spiral “nebulae.” He found that these stars, and the “nebulae” in which they resided, were well outside of the Milky Way. This showed that the Milky Way was just a small part of a vast universe, and the spiral nebulae were actually separate galaxies.



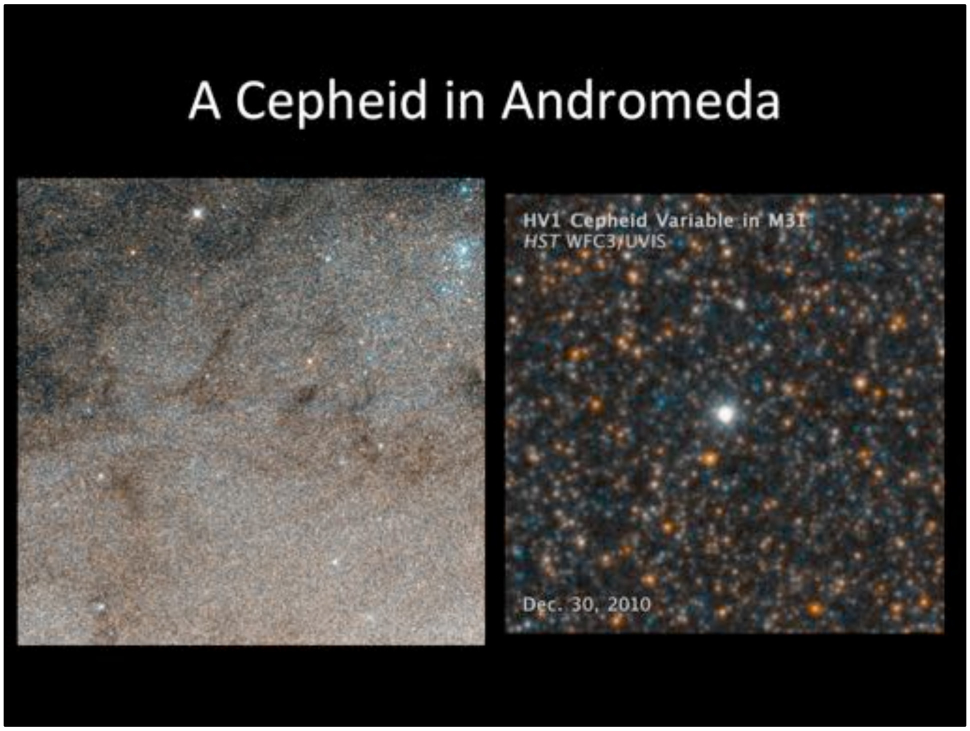
A Cepheid in Andromeda

Cepheid Variable Star V1 in M31

Hubble Space Telescope • WFC3/UVIS

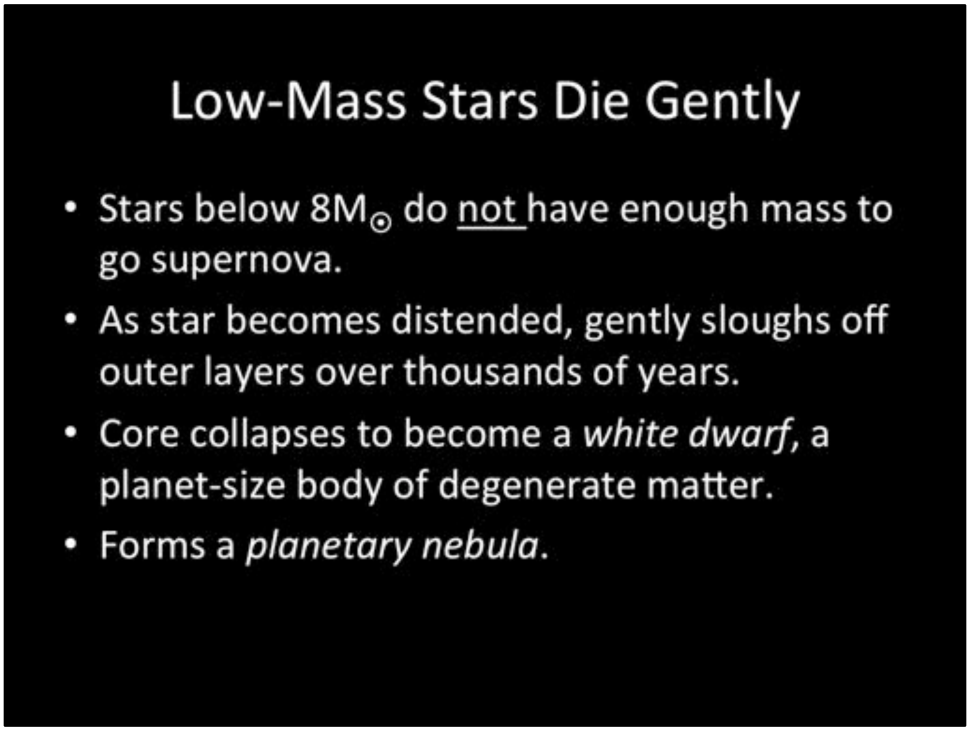
NASA, ESA, and the Hubble Heritage Team (STScI/AURA)

STScI-PRC11-15a



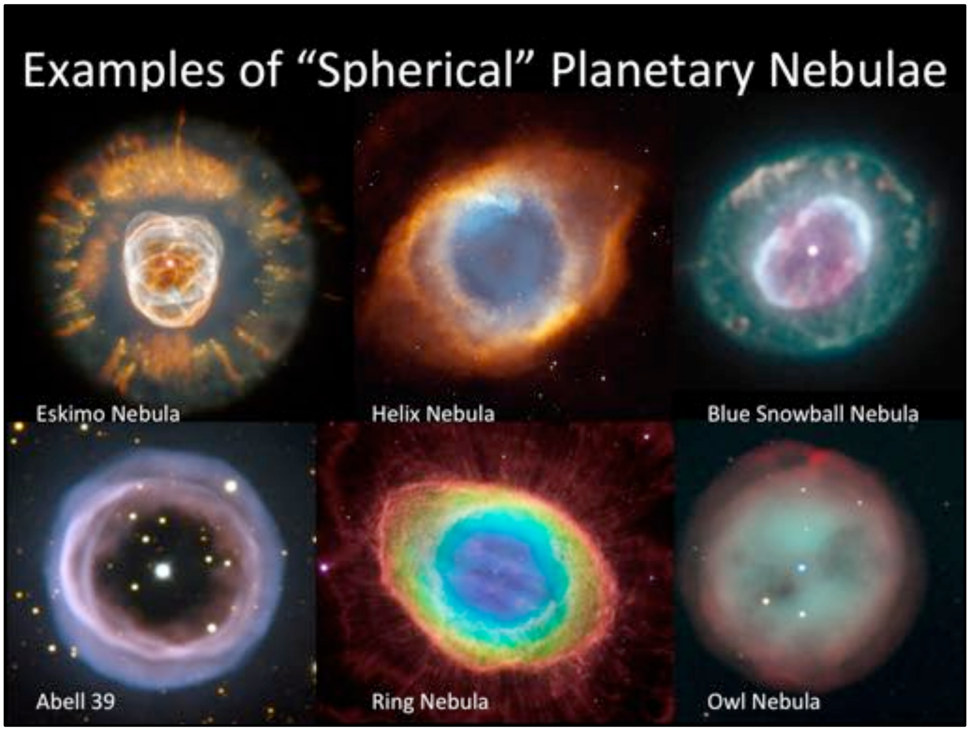
A Cepheid in Andromeda

Left Image – the full Hubble Space Telescope field of view of a portion of the Andromeda Galaxy. Note how many individual stars are visible.



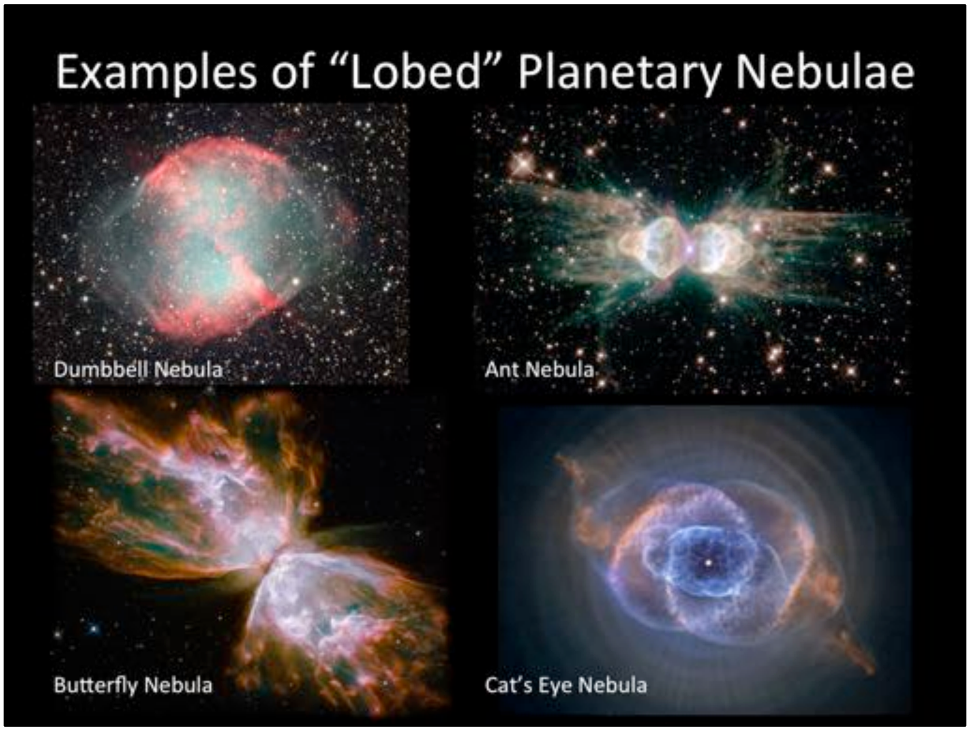
Low-Mass Stars Die Gently

- Stars below $8M_\odot$ do not have enough mass to go supernova.
- As star becomes distended, gently sloughs off outer layers over thousands of years.
- Core collapses to become a *white dwarf*, a planet-size body of degenerate matter.
- Forms a *planetary nebula*.



Examples of “Spherical” Planetary Nebulae

The nebulae consist of the outer layers of dead stars that were sloughed during the final stages of the stars lives. The central stars, known as white dwarfs, are the collapsed cores of the original stars. The white dwarfs are still very hot, maybe 50,000 Celsius, and are emitting a large amount of ultraviolet light. This light goes out into the nebulae and excites the expanding gases, causing them to glow. As the nebulae continue to expand they will grow fainter.

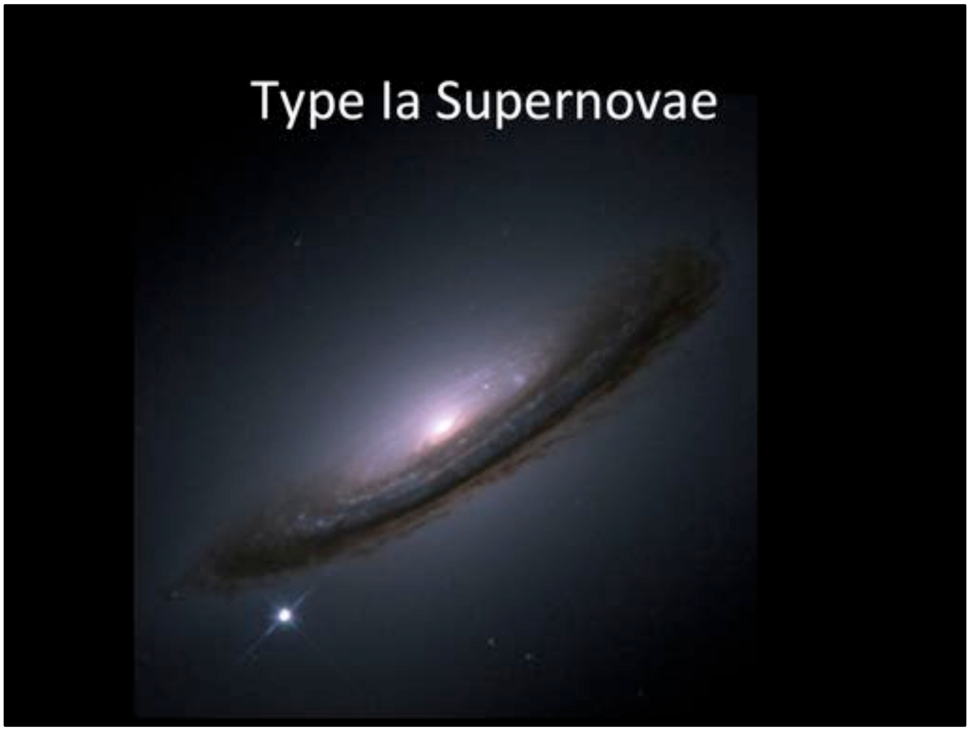


Examples of “Lobed” Planetary Nebulae

The nebulae consist of the outer layers of dead stars that were sloughed during the final stages of the stars lives. The central stars, known as white dwarfs, are the collapsed cores of the original stars. The white dwarfs are still very hot, maybe 50,000 Celsius, and are emitting a large amount of ultraviolet light. This light goes out into the nebulae and excites the expanding gases, causing them to glow. As the nebulae continue to expand they will grow fainter.

A Nearby White Dwarf

A Hubble Space Telescope view of the Sirius star system. The bright star is Sirius A, what we see as the brightest star in the night sky. It has a white dwarf companion, known as Sirius B, which is seen to the lower left of Sirius A. The spikes on Sirius A are known as diffraction spikes, which are the result of mirror supports within the telescope.

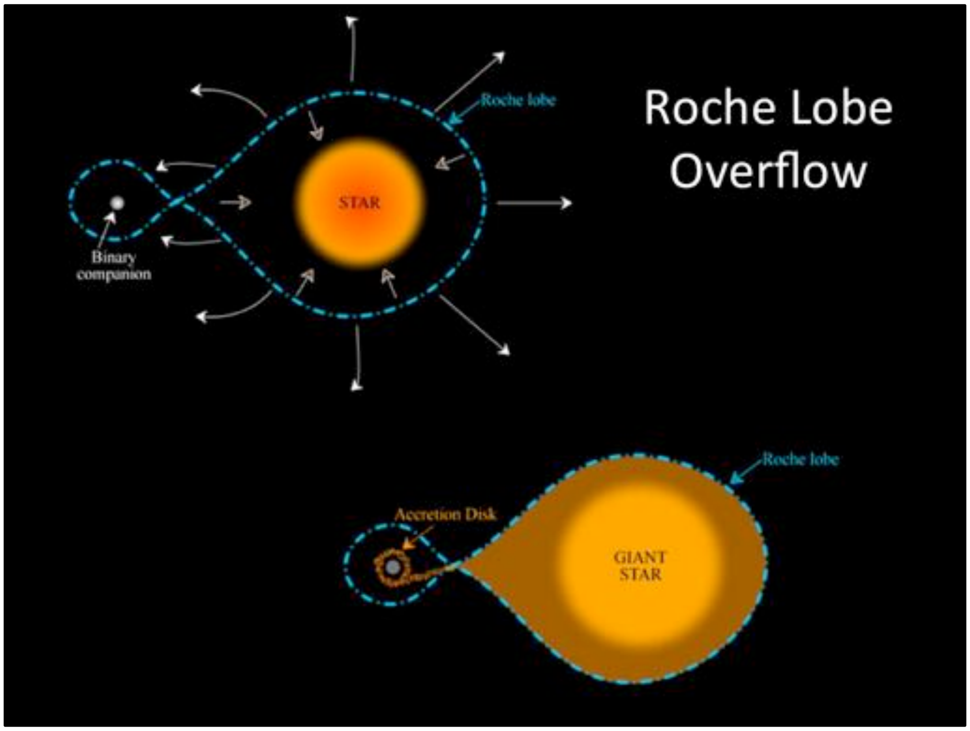


Type Ia Supernovae

Spiral galaxy NGC 4526 and supernova 1994D (the bright spot to the lower left of the galaxy). The supernova was Type Ia – a white dwarf star exploded after it reached the critical mass of 1.4 solar masses. A supernova releases so much energy that it can outshine an entire galaxy. The bright area at the center of the galaxy is the glow of billions of stars.

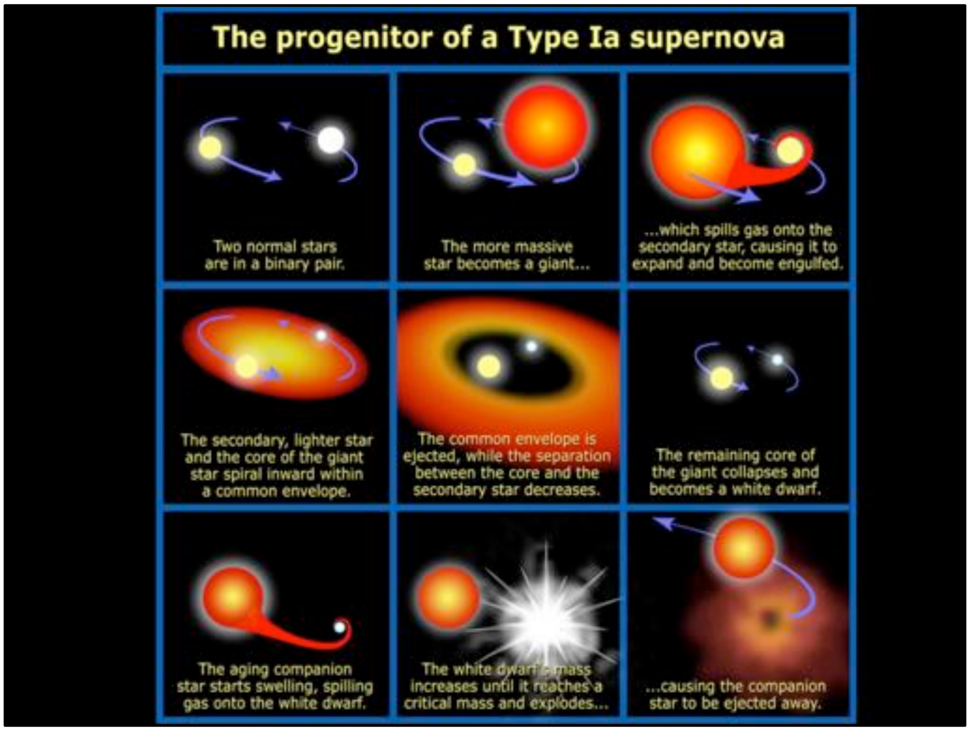
Type Ia Supernovae

A Type Ia supernova occurs in a binary star system that typically consists of a white dwarf star (which was left over from an already evolved low-mass star) and an evolving companion star. A white dwarf has a mass limit of 1.4 solar masses, which is also known as the Chandrasekhar limit. In a binary system where mass transfer occurs (the evolving star spills material onto the white dwarf), the mass spills onto the white dwarf, is compressed by the extreme gravity star, and eventually undergoes fusion to release a large amount of energy known as a nova. This periodically happens, and each nova results in most of the newly added mass being blown off; however, some of the mass remains behind to contribute to the overall mass of the white dwarf star. After many novae, the mass of the white dwarf can eventually pass the Chandrasekhar limit. At this point, electron degeneracy pressure is no longer able to support the star against the increasingly stronger crushing force of gravity and the white dwarf begins to collapse. The temperature immediately begins to rise as the white dwarf starts to collapse and quickly reaches carbon fusion temperatures. The white dwarf beginsfusing all at once and blows itself apart, resulting in a Type Ia supernova.



Roche Lobe Overflow

When a star swells as it nears the end of its life, it can spill material onto a companion if it fills the Roche lobe, an imaginary boundary around the star in which material is gravitationally bound to the star. In a binary system, material can spill from one star to the other through the connection points of the two stars' Roche lobes. This occurs in a system that undergoes a Type Ia supernova.



The progenitor of a Type Ia supernova

Two normal stars are in a binary pair.

The more massive star becomes a giant...

...which spills gas onto the secondary star, causing it to expand and become engulfed.

The secondary, lighter star and the core of the giant star spiral inward within a common envelope.

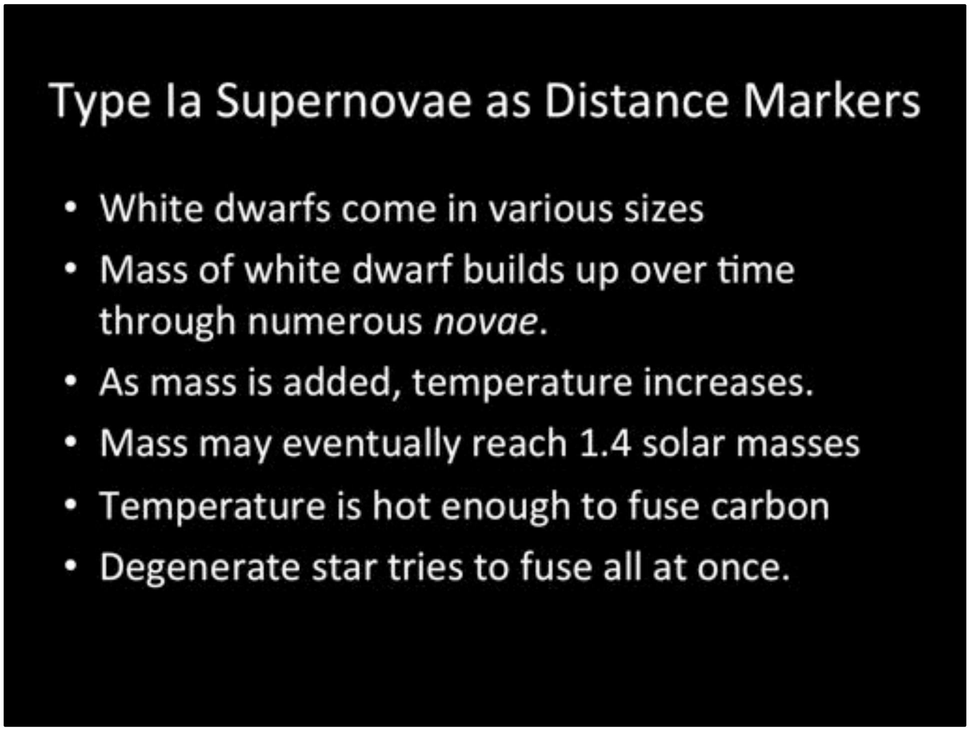
The common envelope is ejected, while the separation between the core and the secondary star decreases.

The remaining core of the giant collapses and becomes a white dwarf.

The aging companion star starts swelling, spilling gas onto the white dwarf.

The white dwarf's mass increases until it reaches a critical mass and explodes...

...causing the companion star to be ejected away.



Type Ia Supernovae as Distance Markers

- White dwarfs come in various sizes
- Mass of white dwarf builds up over time through numerous *novae*.
- As mass is added, temperature increases.
- Mass may eventually reach 1.4 solar masses
- Temperature is hot enough to fuse carbon
- Degenerate star tries to fuse all at once.