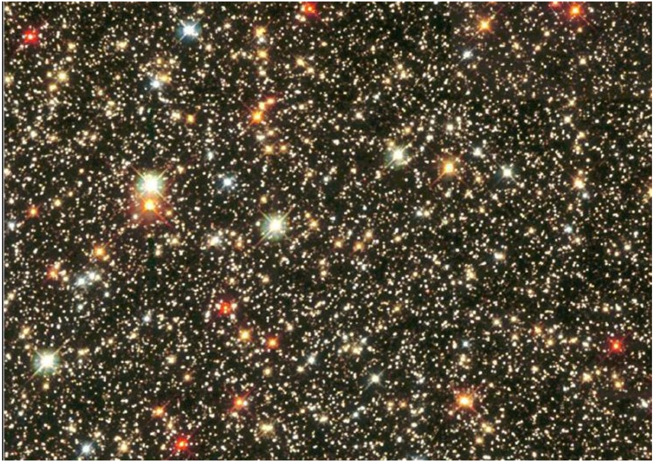
Stars

- We have discussed some aspects of the lives of stars in previous lectures. We've also talked about how we can find things out about stars, from their spectra. In the next couple of lectures we'll talk about what we know about stars.
- How are they born?
- How do they live?
- How do they die?

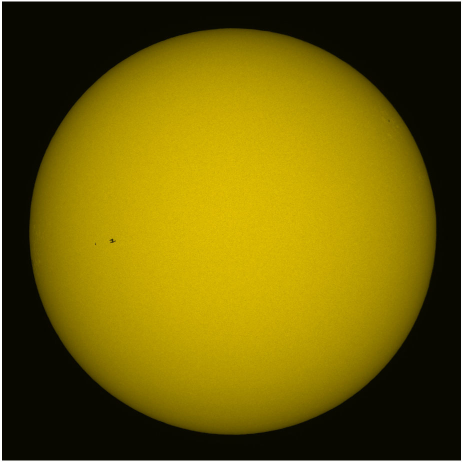
Stars

- Stars come in a huge range of masses, luminosities and colours:



Stars

- The easiest star to study is the closest one: the Sun.

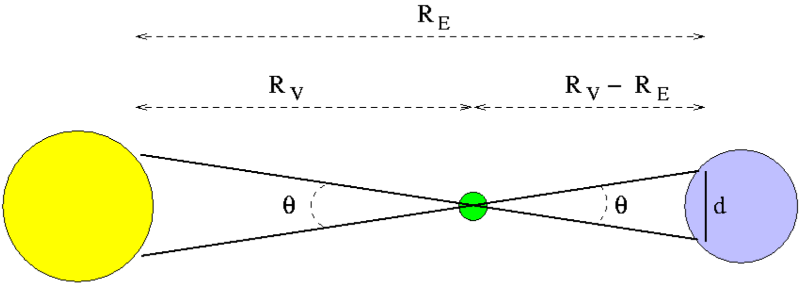


The Sun

- Note that the small dark patch is not a sunspot:

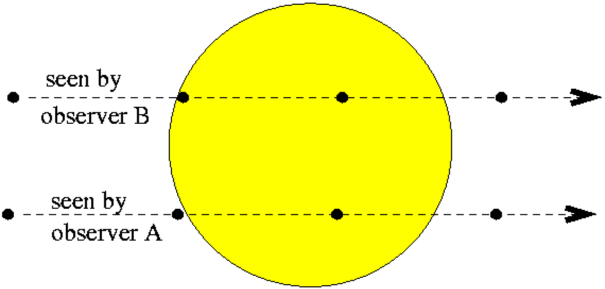
The distance to the Sun

- How far away is the Sun? This question was first answered accurately in the 1700s. Captain Cook led an expedition to Tahiti, which had only just been discovered, to observe a transit of Venus.
- By observing a transit from two different locations on the Earth's surface, you can work out the distance to the Sun.



The distance to the Sun

- The path of Venus across the Sun is different depending on the location.
- The distance derived from data collected during Cook's expedition was very close to the modern accepted value. On average, the distance from the Earth to the Sun is 149,598,000 km.



The luminosity of the Sun

- From its distance, and the Earth's orbit, we can work out the mass of the Sun – it is 2×10^{30} kg. And knowing the distance, we can work out the Sun's luminosity.
- The Sun emits a lot of energy: 3.89×10^{26} J/s. Total amount of energy used by humans since 1980 is 1.2×10^{22}J - enough to keep the Sun going for 0.00003 seconds!
- One of the most fundamental questions about the Sun is, how does it produce this energy?

The luminosity of the Sun

- Combustion? Burning fuel releases heat and light, through chemical reactions.

The luminosity of the Sun

- These reactions release $\sim 10^{-19}$ J per atom, so to produce a luminosity of 3.89×10^{26} W would require that $3.89\times10^{26}/\ 10^{-19}$ = 3.89×10^{45} atoms per second be reacting.
- The Sun contains about 10^{57} atoms.

$$
\begin{aligned}
\text{Lifetime of Sun} &= \frac{\text{number of atoms in Sun}}{\text{rate at which atoms react}} \\
&= \frac{10^{57}}{3.89 \times 10^{45}} \\
&= 3 \times 10^{11}\,\text{s}\ (10,000\ \text{years})
\end{aligned}
$$

The luminosity of the sun

- Archbishop Ussher - Earth formed on 23 October, 4004 BC
- More commonly accepted value - Earth formed about 4.5 billion years ago
- Combustion cannot be the source of the Sun's power

The luminosity of the Sun

- Gravitational contraction? If the Sun were contracting under its own gravity, this contraction would release energy. This idea was proposed by Lord Kelvin and Hermann von Helmholtz.
- Helmholtz's calculations showed that the contraction could have started at most 25 million years ago.
- Better than combustion, but still not long enough

The luminosity of the Sun

- How do we know how old the Earth is? Estimate its age from the decay of radioactive materials. If we know the half life of a radioactive element, and its initial concentration, we can determine the age of a sample containing the element.
- Oldest rocks known on Earth are about 3.8 billion years old. Meteorites are up to 4.54 billion years old.

The luminosity of the Sun

- The actual answer wasn't arrived at until the 1950s. The first clue came from Einstein's Special Theory of Relativity, which showed that mass could be converted into huge amounts of energy:
- $E = mc^2$

The luminosity of the Sun

- The core of the Sun must be extremely hot and dense, because of the extreme pressure it is under. In these conditions, all the electrons are stripped away from the nuclei of the atoms.
- The density and temperature are such that the atomic nuclei, instead of being repelled (as they are all positively charged), can collide and fuse – nuclear fusion.
- The Sun is mostly hydrogen. If the temperature and density in its core are high enough, four hydrogen atoms can combine to form one helium atom.

The luminosity of the Sun

- A helium atom is slightly lighter than four hydrogen atoms, so some energy is released.

$$\begin{aligned} M_H &= 1.673 \times 10^{-27} kg \\ M_{He} &= 6.645 \times 10^{-27} kg \\ (4 \times M_H) - M_{He} &= 0.048 \times 10^{-27} kg \end{aligned}$$

$$\begin{aligned} E &= mc^2 \\ &= 0.048 \times 10^{-27} \times (3 \times 10^8)^2 \\ &= 4.3 \times 10^{-12} J \end{aligned}$$

- This is 10 million times as efficient as combustion!

The lifetime of the Sun

- To maintain its luminosity through nuclear fusion, the Sun needs to fuse hydrogen atoms at a rate of

$$4 \times \frac{3.89 \times 10^{26}}{4.3 \times 10^{-12}} = 3.6 \times 10^{38}$$

- It started off containing about 10^{57} hydrogen atoms. About ten percent of these atoms are in the core, where fusion happens. So its lifetime is given by

$$\frac{10^{56}}{3.6 \times 10^{38}} = 3 \times 10^{18} s$$

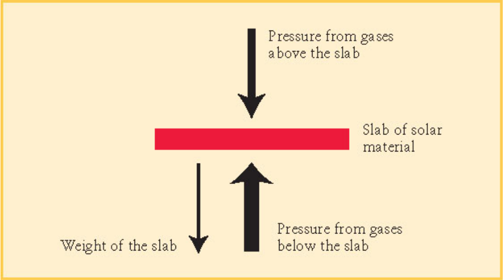
- That's almost 10 billion years.

The lifetime of the Sun

- The Sun's luminosity is powered by the annihilation of 4.3×10^9kg of matter every second.
- This is not really very much - slightly less than the mass of the Great Pyramid of Giza

The core of the Sun

- The Sun is neither contracting nor expanding. It is in a steady state, known as hydrostatic equilbrium.
- What this means is that there is a balance between the forces acting on each part of the Sun:



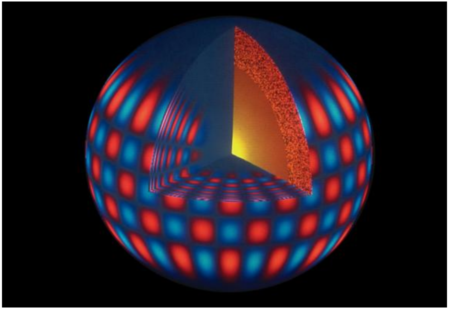
(a) Material inside the sun is in hydrostatic equilibrium, so forces balance

The core of the Sun

- Because the Sun is so dense, an individual photon emitted at the core is scattered, absorbed and re-emitted so often that its energy takes thousands of years to reach the surface.
- The photons finally emitted at the surface don't tell us anything directly about the core. We have to observe things other than photons.

The core of the Sun

- One technique is helioseismology – observing the vibrations of the Sun's surface, caused by waves travelling throughout its volume.



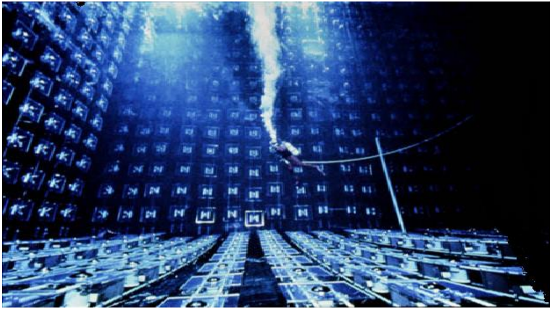
- Just as the waves from earthquakes tell us about the Earth's interior as they travel through it, the way that waves travel through the Sun tells us about its interior.

The core of the Sun

- Another thing you can observe from the Sun is *neutrinos*. These are a type of fundamental particle produced in the nuclear fusion reactions. They hardly ever interact with matter – about 50 trillion are passing through each of us every second.
- The fact that they almost never interact with matter is good, because it means that a neutrino produced in the core of the Sun can reach Earth directly from there.
- But it's bad because it makes them extremely difficult to detect.

The core of the Sun

- One way is to bury a large amount of extremely pure water deep underground (to avoid cosmic rays), and to surround it by sensitive cameras.
- Every once in a while, a neutrino will strike an atom, and a flash of light will be emitted. The direction of the light flash tells you where the neutrino came from.

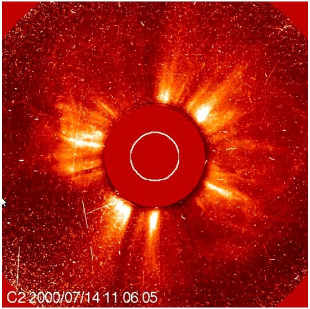


The Solar Neutrino Problem

- Early experiments detected neutrinos coming from the Sun, but only at about a third of the rate predicted by theory.
- This was a problem for a long time, and many theories were advanced to explain it. Was the Sun's core cooler than expected? Could there be a lot of neutrinos with energies too low to be detected?
- The answer turns out to be that there are three different kinds of neutrinos. All the neutrinos produced in the Sun are of one type, but neutrinos can change between types.
- Early experiments only detected one type of neutrino.

The Solar Cycle

- Although the Sun is the closest star to us, much about it is not yet understood. For example, its 11 year cycle - lots of *sunspots*, *flares* and *coronal mass ejections* at maximum, few at minimum.

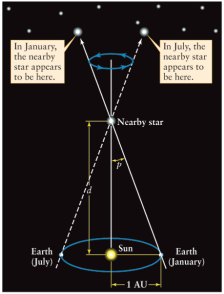


The Solar Cycle

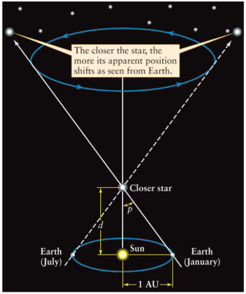
- When there are few sunspots, solar activity is low – and temperatures on Earth tend to be colder.
- For reasons that have yet to be understood, the Solar Cycle stopped entirely in the 17th century. Virtually no sunspots at all were seen for about a century. This coincided with the Little Ice Age in Europe, and Frost Fairs on the Thames.
- The Sun can be an important driver of the Earth's climate. (but currently, the changing composition of the Earth's atmosphere is a much bigger factor)

Stars – apparent motions

- So that's a brief overview of the closest star. Other stars are more difficult to study, because they are much further away.
- How can we measure their distances? For the closest stars, we can measure their parallax – the change in their apparent position due to the motion of the Earth around the Sun:



(a) Parallax of a nearby star



(b) Parallax of an even closer star

Stars – apparent motions

- Remember the definition of a parsec – an object at a distance of one parsec that was one Astronomical Unit across would appear to be one arcsecond across.
- By the same definition, a star at a distance of 1 parsec would have a parallax of one arcsecond. A star at a distance of 2 parsecs would have a parallax of 0.5 arcsecond.
- So, measure the parallax, and you know the distance.
- The closest star, Proxima Centauri, has a parallax of 0.772 arcseconds. So, its distance is 1.3 pc (4.2 light years).

Stars – apparent motions

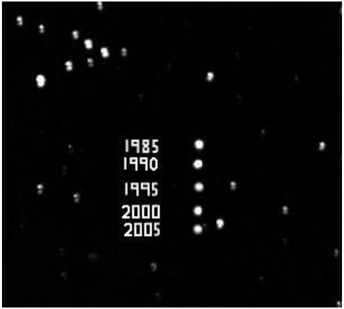
- Parallax is the fundamental basis of all astronomical distances. It is limited in scope to fairly nearby stars, but we base our whole understanding of cosmic distances on what we find out from the closest stars with directly measured distances.
- The HIPPARCOS satellite measured stellar positions to an accuracy of 0.001 arcseconds, so the current limit of parallax measurements is about 1000 parsecs.

Stars – actual motions

- Parallax is an apparent motion, caused by the Earth orbiting the Sun. Stars are also moving through space. This means their positions relative to each other slowly change.
- We can measure the velocity of a star along the line of sight from the Doppler effect. Over enough years, for a close enough star, we can see its motion in the plane of the sky. This is called proper motion.

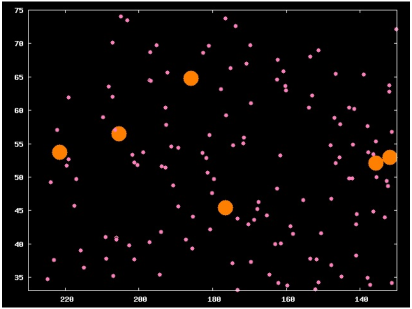
Stars – actual motions

- Barnard's Star has the largest proper motion of any star.



Stars – actual motions

- Over tens of thousands of years, all of today's constellations will eventually become unrecognisable.



Stars – actual motions

- If you know the line-of-sight velocity (from the Doppler effect) and a plane-of-the-sky velocity (from the proper motion and distance), you can work out the velocity of the star relative to the Sun.
- Eg, if a star's proper motion means it is moving at 100km/s across the line of sight, and its spectrum tells us it is moving at 200km/s along the line of sight, its total velocity is given by

$$\begin{aligned} v^2 &= v_{los}^2 + v_{pos}^2 \\ &= 100^2 + 200^2 \\ &= 50000 \\ v &= 50000^{\frac{1}{2}} \\ &= 23km/s \end{aligned}$$

Stars – luminosities

- From a star's parallax, we can determine its distance. Once we know its distance, we can determine its luminosity, from the so-called inverse square law:
- $b = L/4\pi d^2$
- This means that if you had two objects with the same luminosity, one twice as far away as the other, the more distant one would appear a quarter as bright as the nearer one.

Stars – magnitudes

- The brightness of stars is often expressed in *magnitudes*. This is a scale which ultimately comes from ancient Greek astronomy – Hipparchus classified stars roughly so that the brightest were called 'first magnitude' and the faintest 'sixth magnitude'.
- In the 19th century, the system was refined and updated. Astronomers calculated that first magnitude stars were about 100 times brighter than sixth magnitudes, and set the magnitude scale so that a difference of five magnitudes means a factor of 100 change in brightness.
- 1 magnitude then corresponds to a factor of 2.512 in brightness.
- $2.512 \times 2.152 \times 2.512 \times 2.512 \times 2.512 = 100$

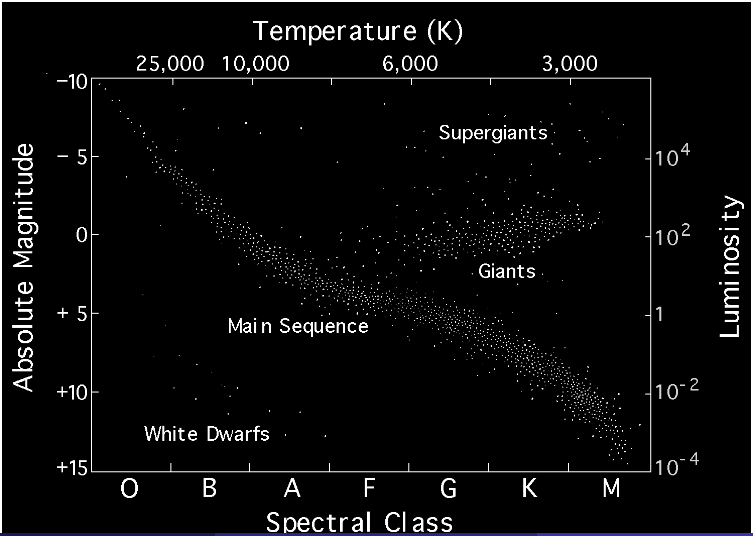
Stars – magnitudes

- In the refined scale, the brightest stars are actually brighter than magnitude 1. Sirius has an apparent magnitude of -1.43.
- The faintest objects that have ever been detected have apparent magnitudes of about 30. $2.512^{31.5}$ = 4 trillion times fainter than Sirius.
- That's about as bright as a cigarette end on the moon would appear to someone on Earth.

Stars- the Hertzsprung-Russell diagram

- We talked in previous lectures about how to measure the temperatures of stars. For all the stars that are close enough to have a luminosity measured, if you plot a graph of their luminosity against their temperature, you find that they are not just scattered randomly, but concentrated in certain areas.

Stars- the Hertzsprung-Russell diagram



Stars - the Hertzsprung-Russell diagram

- This diagram is called the Hertzsprung-Russell diagram (HR diagram for short), after the two astronomers who first developed it in the early 20th century.
- Most stars fall in a band running from top left to bottom right. This is called the *main sequence*. The Sun lies on the main sequence. It and all the other stars on it are in a steady state – they are burning hydrogen at their cores, and the energy released supports them against gravitational contraction.
- The position of a star on the main sequence is determined by its mass. Heavier stars are more luminous and hotter, and so they appear further up to the left.

Stars - the Hertzsprung-Russell diagram

- Most stars that you can see are on the main sequence. One that is not is Betelgeuse. It is both very cool and very luminous, and so it lies way off the main sequence in the supergiant region.

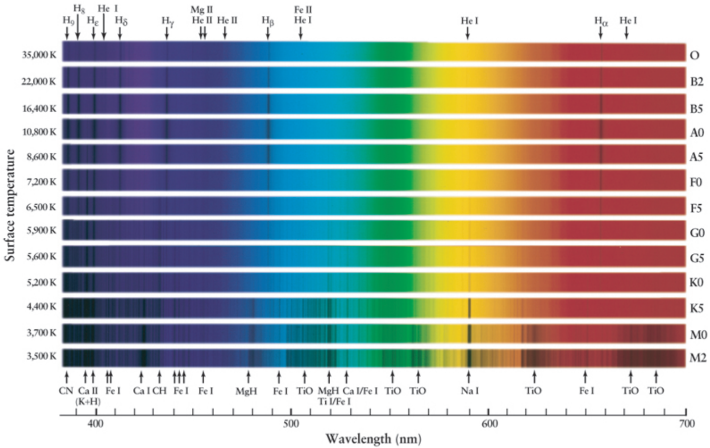
Distances from the Hertzsprung-Russell diagram

- We can estimate stellar distances using the HR diagram. We can measure the temperature of a star from its spectrum, and if we know (or assume) that it is on the main sequence, then we can find out its luminosity. Then, from its luminosity and apparent brightness, we can calculate its distance.

Stellar spectra

- The shape of a star's spectrum is one way to obtain an estimate of its temperature. Another way is by looking at lines in the stellar spectrum. We saw ealier that each element has a distinct spectral 'fingerprint', and you can see a lot of lines in the spectrum of the Sun.
- It turns out that in stars that are hotter and cooler, different sets of lines are seen. The spectral lines that are seen are another way to estimate temperatures.

Stellar spectra



Spectral types

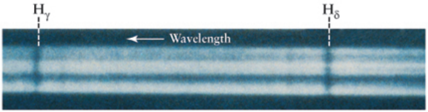
- Stars are classified according to the spectral lines seen into types O, B, A, F, G, K, M. O stars are hottest, M stars are coolest.
- The apparently random lettering scheme is yet another accident of history. The scheme was developed before the relationship between spectral type and temperature was understood.
- A stars have the strongest hydrogen lines, then B stars, etc. The classification scheme used to run from A to Q, but later schemes dropped all the letters except OBAFGKM.

Spectral types

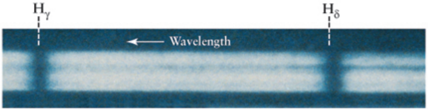
- Curious fact of history – at a time when women in science were very rare, most of the pioneering work on stellar classification was done by women. Annie Cannon played a major role in developing the modern classification scheme while at Harvard, and personally classified 230,000 stars!
- Offsetting the progressiveness of employing women in astronomy was the much lower wage they received compared to male colleagues...

Spectral types

- Any star with a temperature of 10,000K will have a similar spectrum in terms of the lines that are present.
- But the width of the lines will be different, depending on whether the star is a dwarf, giant or supergiant.



(a) A supergiant star has a low-density, low-pressure atmosphere: its spectrum has narrow absorption lines



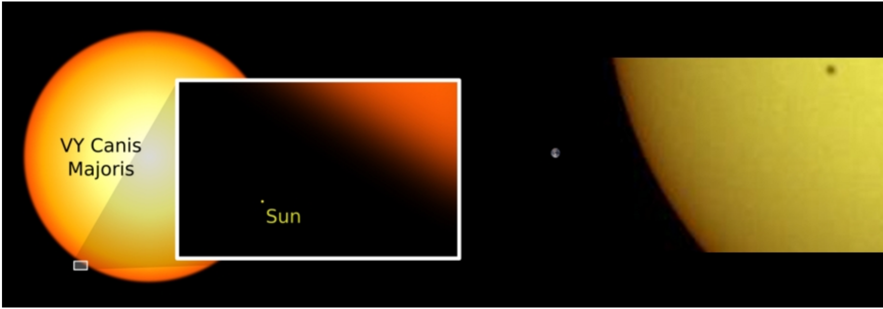
(b) A main-sequence star has a denser, higher-pressure atmosphere: its spectrum has broad absorption lines

Stars – sizes

- We learned earlier that the luminosity of a star is related to its temperature and radius:
- $L = 4\pi R^2 T^4$
- So, given that we can find out the temperatures of stars and their luminosities, we can also find out their radii. There turns out to be a very large range. The largest stars are bigger than Earth's orbit, while the smallest are only a few kilometres across.

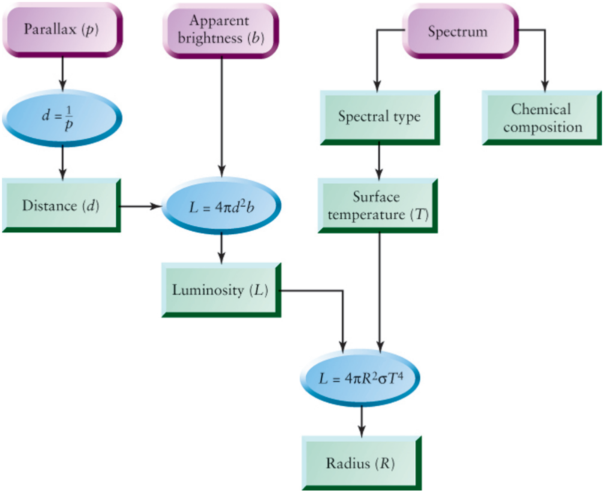
Stars – sizes

- The largest known star is VY Canis Majoris



Stars – (almost) the whole picture

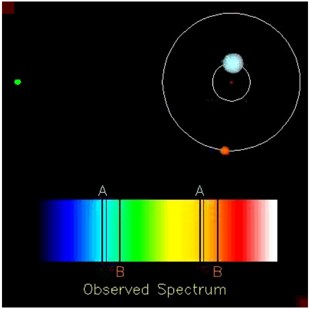
- This diagram summarises how we find out about stars:



Stars – masses

- For a single isolated star, the mass is very difficult to determine
- Luckily, there are many *binary stars* – stars which are orbiting each other. From their orbital motions, we can determine their masses.

- If we can resolve the two components of a binary system, it is called a *visual binary*. Often, the two stars are too close to be resolved, but you can tell there are two stars there if you look at the spectrum, and see two sets of spectral lines.

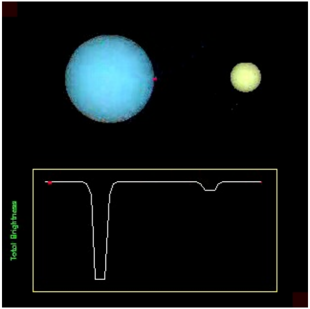


Stars – masses

- The difficulty with binaries is that normally, we don't know how the plane of the orbit is orientated. This complicates the determination of masses.
- For this reason, *eclipsing binaries* are very useful. These are binary stars where once per orbit, one star passes in front of the other as seen from Earth. Thus, we know that the plane of the orbit is edge-on to the line of sight.
- The most famous eclipsing binary is Algol (named from Arabic – the ghoul). Algol fades from magnitude 2.1 to magnitude 3.4 every two days, 20 hours and 49 minutes.

Stars – masses

- There is also a *secondary eclipse*, when the fainter star is hidden.



Stars – masses

- The heavier a star, the denser and hotter its core, and the more vigorous the nuclear reactions that power it. Hence, the brighter it is and the hotter its surface.
- Hotter gases expand, so hotter stars are larger.