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?

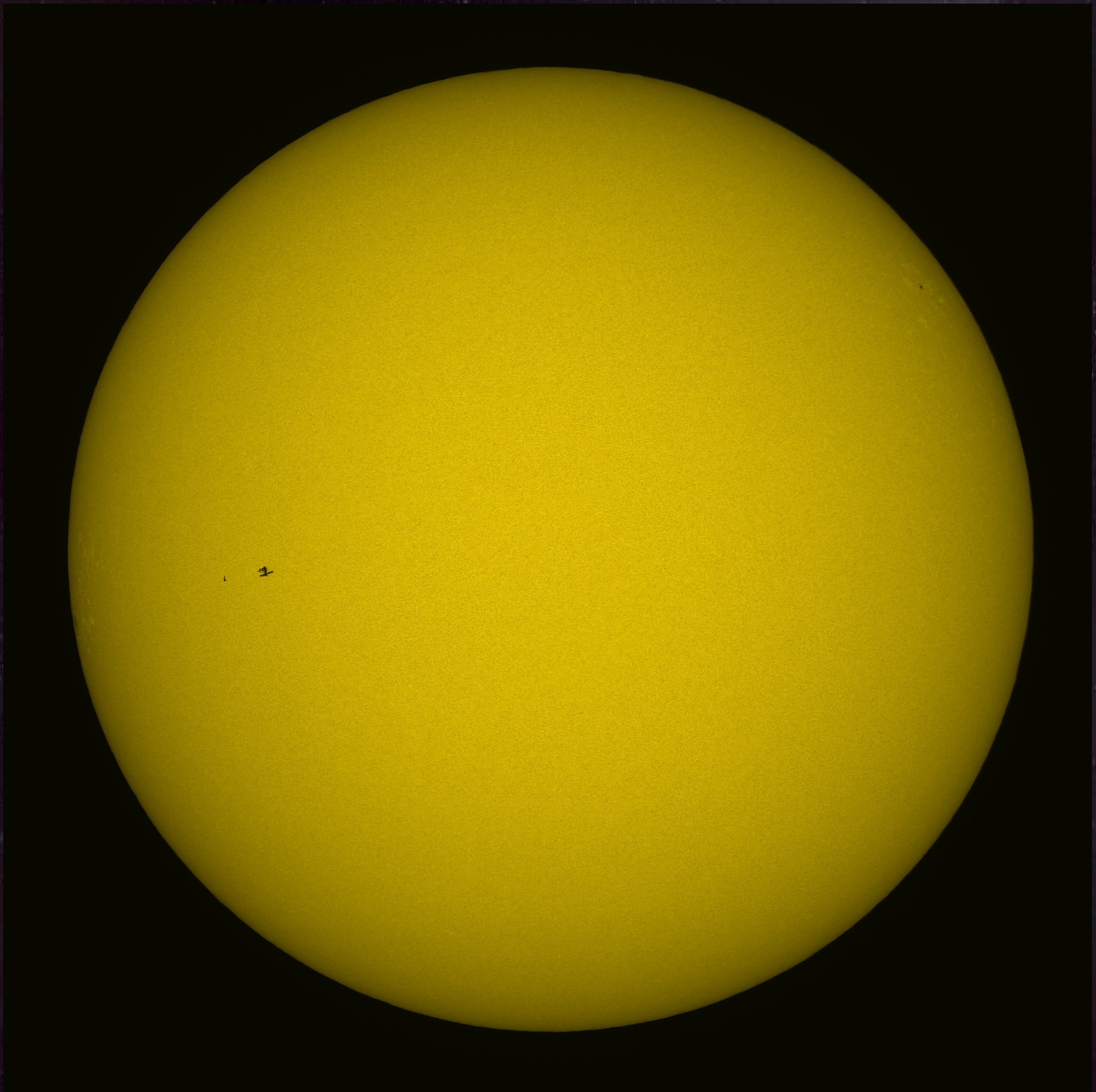
How do they die?

Stars

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

Stars

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



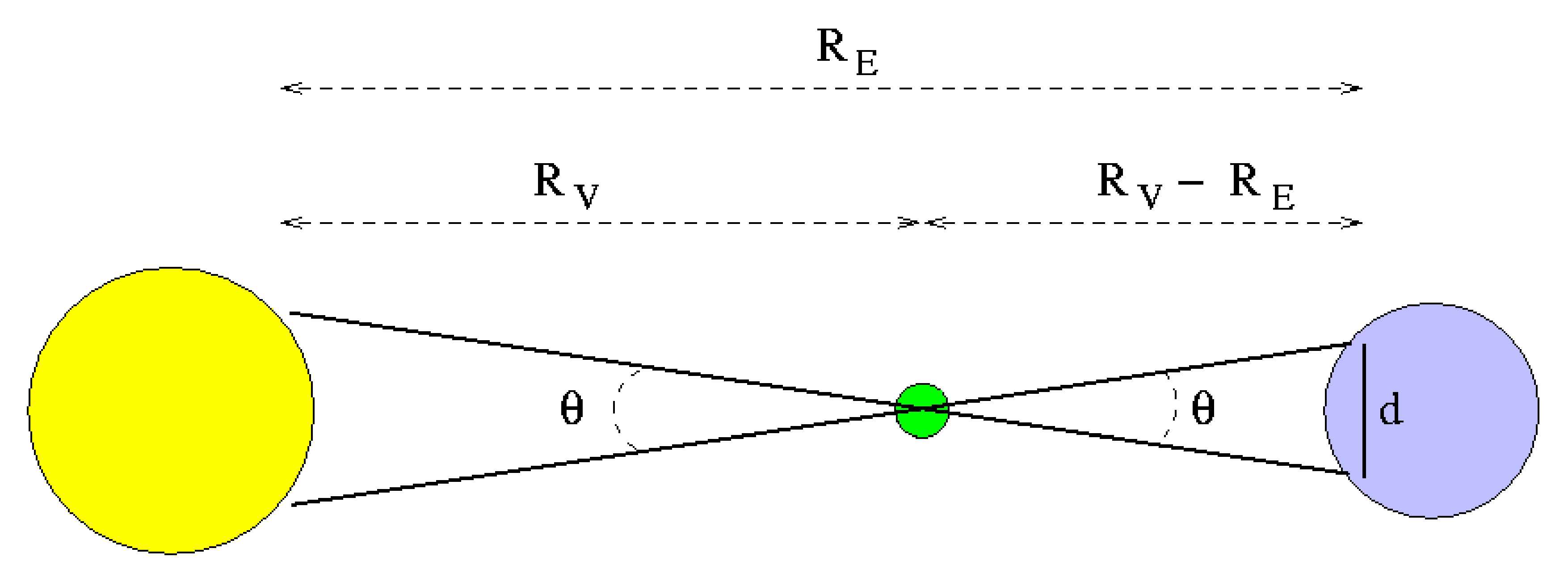
The Sun

Note that the small dark patch is not a sunspot:

The distance to the Sun

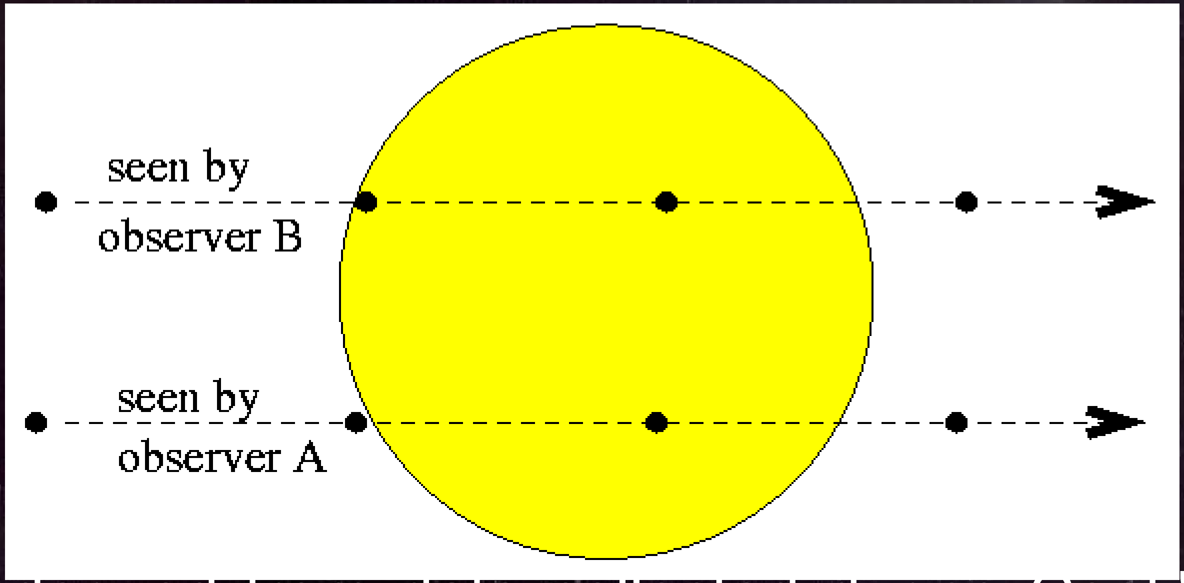
How far away is the Sun? This question was first answered accurately in the 1700s. Captain Cook led an expedition to Tahiti, which had only just been discovered, to observe a transit of Venus.

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 x 10^{30} kg. And knowing the distance, we can work out the Sun's luminosity.

The Sun emits a lot of energy: 3.89x10^{26} W. The total energy usage of the entire human population is estimated to be about 10^{13} W.

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

The Sun contains about 10^{57} atoms. So, the length of time the Sun could sustain a luminosity of 3.89×10^{26} W would be given by

$$\text{Lifetime of Sun} = \frac{\text{number of atoms in Sun}}{\text{rate at which atoms react}}$$

$$= 10^{57} / 3.89 \times 10^{45}$$

$$= 3 \times 10^{11} \text{ s or } 10{,}000 \text{ years}$$

The Earth is much older than this, so combustion as we know it on Earth cannot power the Sun.

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. At around the same time, calculations were showing that the Earth was 4.6 *billion* years old. So, gravitational contraction couldn't be powering the Sun.

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 energy:

$$E = mc^2$$

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 luminosity of the Sun

In the Sun, hydrogen atoms are fusing to form helium. Four hydrogen atoms collide, and produce one helium atom.

A helium atom is slightly lighter than the four hydrogen atoms that produced it. So, according to the equation, some energy is released.

Mass of four hydrogen atoms = 6.693×10^{-27} kg
Mass of one helium atom = 6.645×10^{-27} kg
Difference = 0.048×10^{-27} kg

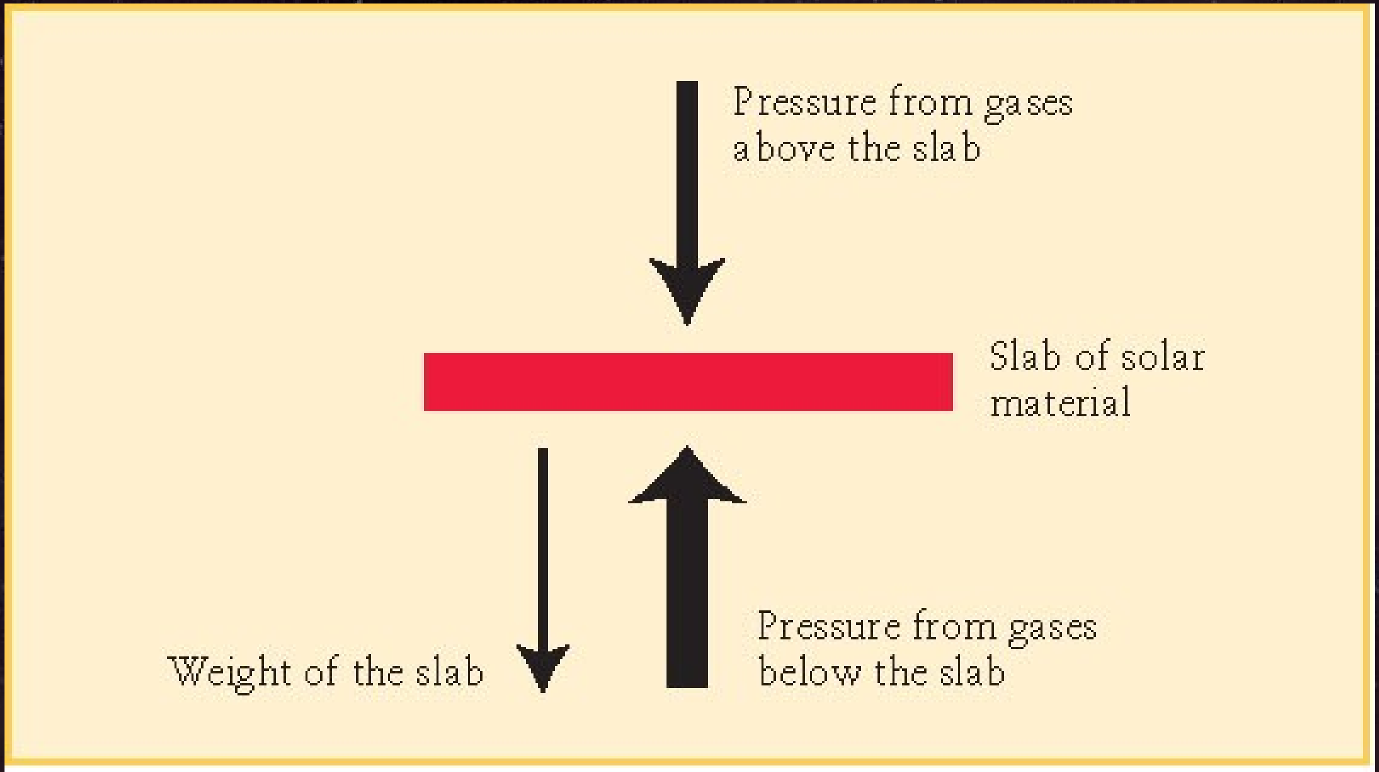
Energy released = mc^2
= $0.048 \times 10^{-27} \times (3 \times 10^{8})^2$
= 4.3×10^{-12} J

This is 10 million times as efficient as combustion!

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:

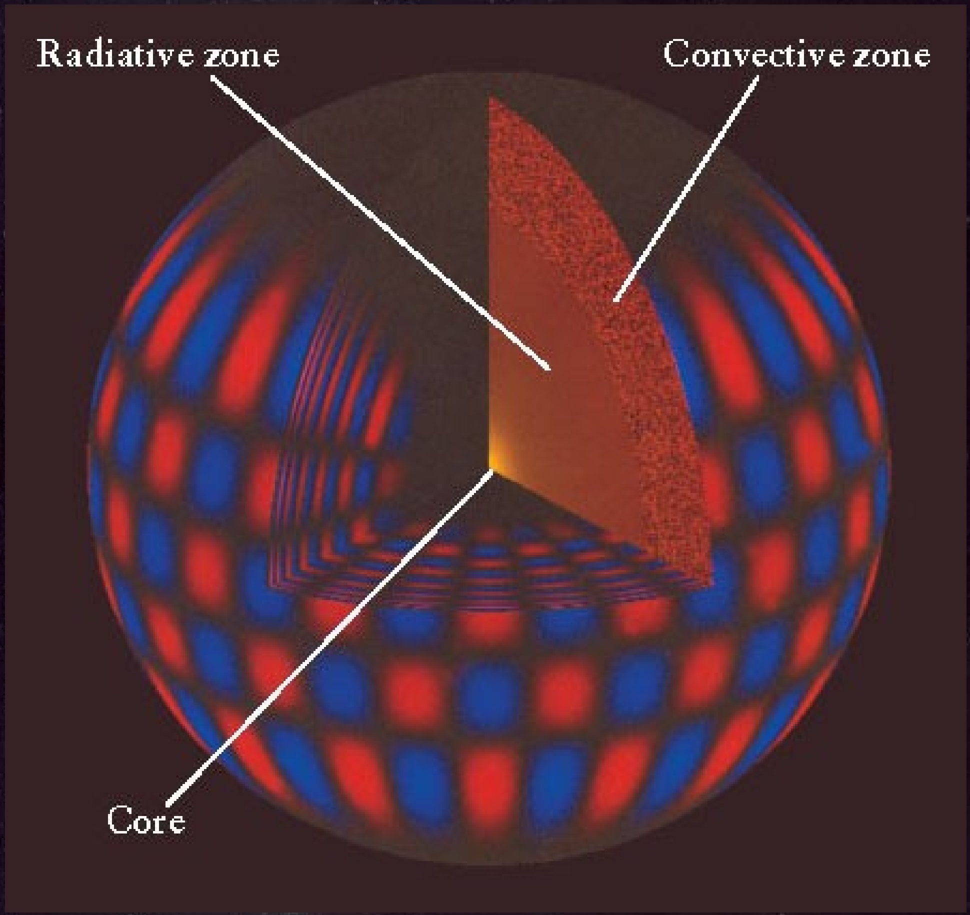


(a) Material inside the sun is in hydrostatic equilibrium, so forces balance

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.



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

The core of the Sun

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.

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?

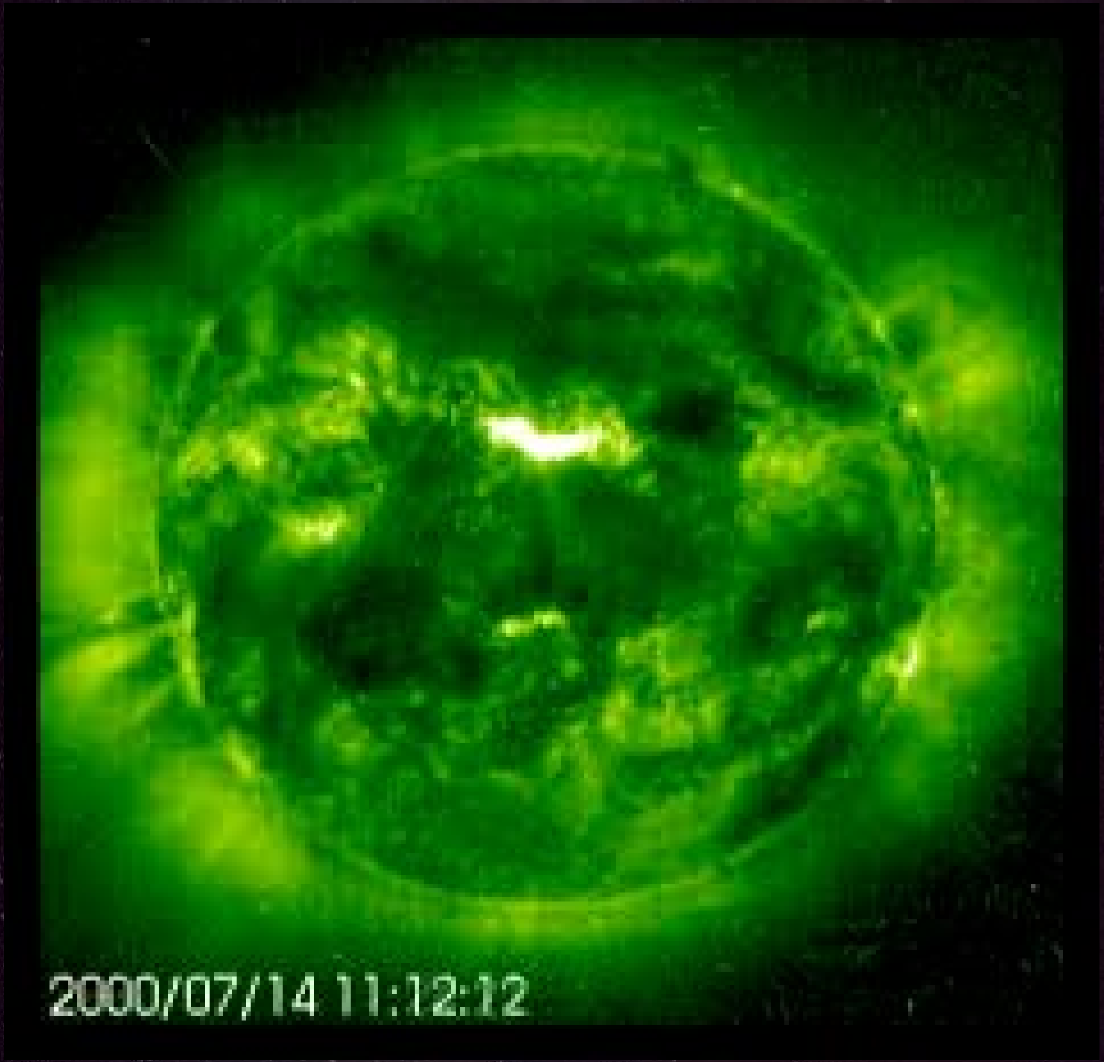
The answer turns out to be that there are three different kinds of neutrinos. All the neutrinos produced in the Sun are of one type, but neutrinos can change between types.

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.

On its surface you can generally see dark patches, or *sunspots.* The number of sunspots varies on an 11 year cycle. When there are lots of sunspots, there is a lot of activity like *solar flares* and *coronal mass ejections*.



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.

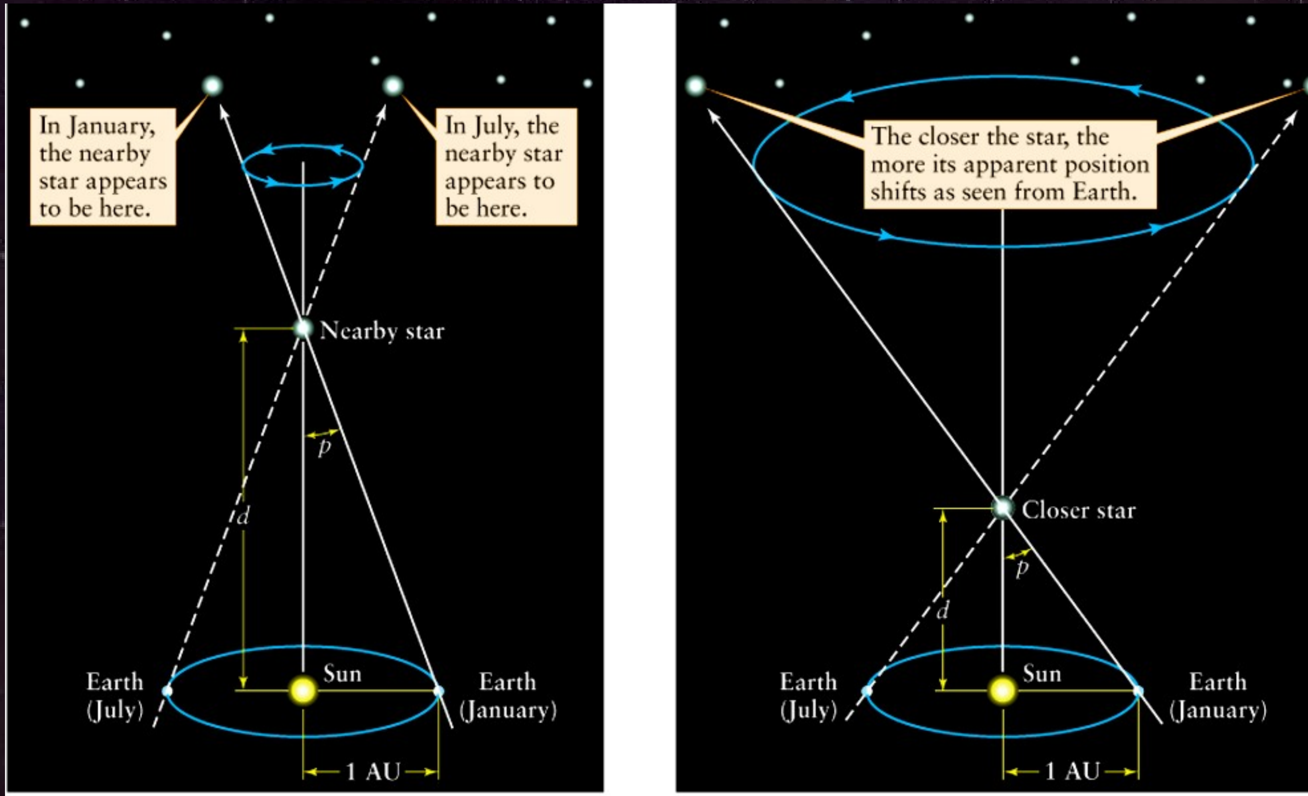
So, the Sun is an important driver of the Earth's climate.

(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

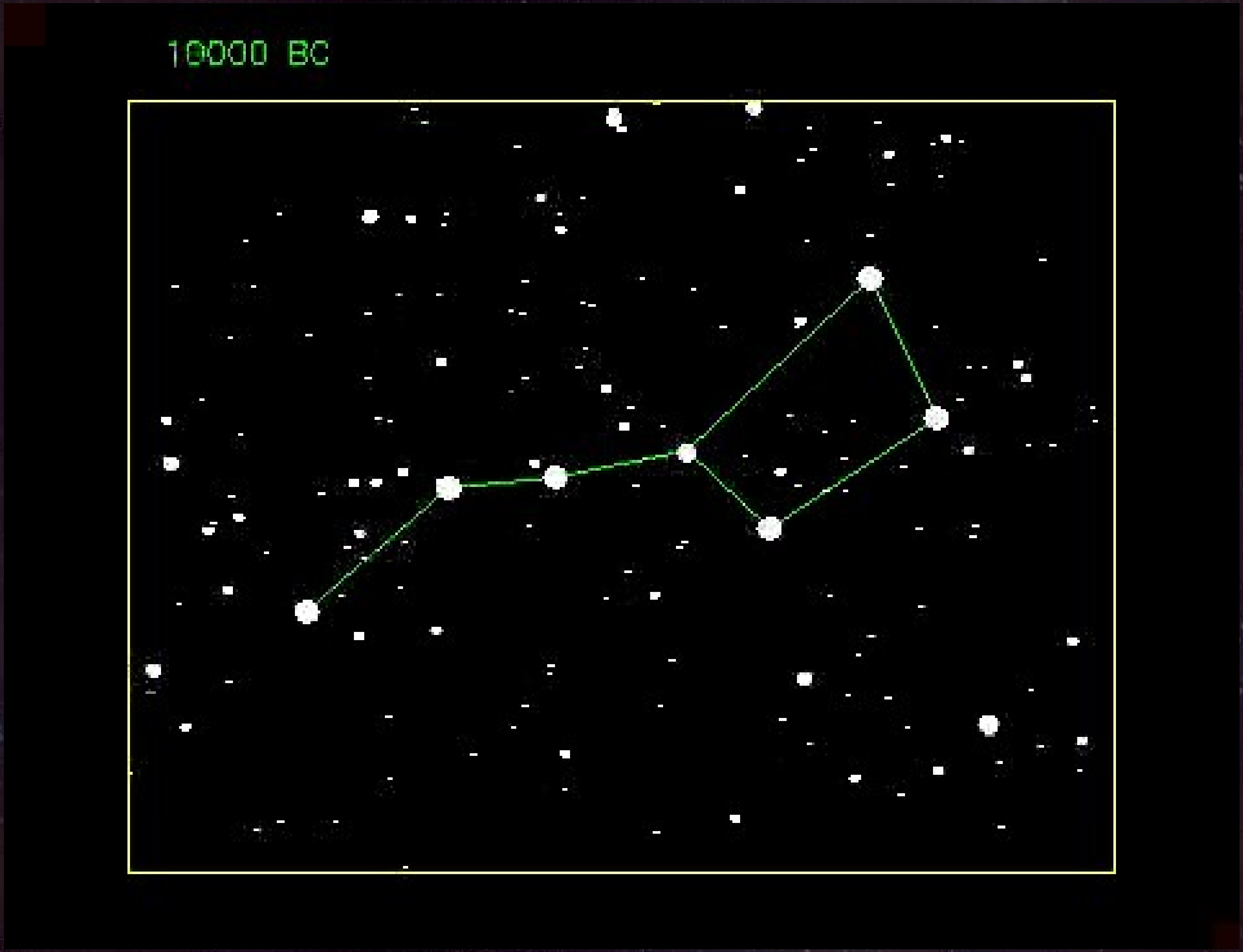
Parallax is an apparent motion, caused by the Earth orbiting the Sun. Stars are also moving through space. This means their positions relative to each other slowly change.

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*.

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 have observations both of a line-of-sight velocity (from the Doppler shift of the spectrum) and a plane-of-the-sky velocity (from the proper motion), you can combine these to 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

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

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 19^{th} 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 x 2.152 x 2.512 x 2.512 x 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.

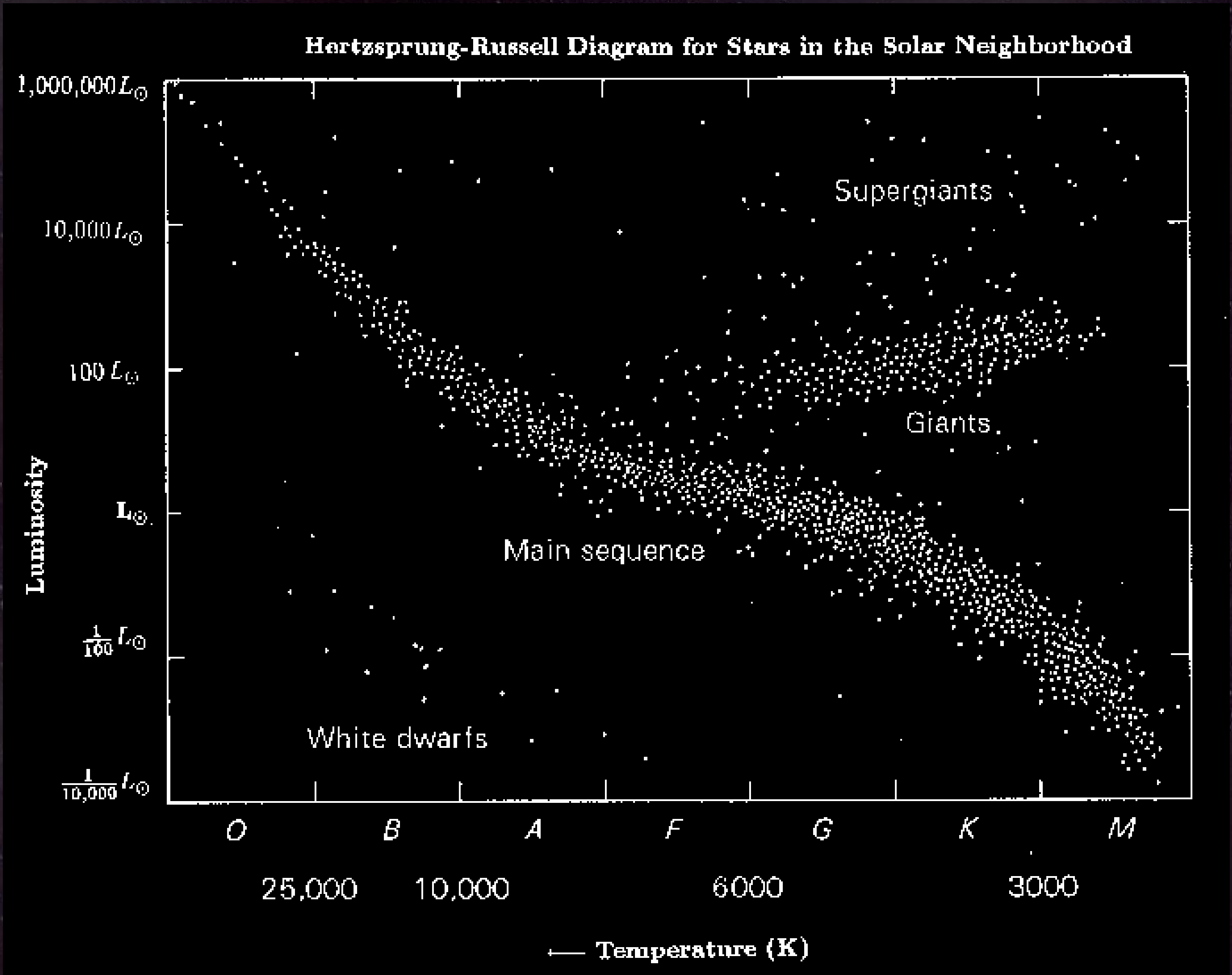
The faintest objects that have ever been detected have apparent magnitudes of about 30. So, they are about $2.512^{31.5}$ = 4 trillion times fainter than Sirius.

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

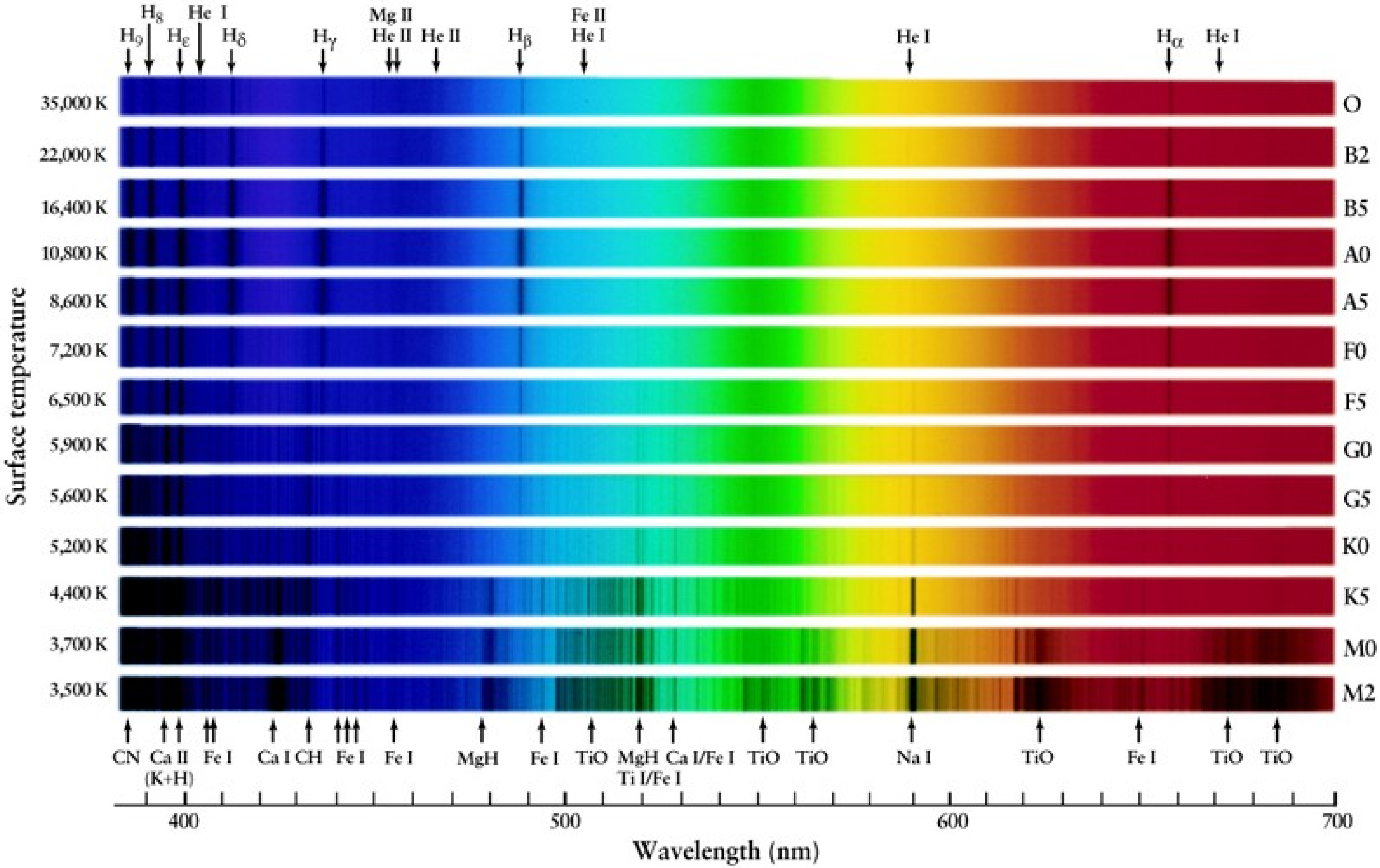
We can estimate stellar distances using the HR diagram. We can measure the temperature of a star from its spectrum, and if we know (or assume) that it is on the main sequence, then we can find out its luminosity. Then, from its luminosity and apparent brightness, we can calculate its distance.

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

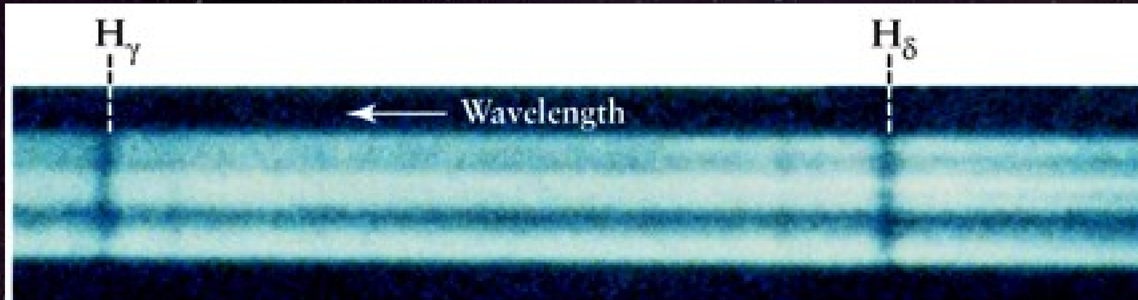
Curious fact of history – at a time when women in science were very rare, most of the pioneering work on stellar classification was done by women. Annie Cannon played a major role in developing the modern classification scheme while at Harvard, and personally classified 230,000 stars!

Offsetting the progressiveness of employing women in astronomy was the much lower wage they received compared to male colleagues...

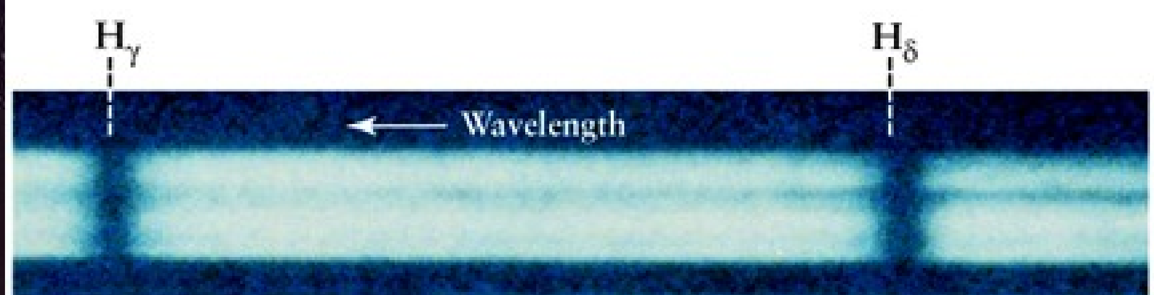
Spectral types

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

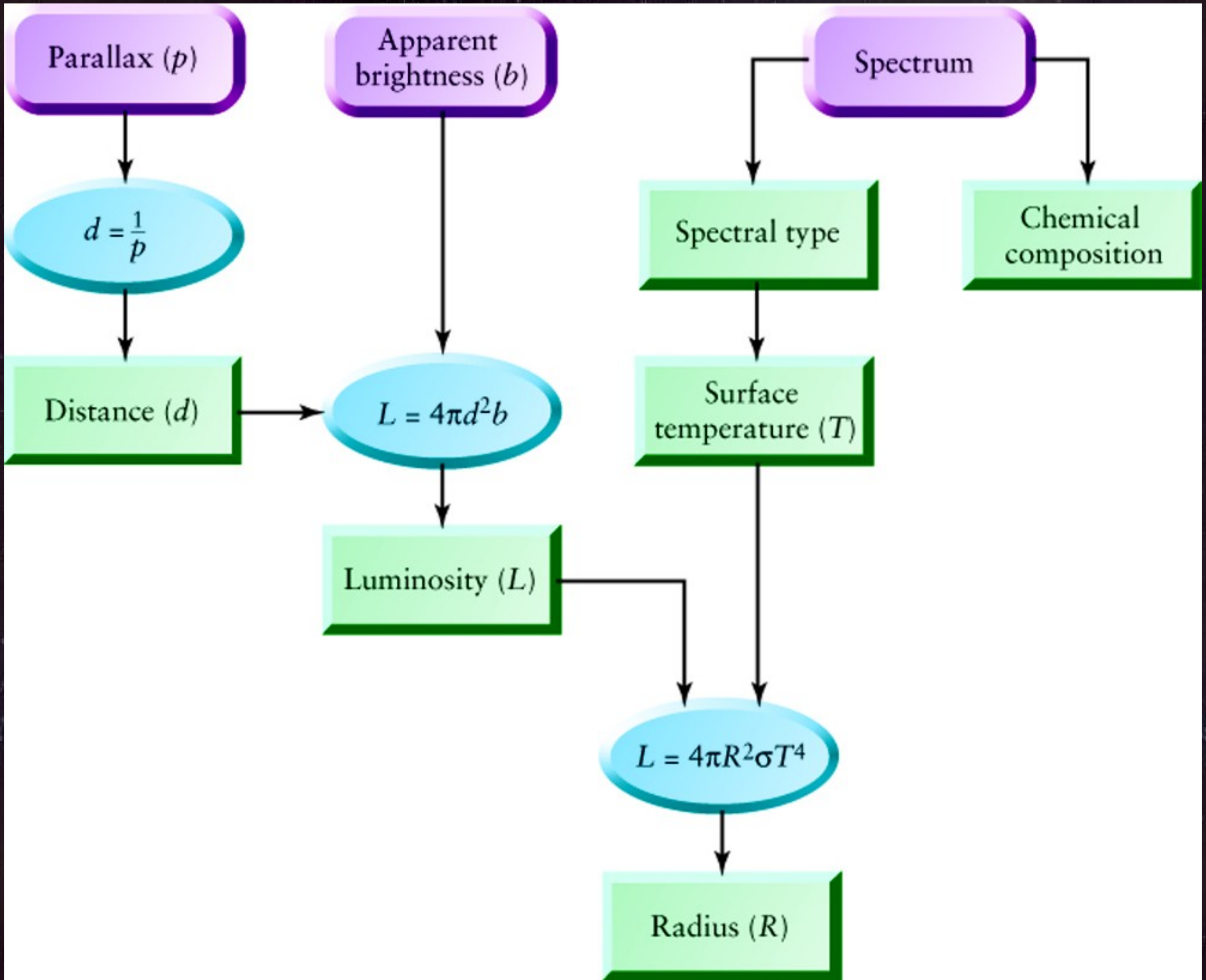
We learned earlier that the luminosity of a star is related to its temperature and radius:

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

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 – (almost) the whole picture

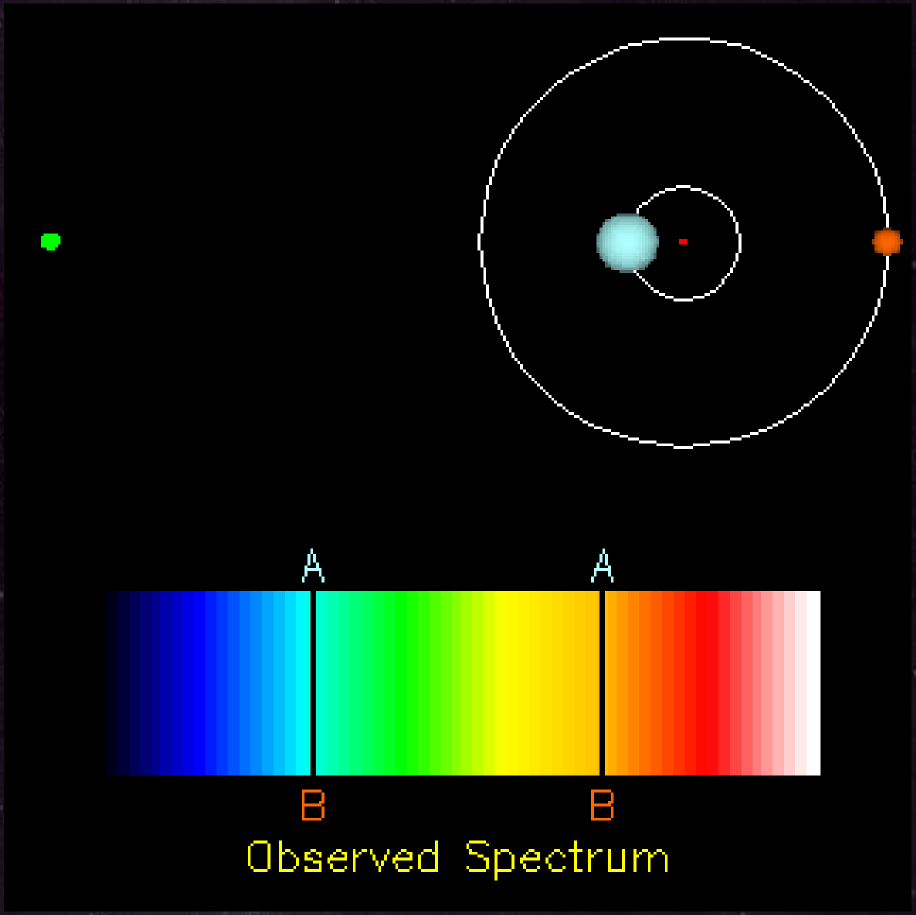
This diagram summarises how we can find out about the properties of stars:



Stars – masses

For a single isolated star, the mass is very difficult to determine, but luckily, it turns out that 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

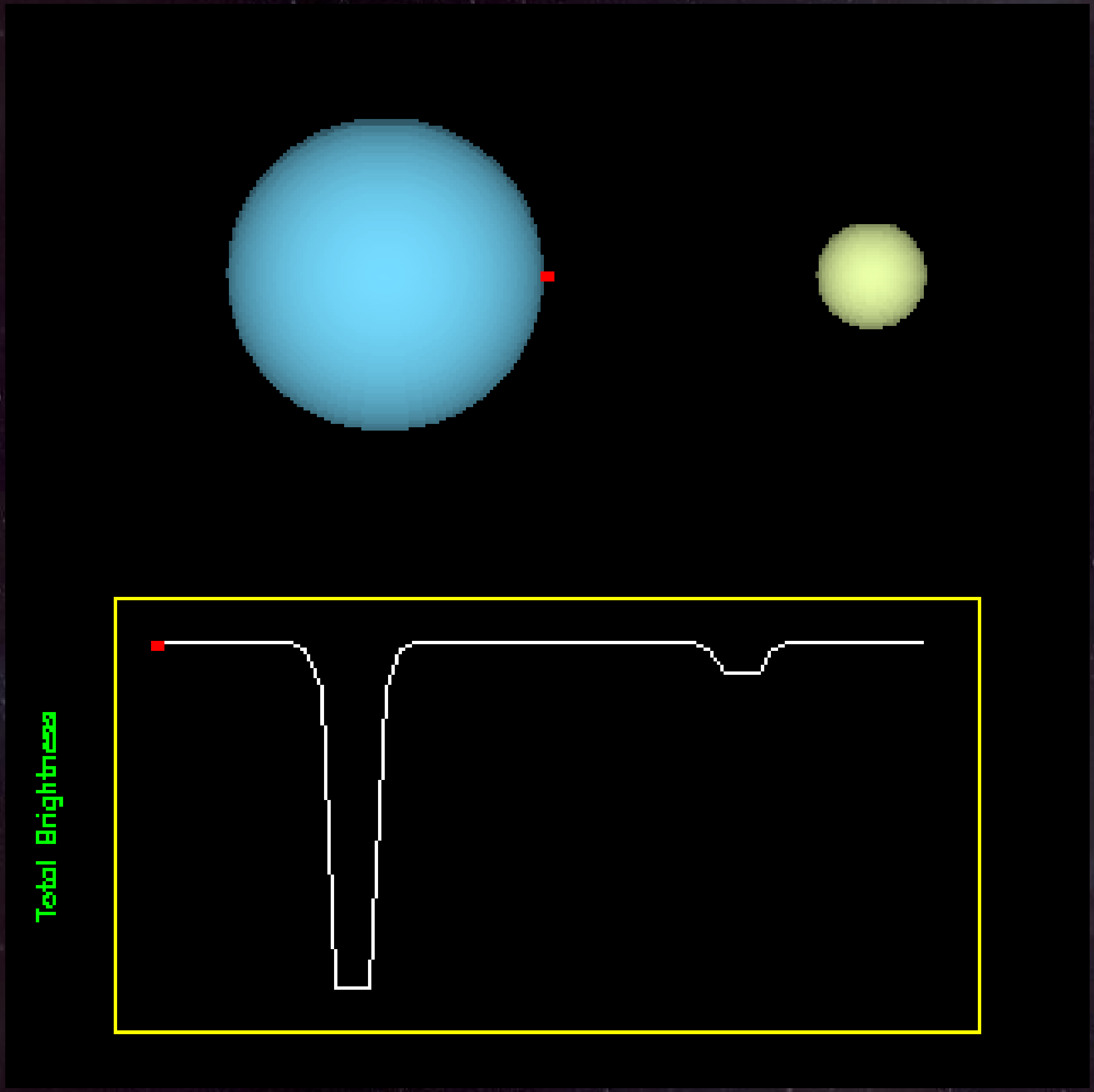
The difficulty with binaries is that normally, we don't know how the plane of the orbit is orientated. This complicates the determination of masses.

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

This diagram shows what happens with eclipsing binaries:

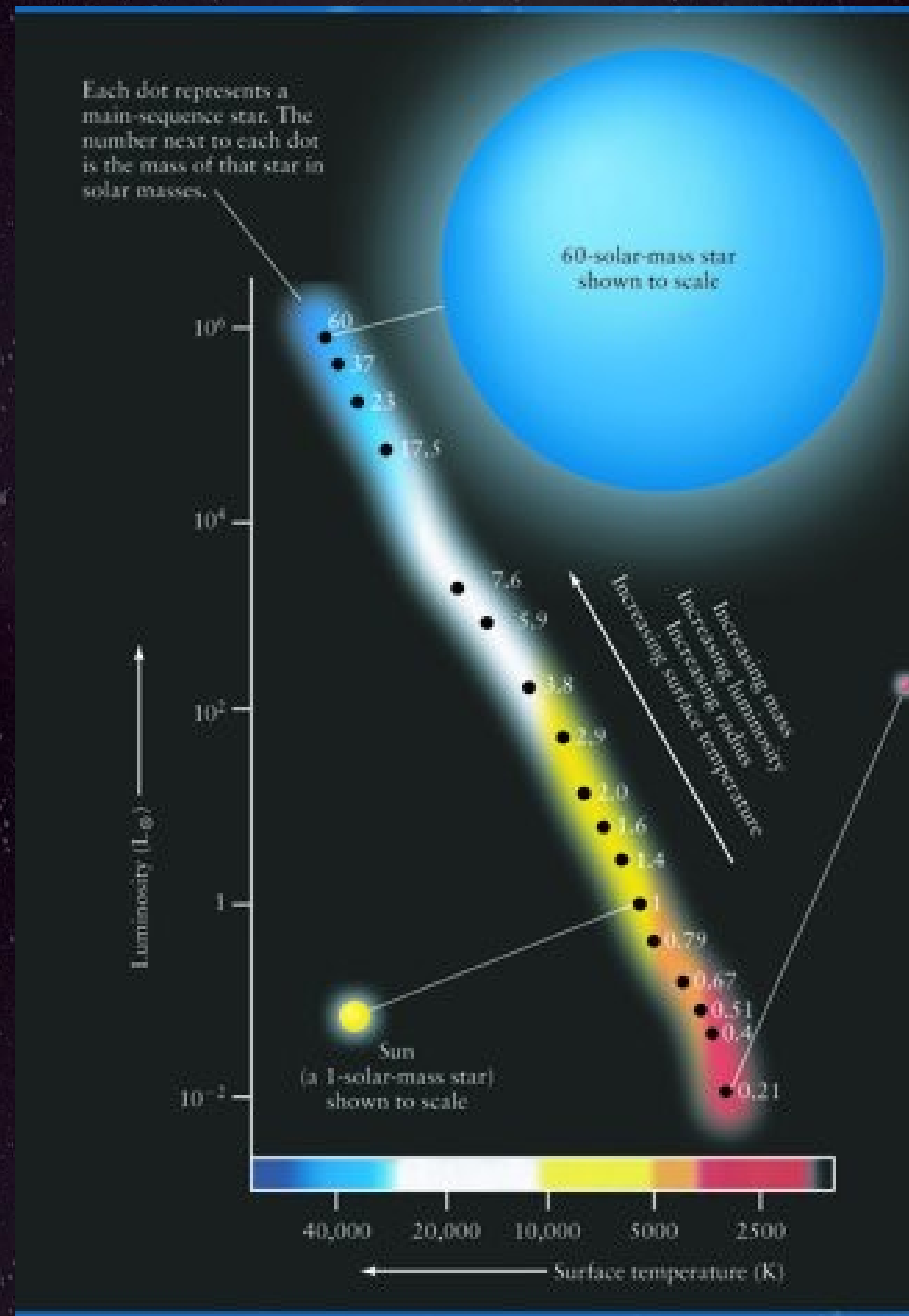


Stars – masses

Many years of observations of binary systems have led to an understanding of the relation between the mass of a star and its position on the main sequence.

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.



The lives of stars

Now that we have seen how we can find out various properties of stars – mass, luminosity, distance, radius – we can start to talk about their lives.

The lives of stars are extremely long – millions, billions or even trillions of years. So how can we understand them at all, when the whole of recorded human history is less than 1% of the life of even the shortest-lived star?

Luckily, we have a huge sample to work with. There are 200 billion stars in our galaxy alone. With such a large number, all born at different times, all with different masses, we see stars at all stages of their lives.

The lives of stars

The most massive stars have the shortest lives. They are also the brightest. This makes it quite easy to work out where star formation is happening, or has recently happened – if you see hot, young bright stars, then they must have formed quite recently.

A great example is the Pleiades – currently very clearly visible, high in the night sky at about 9pm.

The lives of stars

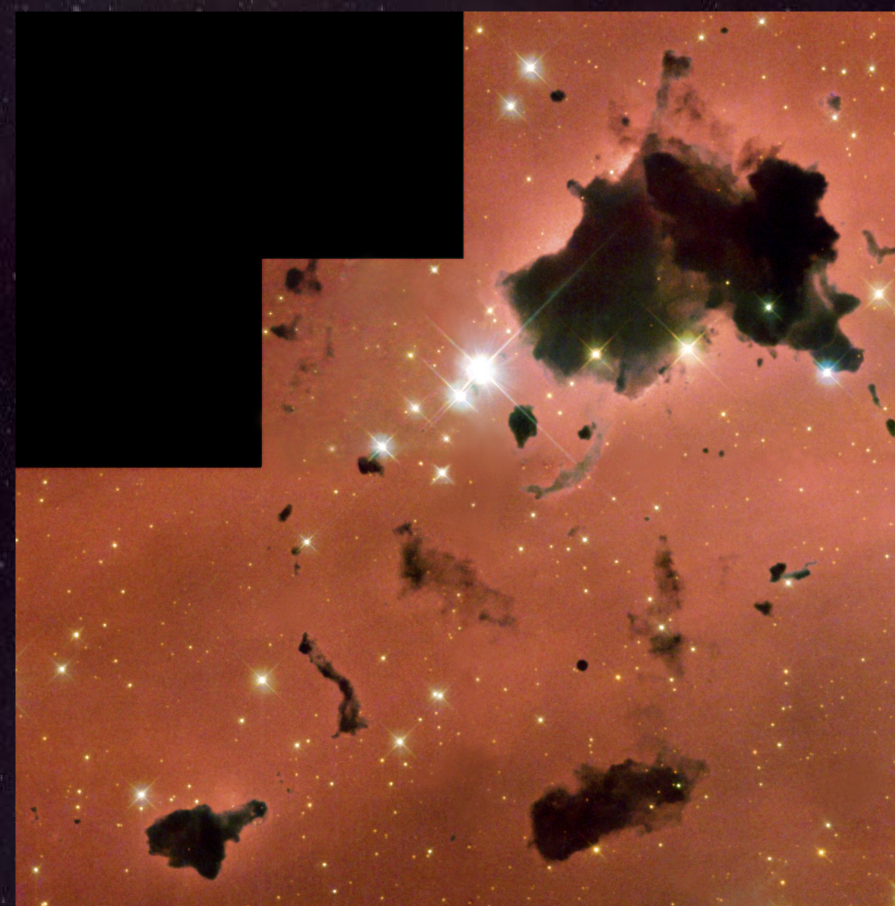
The lives of stars

What you find is that often, where you find hot, blue and therefore massive and young stars, you also find lots and lots of hydrogen gas – like in the Orion Nebula:

The lives of stars

These regions of hydrogen gas, in which stars are forming, are called *HII regions*. The name comes about because hydrogen gas can be either neutral (HI), or ionised (HII), and these regions are ionised, by the light from the stars forming within them.

Looking more closely, we see that within the bright HII regions are dense, dark, cold clumps. These are called Bok globules.



Interstellar extinction and reddening

Interstellar space is not empty: some parts are obviously not empty, like the Orion Nebula. But it was noticed early in the 20th century that star clusters always appear fainter than you would expect from their distance alone. Something in interstellar space is absorbing their light. This is called *interstellar extinction*.

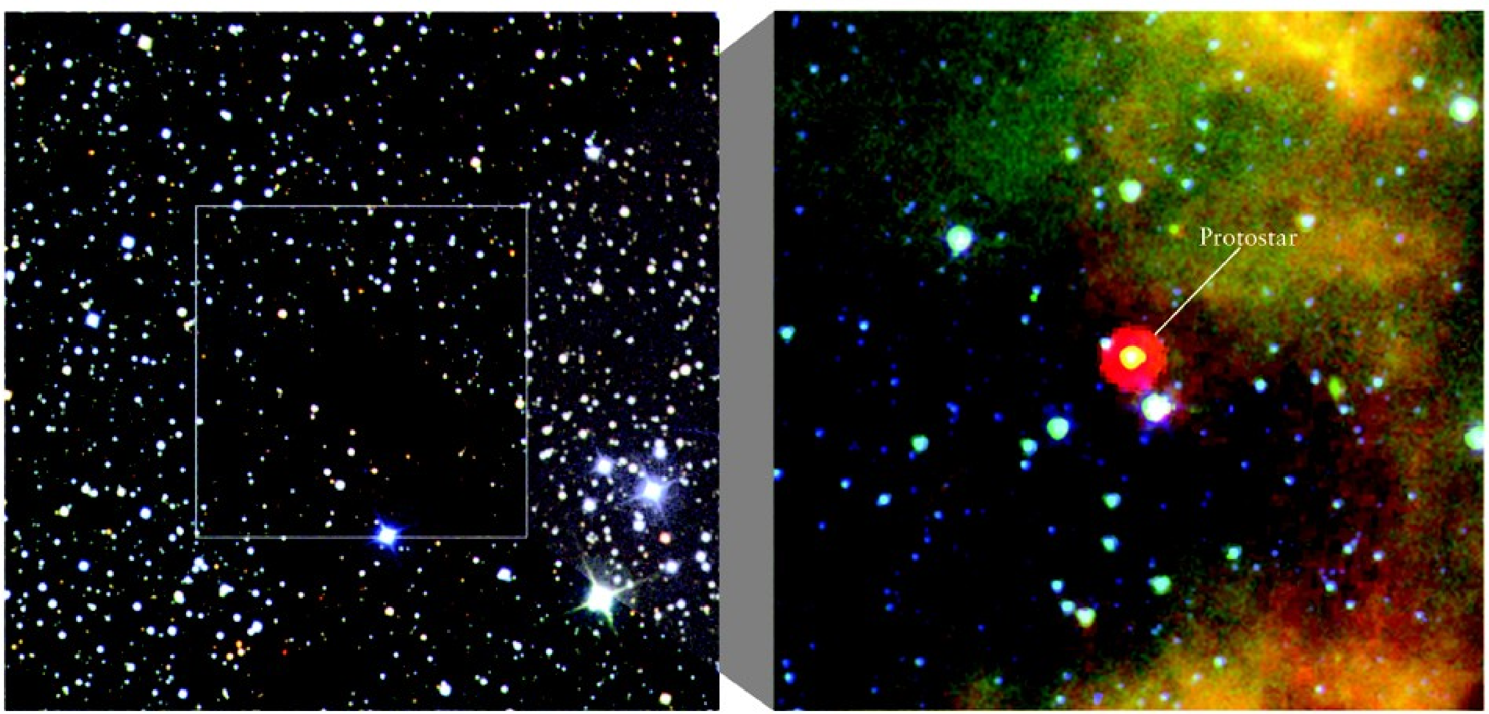
Not only are they fainter, but they are also redder – whatever is absorbing the light is absorbing more blue light than red light. This is *interstellar reddening.*

Interstellar space is full of *dust* – small particles, which scatter more blue light than red light.

Interstellar extinction and reddening

Because the dust absorbs more blue light than red light, by observing the galaxy in red light you can see further through the dust clouds. You can see even further by observing infrared light.

When we look at the dense dark clouds within HII regions in infrared light, we see that they have stars within them.



(a) A dark nebula (b) A hidden protostar within the dark nebula

Star formation

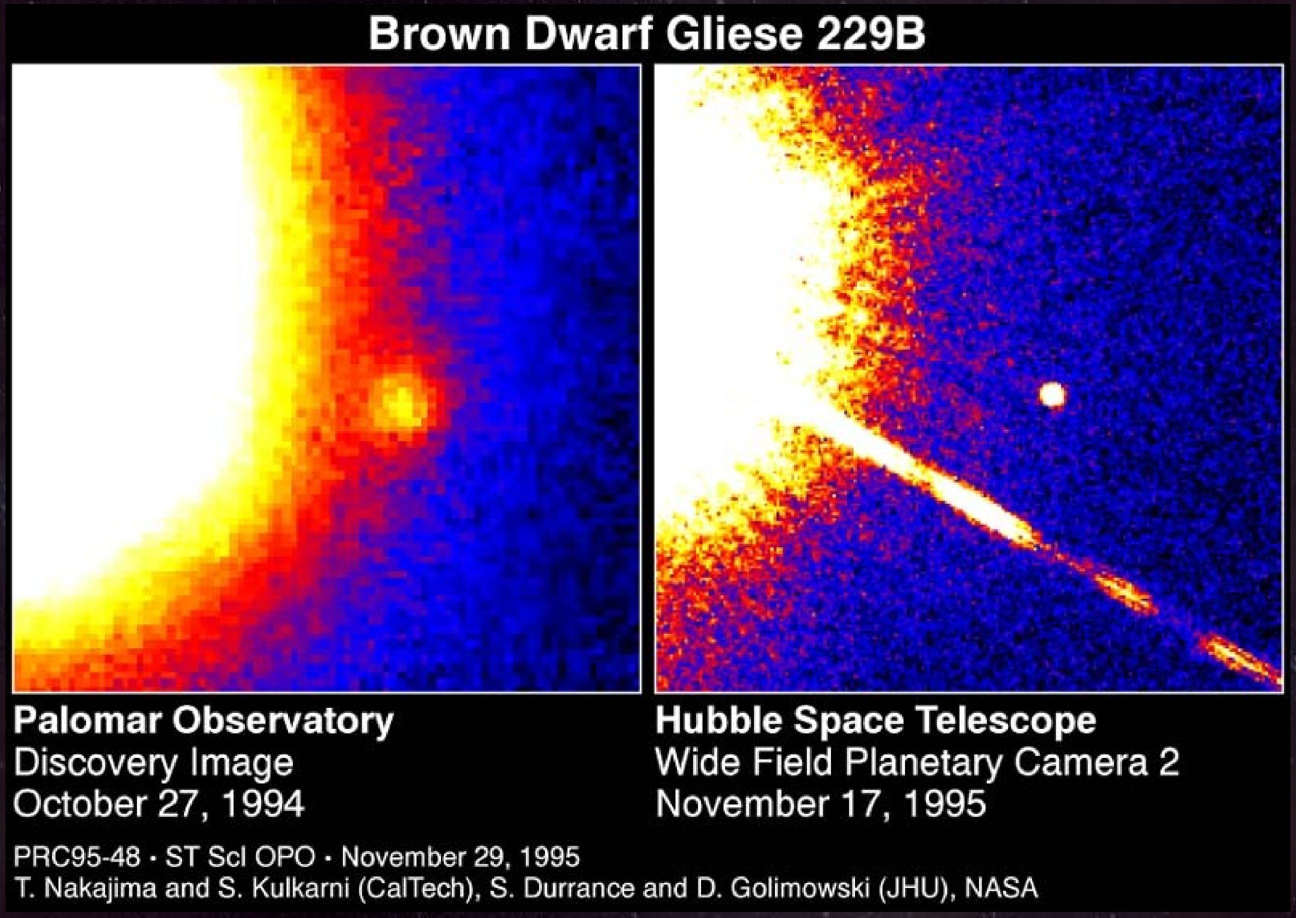
We understand star formation as starting with a large cold cloud of gas and dust in interstellar space. If it is massive enough (and they can have masses of millions of Solar masses), it can begin to collapse.

As it collapses, it will fragment into smaller and smaller packets of gas and dust – star masses are limited because a really massive cloud collapsing would heat up enough for the *radiation pressure* to exceed the force of gravity, stopping the collapse.

When a star-sized packet of gas and dust has formed, it will collapse into a recognisable body – a protostar. As the cloud collapses, it heats up, and eventually begins to shine. At the moment, its luminosity is powered only by its contraction.

Star formation

If the cloud has a mass of more than about 150 solar masses, it will prevent its own collapse. If it has a mass of less than 0.08 solar masses, nothing else will happen – it will contract and cool over billions of years, shining extremely faintly. It will be a *brown dwarf*.



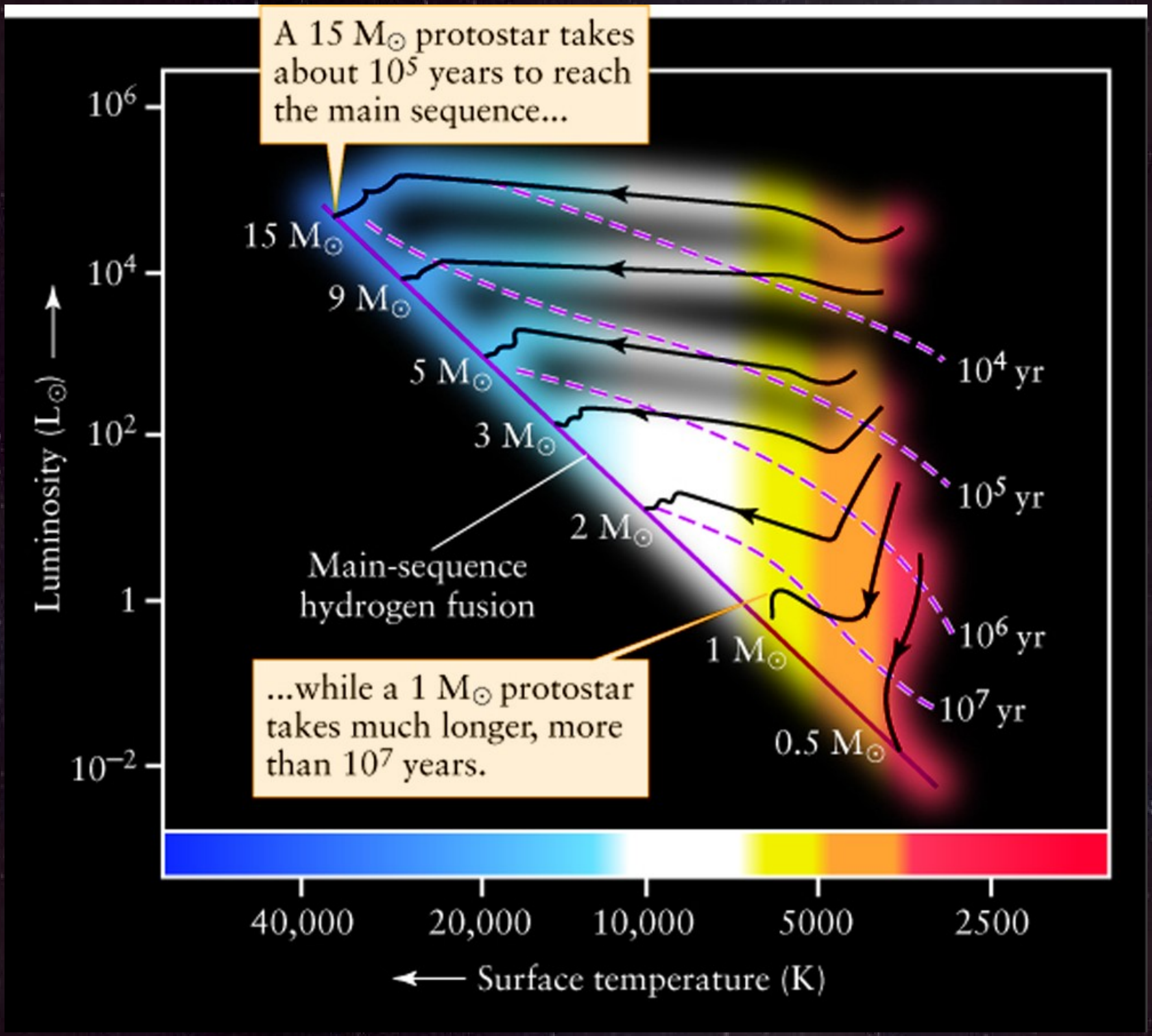
Star formation

If its mass is between these values, then as it contracts, eventually its core will reach a critical temperature of about 3,000,000 K. This is hot enough for nuclear fusion to begin, and the object will become a star.

Its contraction stops, as energy starts to be produced at the centre, and it will evolve over a few thousand years from being large and quite cool to a smaller, hotter, main sequence star.

Star formation

The more massive a star, the more quickly it will reach the main sequence.



Star formation

Typically, hundreds or thousands of stars form in one go. The result is *star clusters* like the Pleiades.

The hot luminous massive members of the cluster “blow away” the cloud of dust and gas from which they formed, and the cluster become visible at optical wavelengths.