Astronomy 101

Studying stars

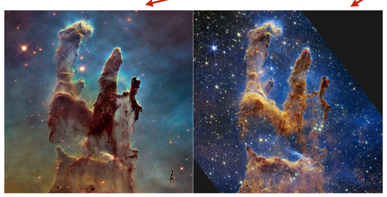
https://openstax.org/details/books/astronomy-2e
Chapters 17, 18, and 19

Stellar Nursery: InterStellar Medium

What are the differences?

- In order to form new stars we need the raw material to make them.
- What does this "raw material" of stars look like?
- How would you detect it?

Hubble (Optical)



JWST (Infrared)

- Our Galaxy contains vast quantities of this "raw material": atoms or molecules of gas and tiny solid dust particles found between the stars.

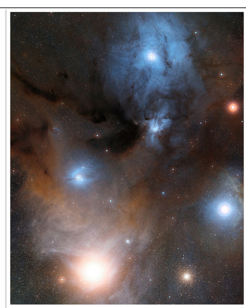
ISM: ingredients

The ISM consists of **gas** and **dust**

Gas is atoms and small molecules:

- 90% hydrogen
- 9% helium
- 1% heavier elements

Dust is larger clumps of particles - about 10^{-7} m in size (wavelength of visible light) - silicates, carbon, iron, some dirty-ice.

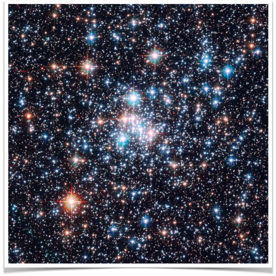


ISM in a nutshell. Nebulae are glowing by the reflecting (blue) and re-radiating (red) starlight. Dark patches are dusts obscuring our view!

Analyzing starlight

Everything we know about stars comes from their light, and they don't all appear equally bright, nor the same color; they differ in:

- Temperature
- Mass
- Energy emission
- Composition
- Etc.



Stefan-Boltzmann law

The energy flux from a blackbody at temperature T is proportional to the fourth power of its absolute temperature. This relationship is known as the **Stefan-Boltzmann law.**

*What we usually measure from a large object like a star is the **energy flux**, the power emitted per square meter of that star.*

The **Stefan-Boltzmann law** and can be written in the form of an equation as

$$F = \sigma T^4$$

- F: The energy flux, given in units of watts per square meter (W/m^2)
- σ: Stefan-Boltzmann's constant
- T is given in Kelvin

Luminosity (L)

Total amount of energy at all wavelengths that a star emits per unit time

$$L = 4\pi R^2 \sigma T^4$$

- L: Luminosity
- R: Radius of star
- T: Temperature of star

In astronomy luminosity is measured in unit of the solar luminosity ($L_\odot$); e.g., star Sirius has a Luminosity of 25 $L_\odot$, so it's 25 times more luminous than the Sun.

Solar Luminosity, $L_\odot$= 3×10^{26} watts

Animation Link

Apparent Brightness (B)

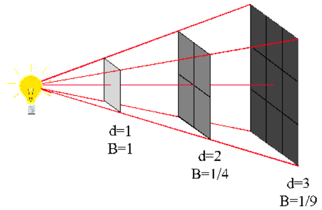
The amount of a star's energy that reaches a given area each second here on Earth

$$B = \frac{L}{4\pi d^2}$$

Luminosity

Brightness

Distance from earth

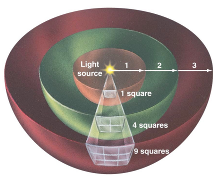


Brightness decreases in a inverse square manner

Luminosity vs. Brightness

Luminosity - absolute brightness - is a property of the star. It is a measure of the total power radiated from the star (wattage). Absolute brightness does not change with distance.

Apparent brightness - how bright a star appears to be. This depends on the distance away and the absolute brightness.



$$\text{apparent brightness} = \frac{\text{luminosity}}{\text{distance}^2}$$

Inverse square law

Question:

For two stars of the same apparent brightness, the star closer to the Sun will generally have

A. a higher flux
B. a hotter temperature
C. a lower luminosity
D. identical physical properties

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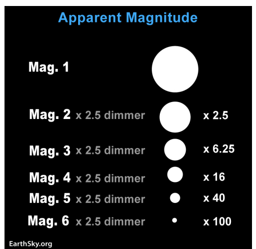
Origin of Magnitude Scale

- Historically brightest stars were first magnitude, next brightest second magnitude... through the faintest stars visible with naked eye at magnitude 6.
- Thus each division on the magnitude scale changes brightness by about a factor of 2.5.
- *Magnitude 1 stars are 100 times brighter than magnitude 6 stars.* Because,

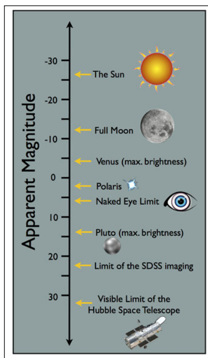
$$2.5^{(6-1)} = 2.5^5 \approx 100$$



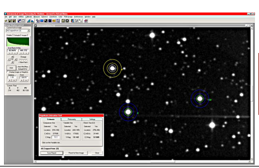
5 units of magnitude difference is a factor of 100 in brightness difference!

https://www.astronomy.com/observing/why-do-astronomers-measure-stars-in-magnitudes/

Apparent Magnitude (m)



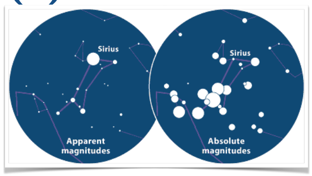
- It is the brightness of any celestial object as seen from earth.
- Negative apparent magnitudes are brighter!
- We calculate magnitude (m) from the flux (F) that we record in CCDs using the formula : $m = -2.5log_{10}(F)$. This flux us same as brightness (B).

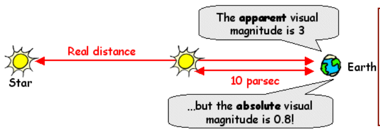


- We take image
- Perform photometry
- We get a magnitude

Absolute Magnitude (M)

The absolute magnitude of a star, M is the magnitude the star would have if it was placed at a distance of 10 parsecs from Earth.



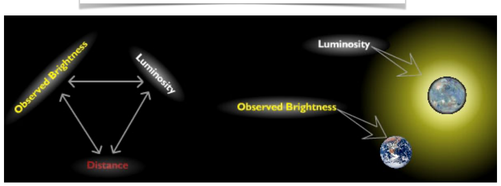


- Can you measure absolute magnitude and distance at the same time?
- The answer is NO!

Distance Modulus (μ)

It is the difference between apparent (m) and absolute (M) magnitudes. We can use it to measure distance (d).

$$\mu = m - M = 5log_{10}\left(\frac{d}{10\ pc}\right)$$



The magnitude equation

This equation helps calculate the difference in brightness for stars with different magnitudes. Also known as distance modulus (μ) equation.

$$apparent\ \ magnitde - absolute\ \ magnitude = 5\log_{10}\left(\frac{distance}{10\ \ pc}\right)$$

$$\mu = m - M = 5log_{10}\left(\frac{d}{10\ pc}\right)$$

Why log?
Logarithm is a mathematical function that tells you what "power of ten" a number is.
A convenient way to categorize numbers that follow "power laws".

$10^{-1} = 0.1$	$\log(0.1) = -1.0$
$10^{0} = 1.0$	$\log(1.0) = 0$
$10^{1} = 10.0$	$\log(10) = 1.0$
$10^{1.5} = 31.6$	$\log(31.6) = 1.5$
$10^{2} = 100.0$	$\log(100) = 2.0$

The magnitude equation

This equation helps calculate the difference in brightness for stars with different magnitudes.

$$apparent\ \ magnitude - absolute\ \ magnitude = 5\log_{10}\left(\frac{distance}{10\ \ pc}\right)$$

Example - What is the difference between apparent and absolute magnitude of a star 10 pc away.

$$apparent\ magnitude - abs\ magnitude = 5log_{10}(\frac{10}{10})$$

$$apparent\ magnitude - abs\ magnitude = 5log_{10}(1)$$

$$apparent\ magnitude - abs\ magnitude = 0$$

$$apparent\ magnitude = abs\ magnitude$$

10 pc is standard “calibration” distance

Apparent and absolute magnitude are the same at the calibration distance!

The magnitude equation

This equation helps calculate the difference in brightness for stars with different magnitudes.

$$apparent\ \ magnitude - absolute\ \ magnitude = 5\log_{10}\left(\frac{distance}{10\ \ pc}\right)$$

$$\mu = m - M = 5log_{10}\left(\frac{d}{10\ pc}\right)$$

What is the difference between apparent and absolute magnitude of a star 100 pc away?

if distance=100 pc

$$apparent\ \ magnitude - absolute\ \ magnitude = 5\log_{10}\left(\frac{100}{10}\right)$$

$$apparent\ \ magnitude - absolute\ \ magnitude = 5\log_{10}(10)$$

$$apparent\ \ magnitude - absolute\ \ magnitude = 5(1)$$

$$apparent\ \ magnitude - absolute\ \ magnitude = 5$$

The magnitude equation

A star has an apparent magnitude 10.0 and an absolute magnitude 2.5. How far away is it?

$$apparent\ \ magnitde - absolute\ \ magnitude = 5\log_{10}\left(\frac{distance}{10\ \ pc}\right)$$

$$\mu = m - M = 5log\left(\frac{d}{10\ pc}\right)$$

$$10 - 2.5 = 5\log\left(\frac{d}{10}\right)$$

$$1.5 = \log\left(\frac{d}{10}\right)$$

$$10^{1.5} = \frac{d}{10}$$

$$d = (10)(10^{1.5}) = 316\ \ pc$$

$$10^{1.5} = 10^{log\left(\frac{d}{10}\right)}$$

(Note - raising 10 “to the power of both sides” gets rid of the log!)

Question:

Which of the following quantities do you need in order to calculate a star's luminosity?

A. apparent brightness

B. Doppler shift of spectral lines

C. color of the star

D. distance to the star

E. A and D

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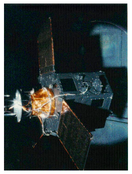
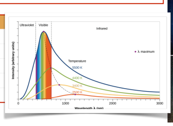


The *Hipparchos* mission measured distance (by parallax) and apparent magnitude. This allows for luminosity determination and a deep study of stars. *Hipparchos* also measure color (next...)

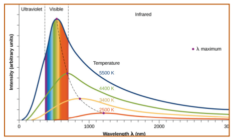
Colors of Stars

- Color of a star tells you how hot or cool the star us qualitatively.
- To have a quantitative measure we first construct a blackbody curve and locate wavelength the peak wavelength.
- We then use Wien's law: ($\lambda_{max} = \frac{3 \times 10^6\, nm \cdot K}{T}$), to calculate temperature.

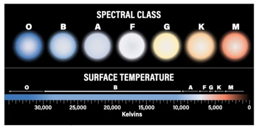
Star Color	Approximate Temperature	Example
Blue	25,000 K	Spica
White	10,000 K	Vega
Yellow	6000 K	Sun
Orange	4000 K	Aldebaran
Red	3000 K	Betelgeuse

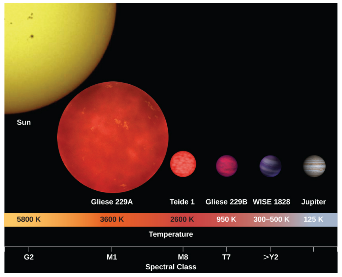


Colors of Stars



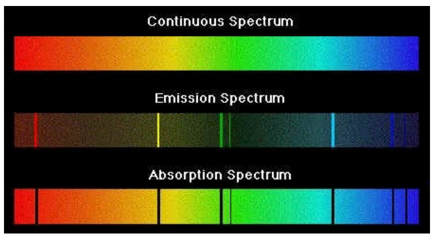
Laws of blackbody radiation





Colors of stars depend on their temperature

Revisiting Types of Spectra



[Animation Link]

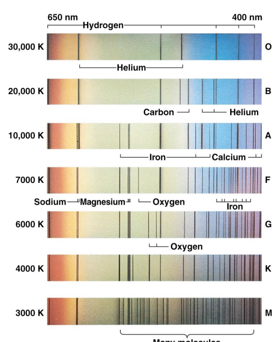
Stellar Spectra

- Measuring colors is only one way of analyzing starlight.
- Another way is to use a spectrograph to spread out the light into a spectrum
- There are seven general categories of stellar spectra, corresponding to different temperatures.
- From hottest to coolest, those categories are:

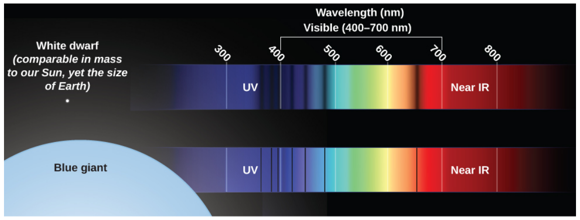
O B A F G K M

Useful Phrase!

Oh **B**e **A** **F**unny **G**oat, **K**ick **M**e.



Stellar Spectra: Effect of Pressure

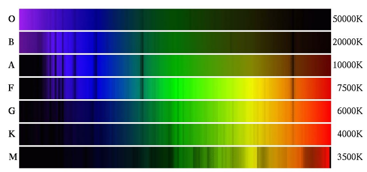


A star that has higher pressure inside will show broader absorption lines

Use of Stellar Spectra

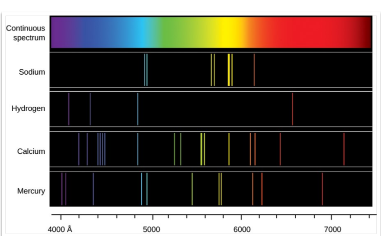
Analyzing the spectrum, we can infer:

- Size
- Composition
- Radial velocity
- Rotation



Representative spectra of stars for various spectral class

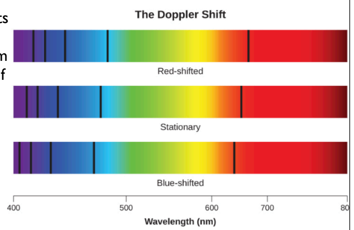
Stellar Spectra: Composition



- Spectral lines of a majority of the known chemical elements have now been identified in the spectra of the Sun and stars.
- If we see lines of iron in a star's spectrum at a particular wavelength, for example, then we know immediately that the star must contain iron.

Stellar Spectra: Velocity

- We observe spectral lines of stars shifts toward the red end of the spectrum (redshift) if the star is moving away from us and toward the blue end (blueshift) if it is moving toward us.
- By measuring these shifts of spectral lines (Doppler effect) we can measure the velocity of the stars using the formula:



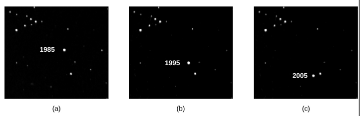
Shift in wavelength → $\Delta\lambda$; Relative velocity → v

Laboratory wavelength → λ ; Speed of light → c

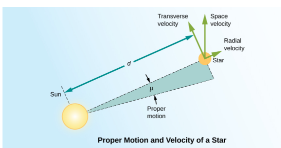
$$\frac{\Delta\lambda}{\lambda} = \frac{v}{c}$$

Proper Motion

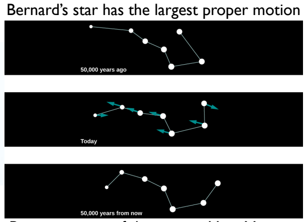
- Proper motion is across the sky
- Radial motion is towards or away from our line of sight



Bernard's star has the largest proper motion



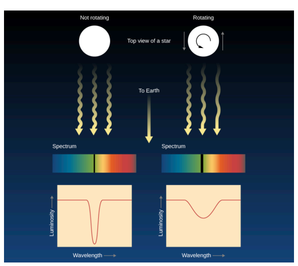
Geometry of stellar motion



Proper motion of the stars in Ursa Major

Stellar Spectra: Rotation

- If an object is rotating, then one of its sides is approaching us while the other is receding
- Due to the Doppler effect, the lines in the light that come from the side of the star rotating toward us are shifted to shorter wavelengths (blueshift) and the lines in the light from the opposite edge of the star are shifted to longer wavelengths (redshift).



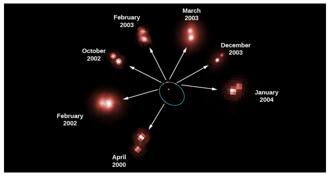
The line gets broaden since one end is redshifting and the other end is blueshifting

Measuring stellar masses

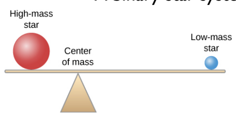
- About half the stars are **binary stars,** two stars that orbit each other, bound together by gravity.
- Mass of a binary star system can be calculated from their orbits using Kepler's law.

$$D^3 = (M_1 + M_2)\ x\ P^2$$

Animation Link

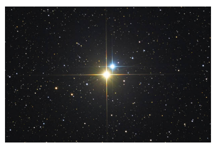


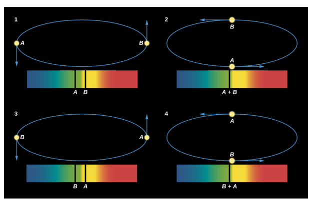
A binary star system



Binary stars

A binary star system in which both of the stars can be seen with a telescope is called a **visual binary**.





A star which appears as a single star when photographed or observed visually through the telescope, but which spectroscopy shows really to be a double star, is called a **spectroscopic binary**.

Animation Link

Question:

A binary star system:

A. Is composed by two stars
B. Is held together by gravity
C. Is useful to find the mass of the component stars
D. Is not always visually detectable
E. All of the above

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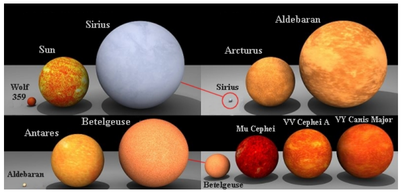
Stellar size

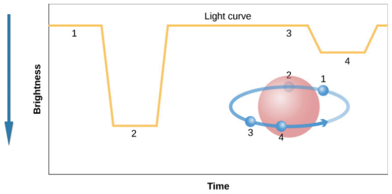
Unfortunately, the Sun is the only star whose angular diameter is easily measured. All the other stars are so far away that they look like pinpoints of light through even the largest ground-based telescopes.



Video Link

Stellar Spectra: Size

Accurate sizes for a large number of stars come from measurements of **eclipsing binary** star systems: stars that are lined up in such a way that, when viewed from Earth, each star passes in front of the other during every revolution



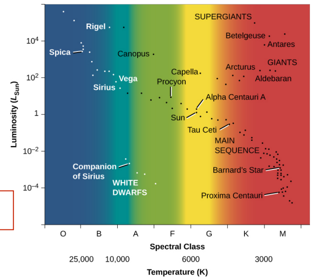
Animation Link

The brightness of the bigger star gets dimmer as the orbiting star revolves

The Hertzprung-Russell (H-R) Diagram

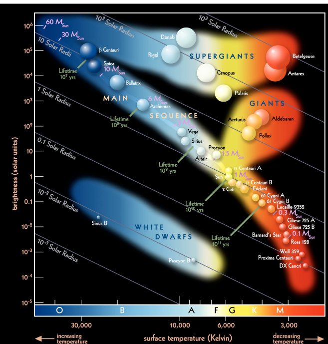
(a) (b)

A relation between spectral class and luminosity of stars



A nice H-R Diagram ⟶

Animation: H-R diagram

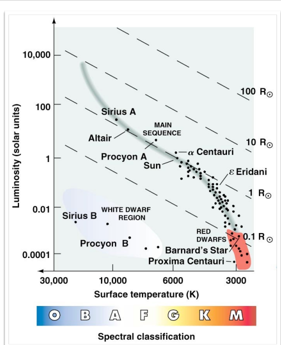


The H-R Diagram

These are the 80 closest stars to us

- The darkened curve is called the main sequence, as this is where most stars are.
- Also indicated is the white dwarf region; these stars are hot but not very luminous, as they are quite small.

- Temperatures on the main sequence range over a factor of 10 (3000-30,000 K).
- Corresponding luminosities range over 8 orders of magnitude.
- Stellar radii also change along the main sequence.

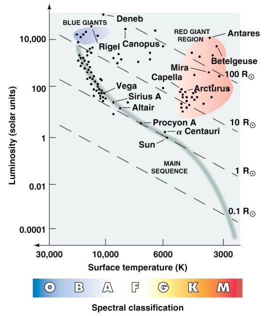


The H-R Diagram

These are the 100 brightest stars to us

- These stars are all more luminous than the Sun.
- Two new categories appear here – the red giants and the blue giants.

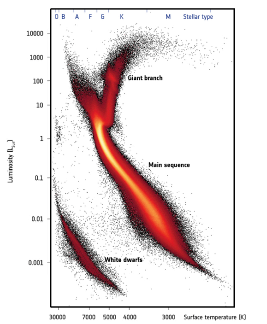
- Clearly, the brightest stars in the sky appear bright **because of their enormous luminosities, not their proximity.**



The H-R Diagram

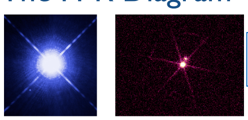
A genreal statistics

- 90 percent of stars lie on the main sequence
- 9 percent are red giants
- 1 percent are white dwarfs.



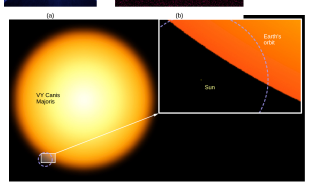
H–R Diagram of Stars Measured by Gaia satellite : there are four million stars in this plot.

The H-R Diagram

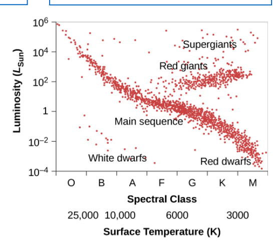


White dwarf companion of Sirius

- Branching out from the main sequence denotes stellar evolution
- Stellar evolution depends on the initial mass of the star



Comparison of our Sun with a supergiant star



Question:

What are the two most important intrinsic properties for classifying stars?

A. distance and surface temperature
B. luminosity and surface temperature
C. distance and luminosity
D. mass and age
E. distance and color

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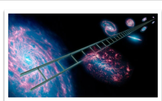
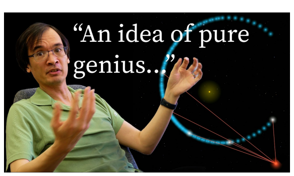
E. distance and color

Cosmic Distance Measurements



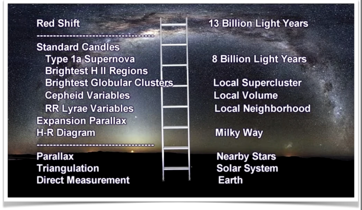
Field medal winner Terence Tao describes distance measurements in astronomy



A must watch set of videos!

Cosmic Distance Ladder: How it Works?

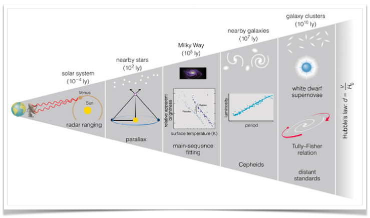
- We start at the first step where we know distance to some object.
- We then calibrate the next step and move up.
- We continue climbing towards the deep Universe by calibrating and moving up in the ladder.



Video: distance ladder

Animation: Scale-down model of Solar System

Cosmic Distance Ladder: in Detail

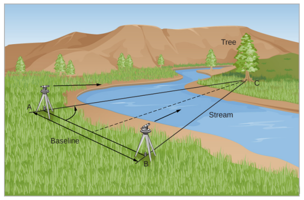


Courtesy: David Darling

- The cosmic distance ladder is the chain of overlapping methods by which astronomers establish a distance scale for objects in the universe, from nearby planets to the most remote quasars and galaxies.
- At every step of the distance ladder, errors and uncertainties creep in.
- Each step inherits all the problems of the ones below, and also the errors intrinsic to each step tend to get larger for the more distant objects; thus the spectacular precision at the base of the ladder degenerates into much greater uncertainty at the very top.

Stellar Distances: Parallax Method

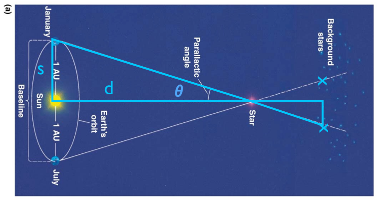
Before studying parallax let us understand triangulation first



- Triangulation in surveying: change of baseline provides two vantage points that crates a triangle.
- By knowing the baseline and the angles that the object makes with te baseline helps solving for the distance to that object.

Stellar Distances: Parallax Method

Parallax is the apparent change in the position of an object against a distance background.



Use Earth's orbit around the Sun to get biggest baseline possible.

Know s, measure θ, determine d.

Determining the Parallactic Angle (θ)

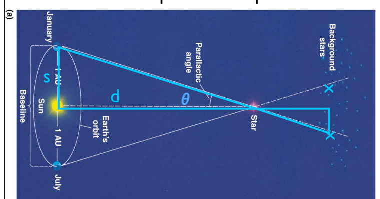
Use telescope to measure shift.

Determine θ from half of measured shift

Use s = 1 AU for baseline

Stellar Distances: Parallax Method

To measure stellar parallax use position of Earth in January (A) and in July(B)



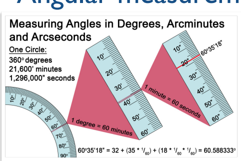
Measure parallax in **arcsecond** - get distance in **parsec**

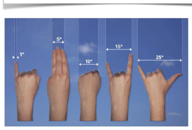
$$d(\text{parsec}) = \frac{1}{\theta(\text{arcseconds})}$$

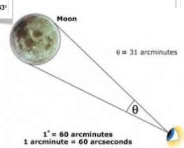
Animation: Astronomical Parallax

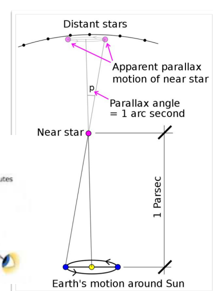
- As Earth revolves around the Sun, the direction in which we see a nearby star varies with respect to distant stars.
- We define the parallax of the nearby star to be one half of the total change in direction, and we usually measure it in arcseconds and using the formula we get distance in parsec.

Angular measurements: arcsecond









Angular measurement is very useful in spherical geometry.

Question:

If the parallax of a star is measured to be 0.1 seconds of arc, its distance is

A. 10 astronomical units
B. 10 parsecs
C. 1 parsec
D. 0.1 parsec
E. 0.1 astronomical units

$$d(\text{parsec}) = \frac{1}{\theta(\text{arcseconds})}$$

Question:

If the parallax of a star is measured to be 0.1 seconds of arc, its distance is

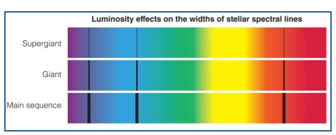
A. 10 astronomical units
B. 10 parsecs
C. 1 parsec
D. 0.1 parsec
E. 0.1 astronomical units

$$d(\text{parsec}) = \frac{1}{\theta(\text{arcseconds})}$$

1/0.1=10 pc

Stellar Luminosity Classes

- For stars with the same temperature the width of absorption lines tells us how compact the stars are.
- The smaller the star, thicker the absorption line is.
- This is because of the pressure inside a star.
- A main sequence star has more pressure than a giant or supergiant star.



$$L = 4\pi R^2 \sigma T^4$$

luminosity $\propto$ radius^2 $\times$ temperature^4

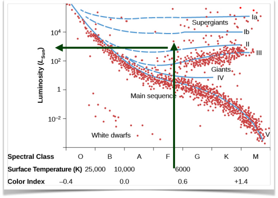
More on Luminosity

Check slide 23 and 4

Spectroscopic Parallax

- When a star is too far way, measuring parallax becomes impossible.
- We can use spectra to get distance!

Procedure:
1. First we measure the apparent magnitude of the star.
2. Then we analyze the spectrum to calculate its temperature and luminosity class.
3. Thereafter, we can read it's luminosity or absolute magnitude.
4. After that, we use the distance modulus formula to calculate distance.

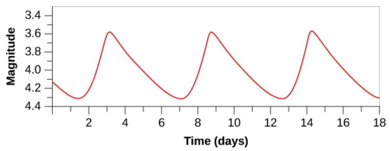


$$apparent\ \ magnitde - absolute\ \ magnitude = 5\log_{10}\left(\frac{distance}{10\ \ pc}\right)$$

Animation

Variable Stars

A star that shows a variation in its brightness is called a variable star.

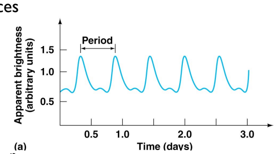


The maximum is the point of the light curve where the star has its greatest brightness; the minimum is the point where it is faintest. If the light variations repeat themselves periodically, the interval between the two maxima is called the period of the star.

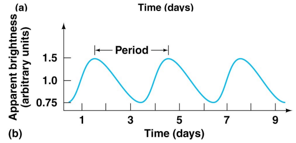
Pulsating Variable stars

Intrinsic variable stars such as RR Lyrae stars and Cepheids can be used to measure distances

RR Lyrae stars: All such stars have essentially the same luminosity curve, with periods from 0.5 to 1 day.

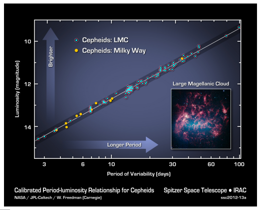


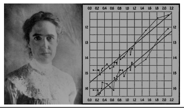
Cepheid variables: Cepheid periods range from about 1 to 100 days.



Stellar Distances: Cepheid Variables

- Cepheids variable stars show a linear relationship between their period and luminosity.
- Longer the period, higher the luminosity.
- Henrietta Swan Levitt discovered this period luminosity relationship.





Henrietta Swan Levitt, and the Harvard college observatory.

Her work laid the foundation of modern cosmology.

Distance Ladder: upto now

- Measuring variable stars luminosity via the light-curve time period expands our ability to measure distances out to 25 Mpc (83 million ly).
- We need a new method beyond the distance