Chapter 5 – the nature of light

The speed of light

Light travels very fast. Early scientists realised during thunderstorms that it travels much much faster than sound.

Galileo made an early attempt to measure its speed. He and an assistant stood on hills and flashed lights at each other. No matter how far apart the hills they chose, the time between one flashing and the other replying never got longer.

One possible conclusion: light travels infinitely fast

A slightly better conclusion: light travels too fast to be measure by human reactions.

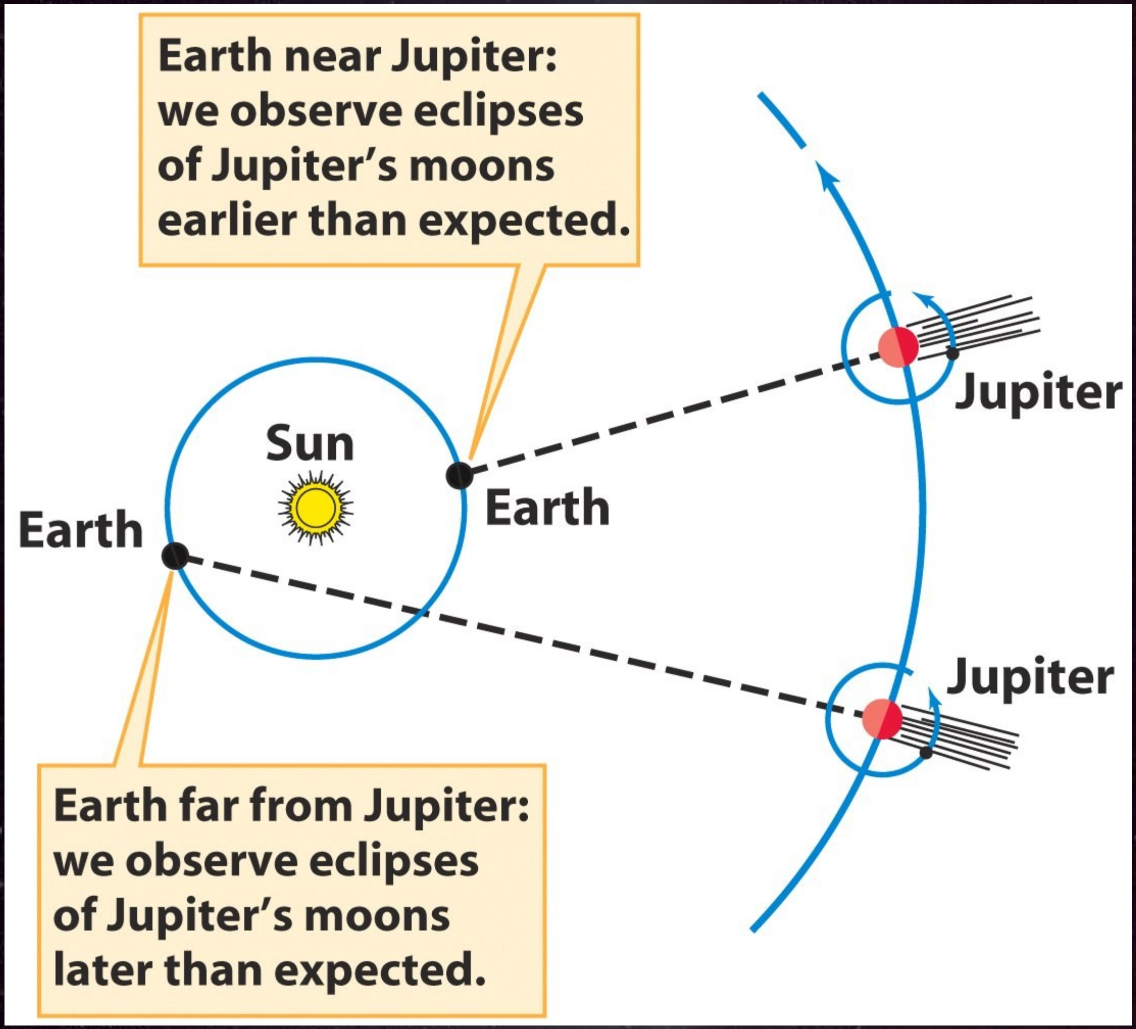
The speed of light

Light travels so fast that you need very long baselines over which to measure it.

Danish astronomer Ole Rømer discovered this when observing the eclipses of Jupiter's moons.

The speed of light

In 1676, Rømer found that the eclipses of Jovian satellites always occurred earlier than predicted when Jupiter was near opposition (that is, when the distance from Earth to Jupiter is smallest), and later than predicted when Jupiter was near conjunction.



The speed of light

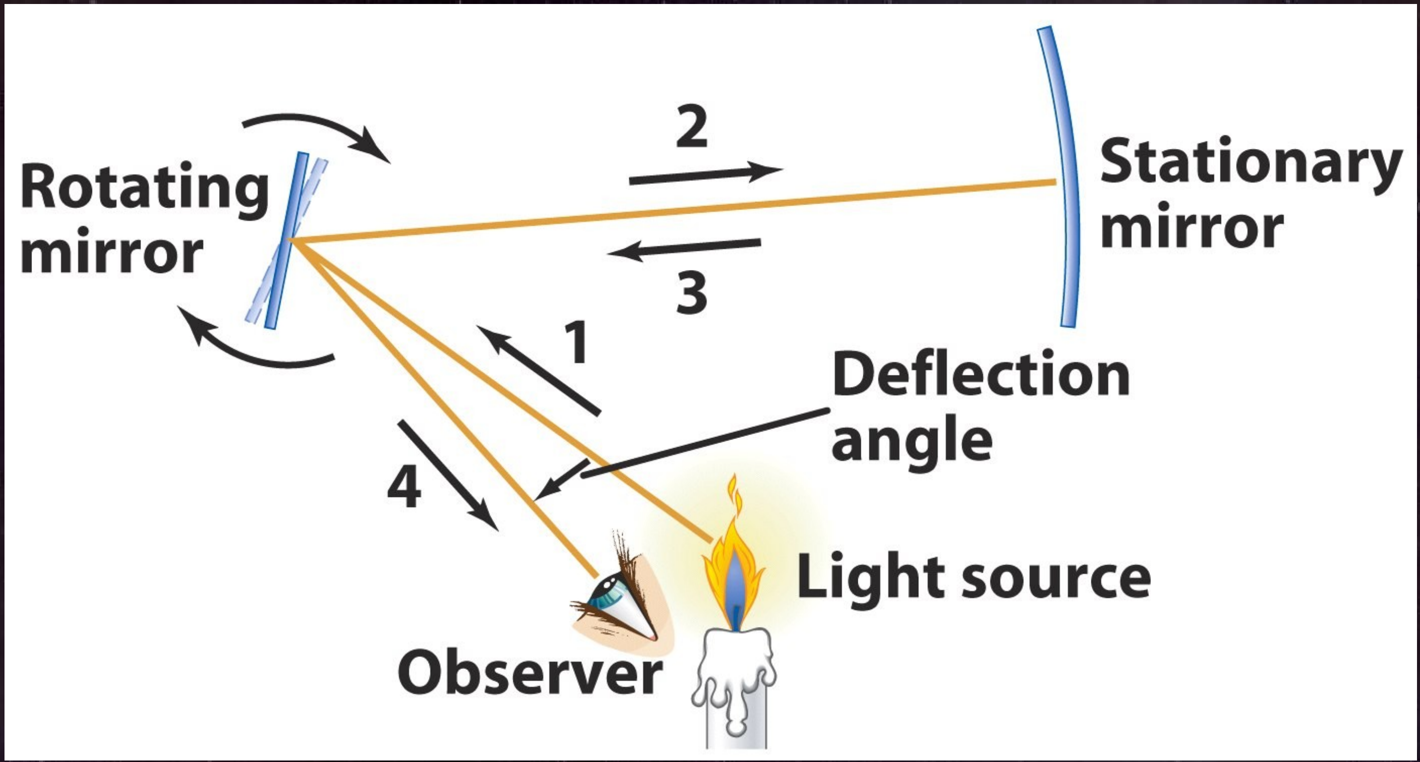
The maximum difference from the predicted times was 8.3 minutes. Rømer correctly interpreted this as the time light takes to travel the distance between the Earth and the Sun.

This distance was not known in Rømer's time, so he couldn't go on to estimate the speed of light.

We now know that this distance – the Astronomical Unit – is 150,000,000 kilometres, and so the speed of light is 300,000 km / s.

The speed of light

In 1850 Fizeau and Foucalt also experimented with light by bouncing it off a rotating mirror.



The light returned to its source at a slightly different position because the mirror has moved during the time light was travelling

Measuring the displacement gave the speed of light.

The speed of light

Modern experiments give the speed of light (in a vacuum) as

$$c = 299{,}792{,}458 \text{ m/s}$$

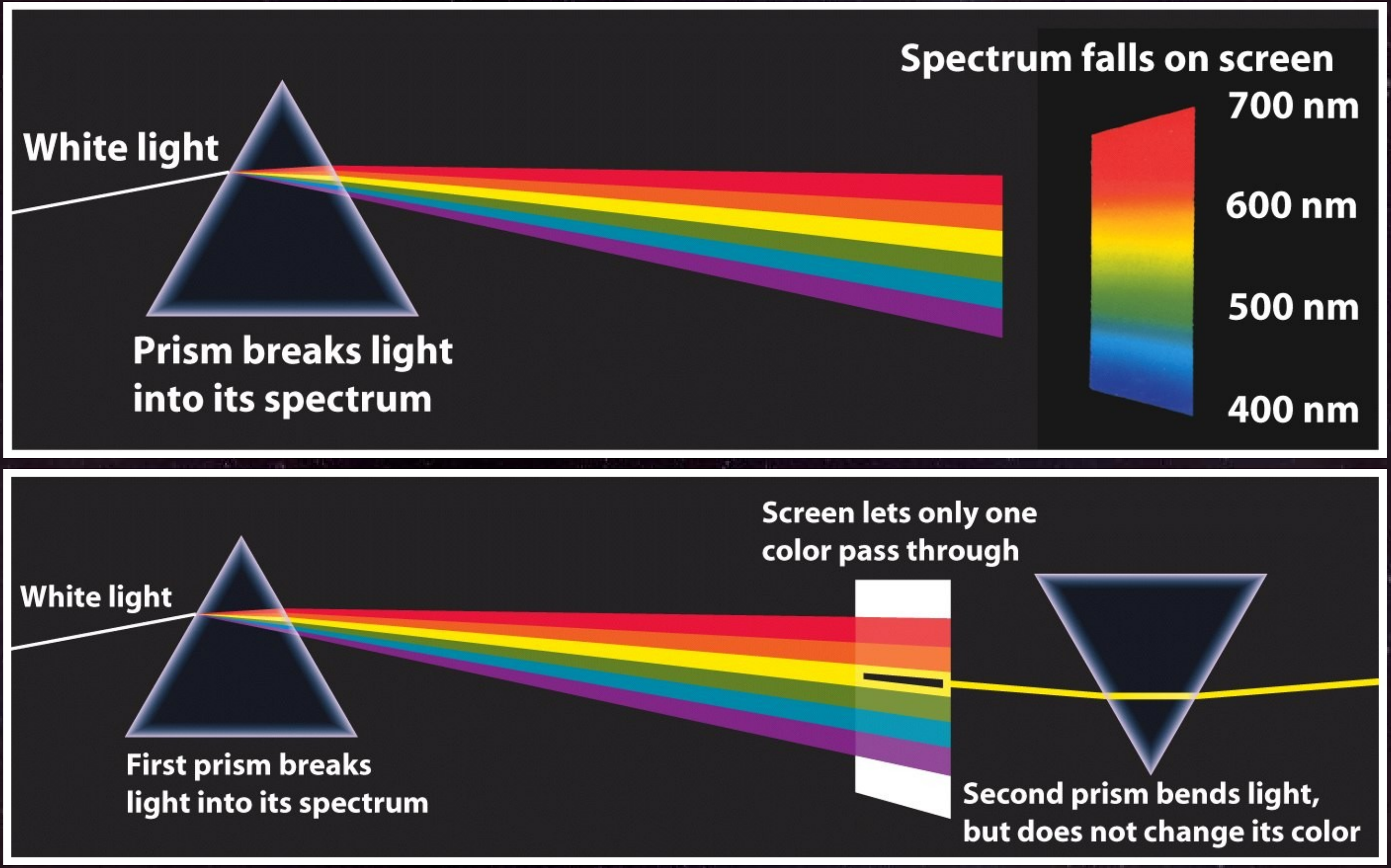
(c is from latin *celeritas*, meaning speed).

Generally it's ok to use $c = 300{,}000{,}000$ m/s = 3×10^5 km/s

c is a very important number in physics, and occurs in many equations: for example, $E=mc^2$

The nature of light

White light is dispersed into colours when it passes through a prism. It used to be thought that this was something to do with the prism itself, rather than the light. Newton proved this wrong.



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.

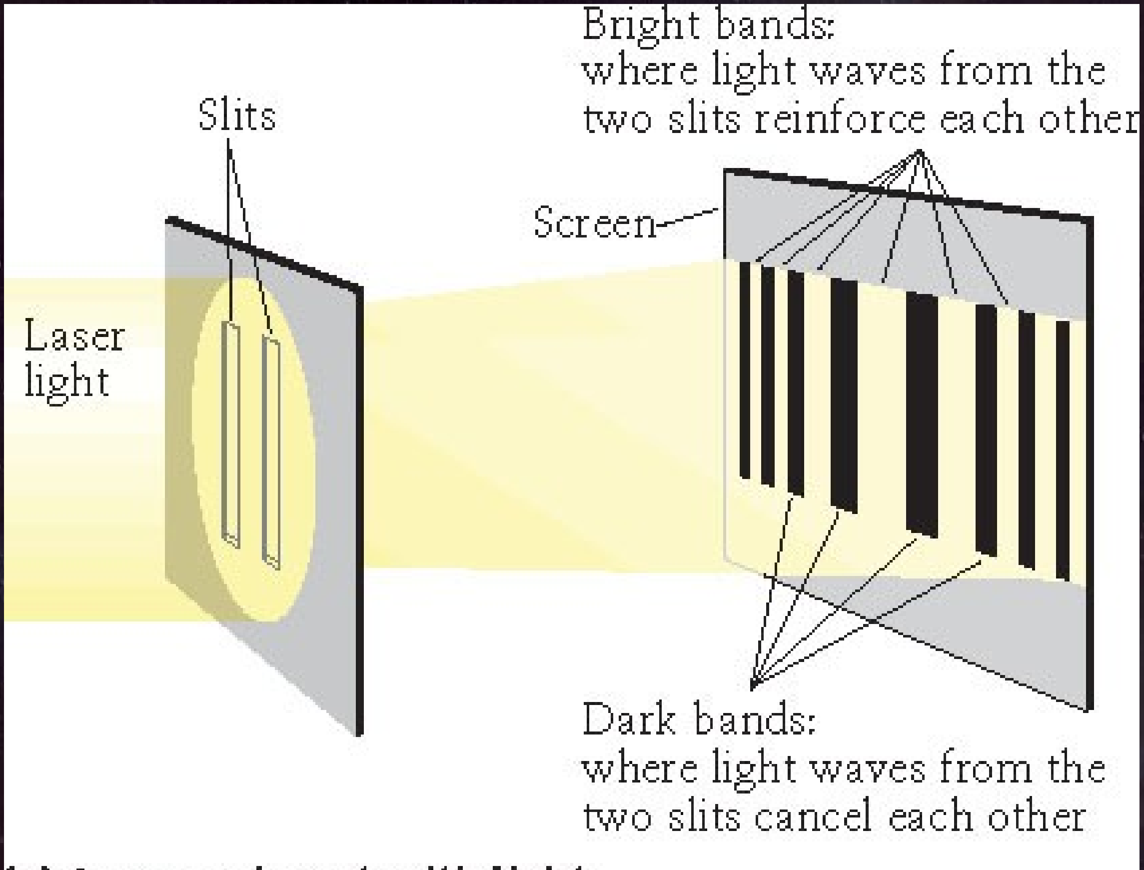
But what is this radiation? Is it particles, or is it waves?

Newton thought light consisted of particles. Huygens (namesake of the recent probe which visited Saturn's largest moon, Titan) thought light travelled in the form of waves.

Newton was the greater celebrity (and the bigger ego!). So his theory was generally more widely believed than Huygens'.

The nature of light – it's a wave...

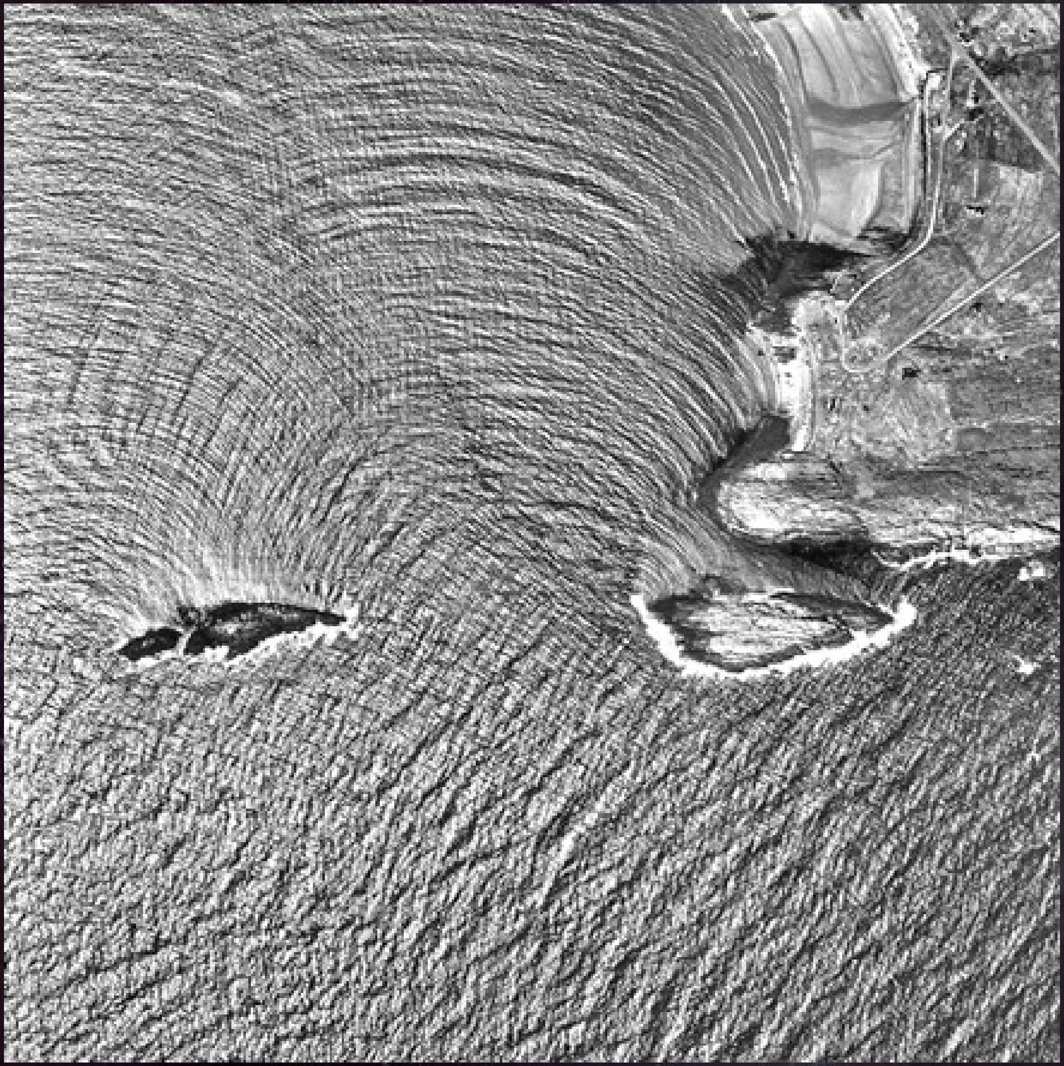
In 1801, Thomas Young carried out an experiment which demonstrated that light travelled as a wave.



(a) An experiment with light

The nature of light – it's a wave...

The pattern of lines is caused by *diffraction* – a phenomenon shown by waves passing through a small gap.



The nature of light – it's a wave...

When there are two nearby gaps, the waves emerging from both interfere with each other, giving the pattern of alternating light and dark lines.

You can see exactly the same effect in water.

The nature of light – it's a wave...

So what is 'waving'?

The answer to this came in the 1860s. Decades of observations had shown strong links between electricity and magnetism – eg an electric current in a wire gives off a magnetic field.

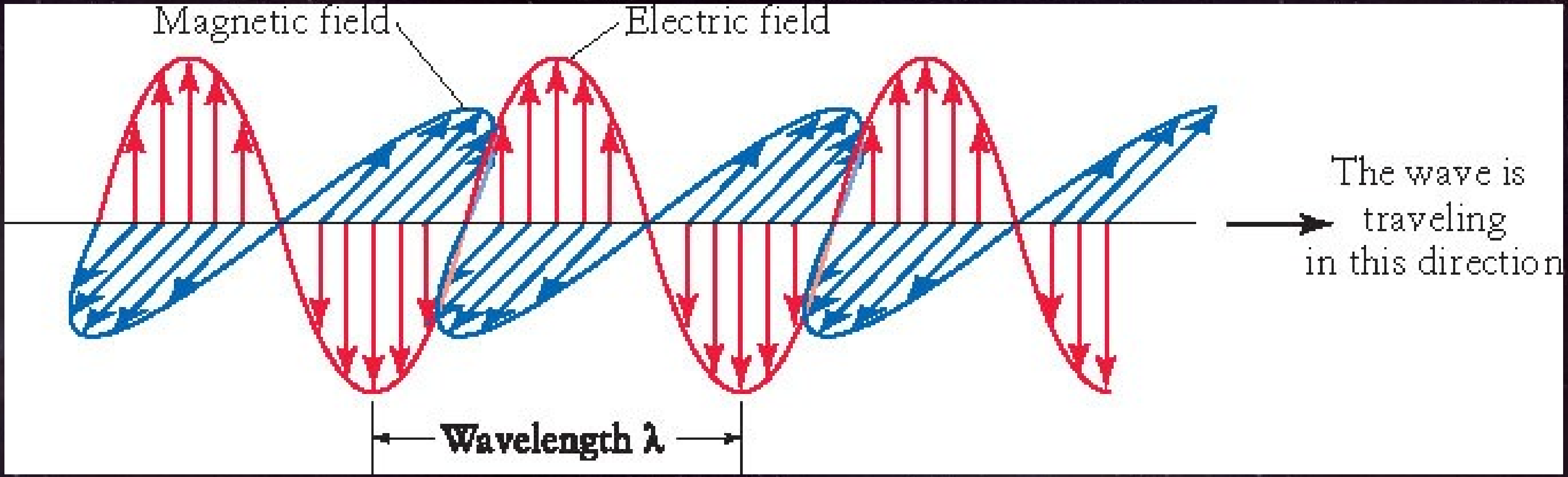
James Clerk Maxwell succeeded in 'unifying' the forces of electricity and magnetism – he described all of their basic properties in four equations.

These equations predicted that the speed of light in a vacuum should be 3×10^8 m/s – exactly equal to the observed value.

The nature of light – it's a wave...

Maxwell and his contemporaries could then understand light as oscillating electric and magnetic fields.

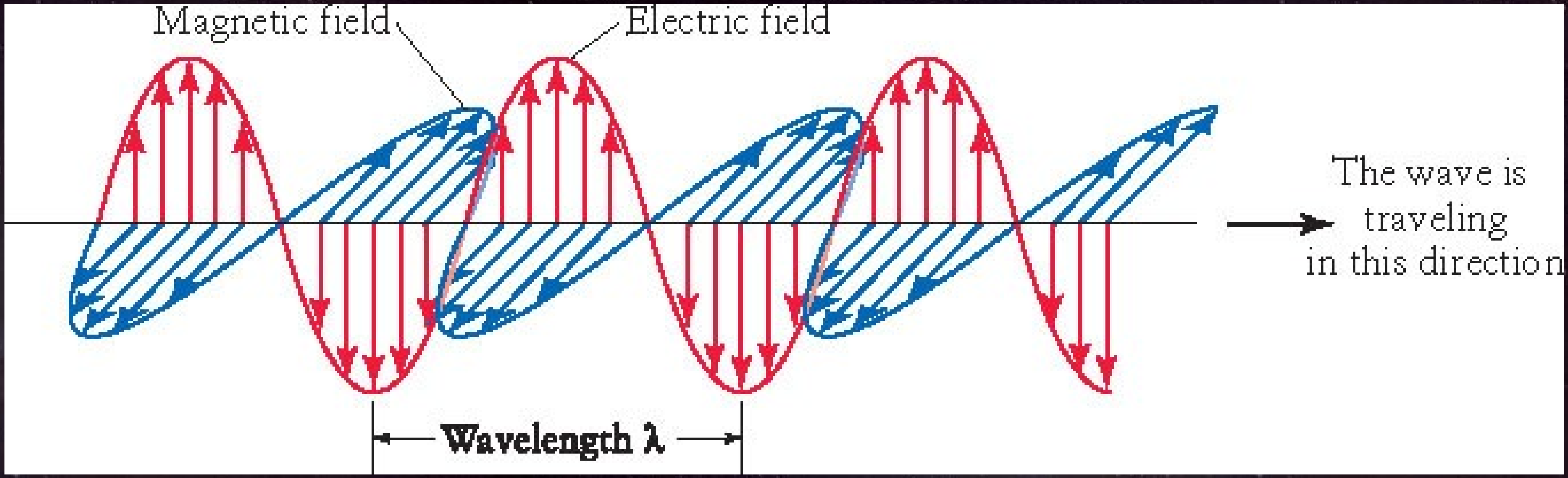
This gives rise to the general term for the kind of radiation of which light is only one example – *electromagnetic radiation*.



The nature of light – it's a wave...

The distance between two wave crests is the *wavelength* of the electromagnetic radiation. For visible light, the wavelength is between 350 and 700 nm (1nm=10^{-9}m)

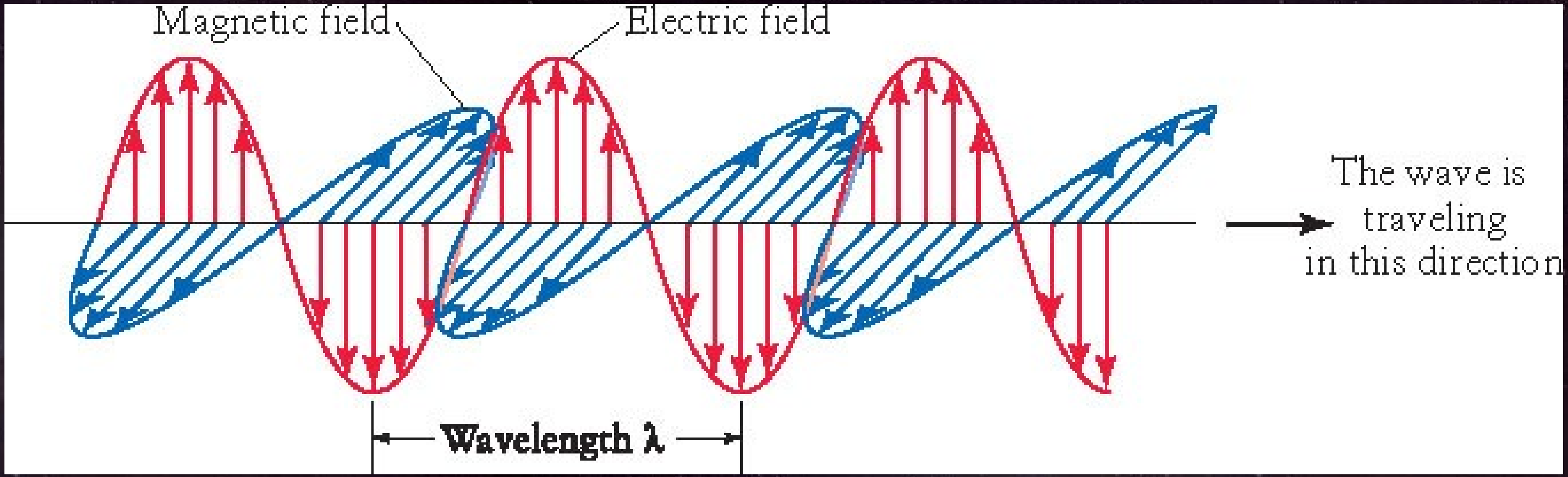
The number of waves which pass a point each second is the *frequency*. The unit of frequency is the hertz (Hz). 1 Hz = 1 wave per second.



The nature of light – it's a wave...

For all electromagnetic radiation, the wavelength and the frequency are related:

$$c = f\lambda$$



Electromagnetic radiation beyond the visible

This equation places no limit on the range of possible frequencies and wavelengths. Maxwell predicted the existence of EM radiation with wavelengths outside the 350-700nm range of visible light.

In fact, this had already been discovered, by William Herschel.

Herschel had noticed that when sunlight was filtered, different filters let through different amounts of heat. He set out to measure this by passing sunlight through a prism, and placing a thermometer in the different colours.

He found that the temperature of the colours increased from blue to red.

He also found that when the thermometer was placed outside the red, it still got hotter.

Electromagnetic radiation beyond the visible

Herschel called the invisible radiation 'calorific rays'. Today this part of the electromagnetic spectrum is called the infrared (from latin *infra*: below)

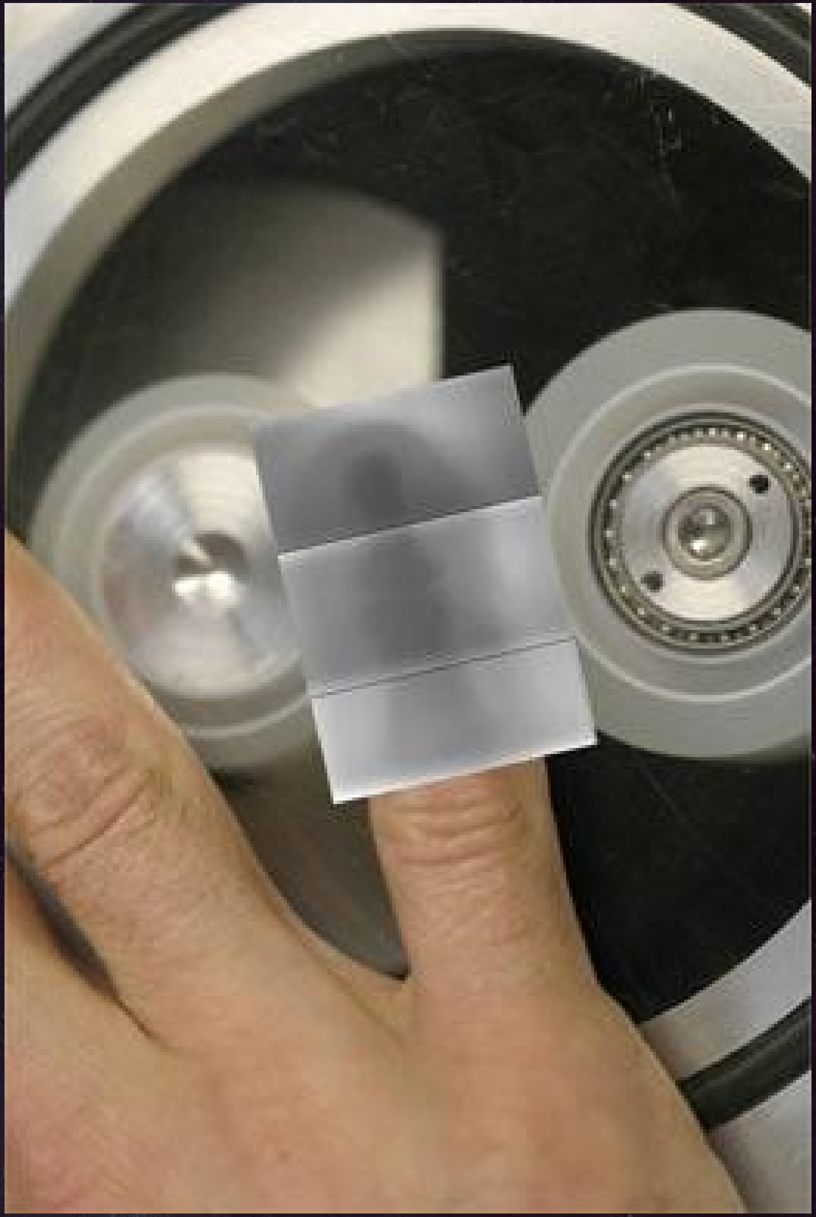
Other discoveries came later. Heinrich Hertz found that electric sparks produced radiation with very long wavelengths, now known as *radio waves*.

Wilhelm Roentgen invented a machine which produced radiation with very short wavelengths, now called *X-rays*.

Home-made X-ray machine!

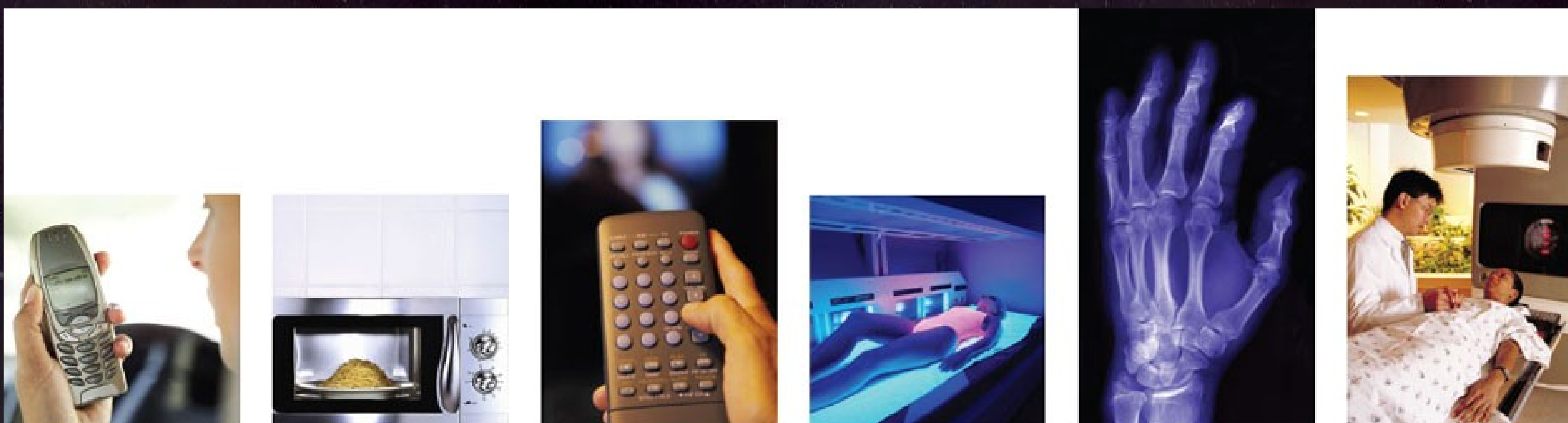
Quick aside: researchers have recently discovered that X-rays are produced by unwinding sellotape.

They made a machine that peeled sellotape at a rate of 3cm per second, and managed to x-ray their fingers.



The electromagnetic spectrum

Visible light turns out to be a very small part of the whole electromagnetic spectrum. Other parts are now familiar in everyday life:



(a) Mobile phone: radio waves

(b) Microwave oven: microwaves

(c) TV remote: infrared light

(d) Tanning booth: ultraviolet light

(e) Medical imaging: X rays.

(f) Cancer radiotherapy: gamma rays

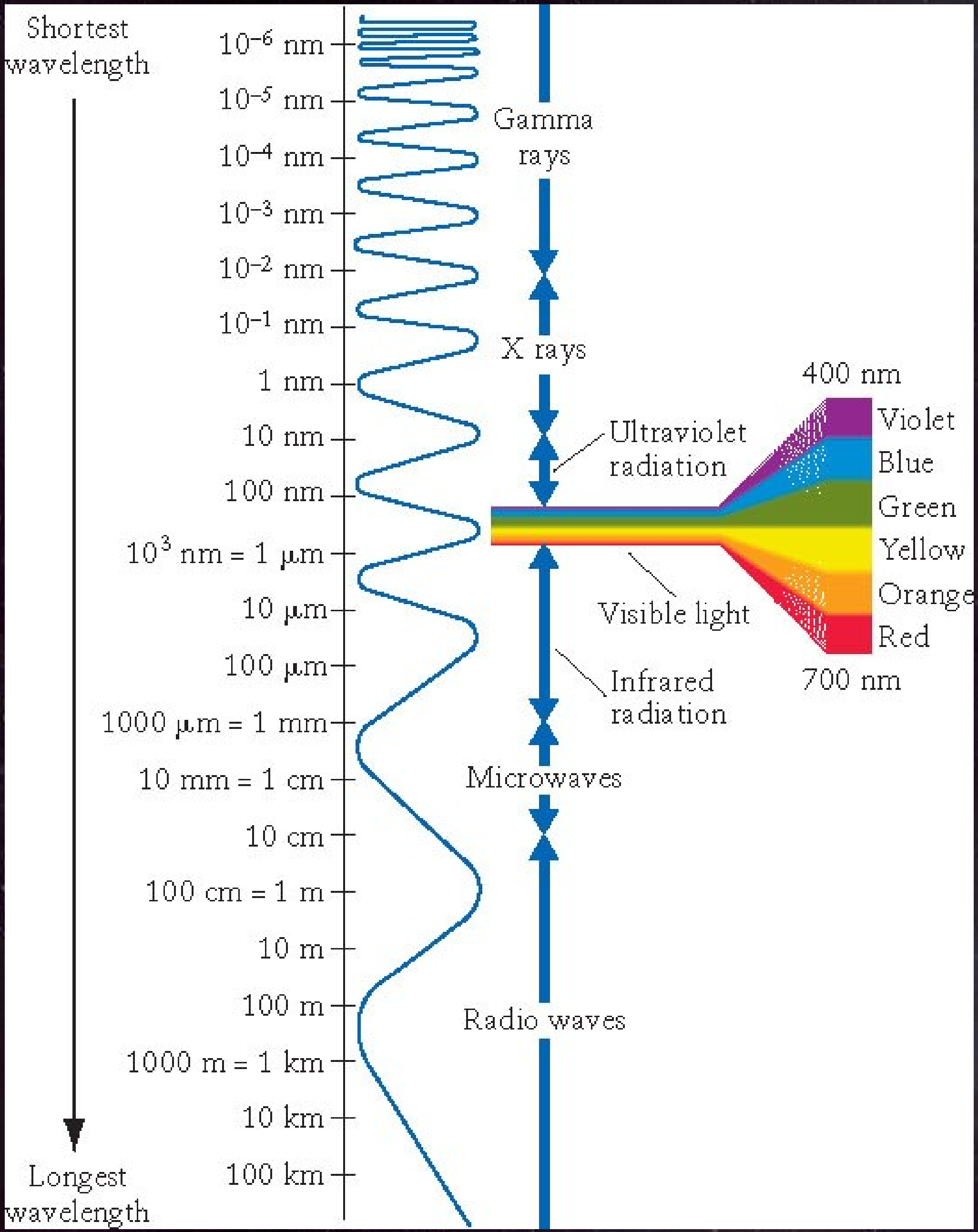
The electromagnetic spectrum

Apart from visible light, which is defined by human physiology, the dividing lines between different types of radiation are arbitrary. Roughly speaking:

gamma-rays have wavelengths of up to 10^{-11}m

X-rays have wavelengths from	10^{-11}	to	10^{-8} m
Ultraviolet:	10^{-8}	to	3.5×10^{-7} m
Visible:	3.5×10^{-7}	to	7×10^{-7} m
Infrared:	7×10^{-7}	to	0.001m
Microwaves:	0.001m	to	0.1m
Radio waves:	longer than 0.1m		

The electromagnetic spectrum



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!

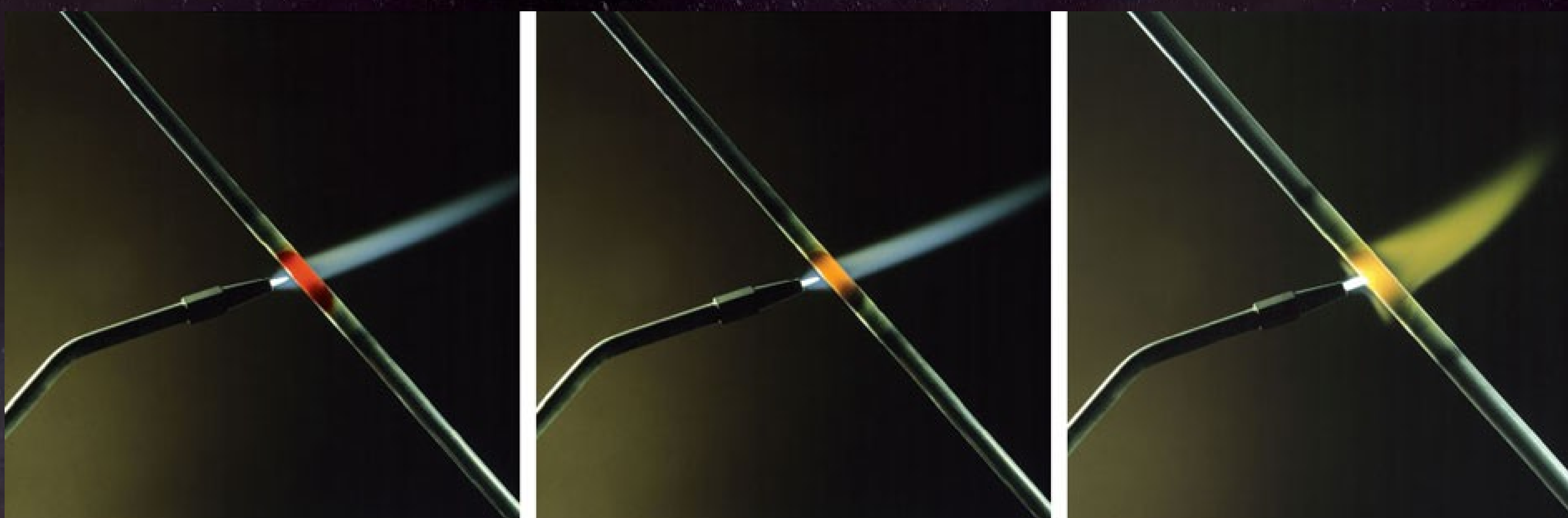
A basic observation about stars is that they are not all the same colour. A very good example of this is β Cygni (Albireo).

The electromagnetic spectrum and temperature

The electromagnetic spectrum and temperature

The colours of stars are related to their temperatures.

We can see this on Earth by heating up metal in a flame. At first, it does not emit any visible radiation as a consequence of being heated. But soon it will start to glow deep red, then orange, then yellow:



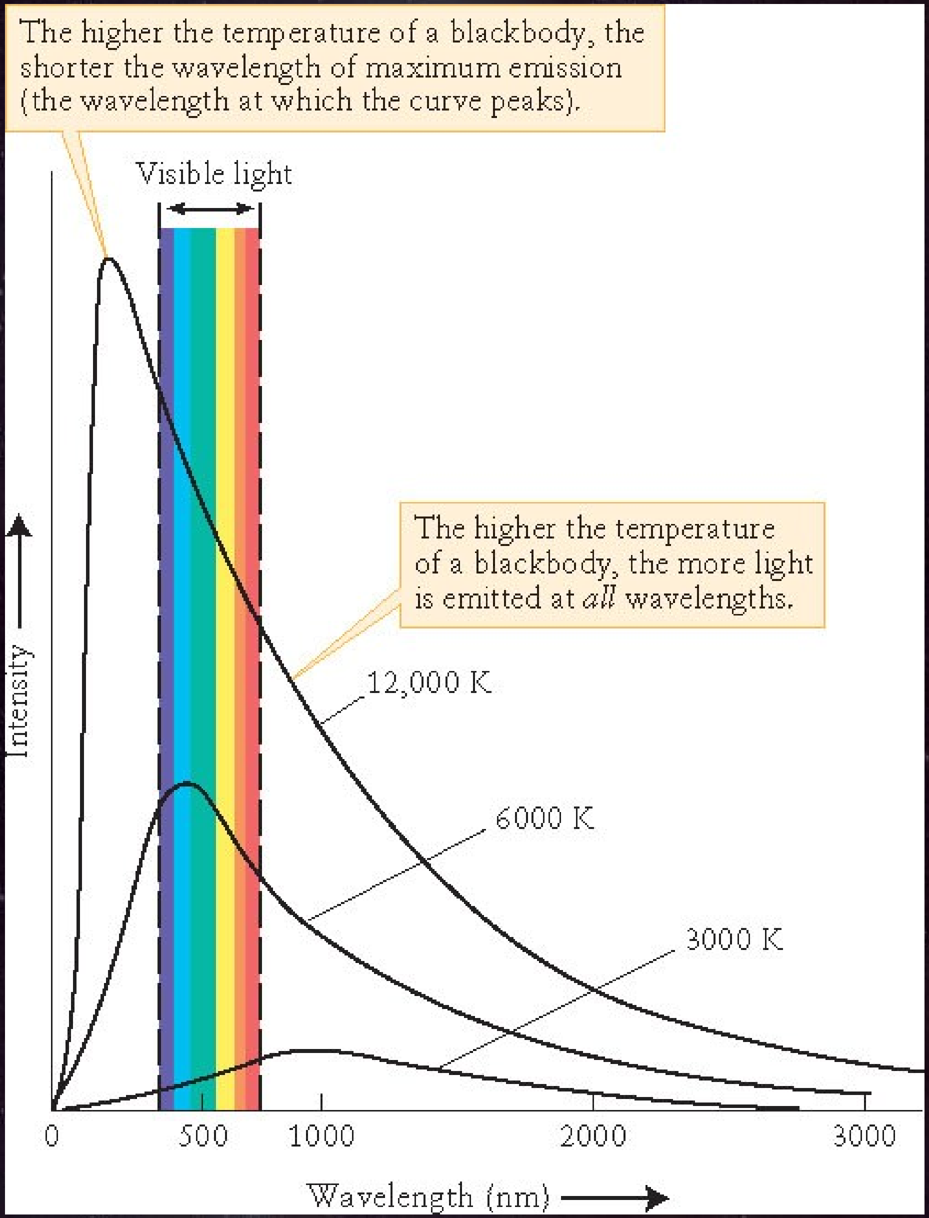
(a) Hot: glows deep red (b) Hotter: glows orange (c) Even hotter: glows yellow

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.



Temperature: units

Note that the units on this figure are K

This is the Kelvin, the fundamental unit of temperature.

$$1\text{K} = 1^{\circ}\text{C}$$

Water freezes at 0C and boils at 100C. Thus, the properties of water define the Celsius scale.

Temperature: units

The Kelvin scale is defined by the fundamental properties of matter: matter is made of atoms, atoms are in constant motion, and their average speed is related to their temperature. The temperature at which atomic motion ceases is called *absolute zero*.

The Kelvin scale starts from absolute zero.

$$0K = -273.15\ C$$
$$0C = 273.15\ K$$

NB: 1K = 1C is true for *changes* in temperature. 1K = -272.15 C.

Journalists frequently get this wrong – particularly in the Guardian!

Black body radiation

The emission from stars is quite similar to the emission from black bodies. This means that we can estimate their temperatures from the shape of their spectra.

The Sun's surface is at a temperature of about 5,800K, and black bodies with this temperature emit radiation with a peak wavelength of about 550 nm

Not at all coincidentally, this is in the middle of the range of wavelengths that our eyes can perceive.

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:

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

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

Astronomical objects

Different types of object emit different types of radiation, and so the different parts of the electromagnetic spectrum each reveal a different facet of the universe.

Radio waves are generally emitted by very cold gas. The gas between the stars emits radio waves.

Microwaves are emitted by cold dust – and also by the universe itself as a consequence of the Big Bang.

Infrared is emitted by warm gas and dust, and is particularly useful for studying the births and deaths of stars.

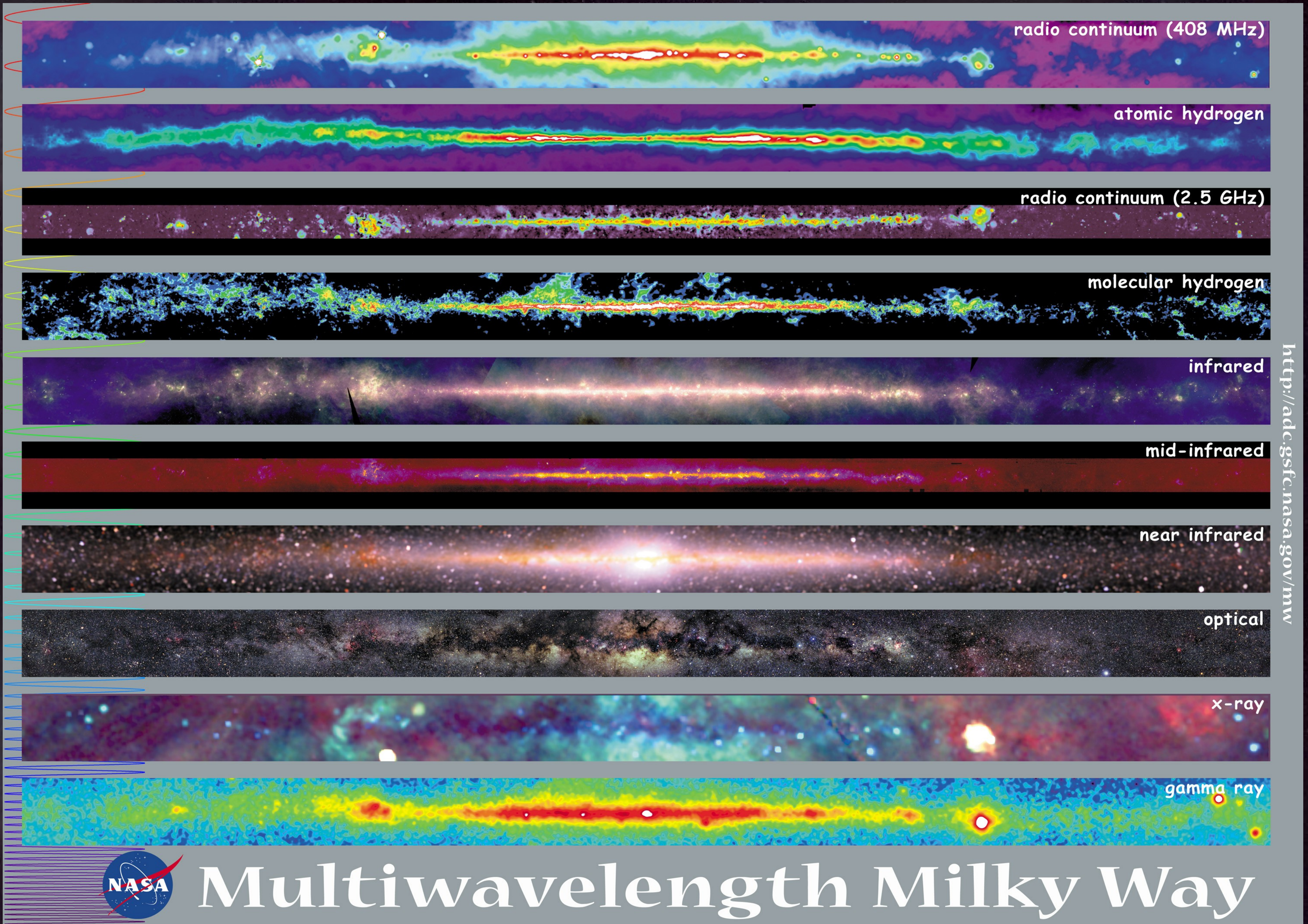
Astronomical objects

Visible light is emitted by hot objects like stars.

Ultraviolet is emitted by the hottest, most massive stars.

X-rays and gamma rays are emitted by extremely hot material (millions of K!). They tell us about some extreme environments – matter spiralling into a black hole, violently exploding stars, and the gas surrounding clusters of galaxies all emit strongly at these wavelengths.

The galaxy at many wavelengths



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 related the total amount of energy emitted to the temperature of a black body.

$$F = \sigma T^4$$

F is the energy emitted per square metre of surface area. 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 is the brightest star in the sky. Its wavelength peaks at 290nm. So, what is its temperature?

$$\lambda = 0.0029 / T$$

So,

$$\begin{aligned} T &= 0.0029 / \lambda \\ &= 0.0029 / 290e\text{-}9 \\ &= 10{,}000\ K \end{aligned}$$

Wien and Stefan-Boltzmann - example

How much more radiation does Sirius emit per square metre of its surface than the Sun does?

$$\frac{F(\text{Sirius})}{F(\text{Sun})} = \frac{T(\text{Sirius})^4}{T(\text{Sun})^4}$$

$$= (10000/5800)^4$$

$$= 8.8$$

The nature of light – Part II

These equations are extremely useful in understanding astronomical objects. However, they caused physicists huge problems in the late 1800s, because they could not be understood within the framework of light being a wave phenomenon.

Max Planck found that he could explain the shape of black body radiation, if he assumed that light was made up of particles.

Albert Einstein used this idea to explain the *photoelectric effect* – light striking a metal can cause the metal to emit electrons.

The nature of light – Part II

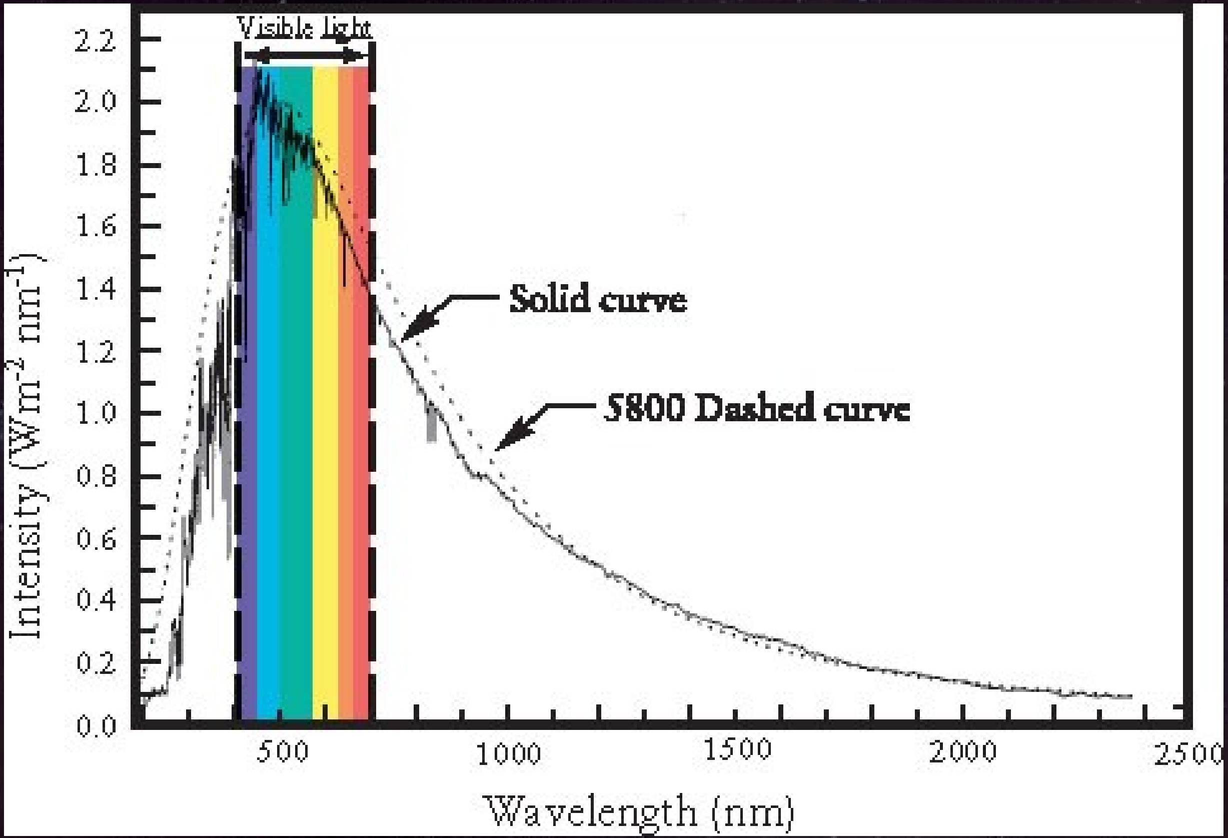
The photoelectric effect proves that light is made of particles. But Young's two-slit experiment already proved that light is a wave phenomenon.

In fact, light behaves *both* as a particle, and a wave, at the same time.

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:

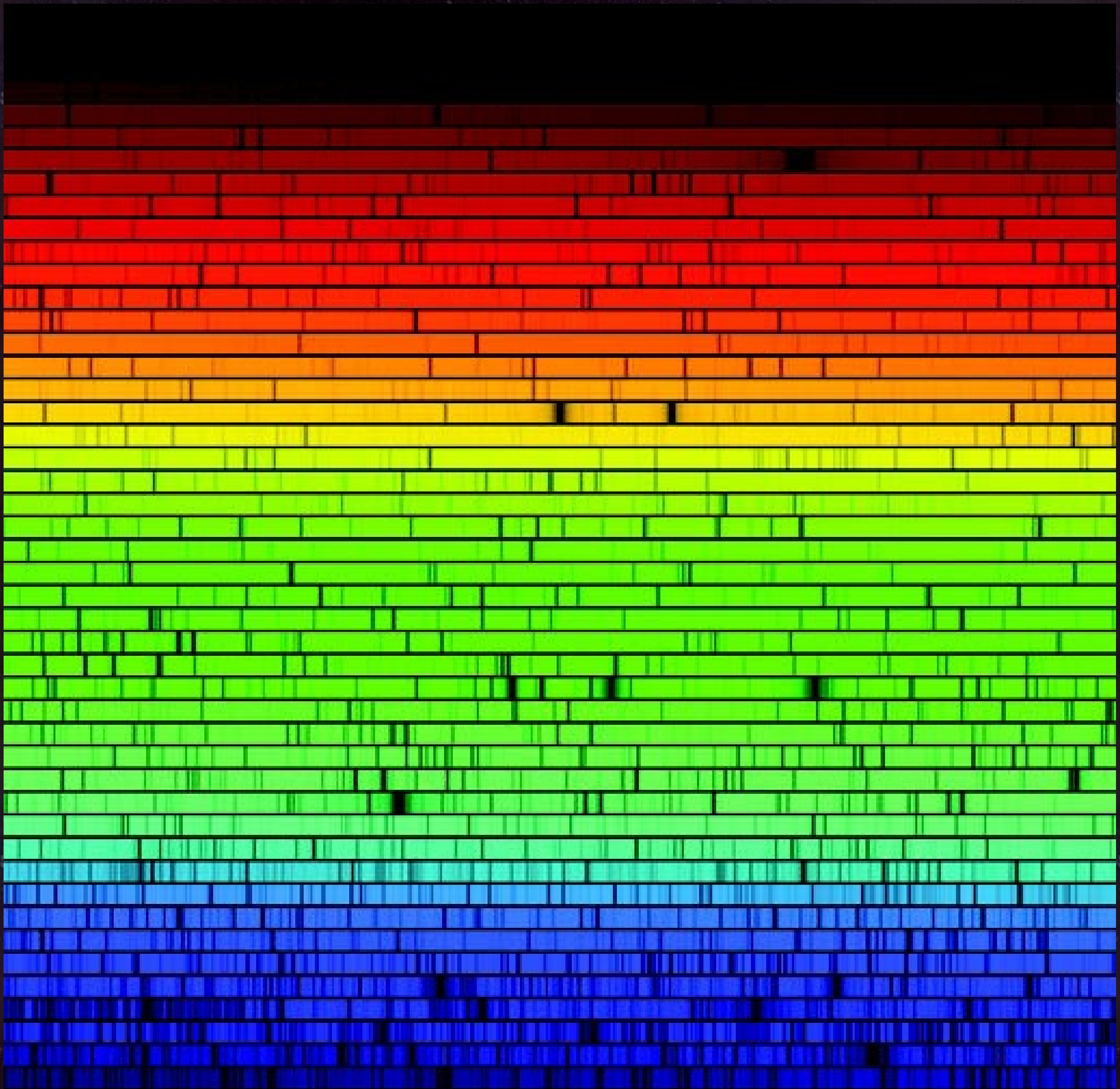


What EM radiation can tell us

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



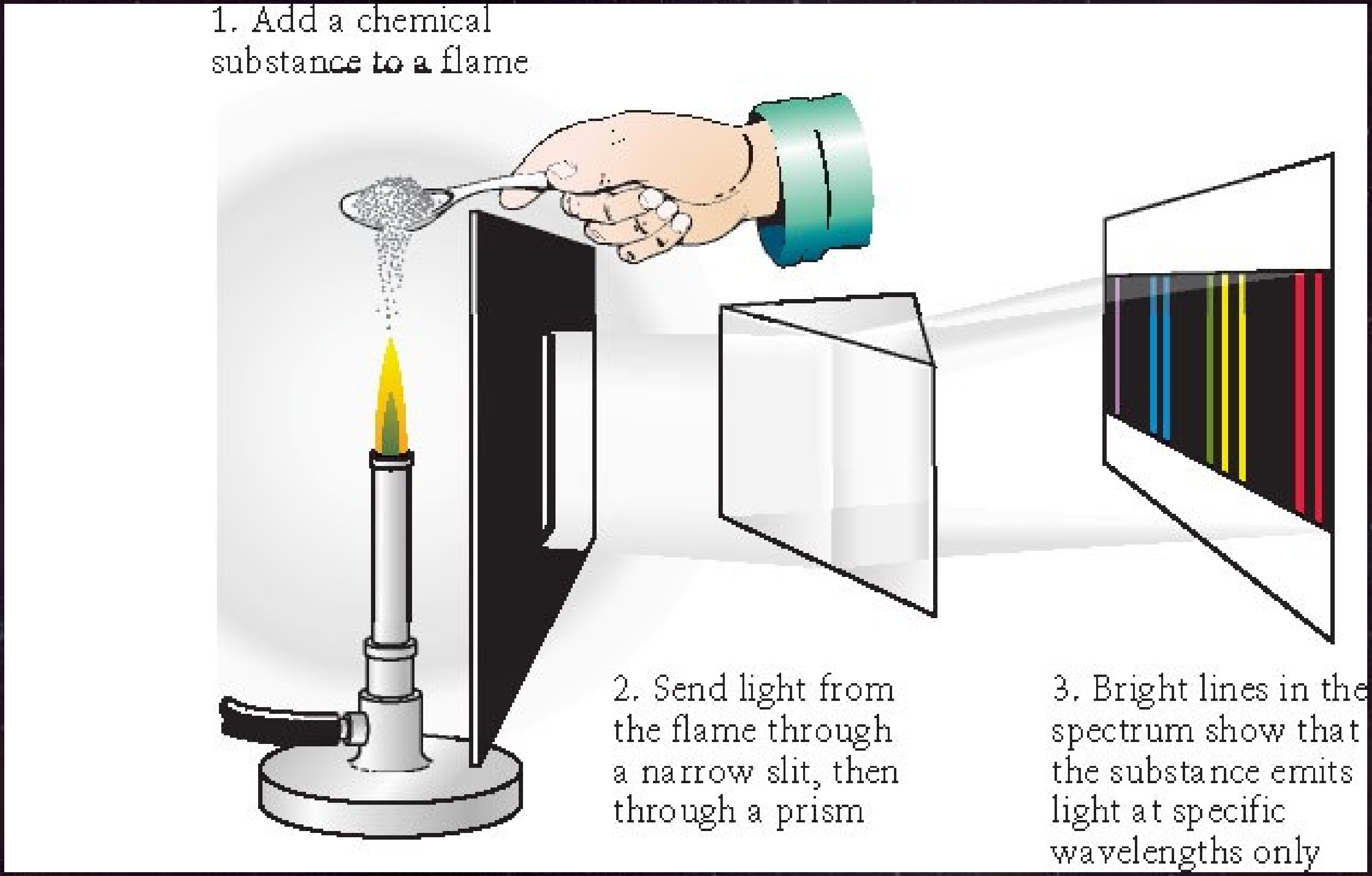
What EM radiation can tell us

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.

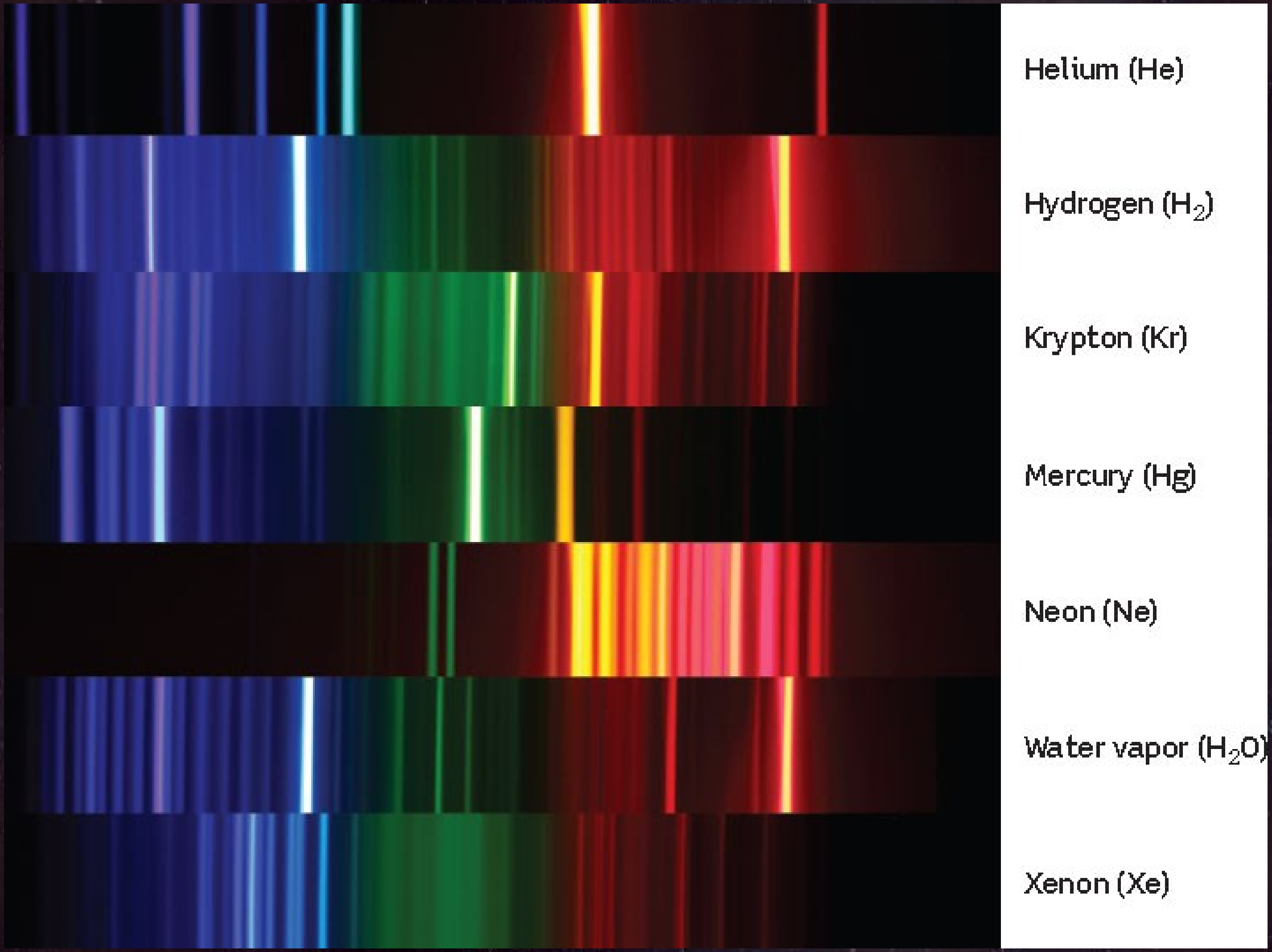
What EM radiation can tell us

19^{th} century chemists Gustav Kirchhoff and Robert Bunsen discovered that each element, when burned in a flame, only gives off light at certain discrete wavelengths.



What EM radiation can tell us

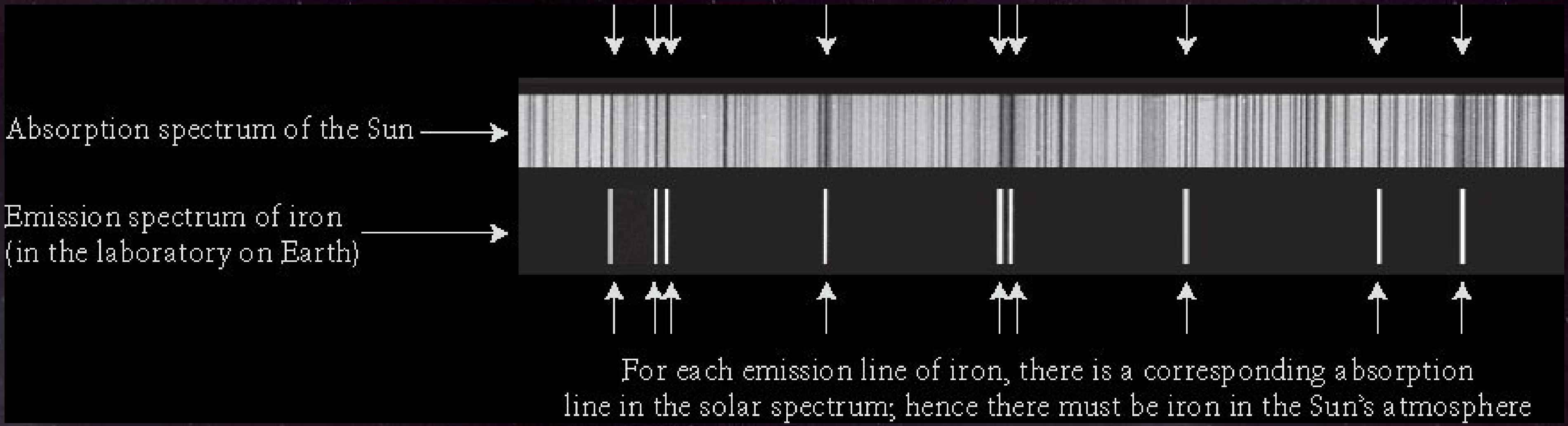
The wavelengths at which light is emitted are different for different elements:



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:



Discovering new elements

Kirchhoff and Bunsen carried out flame tests on mineral water vapour. They observed spectral lines in the blue and in the red part of the spectrum.

They isolated the elements responsible and found that they were new to science. They called them *caesium* (from the latin for blue) and *rubidium* (from the latin for red).

Discovering new elements

When observing a total solar eclipse in 1868, Norman Lockyer observed a spectral line coming from the Sun's atmosphere, which didn't correspond to any element so far observed in the lab.

He proposed that the line was due to a new element, which he called *helium* (from the Greek *Helios*: Sun).

He was proved right: helium was discovered on Earth in 1895 (it is given off by the radioactive decay of Uranium)

Kirchhoff's laws

Clearly, there is a relation between the bright spectrum with dark lines emitted by the Sun, and the bright lines emitted by elements in the lab. Kirchhoff described this relation in the form of three 'laws':

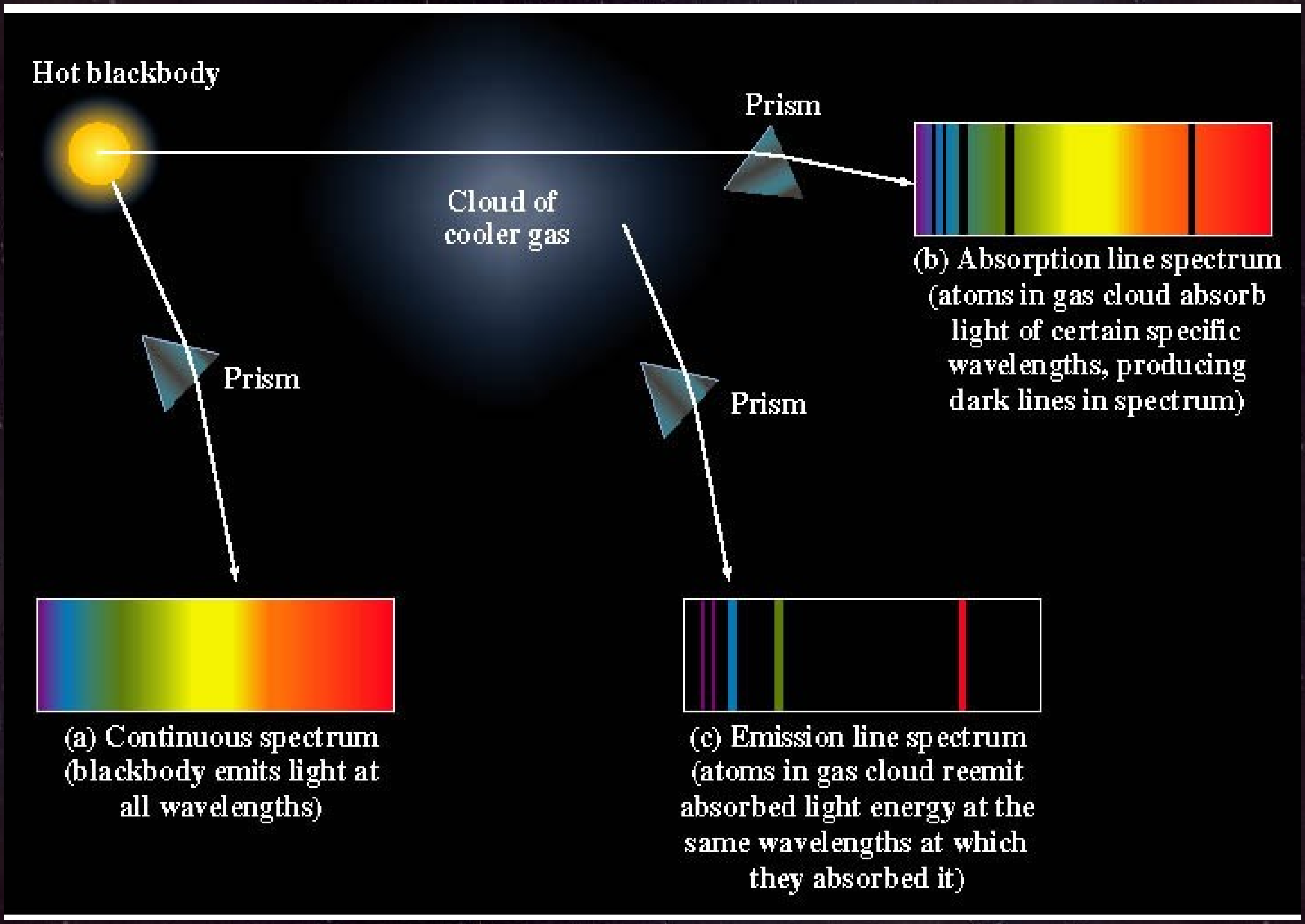
1. A hot opaque body, such as the ideal black body, or a star, emits a *continuous spectrum*.

2. A hot transparent gas produces an *emission line spectrum*.

3. A cool transparent gas in front of a hot opaque body produces an *absorption line spectrum*.

Kirchhoff's laws

The Sun's spectrum can then be understood as being produced as light from the hot surface passes through the cooler atmosphere.



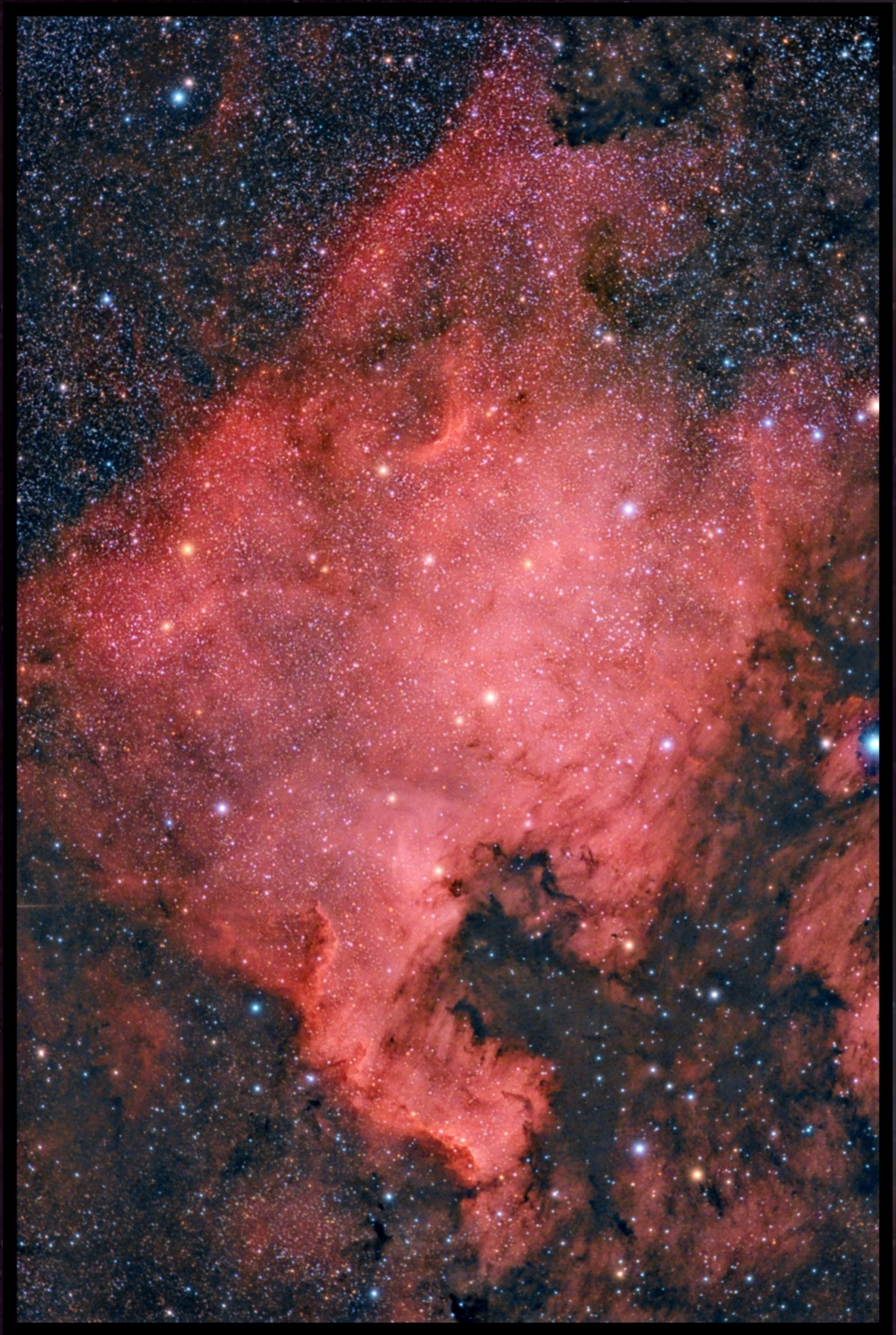
Kirchhoff's laws

Kirchhoff's laws are the foundation of *spectroscopy*. The power of spectroscopy is enormous: we can determine the composition of objects that are at enormous distances from Earth.

One very important observation is that a bright red emission line at 656.3nm is extremely common in the universe.

This red line is emitted by hydrogen, and hydrogen is the most abundant element in the universe.

Kirchhoff's laws



Why different atoms emit different spectral lines

The fact that different atoms absorb and emit radiation only at particular wavelengths tells us a great deal about extremely distant astronomical objects.

Much closer to home, it also tells us about the fundamental structure of matter. It cannot be explained by the wave theory of light, and the reasons why matter behaves in this way did not become clear until the 20^{th} century.

The structure of matter

Ernest Rutherford made a surprising discovery about the nature of matter, a few years after the discovery of the electron.

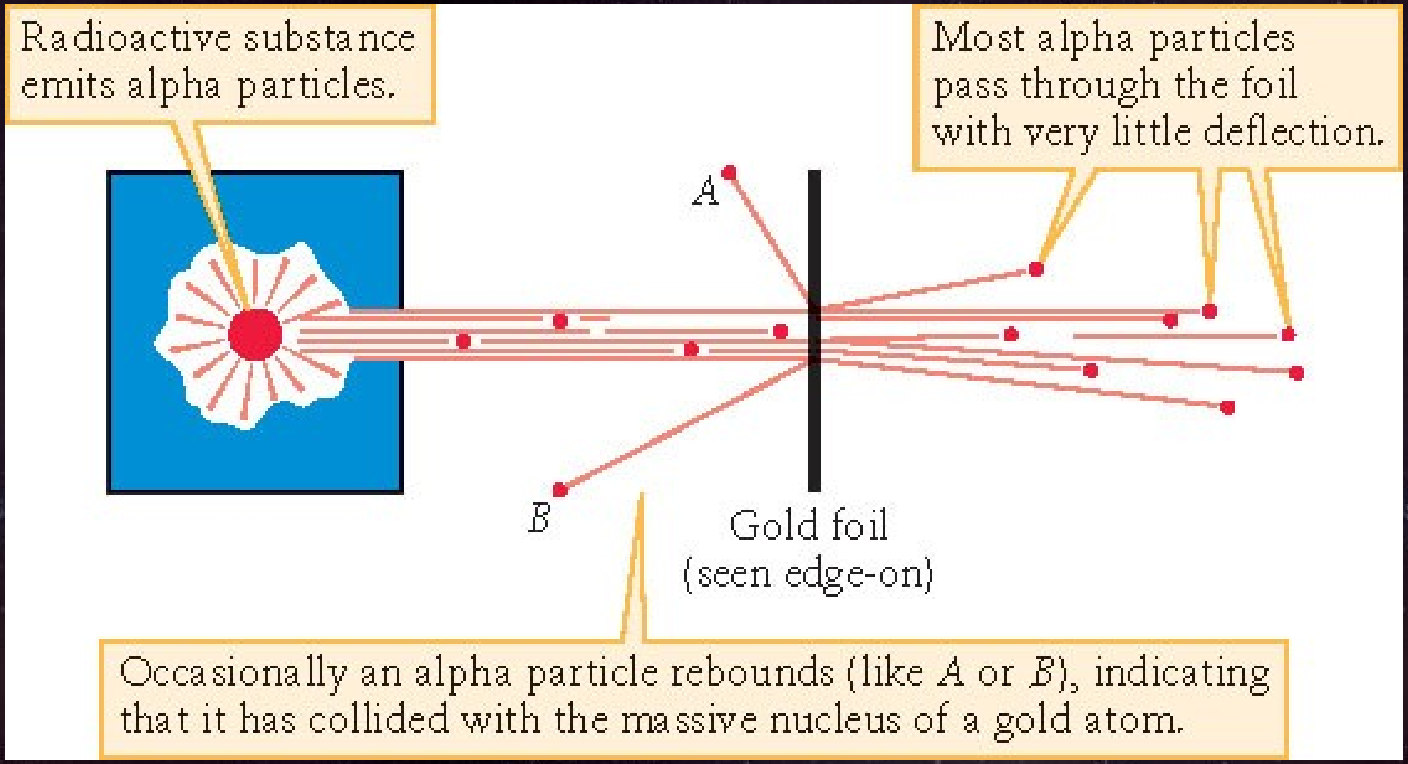
He fired alpha particles (a form of radiation) at a sheet of extremely thin foil, only a few atoms thick. He expected that most of the helium atoms would be deflected a small amount by the electrons in the gold foil.

This kind of experiment (firing particles at other particles, to investigate the very small scale structure of matter) is still fundamental to atomic research today, but on a vastly bigger scale (eg CERN)

The structure of matter

In fact, most of the helium atoms passed through with almost no deflection at all. A very small number were deflected by a large amount.

This showed that the atoms in the gold had the vast majority of their mass concentrated in a very small volume.



The structure of matter

Rutherford said he was as surprised as if he'd fired a cannonball at a piece of tissue paper and seen it rebound.

His result led to the understanding of an atom as consisting of a very small and dense *nucleus*, containing almost all of the mass of the atom, surrounded by a shell of electrons.

If an atom were the size of a football field, its nucleus would be about 1cm across.

The structure of matter