Astronomy

The Nature of Stars

- Distances to stars
- A Star's brightness and Luminosity
- A Magnitude scale
- Color indicates a Star's temperature
- A Star's spectrum reveals Chemical Composition
- The Size of Stars
- H-R Diagrams
- A Star's size and its spectrum
- Binary Stars and their mass
- Binary Stars in close orbits
- Eclipsing Binary and Star Size

http://physics.wm.edu/~hancock/171/
Measuring Stars
Measuring astronomical distances

For measuring distances to 'near by' stars, parallax is used. The ancients astronomers looked for parallax shifts of stars. They found nothing and could only conclude that stars are very far away. The first successful measurement of a stellar parallax was by Friedrich Bessel in 1838 for the star 61 Cygni.
Parallax is the apparent shift of an object because of a change in the observer's position. To measure parallax, astronomers use the largest shift of their position they can, namely the position of the Earth on opposite sides of its orbit like from January to July.
Parallax

We define the “parsec” or “pc” as the distance that causes 1 arcsec of parallax. One arcsecond is the size of a penny at 2.5 miles!

\[ 1\text{pc} = 3.26 \text{ ly} \]
\[ 1\text{pc} = 3.09 \times 10^{13} \text{ km} \]
\[ 1\text{pc} = 2.06 \times 10^5 \text{ AU} \]

- We can then use a measured parallax to find distance
  - The measured parallax \( (p) \) should be given in arc seconds
  - The distance of an object \( (d) \) is then given in parsec or pc

\[ d_{\text{pc}} = \frac{1}{p_{\text{arc sec}}} \]
Example: distance to the closest star

- Proxima Centauri
  - $p = 0.772$ arc seconds
  - $d = \frac{1}{0.772}$ pc $= 1.30$ pc
- This is a very convenient unit for stellar distances
  - Can measure parallax up to about 500 pc
  - That’s $0.002$ arc seconds (width of a hair at 2.5 mi)
- Astronomers normally use parsecs (not light years for distances).
- We have measured parallax for $>100,000$ stars. The ESA Hipparcos satellite measured parallaxes as small as $0.001$ arcseconds.
Luminosity, Apparent Brightness and the Inverse Square law

- **Luminosity** is the total amount of light energy emitted per second. The units are Watts (Joules/second). The luminosity of the Sun is $3.0 \times 10^{26}$ W.

- **Brightness** is the total light energy that passes through 1 m$^2$ per second. The units are W/m$^2$. Since the area of a sphere is $4\pi r^2$. The brightness of a star is then the luminosity divided by the surface area of the star.

- **Apparent Brightness** is the light energy that passes through 1 m$^2$ at some distance from a star. It is the rate that light energy gets to the observer. The relationship between apparent brightness and luminosity is called the inverse square law:

$$b = \frac{L}{4\pi d^2}$$
The Inverse square law

With greater distance from the star, its light is spread over a larger area and it appears dimmer.

The inverse square law is a geometrical effect that occurs in lots of situations. The light spreads out, it expands in both the horizontal and vertical. If you double your distance from a light source, the energy over 1 m\(^2\) decreases by a factor of 4. Triple the distance and it goes down by a factor of 9.
Luminosity of Stars

What an astronomer measures is the apparent brightness (photometry). We can find the luminosity of a star if we know its distance and apparent brightness. If we rearrange the inverse square law to:

$$L = 4\pi d^2 b$$

From the earth, the Sun's brightness ($b_\odot = 1370 \text{ W/m}^2$) and distance are known. If we take a ratio with a star's apparent brightness and cancel the $4\pi$'s:

$$\frac{L}{L_\odot} = \left(\frac{d}{d_\odot}\right)^2 \frac{b}{b_\odot}$$

If we know $b$ and $d$, we can solve for the stars luminosity ($L$). Compared to the Sun, stars have a wide range of luminosities.
For stars within a 1000 pc$^3$ volume, stars have a large range of luminosity from $10^{-4}$ L$\odot$ to 10L$\odot$. What is the 'Absolute Magnitude' horizontal scale?
Astronomers use a scale going back to Hipparchus. Absolute magnitude is the luminosity of a star if it were located at 10 pc. The Sun at 10 pc has an absolute magnitude of 4.8. Note: larger positive magnitudes are dimmer stars. The relationship between apparent (m) and absolute (M) magnitude is:

\[ m - M = 5 \log d - 5 \]

Where \( d \) is the distance to the star.
Wein's law tells us how the most common wavelength (color) is related to the star's surface temperature. Astronomers use filters to determine the color (and thus temperature of a star). The filters transmit different wavelengths. The filters are normally referred to as U (ultraviolet), B (blue) and V (visible). Using this three standard filters, the peak wavelength can be determined.
By taking the ratios of the brightness of stars with the standard filters \( b_V/b_B \) or \( b_B/b_U \), the temperature of the star can be determined.
Spectroscopy of Stars

A cold cloud of gas with a star behind the gas show the elements of the gas from their absorption spectra. A star shows a continuous spectrum (a blackbody spectrum) with absorption lines of the elements in the outer atmosphere of the star. Hydrogen Balmer spectral lines are prominent in the spectra of some starts and not in other. Other heavier elements such as helium, calcium, sodium and iron are present especially in stars that don't have prominent hydrogen Balmer lines. Because of the diversity of spectral lines from stars, astronomers in the 1800s started to classify stars by their spectral type or 'spectral class'.

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In 1872, the Harvard College Observatory started a project to classify the spectra of stars. The tedious work was primarily done by women (at low wages!). In 1918 and updated in 1924, the Harvard project published the results of 225,300 stars. The stars were classified according to their spectral class as OBAFGKM. In 1925, Celicia Payne (one of the first women to earn a Ph.d in astronomy) showed that the spectral classes were actually directly related to the surface temperature of stars.
The meaning of the letters OBAFGKM are shown in the table above. In 1995, the L, T and Y classes were added for stars with very low surface temperature (brown dwarfs). The coolest has a temperature of 285 K (80 F).
The main types of stellar spectra and the dominate spectral lines. More recently each of the main types has been divided into 10 subdivisions (zero through 9) such as G5.
Each element has a characteristic temperature range where the element produces a prominent spectra lines. For example, He I (un-ionized Helium) peaks at B0.
The Size of a Star

We know a star is a blackbody and that the luminosity is given by the Stefan-Boltzmann law:

\[ L = 4\pi R^2 \sigma T^4 \]

Where \( R \) is the radius, \( \sigma \) is a constant \( (5.67 \times 10^{-8} \text{ W m}^{-2} \text{ K}^{-4}) \) and \( L \) is the luminosity. We discussed earlier how the luminosity of a star can be measured. If the temperature is known from the star's spectral class, the radius of the star can be determined. Using a ratio of luminosities of the Sun and star and solving for the ratio of \( R \) and \( R_\odot \) we have:

\[
\frac{R}{R_\odot} = \left(\frac{T_\odot}{T}\right)^2 \sqrt{\frac{L}{L_\odot}}
\]
Given the distance to a star from a parallax measurement and the spectral type, the size (radius) of a star can be determined. With a few exceptions like Betelgeuse, the radius of a star is not known from direct observation with a telescope. Using the temperature and luminosity method, the radius of a white dwarf can be determine. The radius of a white dwarf is about the same as that of the Earth.
In the early 1900's, Hertzsprung and independently Russell discovered a pattern when the surface temperature and luminosity of stars are plotted. This diagrams are now know as H-R diagram. Most stars (90%) are on the red curve known as the main sequence. Bright stars are near the top. Cooler stars are on the right.
When the size of stars are plotted, we can see the areas in the upper right are very large stars (giants and super giants). Small stars like white dwarfs are in the lower center region. Our Sun is a very typical main sequence star.
Large stars and small stars can have the same temperature. The spectra of two B8 stars (one a supergiant and one a main sequence) are show. The H lines of the supergiant are narrow while the main sequence star are broad. In the supergiant, the atmosphere is less dense and the lines are not collision broadened. In the main sequence star the denser atmosphere broadens the H lines.
In 1938, Morgan and Keenan developed the luminosity classification. Luminosity classes are identified with roman numerals. Knowing the luminosity class and spectral class the luminosity of the star can be determined. If the stars apparent brightness is measure using photometry, the inverse square law give the distance to the star. This is called spectroscopic parallax but it has nothing to do with measuring a parallax angle. This is very powerful but only gives distance correct to $\sim 10\%$.

Figure 17-18

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Binary Stars

Stars that lie near one another from the Earth's viewpoint are called double stars. Optical double stars are stars that are two stars that are far apart but lie along the same line of sight from the Earth. Many double stars are two stars in orbit around one another. When we can actually see the two stars orbiting, these are called visual binary stars. The total mass of both stars in a binary system can be determined using Kepler's law:

$$M_1 + M_2 = \frac{a^3}{p^2}$$
To use Kepler's law, you need distance to the system and the angular separation of the stars to determine a (semimajor axis). The period is determined by watching how long it takes for one orbit (10 years in this case).
Knowing $p$ and $a$, Kepler's law gives the sum of the masses. By plotting the orbits of the two stars, the center of mass of the system (CM) can be determined. The CM lies at the common focus of the two elliptical orbits. This determines $M_1/M_2$. Given $M_1 + M_2$ from Kepler's law, the individual mass can be found.
Knowing the mass of main sequence stars shows an important relationship to luminosity. If the mass and luminosity are plotted, there is clear connection between mass and luminosity. Note the 'log' scale on the vertical axis. If the luminosity of a star is known, the mass can be found.
Mass and Temperature

For main sequence stars, the mass-luminosity relation and the H-R diagram give an immediate connection of the mass of a star and its temperature. The bigger the star the hotter. Smaller stars are cooler.

This relationship is because of the hydrostatic and thermal equilibrium of the nuclear fusion process. Bigger stars are more luminous (more fusion) and hotter. Models show a star must be $0.08M_\odot$ for fusion to start in the star's core.
If the stars are too far away or too near to one another to resolve the individual stars, spectroscopic methods can be used. As the stars orbit one another, the Doppler shift of spectral lines of the individual stars give the velocity of the individual star. This is the velocity along the line of sight so a binary system should be edge-on for this method to work.
Spectroscopic Binary Stars

The radial velocity curve shows the period. From the radial velocity curve, the ratio of masses can be determined. The sum of the masses is determined from the orbital speeds of the two stars. This information allows the masses to be found. Unfortunately, the tilt of the system from the Earth's viewpoint makes the masses uncertain for a spectroscopic binary.
Sometimes we see a binary star system where the stars eclipse one another. As the light curves show, the light curves give different information. The period is clear in a partial, total or tidal eclipse. As one star moves behind the other, information about the stellar atmosphere can be deduced. The ratio of the surface temperature can be found. How the light is cut off can give the radius of the stars.
In this image a dimmer M6 main sequence star passes in front of a brighter white dwarf. The binary seems to almost disappear.