Course notes - reminder

Lecture notes, problem sheets and answers available at:

http://www.star.ucl.ac.uk/~rwesson/PHAS1511

Very broad overview

In PHAS1511 we have covered:

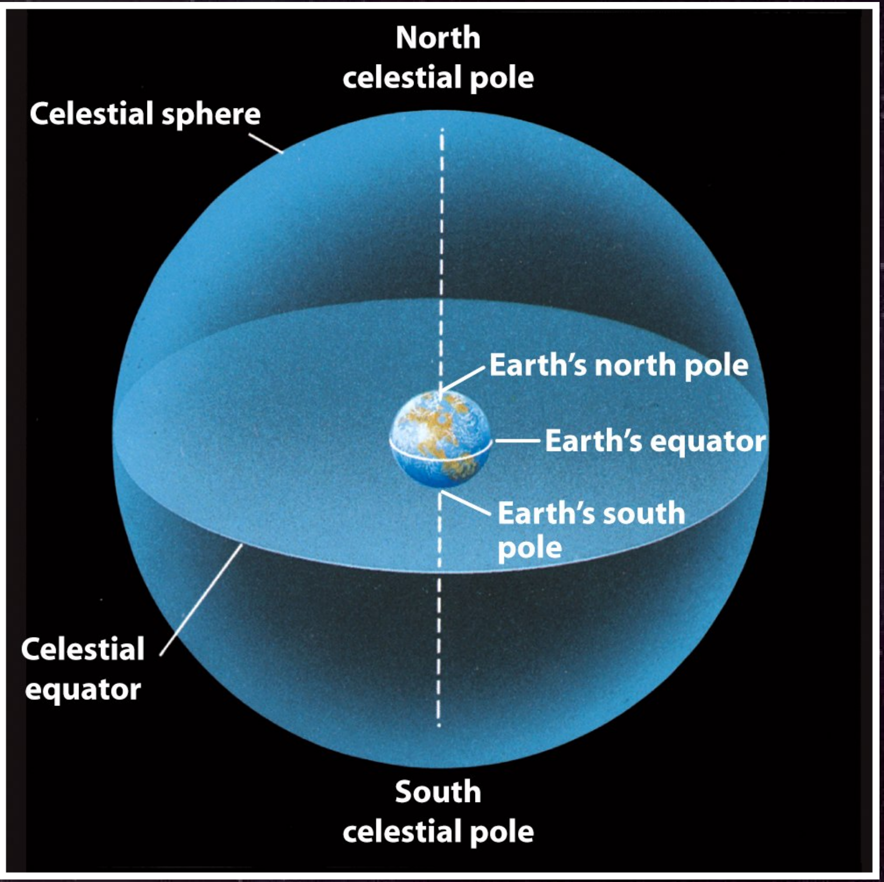
- The celestial sphere – how to find astronomical objects
- The nature of light – what it is, and what we can learn from it
- The structure of matter – atoms, energy levels
- Telescopes – how we observe astronomical objects
- Stars – how they are born, live and die
- Galaxies and the distant universe – how the Universe began and might end

Tonight I will go over some of the most important parts again.

The celestial sphere

There is no perspective in the night sky – all things look equally distant. So we refer to the *celestial sphere*.

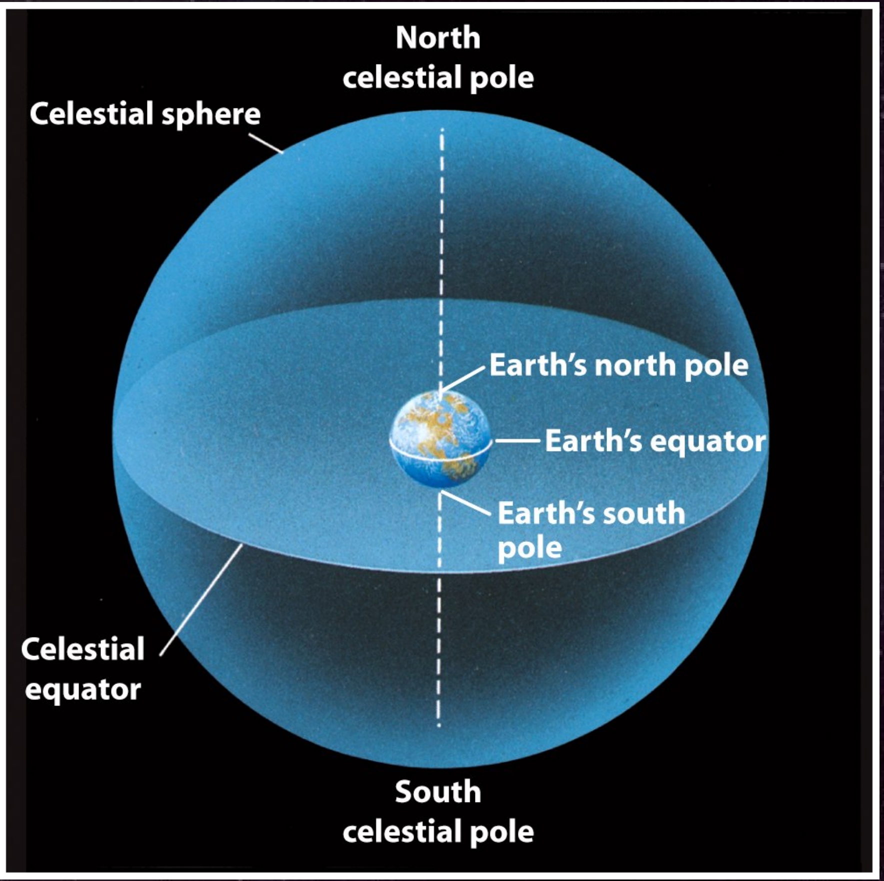
By analogy to longitude and latitude on the Earth, we can develop a convenient coordinate system for the night sky. The celestial poles are defined by the points in the sky towards which the Earth's poles point.



The celestial sphere

The *meridian* is the line joining North and South which passes directly overhead.

The celestial equator is the line equidistant from both celestial poles – exactly similar to the Earth's equator.



Right Ascension and Declination

The angle between the celestial equator and an object in the night sky is called its *declination* – similar to latitude on Earth's surface. Declinations are positive in the northern hemisphere and negative in the south.

The Pole Star, Polaris, has a declination of 89°15'51” - so it is not quite at true north, but it's close enough for navigation.

Right Ascension and Declination

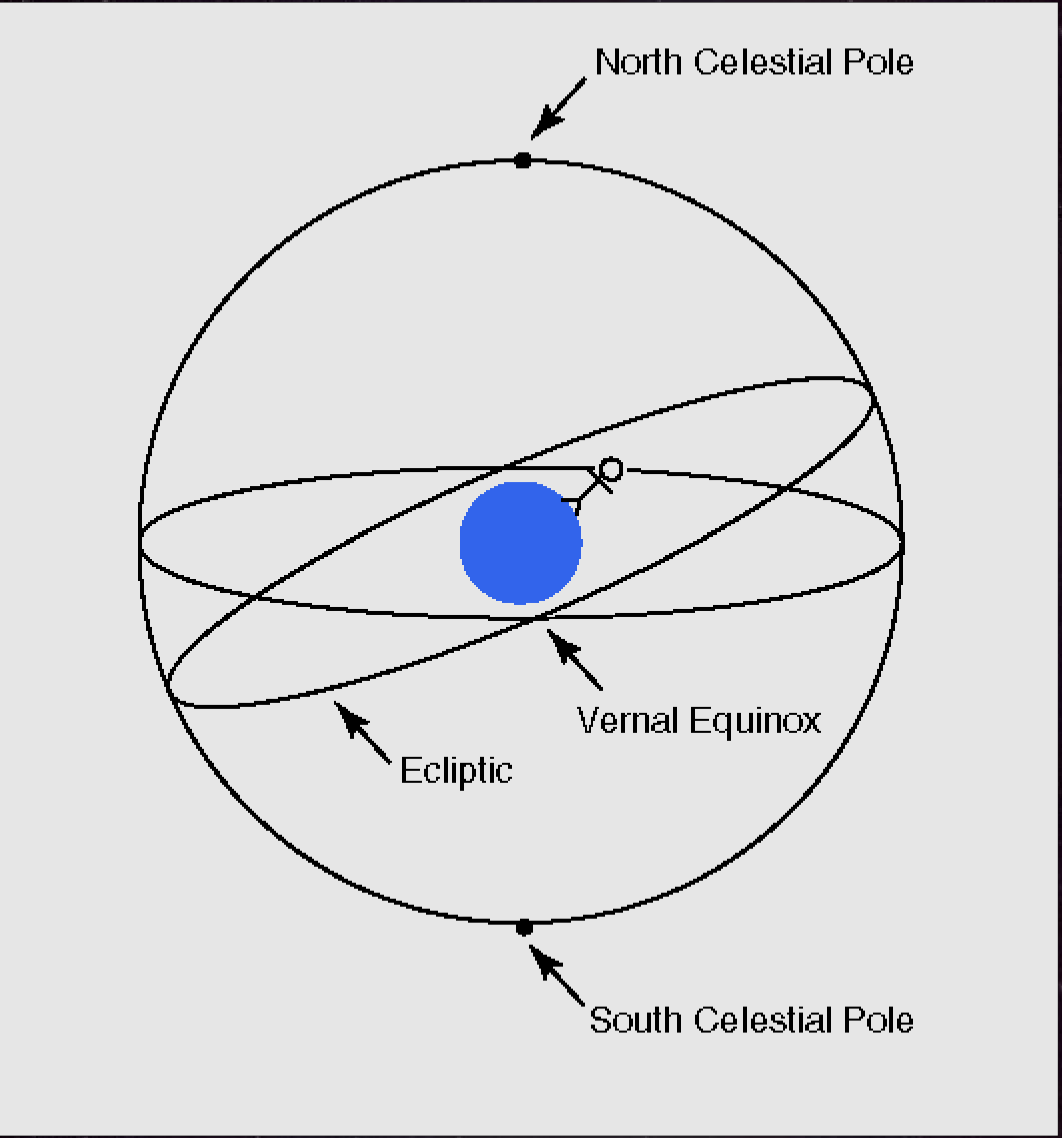
The celestial equivalent of longitude is called *Right Ascension*. (In)conveniently, it is not measured in degrees but in hours, minutes and seconds.

Longitude on Earth is arbitrarily defined as being zero in Greenwich. Similar on the sky, an arbitrary point needs to be defined as having a Right Ascension of zero.

Because of the tilt of Earth's rotational axis, the Sun crosses the celestial equator twice a year – at the equinoxes. RA=0 at the point where the Sun crosses from the Southern hemisphere into the Northern hemisphere.

Right Ascension and Declination

The path the Sun moves along is called the *ecliptic*.



Right Ascension and Declination

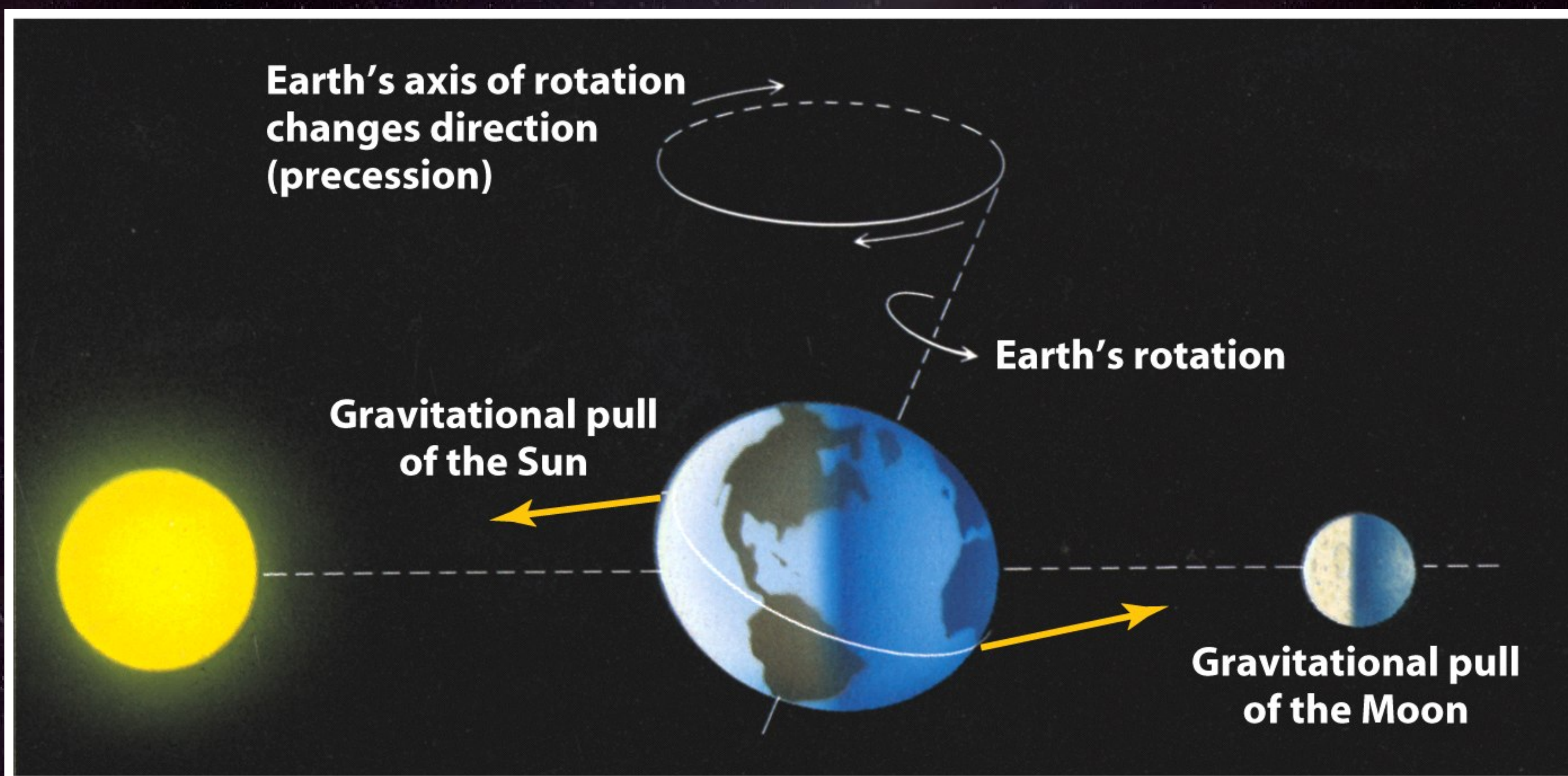
The point at which RA=0 is called the *First Point of Aries.* But it does not lie in Aries.... because of precession, it has moved and is now in Pisces.

After the First Point of Aries has crossed the meridian, then the time until a given object will pass the meridian is equal to its Right Ascension.

So Right Ascension being in hours, minutes and seconds is convenient after all. But it is easy to confuse seconds of time in RA with seconds of arc in declination.

The changing sky

Earth is not quite a perfect sphere – it bulges at the equator. The gravitational pull of the Moon on the bulge causes the direction that the Earth's rotational axis points to change over thousands of years.

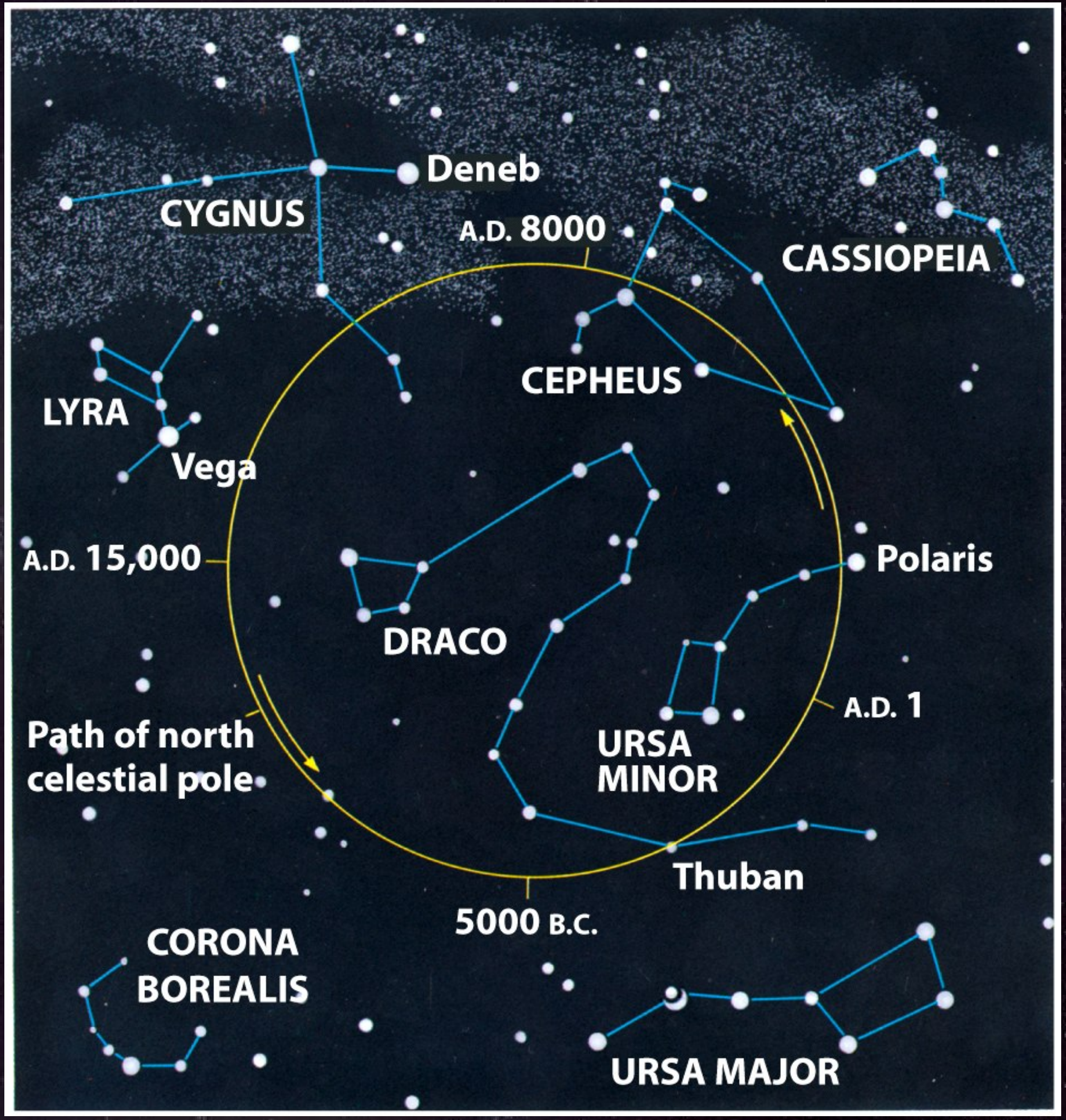


The changing sky

The position of the celestial pole moves around a circle every 26,000 years. This effect is called *precession*.

It means that Right Ascensions are not fixed and constant, but change slowly over time.

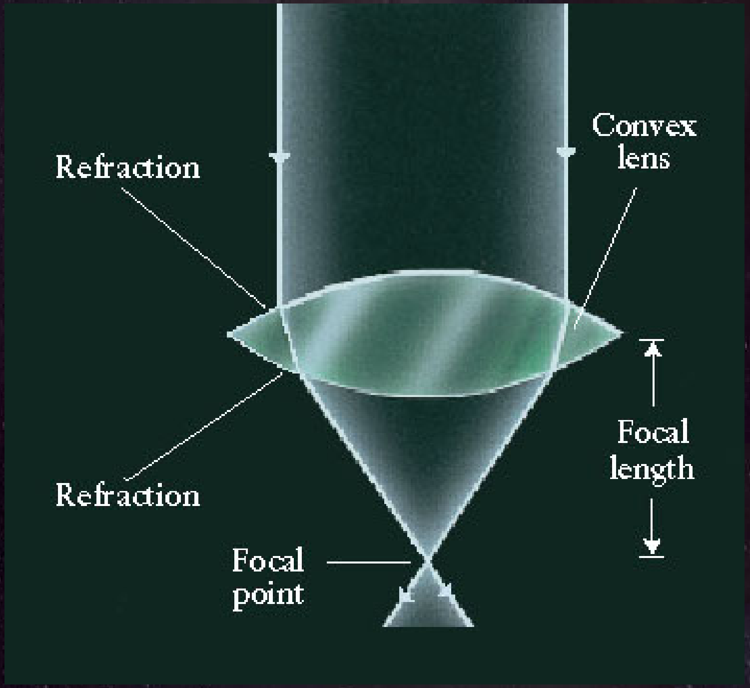
RAs are given with respect to a particular *epoch* – normally 2000.0, at the moment.



Telescopes - refractors

We learned earlier that EM radiation in a vacuum travels at *c*, the speed of light: 300,000 km/s. But it travels more slowly in a transparent substance like glass. This is called *refraction*.

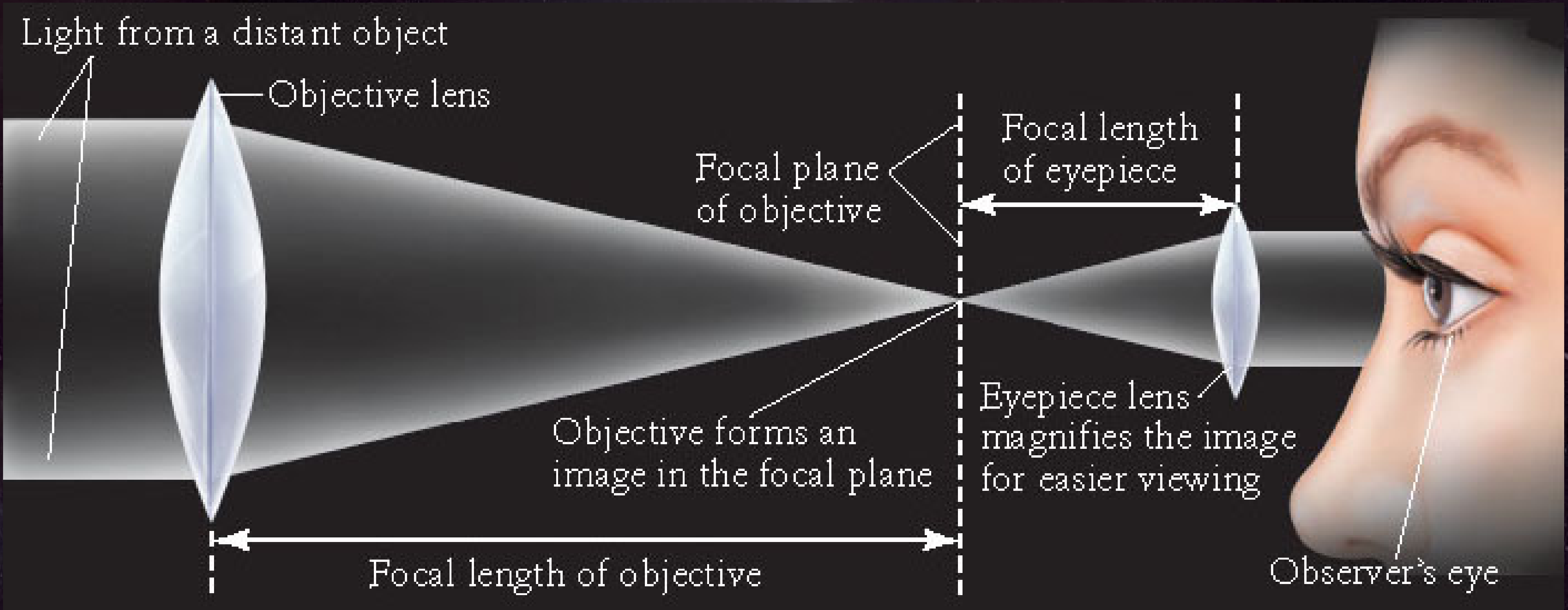
With the right shaped piece of glass, you can *focus* the light from a distant object, making it appear larger and brighter.



Telescopes - refractors

If you put a piece of film, or a CCD, at the *focal plane*, you could record an image.

Alternatively, you could put a second lens behind the first, to magnify the image and make it easy to view with the human eye. That, basically, is the principle of a *refracting telescope*.



Telescopes - refractors

The first telescopes, used in the early 1600s, were refractors. Galileo used a small refractor to stunning effect, discovering craters on the Moon, satellites around Jupiter, sunspots, and the phases of Venus and Mercury. Astronomy was revolutionised.

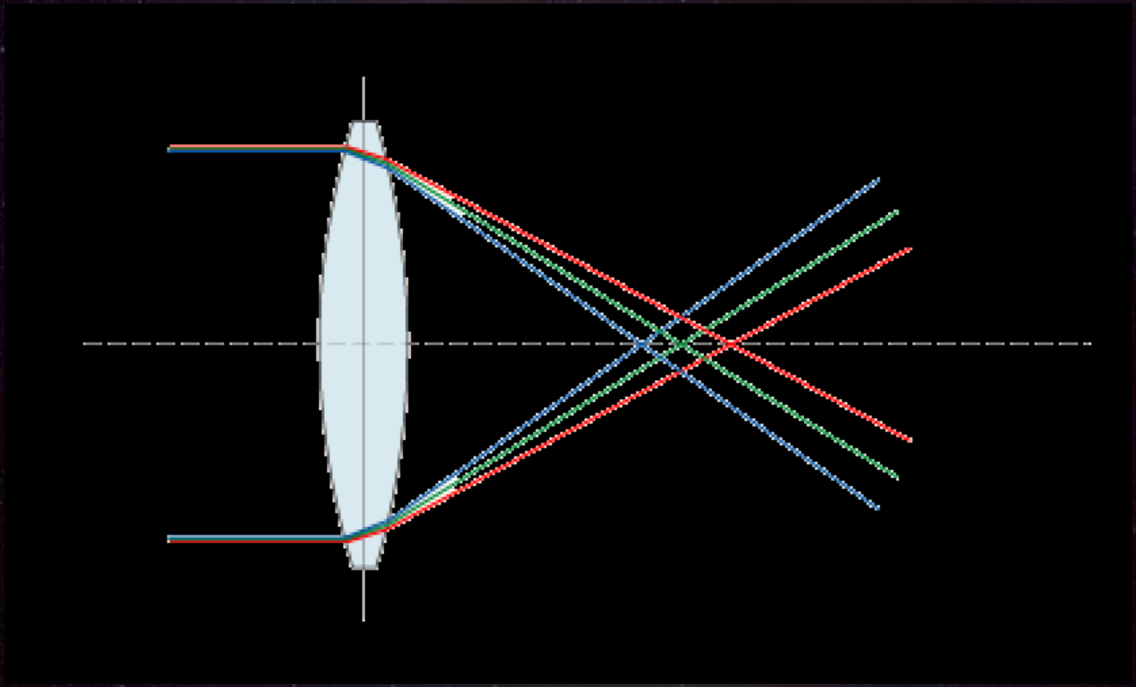
Galileo's telescope had a lens 3cm across. The human eye has a lens about 5mm across.

The *light-gathering power* of a telescope is proportional to the *area* of its lens, and therefore the *square* of the diameter. Galileo's telescope made things appear $(3/0.5)^2 = 36$ times brighter than the appear to the naked eye.

Refractors - disadvantages

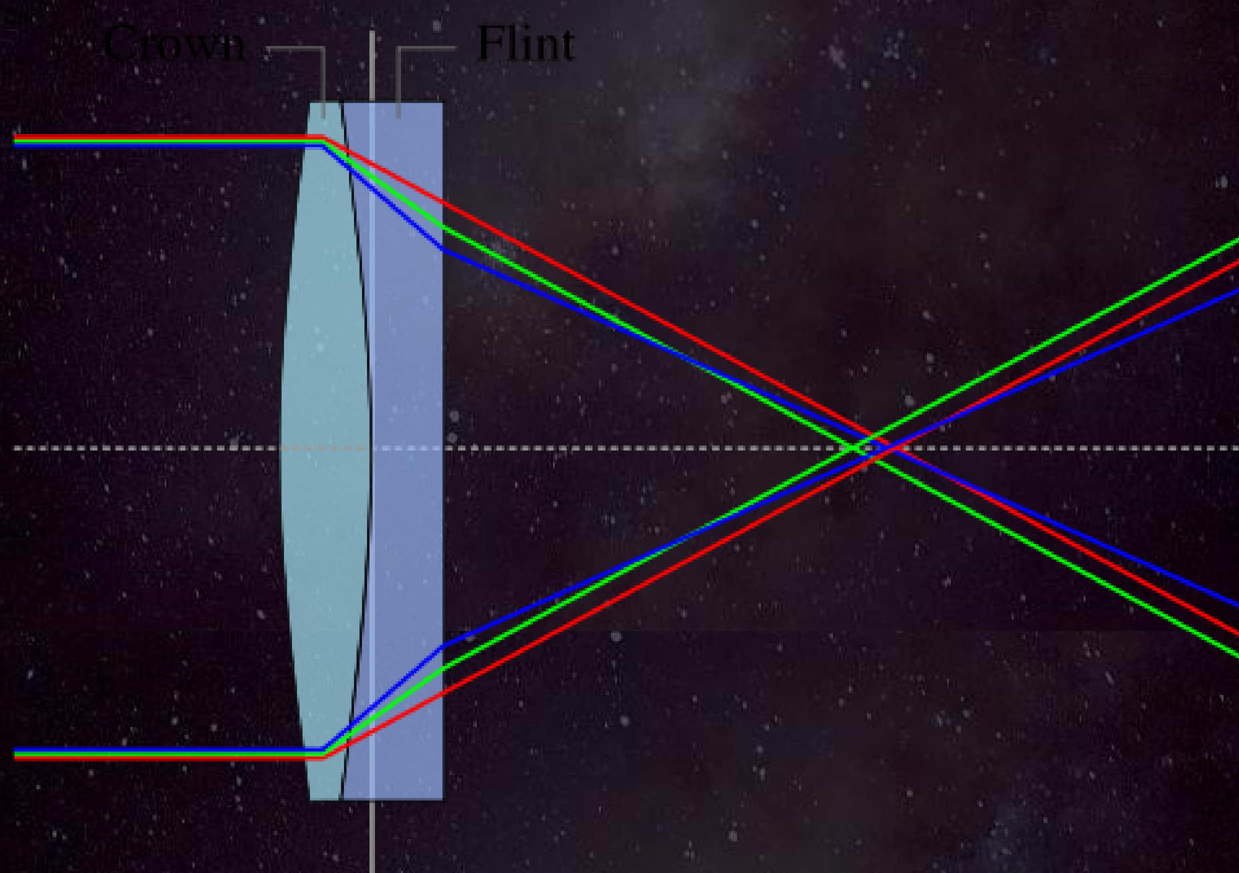
Refractors have a number of issues that ultimately limit their capabilties.

First is the problem of *chromatic aberration*: when light is refracted, the amount of refraction depends on the wavelength of the light: blue light is refracted more than red light, so the focal point is different for different colours.



Chromatic aberration

You can go some way towards eliminating chromatic aberration by using a second or third piece of glass. However, more glass = more cost. This limits the practical size of refractors.



Optical quality

Another problem with refracting telescopes is the quality of the glass. You want to lose as little light as possible when looking at astronomical objects, and this means you need very high quality glass, as free as possible from imperfections.

Higher quality glass = more expensive.

Weight distribution

Yet another problem with refractors is that the bigger the lens, the heavier it is. This means you need a very sturdy tube to hold it in place.

A large lens will also be distorted by its own weight as it is moved around, compromising the optical quality.

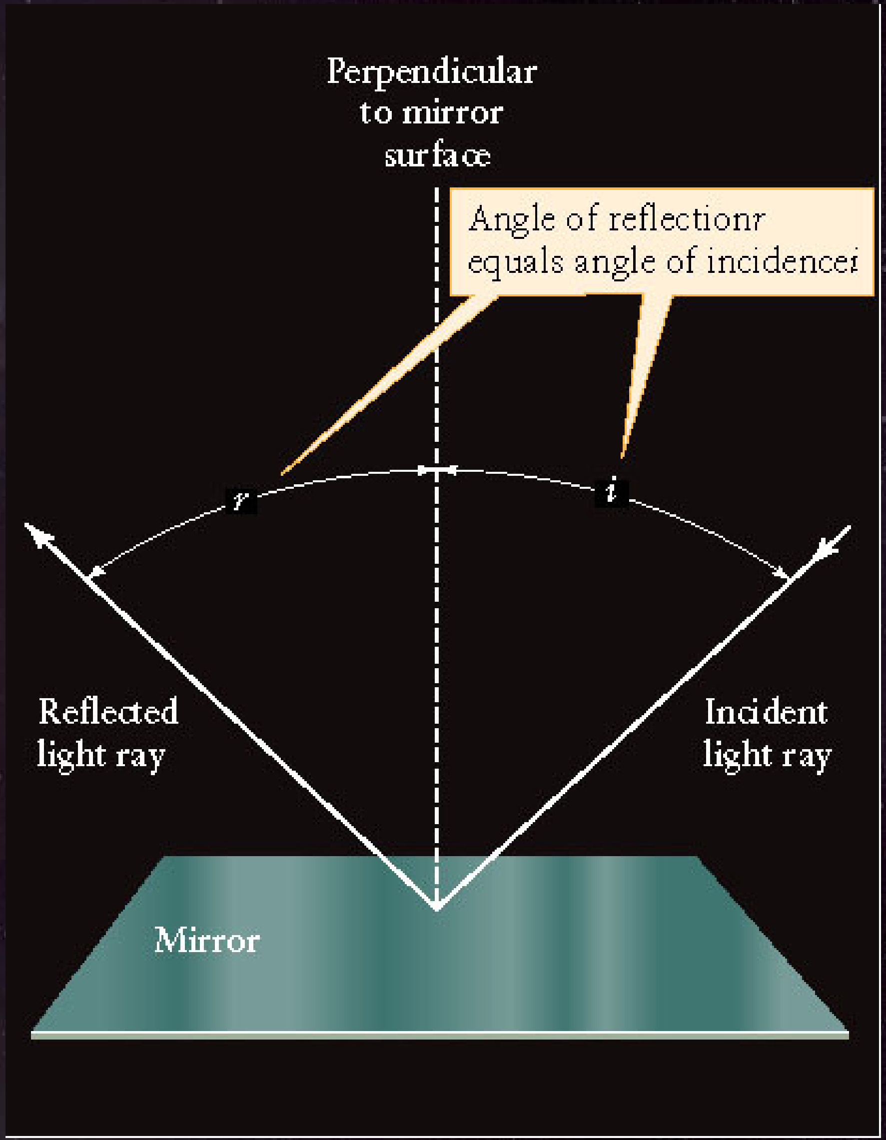
For this reason, the largest useful refractor ever built had a lens with a diameter of 40 inches / 1 metre. For comparison, the Radcliffe telescope at ULO is one of the largest refractors in the UK, and has a lens with a diameter of 24 inches / 60 cm.

Reflectors - advantages

Reflecting instead of refracting light has many advantages:

1. Reflection is not wavelength-dependent. All light, no matter what its wavelength, is reflected at an angle which is the same as the *angle of incidence*.

This means there is no chromatic aberration.



Reflectors - advantages

2. While a refracting lens needs to be of extremely high quality throughout its volume, a reflecting mirror only needs to be of high quality on its surface.

What you put behind the mirror to support it makes no difference, so it's much cheaper to construct a large, very high quality mirror, than it is to construct a large very high quality lens.

Reflectors - advantages

3. Unlike a lens which has to sit at the end of a tube, far from the pivot, a mirror can be positioned close to the pivot.

Also, while internal flexure of a lens gets more and more difficult to avoid for larger lenses, mirrors do not suffer so much from this.

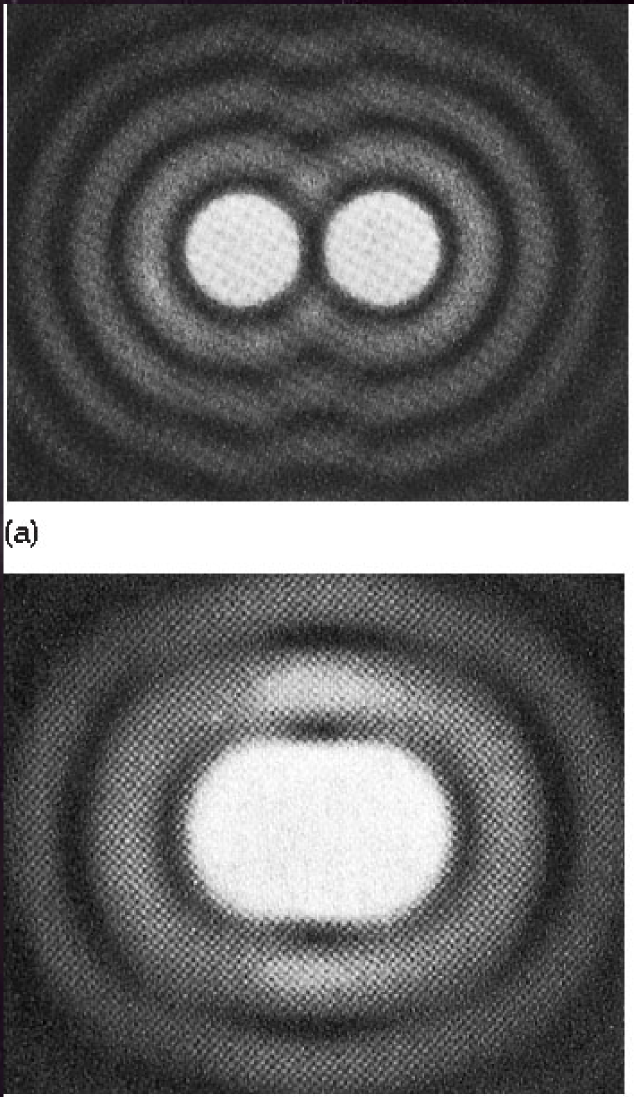
For these reasons, all the telescopes used today for professional astronomy, and most amateur telescopes as well, are reflectors.

The largest optical telescopes in the world are the twin Keck telescopes on Hawaii, with 10m mirrors. At about 10 times the diameter of the largest refractor, they have 100 times the light-gathering capability.

Limits to observations

Why make big telescopes? First of all, you can gather more light. The 10m Keck telescope can see things 10 million times fainter than Galileo's 3cm telescope could.

The second reason is that a larger lens or mirror can *resolve* smaller objects. There is a fundamental limit to how small an object any telescope can resolve, caused by *diffraction*. The smaller a telescope aperture, the more it diffracts light, so larger telescopes suffer from less diffraction.



(a) Two light sources with angular separation greater than angular resolution of telescope: Two sources easily distinguished

(b) Light sources moved closer so that angular separation equals angular resolution of telescope: Just barely possible to tell that there are two sources

Limits to observations

For a perfectly constructed and polished mirror or lens, the *diffraction limit* is given by

$$\theta = 2.5 \times 10^{-4}\ \lambda/D$$

where is the resolution limit, is the wavelength in nanometres, and D is the diameter of the mirror or lens.

So, for visible light (500nm), the human eye's diffraction limit is 2.5×10^{-4} x 500 / 0.005 = 25 arcseconds

For the Hubble Space Telescope, with a 2.4m mirror, the diffraction limit is 2.5×10^{-4} x 500 / 2.4 = 0.05 arcseconds

For the 10m Keck telescope, the limit is 2.5×10^{-4} x 500 / 10 = 0.0125 arcseconds

Limits to observations

In practice, the Hubble Space Telescope can achieve its diffraction-limited resolution, but the Keck could not, originally.

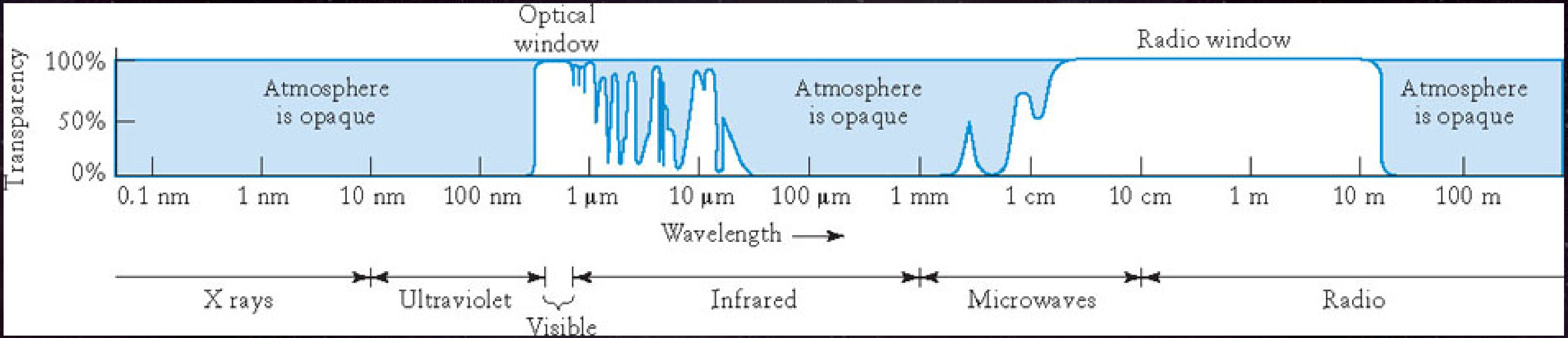
This is because the Keck is on the surface of the Earth, underneath the atmosphere. The atmosphere is in constant motion, and this 'smears' images out a bit. It is the reason stars 'twinkle'.

The resolution limit imposed by the atmosphere is called the *seeing*. At the very best sites, the seeing might typically be ~0.6 arcseconds. At Mill Hill, it is normally 3-4 arcseconds.

I have seen ~10 arcsecond seeing on La Palma...!

More advantages of space

Another problem with the atmosphere is that it absorbs very strongly at many wavelengths:



If you want to observe gamma rays, x-rays, UV or sub-mm radiation, you need a space observatory. For sub-mm, you can at least put your observatory at very high altitudes, above most of the water vapour that absorbs strongly at these wavelengths.

The nature of light

Light is electromagnetic radiation, and the different colours correspond to different wavelengths. A prism bends light of different wavelengths by different amounts.

But what is this radiation? Is it particles, or is it waves?

Strangely, it is both; light can behave both as a particle and a wave. It *diffracts*, like sea waves entering a harbour, but it can also knock electrons out of a metal, in a way that is only explicable in terms of particles.

The electromagnetic spectrum and temperature

Electromagnetic radiation is one of the main ways we can investigate astronomical objects. So, what can we find out from it?

Luckily, a huge amount!

A basic observation about stars is that they are not all the same colour. A very good example of this is β Cygni (Albireo).

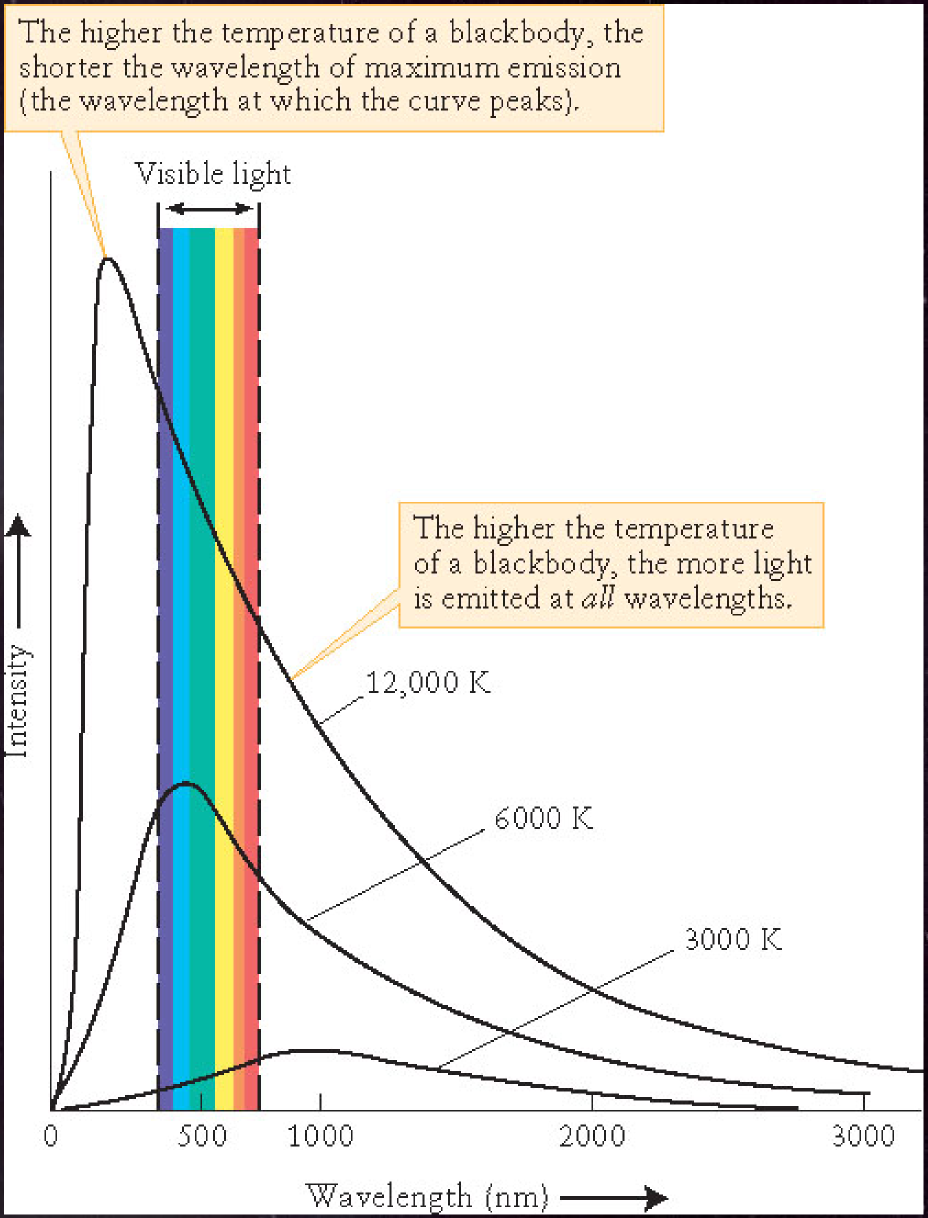
The electromagnetic spectrum and temperature

The electromagnetic spectrum and temperature

The hotter an object is, the shorter the wavelength of light it emits.

In the idealised case of a *black body* (that is, one that absorbs all the radiation that falls on it), the radiation emitted at a given temperature has a simple form, shown in the figure.

EM radiation of *all* wavelengths is emitted by any black body.



Black body radiation

There is a very simple relation between the temperature of a black body, and the wavelength at which its emission will peak:

$$\lambda = \frac{0.0029 \text{ m}}{T}$$

This relationship was discovered by Wilhelm Wien in 1893, and is called *Wien's Law*.

Black body radiation

Wien's law tells us the temperature of a black body, if we know the wavelength where its emission peaks.

Another very useful equation relates the total amount of energy emitted to the temperature of a spherical black body, and its area.

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

L is the energy emitted; R is the radius. σ is a constant. So, if you doubled the temperature of an object, you would increase the amount of energy it emitted by a factor of 16.

This equation is called the *Stefan-Boltzmann Law*, after the two physicists who discovered it.

Wien and Stefan-Boltzmann - example

Sirius, the brightest star in the sky, has a radius 1.7 times that of the Sun, and a surface temperature of 10,000K. How much brighter is Sirius than the Sun?

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

$$\frac{L(\text{Sirius})}{L(\text{Sun})} = \frac{R(\text{Sirius})^2 \times T(\text{Sirius})^4}{T(\text{Sun})^2 \times T(\text{Sun})^4}$$

$$= 1.7^2 \times (10000/5800)^4$$

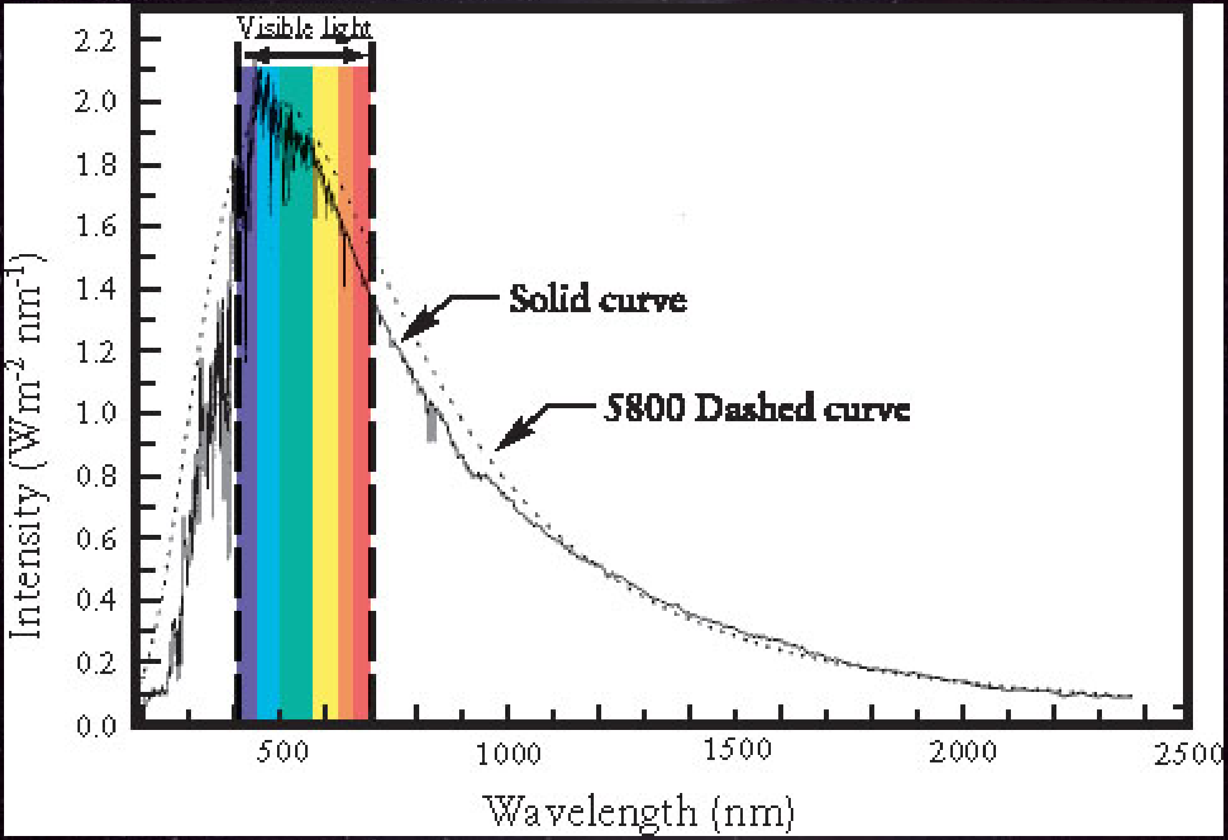
$$= 25.5$$

So Sirius is 25.5 times brighter than the Sun.

What EM radiation can tell us

Using Wien's law, we can use the fact that stars are quite like black bodies to estimate their temperatures. But so far we don't know anything about their composition.

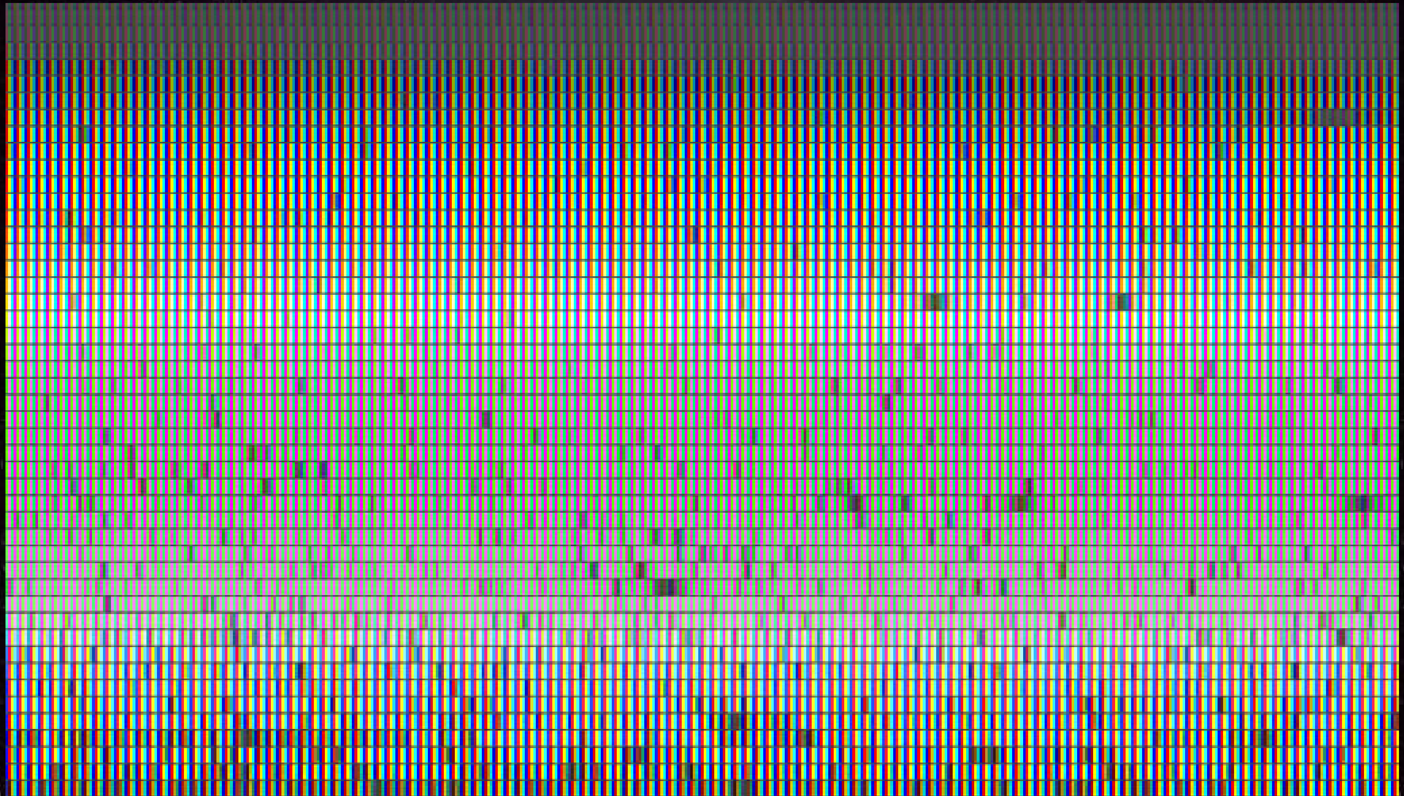
Stars are not exactly like BBs:



What EM radiation can tell us

The difference between a stellar spectrum and a black body can tell us about what the star is made of.

Joseph von Fraunhofer made a major advance in astronomy by examining the spectrum of the Sun at very high magnification. He found that it was full of dark lines.



What EM radiation can tell us

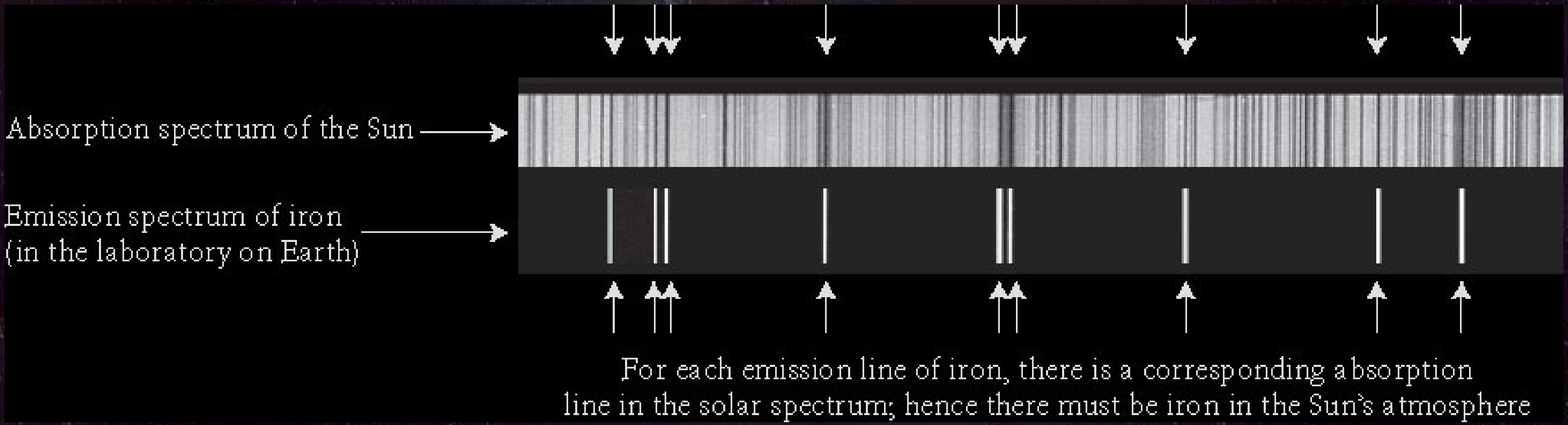
The meaning of the dark lines became clear from *flame tests* – if you throw some salt into a flame, you will see that you get a bright yellow light.

If you analysed that light, you'd find that it was being emitted at exactly the same wavelengths as the two particularly dark absorption lines in the yellow part of the solar spectrum.

What EM radiation can tell us

Clearly, the two dark lines in the yellow part of the Sun's spectrum must be caused by sodium in its atmosphere.

Other lines correspond with the light emitted by other elements in flame tests, and so those elements must also be present – for example, iron:



Light and motion

So, for continuous spectra, the peak wavelength tells us the temperature of the emitting body. For line spectra, the wavelengths of the lines tell us what elements there are in the emitting gas.

Another thing we can tell from spectroscopy is how fast things are moving, along our line of sight.

This is possible because of the *Doppler effect* – familiar to all from the sound of cars going by. The effect occurs for EM radiation as well.

Light and motion

This means that if you know what wavelength some radiation was emitted at (as you would for, say, a hydrogen Balmer line), then the observed wavelength tells you the velocity of the object along the line of sight.

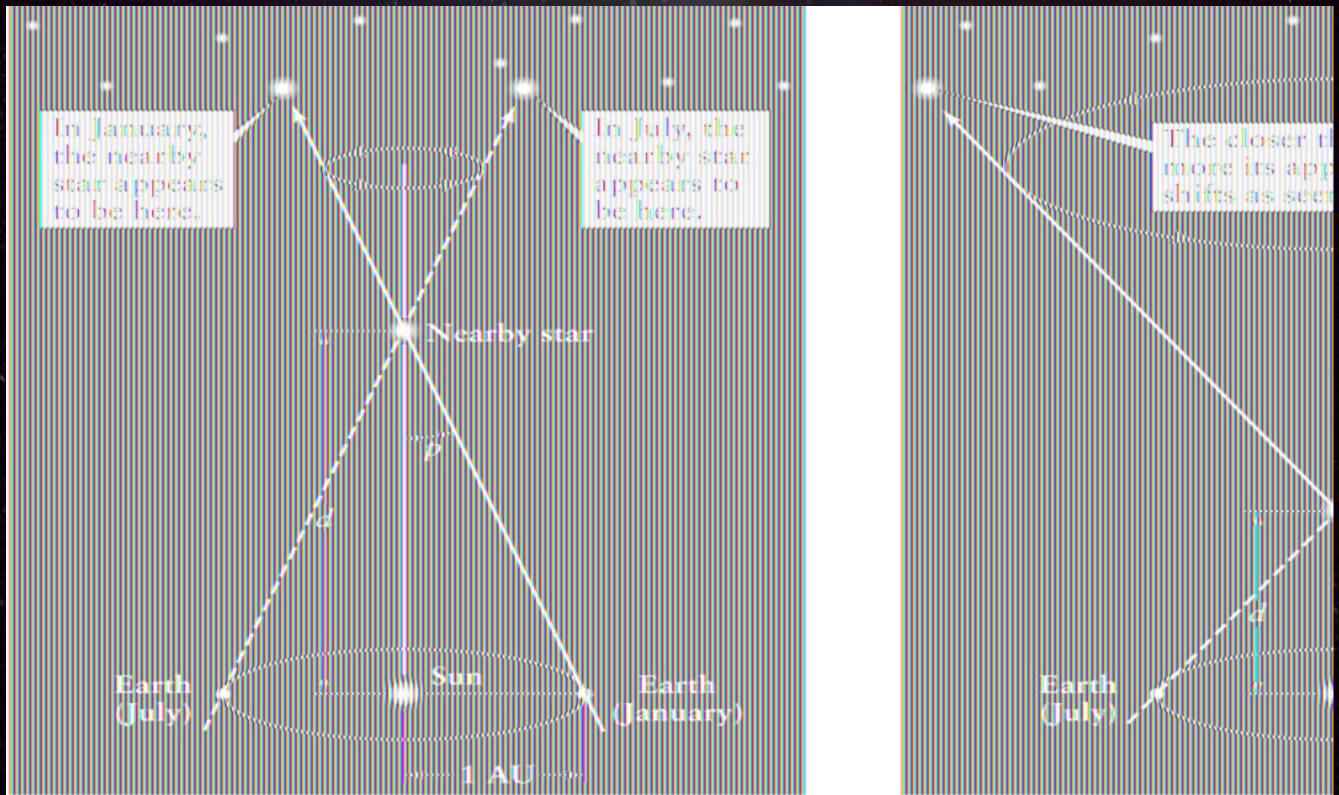
The change in wavelength is related to the velocity by a simple equation:

$$\Delta\lambda/\lambda = v/c$$

So, for example, in the spectrum of Sirius, you see the Balmer alpha absorption line at 656.260 instead of 656.277 nm. This means that Sirius is moving towards us at 7.7km/s

Stars – apparent motions

Even the closest stars are extremely distant from Earth. 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 close

Stars – apparent motions

A star at a distance of 1 parsec would have a parallax of one arcsecond – this is the definition of parsec, which is short for *parallax 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 – 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

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

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

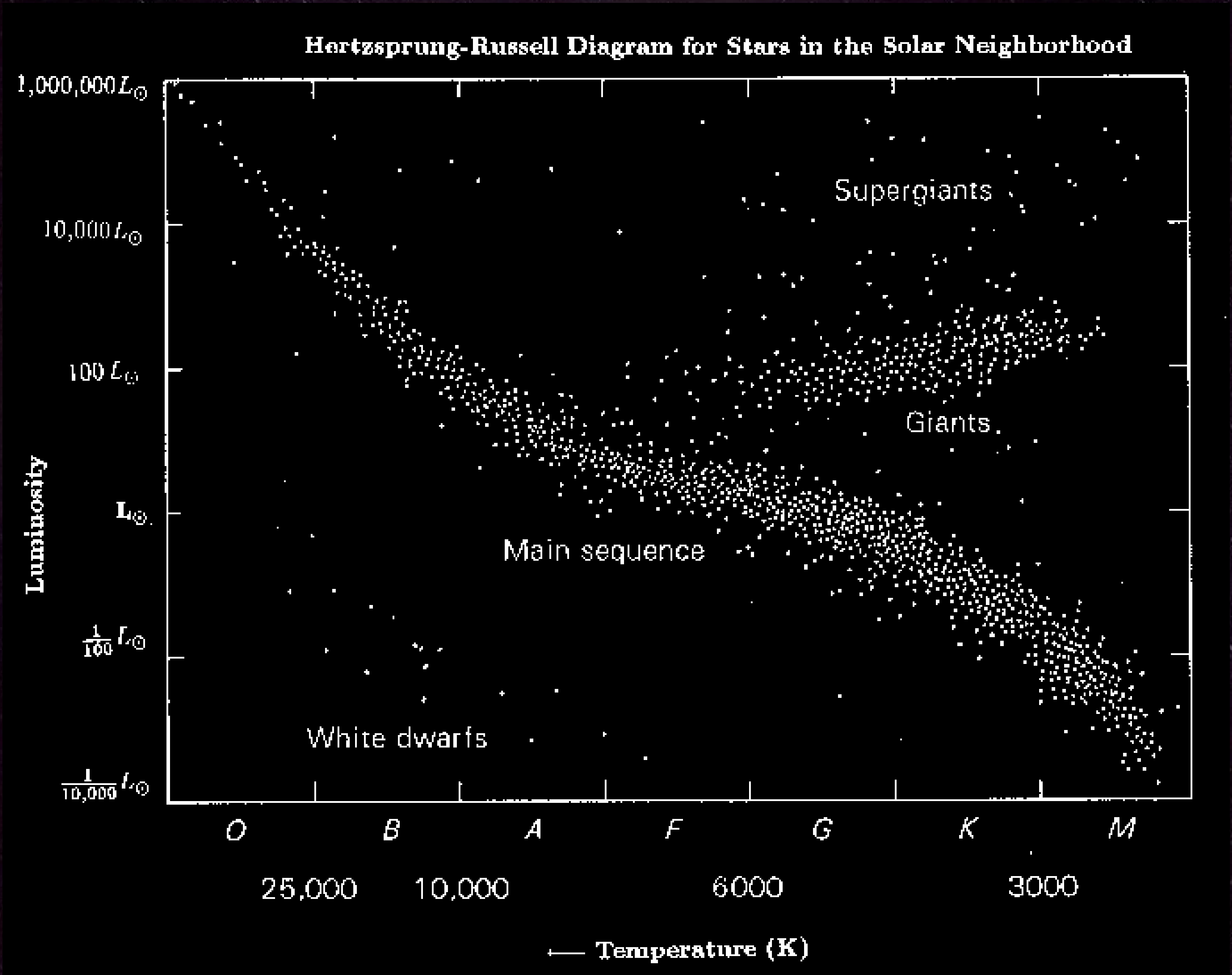
Stars – luminosities

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 - 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.

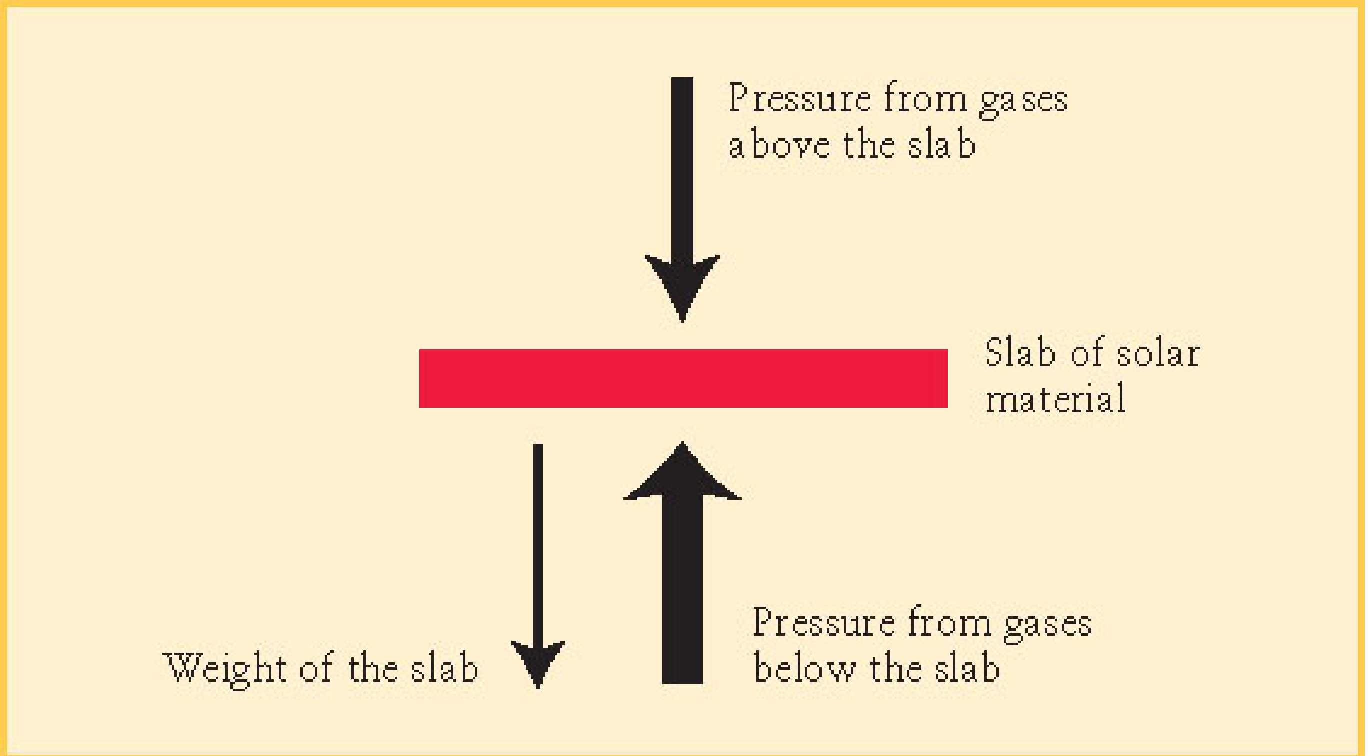
Most stars fall in a band running from top left to bottom right. This is called the *main sequence*. The Sun lies on the main sequence. It and all the other stars on it are in a steady state – they are burning hydrogen at their cores, and the energy released supports them against gravitational contraction.

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.

Main sequence stars

Stars on the main sequence are steadily burning hydrogen at their cores. They are neither contracting nor expanding, but are 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 star:



Stars – sizes

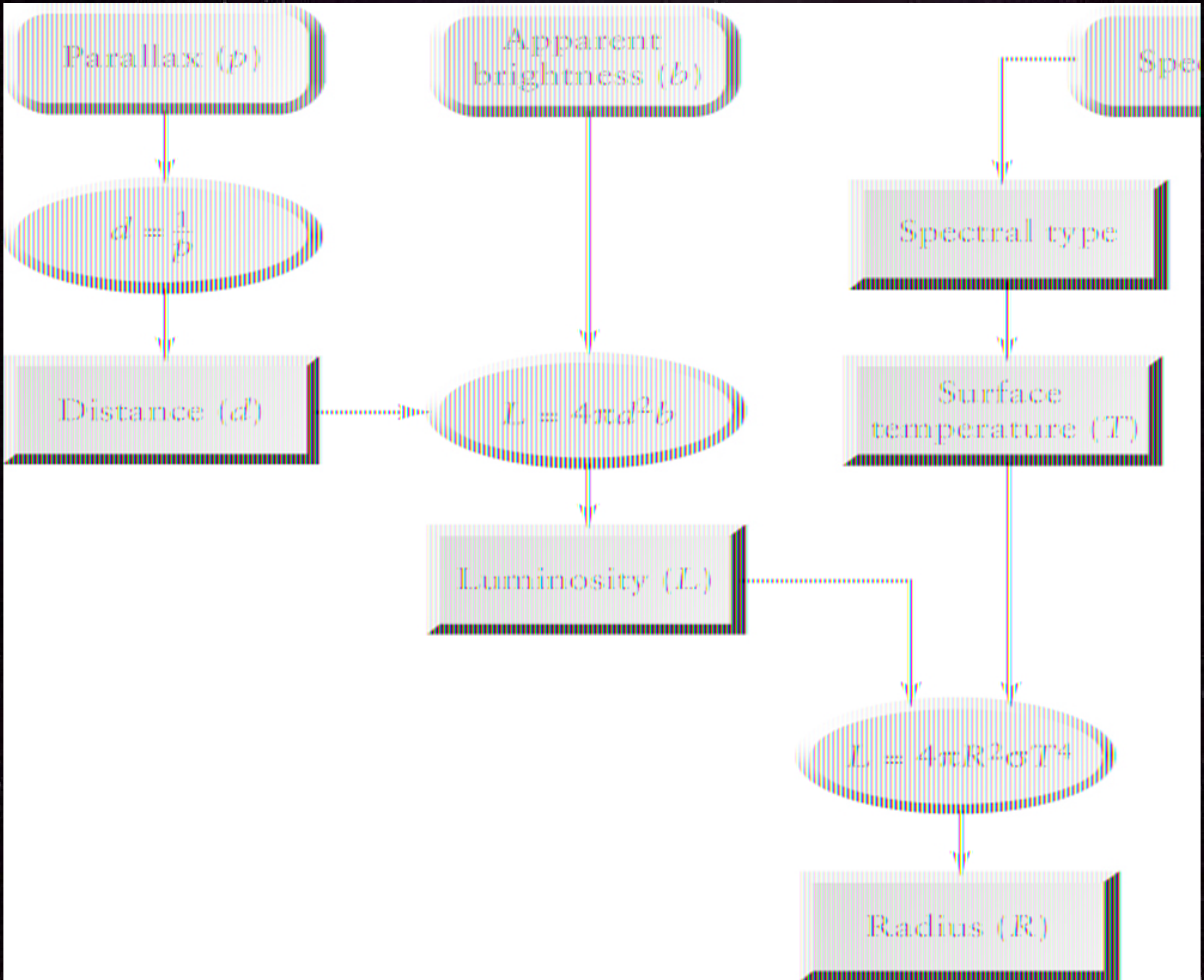
We learned earlier that the luminosity of a star is related to its temperature and radius:

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

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

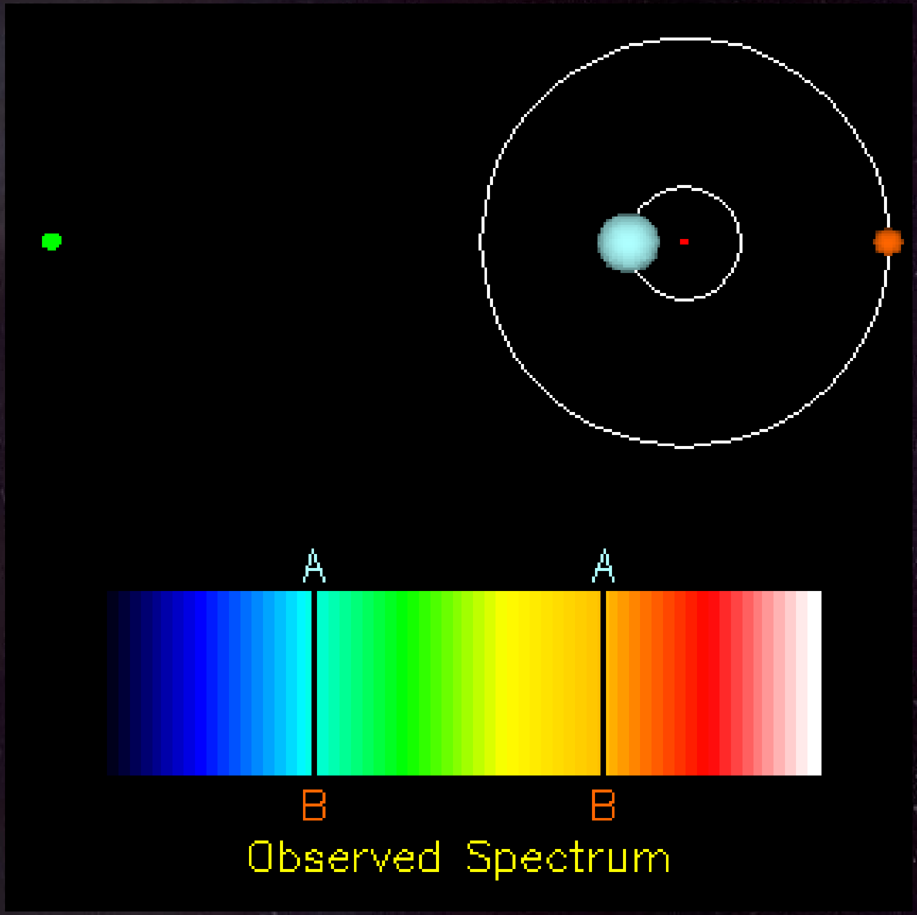
This diagram summarises how we can find out about the properties of stars:



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

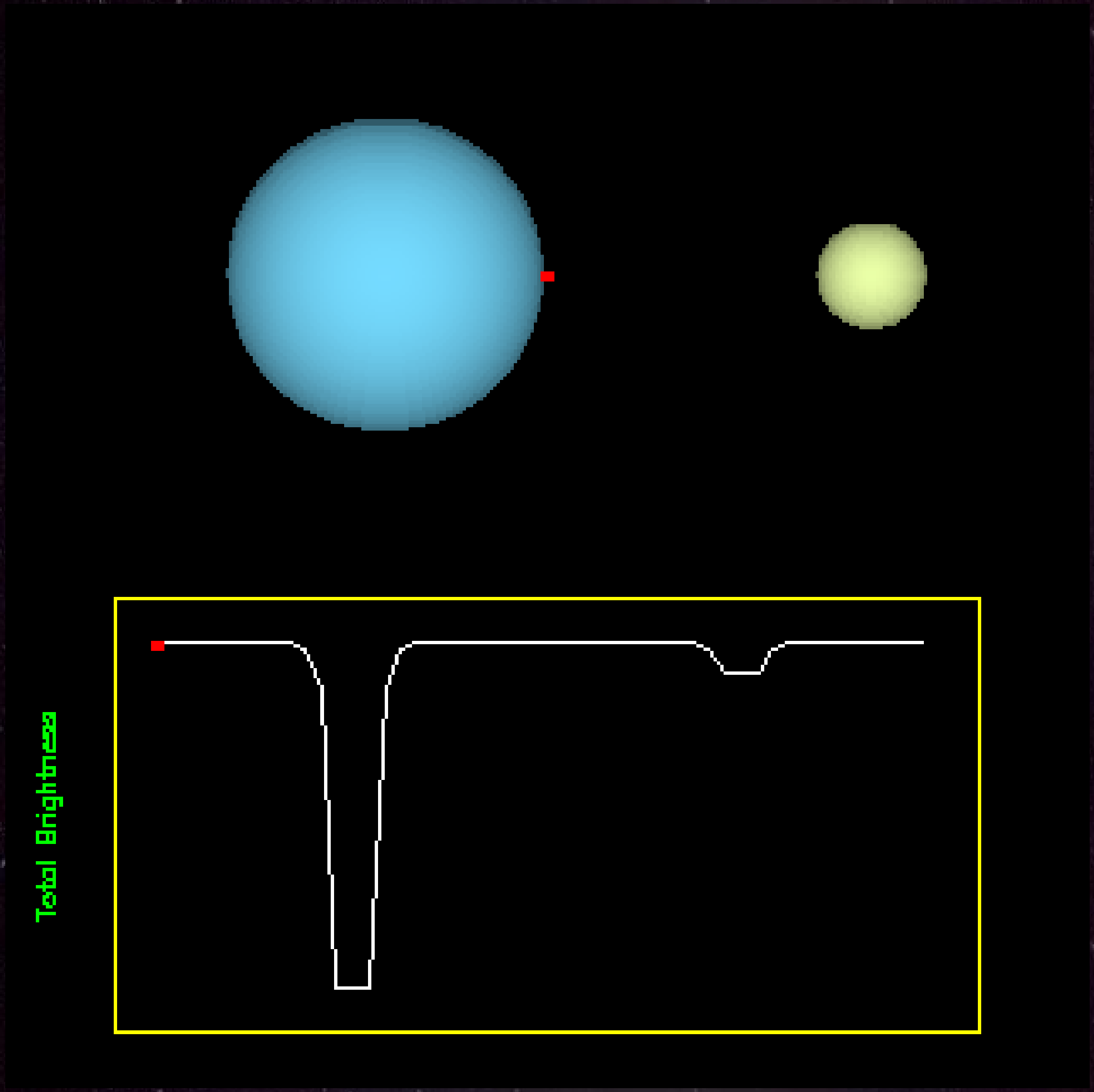
The difficulty with binaries is that normally, we don't know how the plane of the orbit is orientated. This complicates the determination of masses.

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:

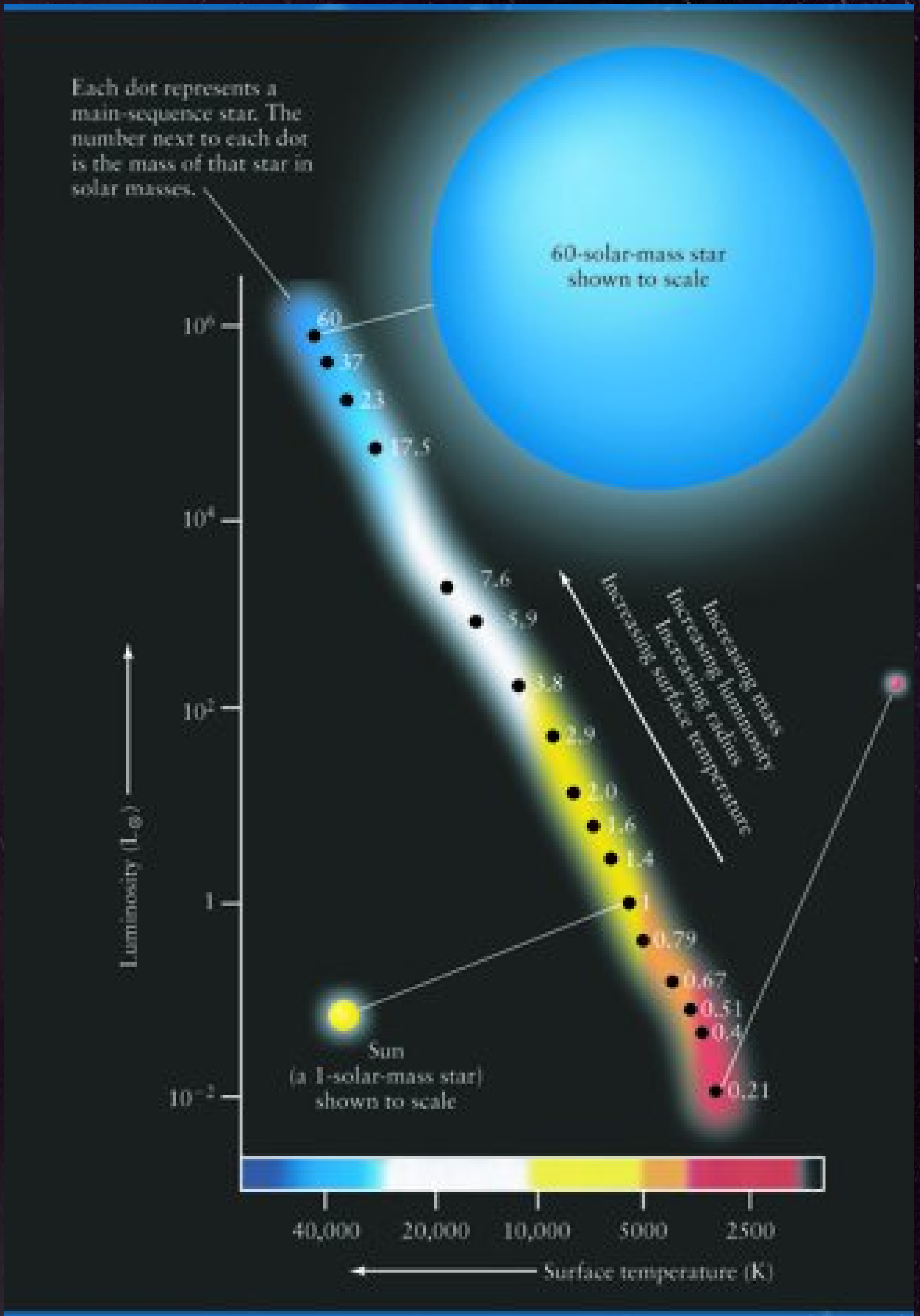


Stars – masses

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.



Stellar lifetimes

Stars stay on the main sequence until they run out of hydrogen in their cores. The time this takes depends on the mass – more massive stars burn their fuel much more quickly.

Stellar lifetimes range from a few million years for very massive stars to hundreds of billions of years for the lightest.

The deaths of stars

When the fuel runs out, the balance between gravity pulling material in and gas pressure pushing it out breaks down. The core begins to contract because energy is no longer being produced.

As the core contracts, it gets hotter and hotter, as the pressure increases. What happens next depends on the mass of the star.

For stars with less than 0.4 $M_{\odot}$, the temperature does not get hot enough for anything else to happen. The star will end its life as an inert ball of helium, just radiating away its internal heat.

But the universe is not yet old enough for any stars this light to have burned all their hydrogen.

The deaths of stars

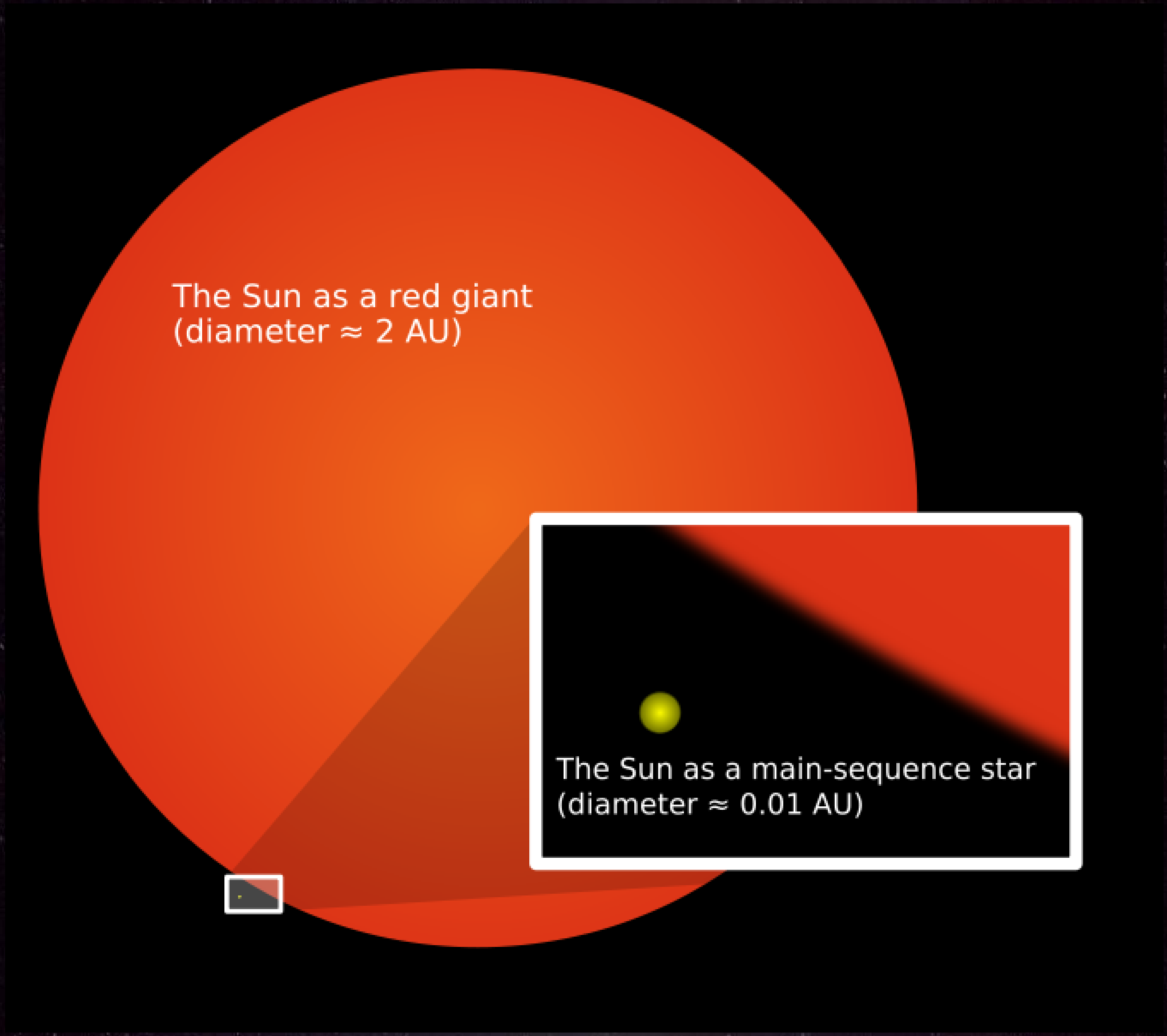
For stars heavier than $0.4M_{\odot}$ and lighter than 2 or 3 $M_{\odot}$, the core contraction and heating makes the outer layers expand and cool greatly. The star becomes cooler but much larger and more luminous. It is a *red giant*.

The core will eventually heat up to a temperature of 100 million K. Just as hydrogen nuclei can fuse to form helium, releasing some energy, so helium nuclei can fuse to form carbon and oxygen, releasing some energy. But the temperature and density need to be much higher, and less energy is released per atom.

When the core temperature reaches 100 million K, helium fusion begins, and the star is once again in a state of equilibrium.

The deaths of stars

Red giants are extremely large!



The deaths of stars

For a black body: $L \propto R^2T^4$

The temperature drops by a factor of ~2, but radius goes up by a factor of ~100.

So, the luminosity increases by a factor of $(100^2 \times 0.5^4) = 600$

The deaths of stars

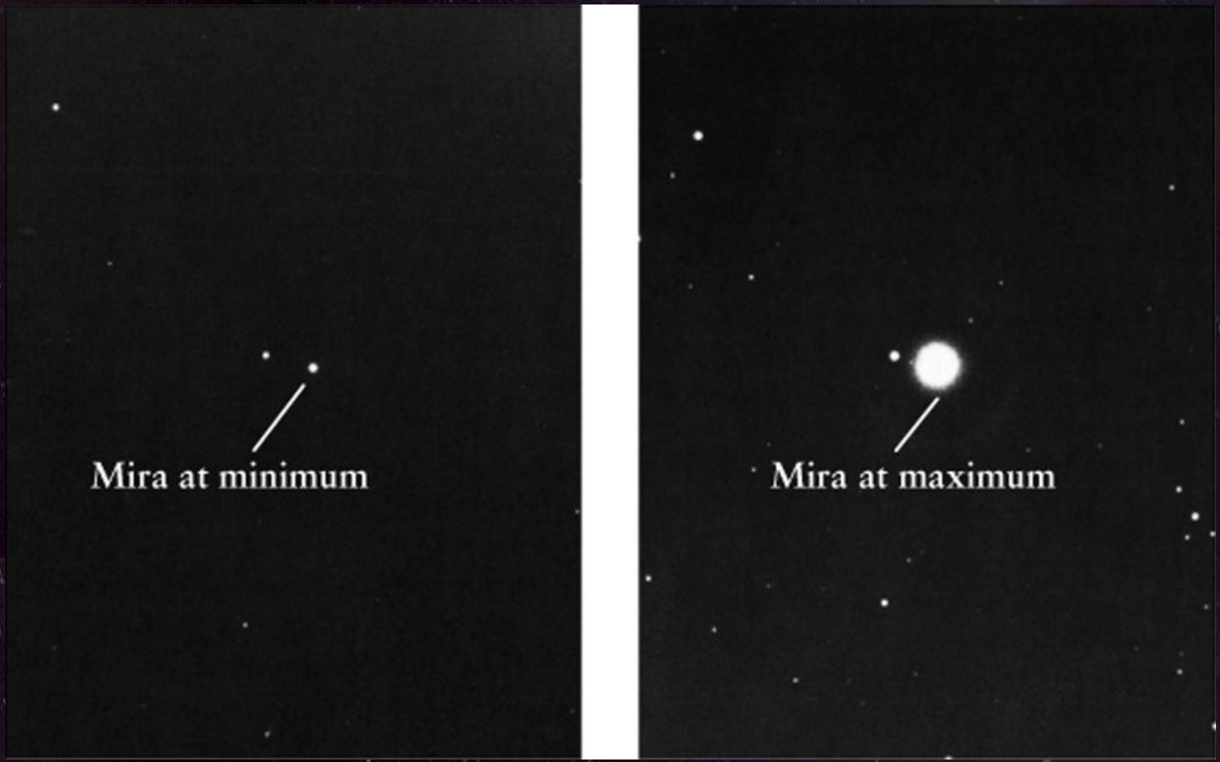
While helium is burning in the core, hydrogen burning continues in a shell around the centre of the star. What happens when helium runs out in the core?

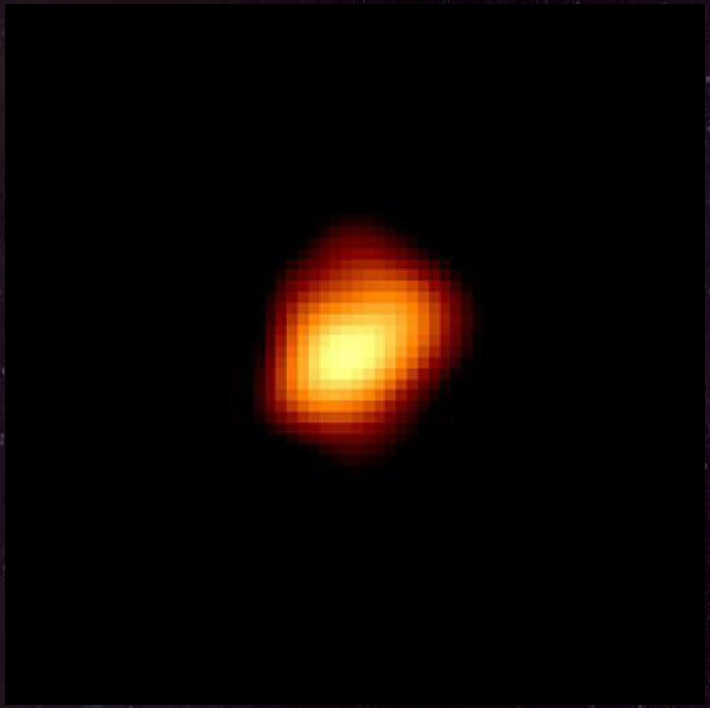
Again, the core will contract and heat, the star will expand again. An inert carbon-oxygen core is surrounded by a helium-burning shell and a hydrogen-burning shell.

The rate of helium burning is proportional to T^{40}!! In a thin shell, a small variation in the pressure causes a small change in the temperature, which causes a large change in the reaction rate. The burning is extremely unstable, and the star begins to shed its outer layers.

The deaths of stars

Unstable helium burning means that evolved stars almost always go through phases where they are pulsating, and therefore varying in brightness. A great example is Mira.

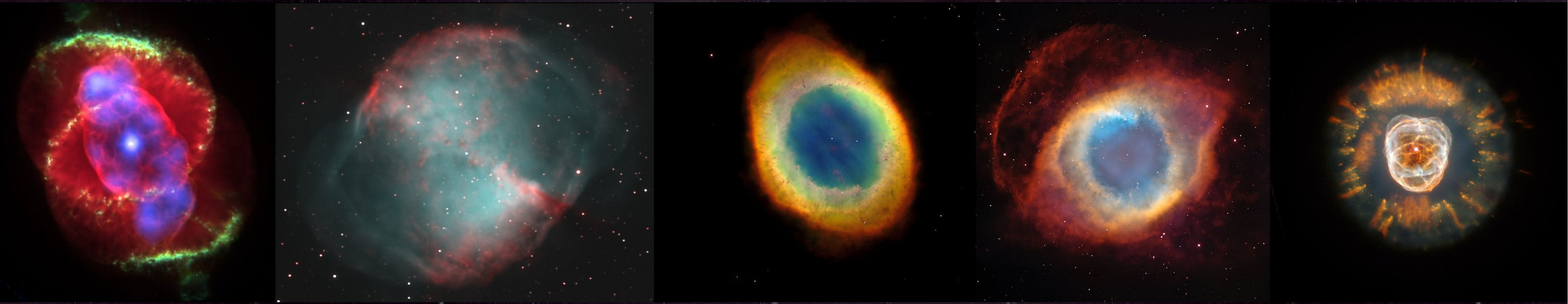




The deaths of stars

Instabilities and pulsations drive away the outer layers from stars. Red giants can lose 10^{-7} solar masses per year. For comparison, the Sun loses about 10^{-14} solar masses per year via the solar wind.

If the mass of the star is lower than about 8 solar masses, this mass loss eventually puts an end to its evolution. The reduced pressure stops the nuclear reactions. The atmosphere drifts away, and is lit up by the exposed core. A *planetary nebula* has formed.



Note that planetary nebulae were so-called because they looked a bit like planets in early telescopes

The deaths of stars

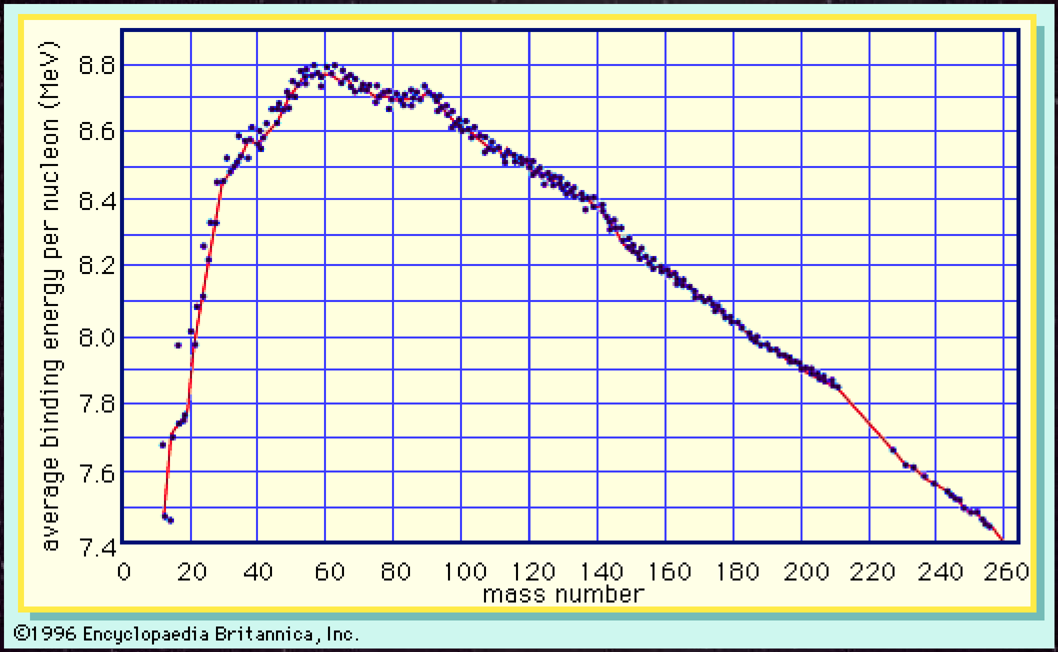
Stars with masses greater than ~4$M_\odot$ are heavy enough that nuclear reactions can still proceed in the core despite mass loss. The core will eventually get hot enough for carbon to undergo fusion, forming oxygen, neon, sodium and magnesium.

Stars with M>~8Mo will then begin *neon fusion*, then *oxygen fusion*, then *silicon fusion*. Each step proceeds more and more quickly. The main sequence, hydrogen-burning phase lasted a few million years. Helium burning lasts a few hundred thousand years. Carbon fusion takes a few hundred years, neon fusion a year, oxygen fusion a few months, and silicon fusion is over and done with within a day.

What next?

The deaths of stars

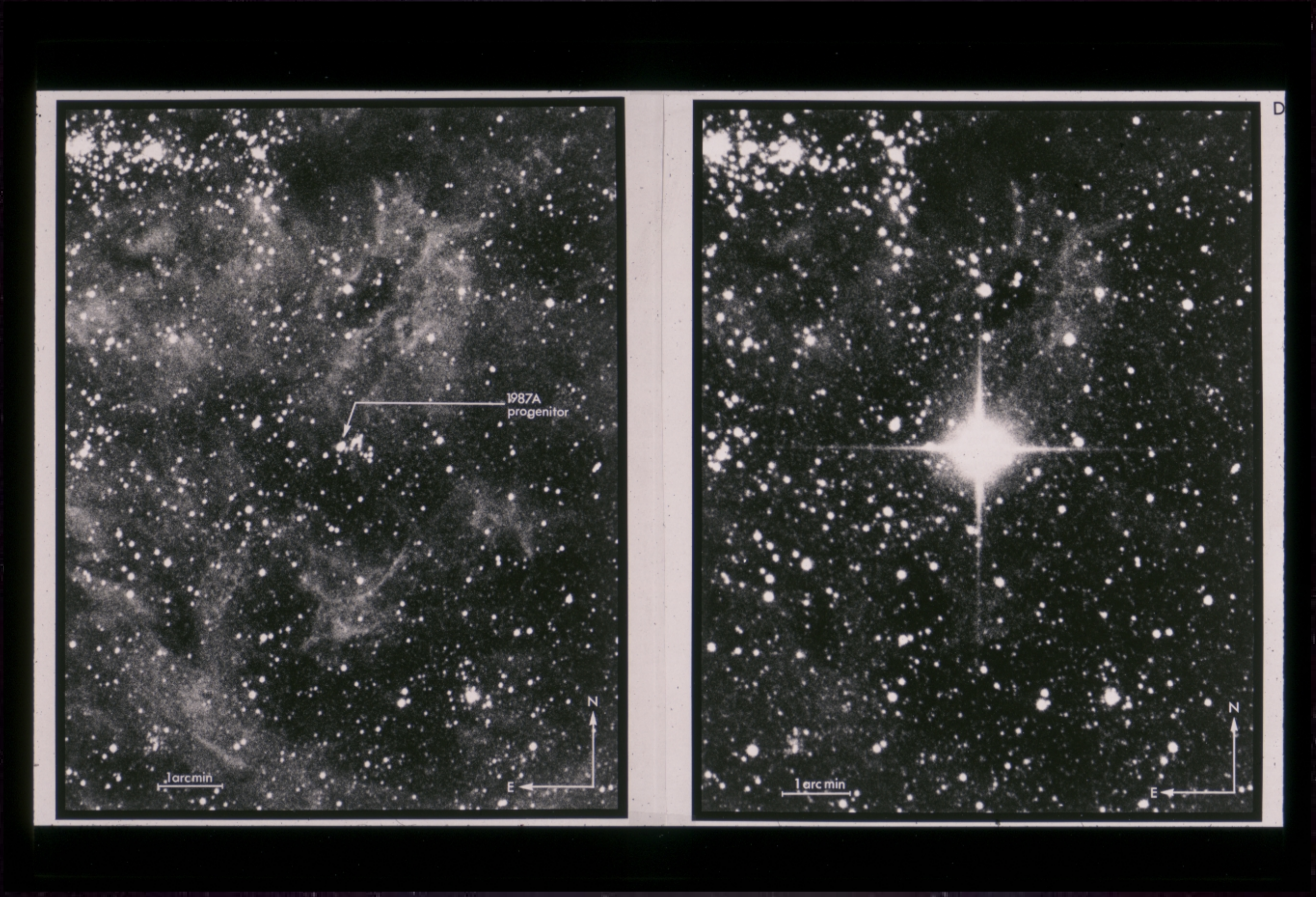
Nuclear fusion releases energy if the product is more tightly bound than the atoms that went into it. This graphs shows how tightly bound atomic nuclei are:



The most stable nucleus is iron. Once silicon has fused to form iron, the star has nowhere to go. The core's energy source runs out suddenly.

The deaths of stars

The core collapses. The outer layers are suddenly unsupported, and fall in. They crash into the core, and a huge shock wave rebounds outward, destroying the star in a *supernova*.



The deaths of stars

Supernovae briefly shine as brightly as a galaxy – and emit as much energy as the whole rest of the *universe*!!

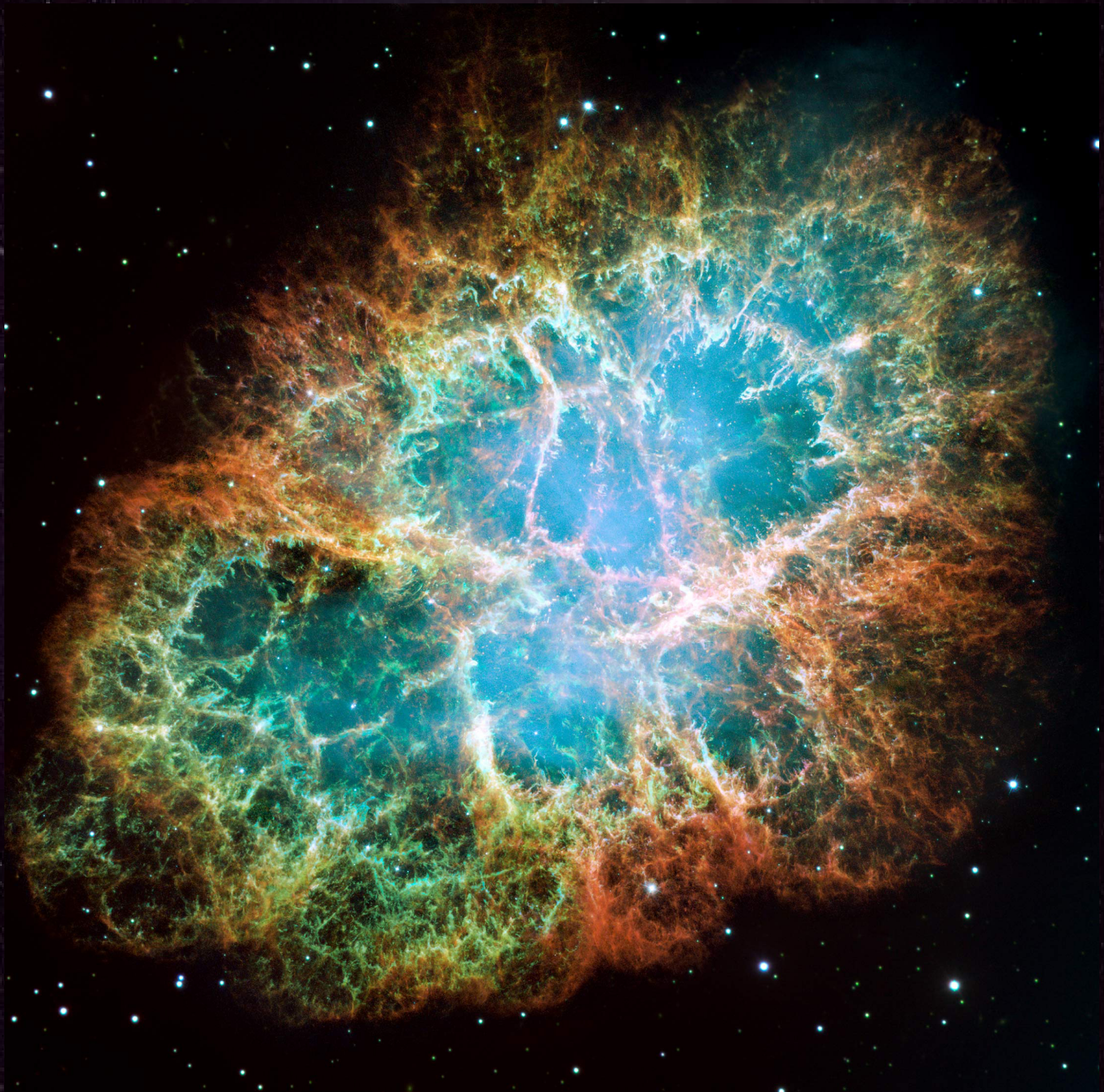
Most of this energy is carried away in the form of neutrinos. A burst of neutrinos from Supernova 1987A was detected on earth – one of the first major successes in neutrino astronomy.

What is left behind? A *supernova remnant* – the slowly fading outer layers of the star, moving away into space.

And at the centre – something exotic.

The deaths of stars

Most famous supernova remnant is the Crab Nebula – the result of an explosion seen by Chinese astronomers in 1054.



The deaths of stars

For a relatively low-mass supernova, the remaining object at the centre might be a white dwarf. Mostly, though, the mass of the remaining core is enough that protons and neutrons are compressed together into neutrons, and you get a *neutron star.*

A neutron star might be as massive as the Sun but only a few miles across.

If the star was massive enough, its remnant core will be so massive and so dense that even light cannot escape from it. It will be a *black hole*.