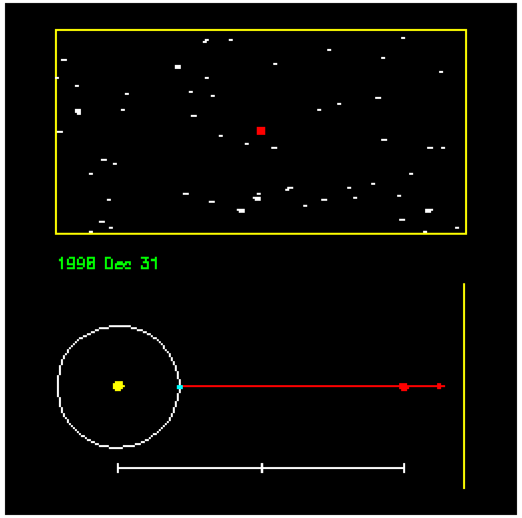
Estimating the distance of Stars

Featuring our old favourite…. The Hertzsprung-Russell diagram.

What's in this presentation

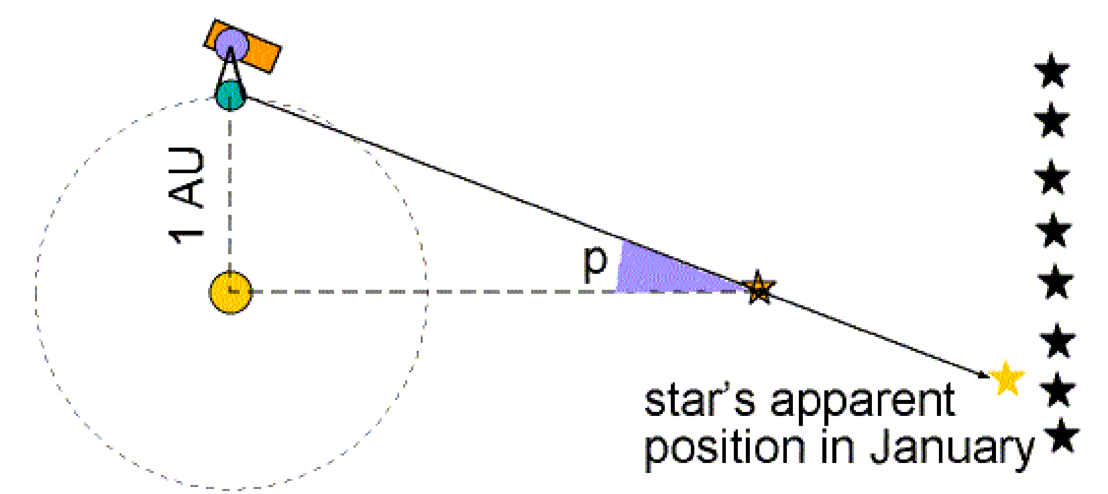
- Estimation of Distance using Heliocentric Parallax
- Estimation of Distance using Magnitudes
  - Colour, Temperature & Luminosity
  - System of Magnitudes
  - Absolute Magnitude & Apparent Magnitude
  - An Example "How far away is Altair"
- Estimation of Distance using redshift

Estimation of Distance using Heliocentric Parallax



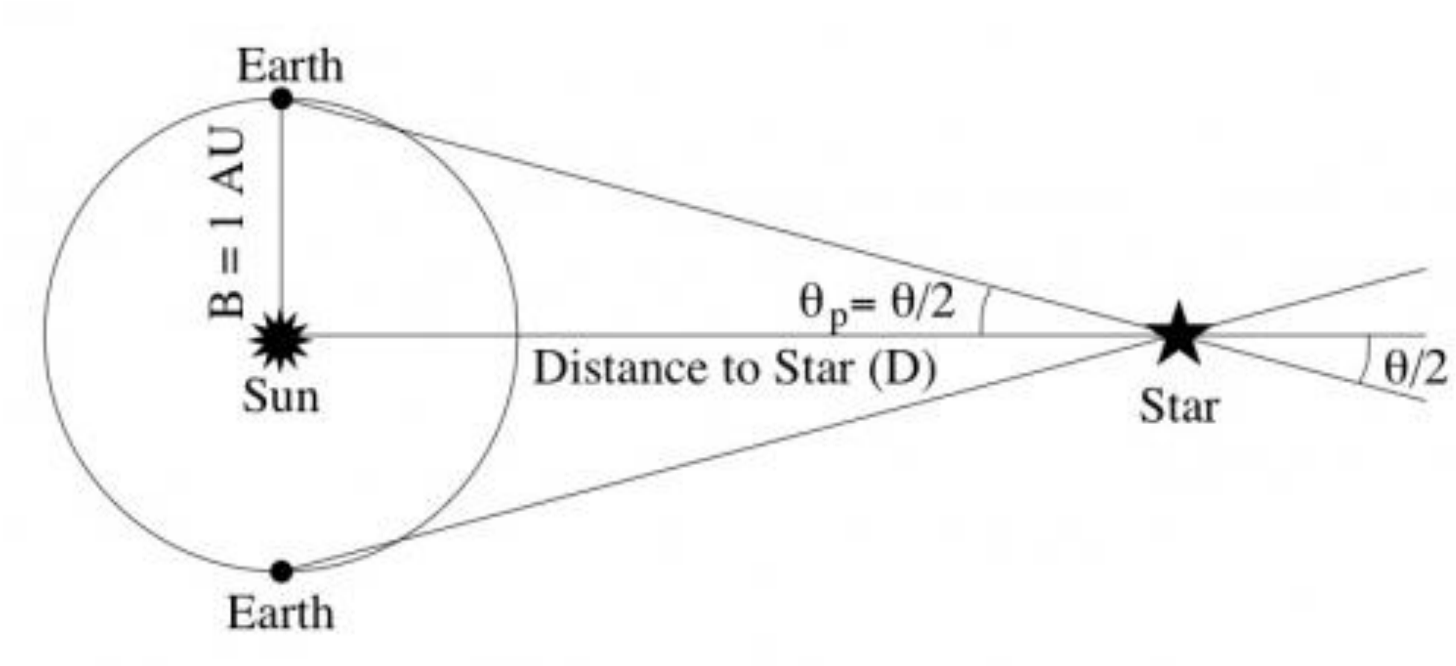
1 Parsec is the distance (D) formed by an angle of 1 acrsec with a baseline of 1AU.
D = 1AU x tan (90°– 0° 0' 1") or 149.6 x10^6 x tan(90-1/3600) = 3.086 x 10^{13} km.
A Parsec is a compound of PARallax and arcSECond

Estimation of Distance using Heliocentric Parallax



Stellar parallaxes need largest possible baseline

Estimation of Distance using Heliocentric Parallax



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Estimation of Distance using Heliocentric Parallax

- So 1 parsec = 3.086×10^{13} km.
- That is 30,860,000,000,000 km
- Compared to a light year.
- A light year (ly) is 9.461×10^{12} km.
- So a parsec is a little over 3 times bigger than a light year.

Estimation of Distance using Heliocentric Parallax

- Let’s use Altair as an example
- Altair’s parallax angle (from Stellarium) is 0.1945 arcsec
- A parsec is the distance formed by a parallax angle of 1 arcsec so by simple ratio we have 1/0.19495 or 5.1414 pc
- There are 3.26 light years in a parsec so Altair is 3.26 x 5.1295 or 16.722 ly

Estimation of Distance using Heliocentric Parallax

- What possible errors could there be in this method?
  - The distances involved mean the parallax angle is exceedingly small and so they are difficult to measure accurately even using a base line of the Earths orbit 6 months apart.
  - Sighting errors, caused by the earths atmosphere may lead to inaccurate angle measurement.
  - The Hipparchus satellite1989-1993 measured parallax angles for around 120,000 stars to 1 milliarcsecond or 1/1000th of an arcsecond and a further 1 million stars to 25 milliarcseconds.
  - This pushed back the distance that parallax can be used to around 2000 ly.

Estimation of Distances using Magnitudes

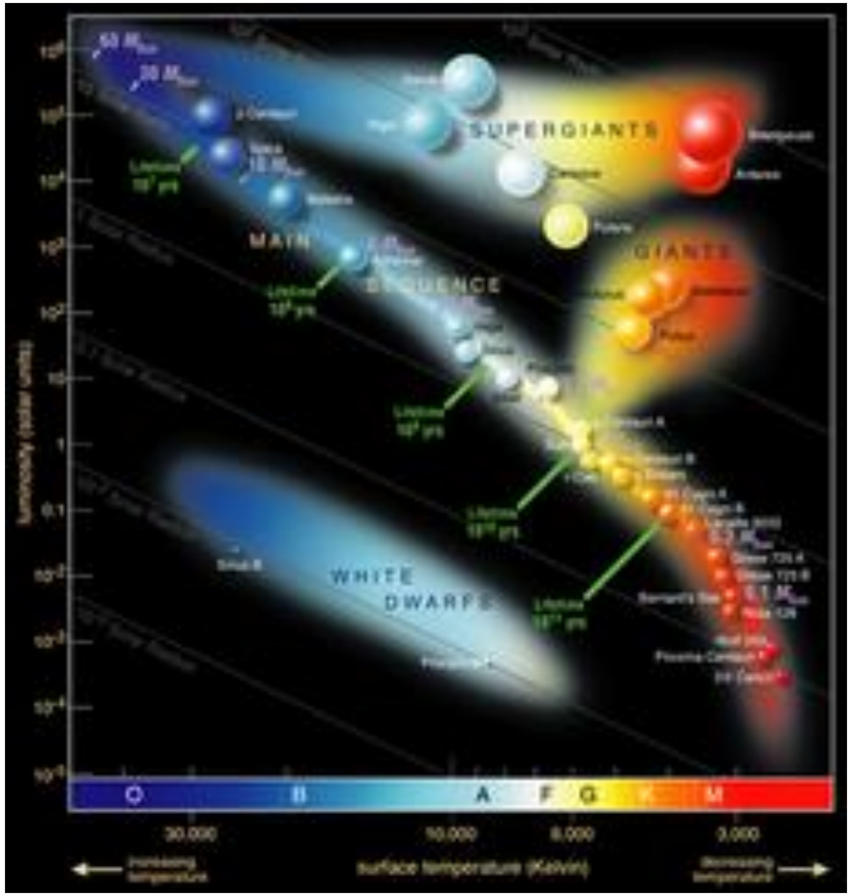
- Colour & Temperature
- Luminosity
- System of Magnitudes
- Absolute and Apparent Magnitudes
- Inverse Square Laws
- Estimating Distance

Colour & Temperature

Here’s our old friend the Hertzsprung Russell diagram.

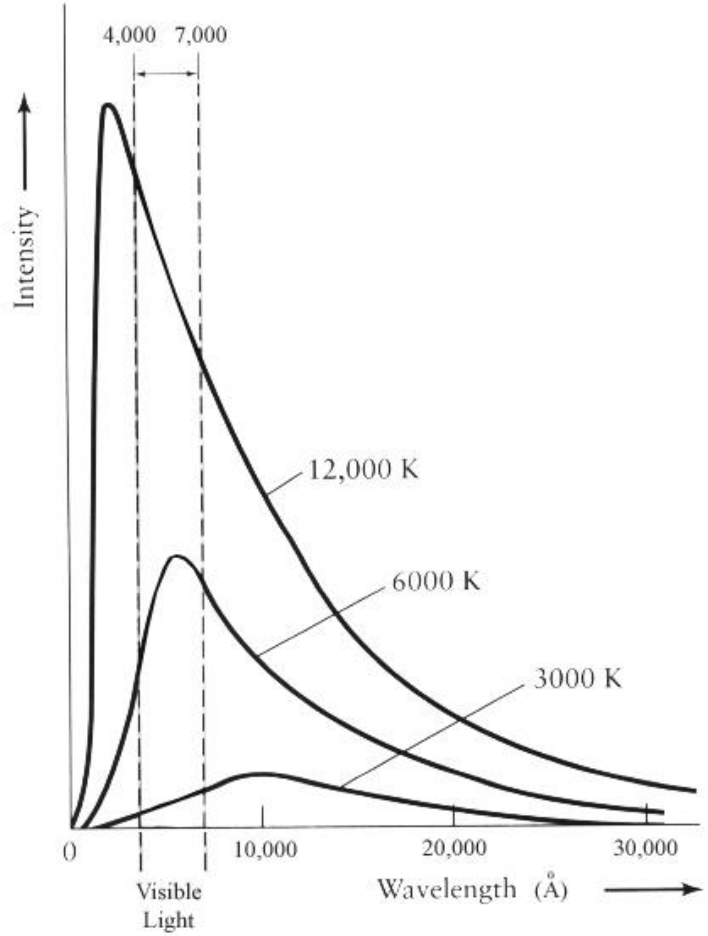
Along the horizontal it shows colour and temperature.

A *blackbody* refers to an opaque object that emits *thermal radiation*. A perfect blackbody is one that absorbs all incoming light and does not reflect any. At room temperature, such an object would appear to be perfectly black (hence the term *blackbody*). However, if heated to a high temperature, a blackbody will begin to glow with *thermal radiation*. As the temperature of a blackbody increases, the total amount of light emitted per second increases, and the wavelength of the spectrum's peak shifts to bluer colors.



Colour & Temperature

- All bodies (objects) emit and absorb **infrared radiation**. They do this whatever their **temperature**. The hotter the body:
  - the more infrared radiation it gives out in a given time
  - the greater the proportion of emitted radiation is visible light
- **Black bodies**
- Stars are considered to be black bodies because they are very good emitters of most wavelengths in the **electromagnetic spectrum**. This suggests that stars also absorb most wavelengths. Whilst there are a few wavelengths that stars do not absorb or emit, this figure is very low, so they can be treated as black bodies. Planets and black holes are also treated as nearly perfect black bodies.



Luminosity

- Luminosity is the total energy that a star produces in one second. It depends on both the radius of the star and on its surface temperature. (Watts or Joule/s)

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

- If we take out the constants σ (the Stefan-Boltzmann constant) and 4π, we are left with the product of the surface temperature raised to the power of 4 and the radius raised to the power of 2 (or squared).
- Now you may be thinking “But how do we know the radius?”. The answer is we can use a radius calculated by another method or we can relate the radius to that of the Sun.
- The equation can be rewritten now as simply.

  - $L = T_{☼}^{4} \times R_{☼}^{2}$

  where $T_{☼}$ and $R_{☼}$ are the temperature and radius of the Sun & L is the luminosity of the star as a factor of the luminosity of the Sun.

System of Magnitudes

- The ancient Greek astronomer Hipparchus developed a system of classifying stars based on their apparent brightness.
- He called the first stars to come out at night 1st magnitude stars and so on down to the 6th order of magnitude (the limit of naked eye observing). Which is why the number gets bigger as the stars get fainter.
- As time went on and telescopes became available then fainter stars could be detected, requiring bigger numbers.
- In 1850 the English astronomer Norman Robert Pogson proposed the system presently in use. A difference of one magnitude is defined as a difference of brightness of 2.512 times. A difference of 2 would be a difference in brightness of 2.512 x 2.512 or 2.512^2
- After a difference of five magnitudes the difference in brightness is 100 times. After standardization and assignment of the zero point, the brightest class was found to contain too great a range of luminosities, and negative magnitudes were introduced to spread the range.

Absolute & Apparent Magnitudes

- Apparent magnitude is the brightness of an object as it appears to an observer on Earth.

- The Sun's apparent magnitude is -26.7, that of the full Moon is about -11, and that of the bright star Sirius, -1.5. The faintest stars visible through the largest telescopes are of (approximately) apparent magnitude 20.

- Absolute magnitude is the brightness an object would exhibit if viewed from a distance of 10 parsecs (32.6 light-years). The Sun's absolute magnitude is 4.8.
  - So we are obviously much closer to the Sun than 10pc, how much closer?
  - Light from the sun takes 8 minutes (8 light minutes) to get to us, so as an approximation
  - 8/32.6x365x24x60 or 8/17134560th of 10 pc and 1 pc is 3.086×10^{13} km
  - So 8/17134560 x 10 x 3.086×10^{13} = 144 million km or 90 million miles

Inverse Square Laws

- There are many inverse square laws in physics; Newton's law of universal gravitation is one and there are many more.
- An inverse law is where the property in question
- (lets call it Resolve)
- gets weaker or smaller as the property it is related to gets bigger
- (lets call this property Time).
- We all know that for most people Resolve weakens over Time.
- A square law relates one property to the square of the other;
- e.g. Hassle is proportional to number of children squared.
  - $H \alpha NoC^2$
    - So two children cause 4 times or 2^2 the hassle of one child.
- Or we could express it as an inverse square law and say Me Time is inversely proportional to number of children squared.
  - $MT \alpha 1/NoC^2$

Estimating Distance

- We now have all the required elements to estimate the distance to a star, we just need to bring them together.
- We need to know the apparent magnitude (ApMag) and the absolute magnitude (AbMag), how to use them to get to the relative brightness of the star at 10 parsecs (where AbMag is taken from) then use the inverse square law to find the distance.
- So, unfortunately there is some maths involved now. This is only here to show that it does indeed work and if you're not into the maths then just switch off for a second and join in at the final result. ☺
- In the magnitudes slide we said the difference in magnitude between 1 and 6 was equivalent to a difference in brightness of 100 times, meaning each magnitude is 2.512 times a bright as the last. We need to take the 5th root of 100 to get ≈2.512.
- i.e. $2.512 \times 2.512 \times 2.512 \times 2.512 \times 2.512 \approx 100$
- Or $2.512 \approx \sqrt[5]{100}$
- Or $2.512^5 \approx 100$
- Or difference in brightness = $\sqrt[5]{100}^{\text{(diff in mag)}}$

Estimating Distance

- If we use the absolute mag and the apparent mag and the previous result we can get the difference in brightness.
- We then use the inverse square law to get an estimation of the distance.
- So lets do it:
- Altair has an Absolute Mag of 2.2 and a Apparent Mag of 0.75
- That is a difference in brightness of $\sqrt[5]{100}^{\,(2.2-0.75)} = 3.802$
- We use this in our inverse square law as follows
- $B_1/B_2 = (D_1/D_2)^2$ The ratio of the brightness (B_1/B_2) is the same as the ratio of the distances squared $(D_1/D_2)^2$
- $3.802 = (10/D_2)^2$
- $\sqrt{3.802} = (10/D_2)$
- $D_2 = 10/\sqrt{3.802}$ in parsecs $D_2 = 10/\sqrt{3.802} \times 3.26156$ in light years
- Altair is 16.7267 ly away. Stellarium says 16.73ly

Estimating Distance

- That was a broken down, step by step way of finding the distance to a star from the magnitudes.
- It is usual to those steps combined into a single formula called the distance modulus formula.
- **$M = m + 5 – 5 \times \log d$**
  - M =absolute magnitude
  - m = apparent magnitude
  - d = distance
- $2.2 = 0.75 + 5 – 5 \times \log d$
- $2.2 = 5.75 – 5 \log d$
- $\log d = (5.75-2.2)/5$
- $d = 10^{(5.75-2.2)/5}$
- d = 5.1286 pc or 16.719 ly

Estimating Distance

- I will now show that my step by step method and the distance modulus formula are the same for all cases, not just Altair.

- **$d \approx 10/\sqrt{\ } 2.512^{(M-m)}$**
- **$d = 10/\sqrt{\ }\ {}^{5}\sqrt{100}^{(M-m)}$**
- When using powers the order isn't important
- **$d = 10/{}^{5}\sqrt{10}^{(M-m)}$**
- **$d = 10/10^{(M-m)/5}$**
- **$\log d = \log 10 - \log 10^{(M-m)/5}$**
- **$\log d = 1 - (M-m)/5$**

- **$M = m + 5 - 5 \times \log d$**
- **$M - m = 5 - 5 \times \log d$**
- **$M - m/5 = 1 - \log d$**
- **$1 - (M-m)/5 = \log d$**

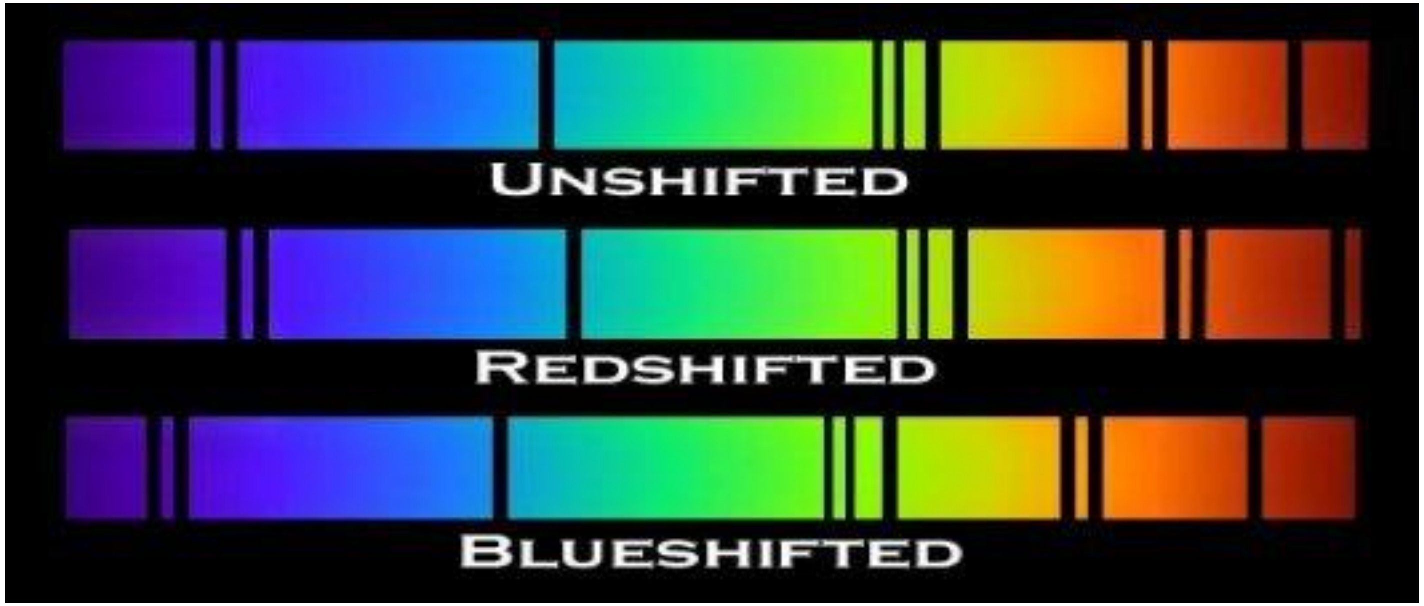
Because we have used symbols, this is now a mathematical proof

Estimating Distance using Redshift

- Which redshift?
  - Doppler Redshift
    - Light behaves like a wave, so light from a luminous object undergoes a Doppler-like shift if the source is moving relative to us.
  - Relativistic Redshift
    - For objects moving at close to the speed of light, time dilation must be taken in into account. Special Relativity
  - Gravitational Redshift
    - Objects in different gravitational fields accelerate a different rates and so experience a redshift. General Relativity.
  - Cosmological Redshift
    - The red shifts observed in distant galaxies etc are not exactly due to the Doppler phenomenon, but are rather a result of the expansion of the Universe.

Estimating Distance using Redshift

The red shift of a distant galaxy or quasar is easily measured by comparing its spectrum with a reference laboratory spectrum. Atomic emission and absorption lines occur at well-known wavelengths. By measuring the location of these lines in astronomical spectra, astronomers can determine the red shift of the receding sources.



As a result of the expansion, at very large redshifts, much of the ultraviolet and visible light from distant sources is shifted into the infrared part of the spectrum. This means that infrared studies can give us much information about the ultraviolet and visible spectra of very young, distant galaxies.

Estimating Distance

- In Summary:
  - We looked at estimation by parallax
  - We defined what a parsec was
  - We estimated how far away Altair was using the parallax angle from Stellarium
  - We saw what could affect the accuracy.
  - We talked about how colour gives rise to temperature and how the radius and temperature give us luminosity.
  - We defined Absolute magnitude and Apparent magnitude as the luminosity at 10pcs and from as viewed from Earth.
  - We used the definition of levels of magnitude to work out the difference in brightness.
  - We then used the inverse square law to find the distance of Altair and reassuringly it is still 16.73 ly from Earth.
  - Finally we had a quick look at using redshift to estimate galactic distances. The details will be left for another discussion.

Thank You