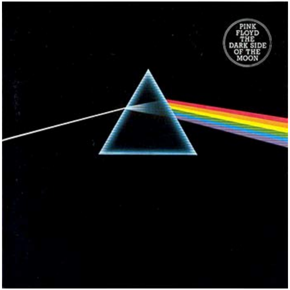
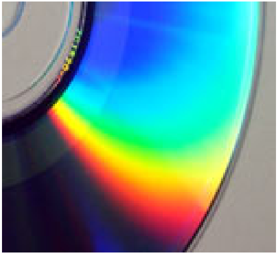
Spectrographs

- We've talked a lot about spectra, but not said anything yet about how they are obtained.
- Newton did a little bit of early spectroscopy, using prisms. But prisms have some of the same inherent disadvantages as refracting telescopes - they absorb light and need to be of very high quality.



Spectrographs

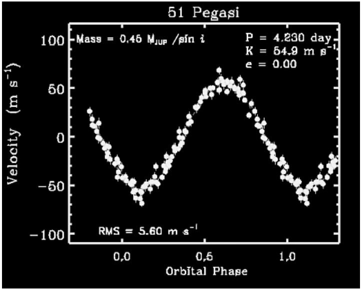
- A better way is to use *gratings*. You can see how gratings work if you hold a CD or DVD at an angle to a source of light. The fine rulings on the surface reflect and *diffract* the light, and different wavelengths are diffracted by different amounts.



- Gratings can disperse the light much much more than prisms can, so you can study objects in much more fine detail.

Spectrographs

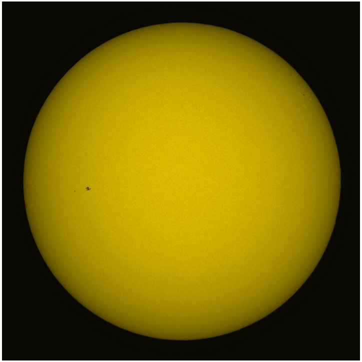
- There is always a trade-off with spectrographs. The more you disperse the light, the longer your exposure needs to be to detect it.
- Ultra-high resolution spectroscopy can detect motions equivalent to walking pace from the Doppler effect.
- The first extra-solar planet was discovered with a spectrograph that could measure velocities of 7m/s - about the speed of a runner on a four minute mile.



Stars

What is a star?

- Astronomers since ancient times hypothesised that the stars in the night sky were the same type of object as our Sun, but very far away.
- The Sun and all the stars are huge spheres of gas, which shine with their own light.



What is a star?

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

Magnitudes

- The brightness of stars is often expressed in *magnitudes*.
- In ∼135BC, Hipparchus classified stars so that the brightest were called ’first magnitude’ and the faintest ’sixth magnitude’.
- In the 19th century, 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.
- Each step on the scale then corresponds to a factor of 2.512 in brightness.
- $2.512 \times 2.152 \times 2.512 \times 2.512 \times 2.512 = 100$

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.

Apparent magnitudes

- These magnitudes are **apparent magnitudes.** They allow us to compare the brightnesses of stars as seen from Earth.

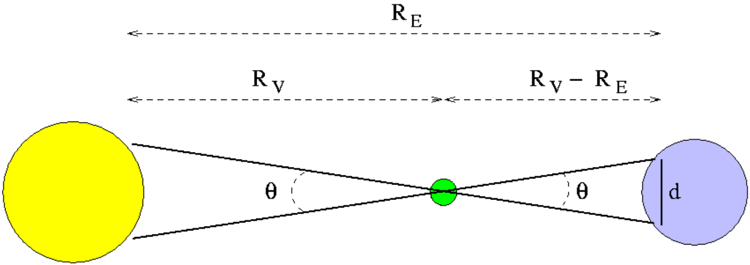
- The magnitude of Sirius is -1.47; Canopus is -0.72. But Canopus is actually more than 500 times brighter than Sirius.

Absolute magnitudes

- The **absolute magnitude** of a star is the apparent magnitude it would have, if it was 10 parsecs away from Earth.
- The absolute magnitude of the Sun is about +4.5. Sirius's is 1.42; Canopus is -5.5. Alnilam (middle star of Orion's Belt) is -9.2 - it emits as much energy in a minute and a half as the Sun does in a year.

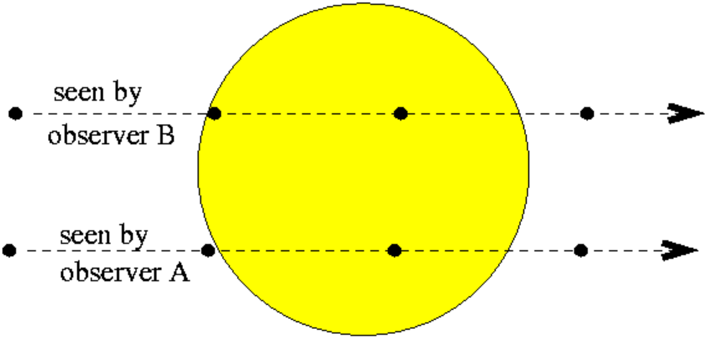
How far away are stars?

- 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.



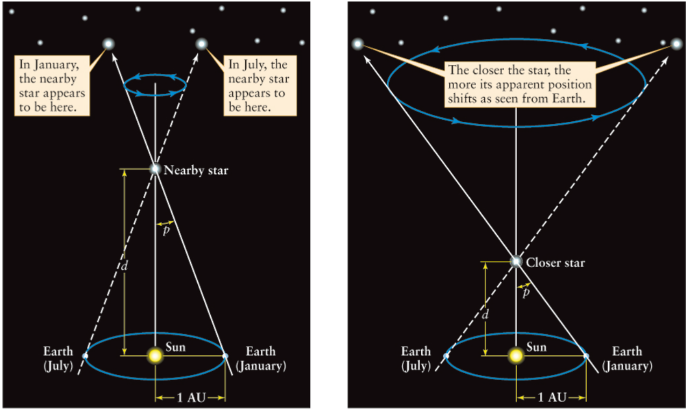
How far away are stars?

- 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.



How far away are stars?

- How can we measure the distances to other stars? 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

How far away are stars?

- 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).

How far away are stars?

- 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.

How stars shine

- 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?

How stars shine

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

- This could power the Sun for about 10,000 years

How stars shine

- 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.

How stars shine

- Oldest rocks known on Earth are about 3.8 billion years old. Meteorites are up to 4.54 billion years old. Other solar system bodies are similarly ancient. So, Sun must have been shining for at least that long.

How stars shine

- Einstein's Special Theory of Relativity showed that mass could be converted into huge amounts of energy:
- $E = mc^2$

How stars shine

- 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.

How stars shine

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

$$\begin{aligned}
\texttt{Mass of 4 H atoms} &= 6.692 \times 10^{-27} kg \\
\texttt{Mass of 1 He atom} &= 6.645 \times 10^{-27} kg \\
(4 \times M_H) - M_{He} &= 0.047 \times 10^{-27} kg
\end{aligned}$$

$$\begin{aligned}
E &= mc^2 \\
&= 0.047 \times 10^{-27} \times (3 \times 10^8)^2 \\
&= 4.3 \times 10^{-12} J
\end{aligned}$$

- 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

How stars move in space

- The stars are moving through space. This means their positions relative to each other slowly change.
- Over enough years, for a close enough star, we can see its motion in the plane of the sky. This is called proper motion.

How stars move in space

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

Animation - available in screen version

How stars move in space

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

Animation - available in screen version

How stars move in space

- 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

$$\begin{aligned} v^2 &= v_{los}^2 + v_{pos}^2 \\ &= 100^2 + 200^2 \\ &= 50000 \\ v &= 50000^{\frac{1}{2}} \\ &= 223 km/s \end{aligned}$$

Luminosities

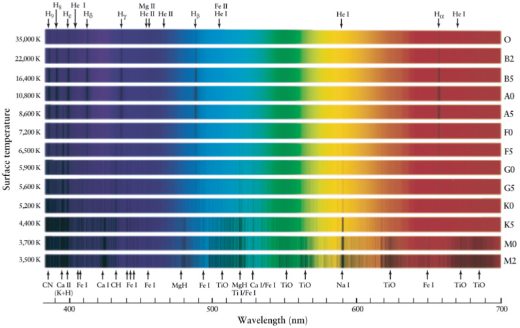
- From a star's parallax, we can determine its distance. Once we know its distance, we can determine its luminosity, from the so-called inverse square law:

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

- 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.

Spectral types

- Hipparchos classified the stars according to brightness. Much later, in the 1860s, Angelo Secchi classified them in a different way
- He looked at their spectra, and found that they showed great variation.



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.
- O stars are the hottest (20-40,000 K), and M stars are the coolest (2-3,000 K)

Spectral types

- Curious fact of history – at a time when women in science were very rare, much 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...

The Hertzsprung-Russell diagram

- An amazing tool in understanding stars is the **Hertzsprung-Russell diagram** (named after Einar Hertzspring and Henry Norris Russell).
- To create an HR diagram, all you have to do is sort stars by their spectral type or temperature, and then by their absolute magnitude.
- When you plot a graph of the luminosity of stars against their temperature, you find that they are not scattered randomly but are concentrated in certain areas.

The Hertzsprung-Russell diagram

Animation - available in screen version

The Hertzsprung-Russell diagram

- 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.

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.