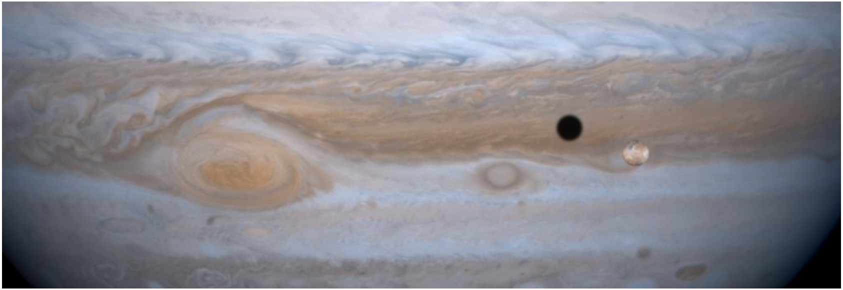
The nature of light

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.

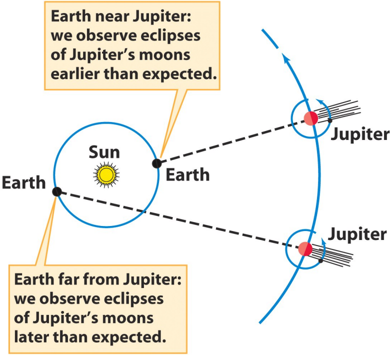
The speed of light

- 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.

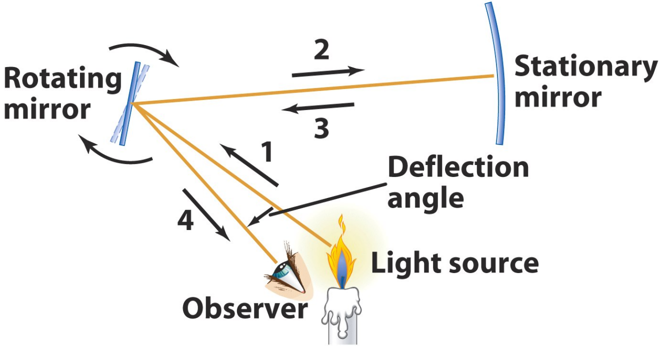


The speed of light

- 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.

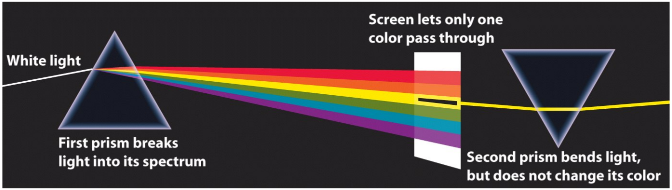


The speed of light

- Modern experiments give the speed of light (in a vacuum) as
- c = 299,792,458 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.

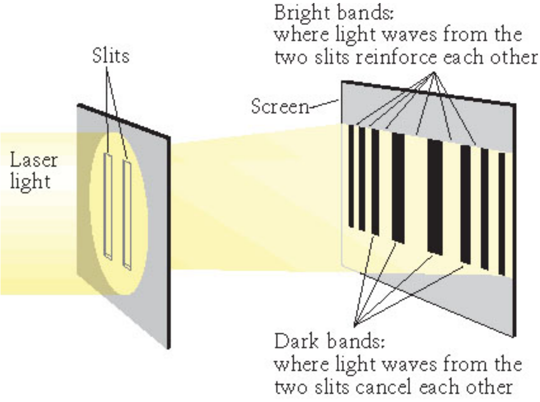


The nature of light

- 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...

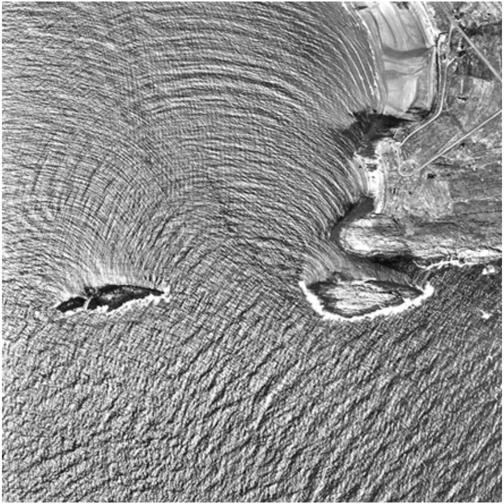
- In 1801, Thomas Young carried out an experiment which demonstrated that light travelled as a wave.



(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...

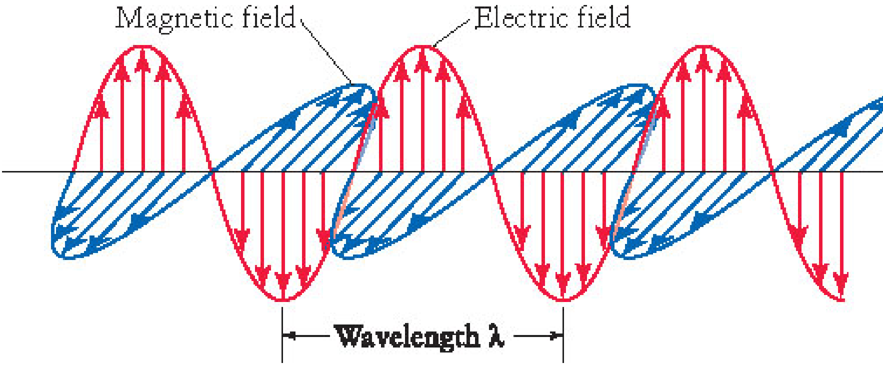
- When there are two nearby gaps, the waves emerging from both interfere with each other, giving the pattern of alternating light and dark lines.
- You can see exactly the same effect in water.

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.

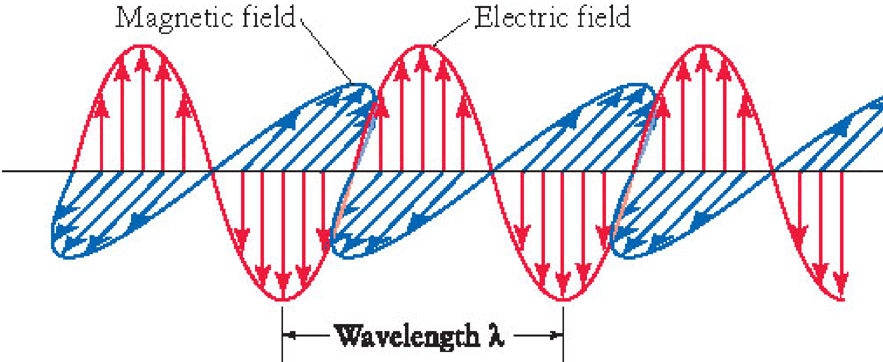
The nature of light – it's a wave...

- 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*.



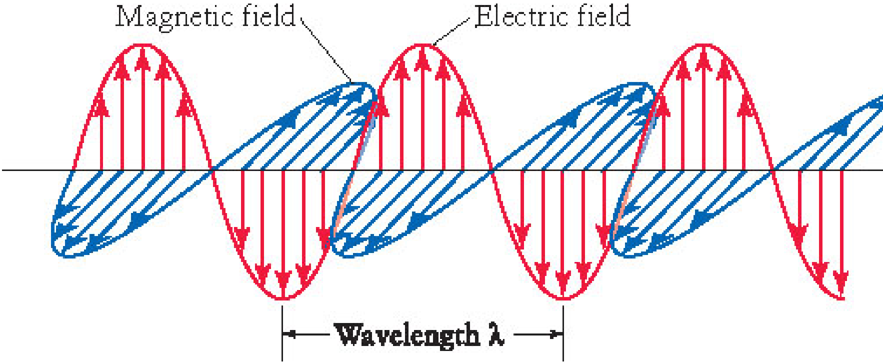
The nature of light – it's a wave...

- 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

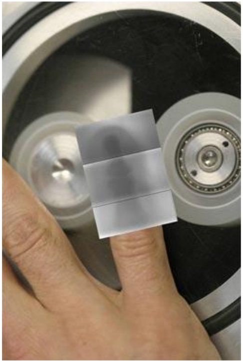
- This equation places no limit on the range of possible frequencies and wavelengths. Maxwell predicted the existence of EM radiation with wavelengths outside the 350-700nm range of visible light.
- In fact, this had already been discovered, by William Herschel.
- Herschel had noticed that when sunlight 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*.

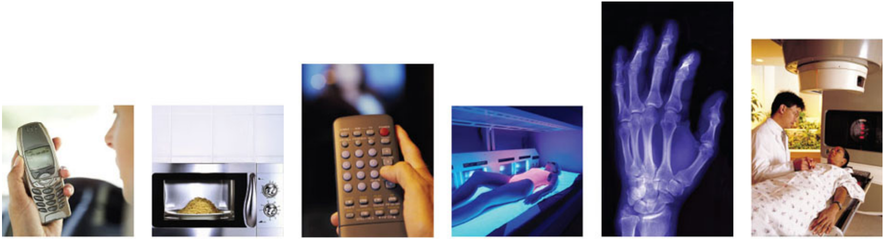
Home-made X-ray machine!

- 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

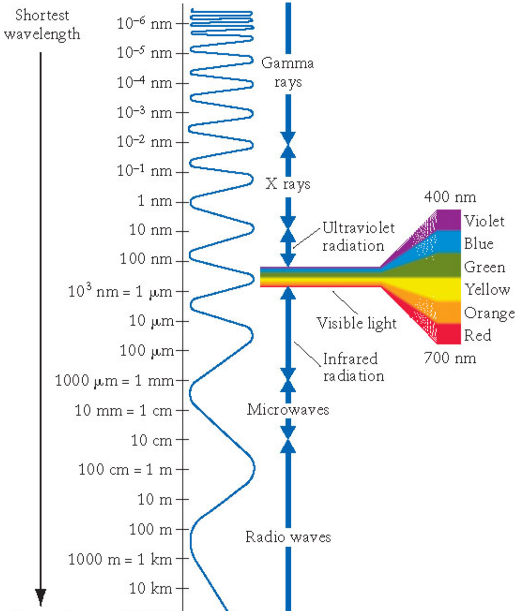
(e) Medical imaging: X rays.

(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



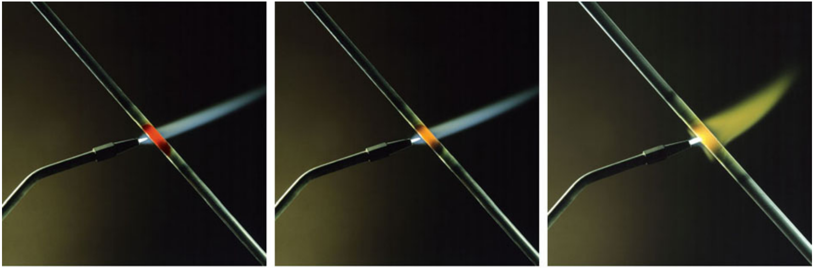
The electromagnetic spectrum and temperature

- 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

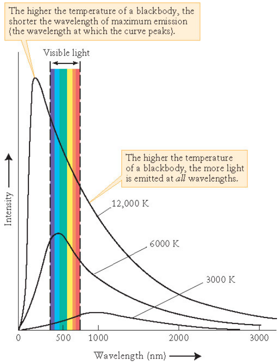
- The colours of stars are related to their temperatures.
- We can see this on Earth by heating up metal in a flame. At first, it does not emit any visible radiation as a consequence of being heated. But soon it will start to glow deep red, then orange, then yellow:



(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.
- 1K = 1°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!

Temperature: units

perception that climate change is way down the road in the future anc affects only remote parts of the world," she told a press conference today. "This report says climate change is happening now. It is happening in our own back yard."

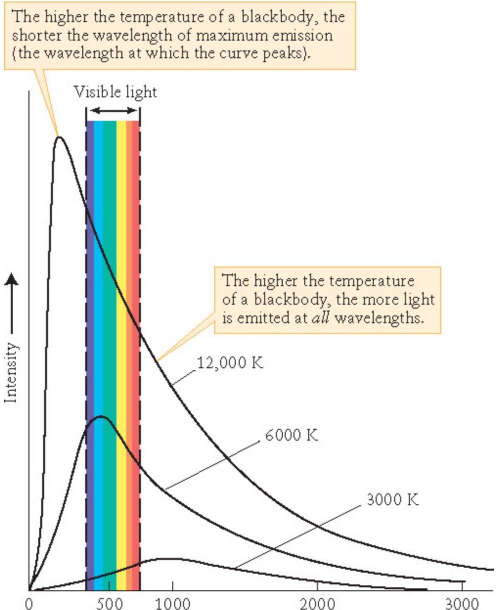
Average temperatures in the US have risen by1.5F (-17C) over the la 50 years, the report said. Rainfall in major storms has increased 20% over the last 100 years - with the heaviest downpours in the north-ea Sea levels have risen up to eight inches along some parts of the east coast.

The consequences of those changes are rippling through every regic of the US between Alaska and Hawaii - from the disruption of salmon

Units reminder

- Watch out for the difference between the **size** of the unit, and the **zero point** of the scale
- $1\text{K} = 1^\circ\text{C} = 1.8^\circ\text{F}$
- $273.15\text{K} = 0^\circ\text{C} = 32^\circ\text{F}$

Black body radiation



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:

$$\lambda_{peak} = \frac{0.0029m}{T}$$

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

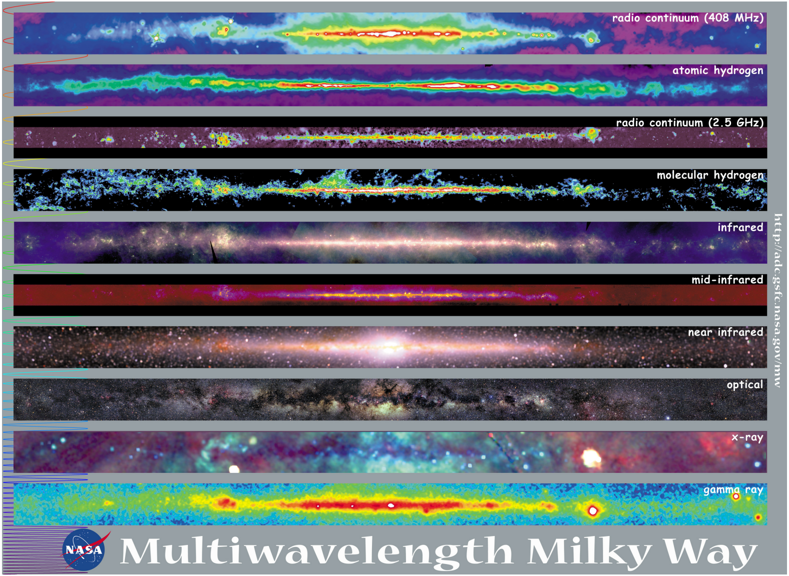
Astronomical objects

- 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 light** is emitted by the hottest, most massive stars.
- **X-rays and gamma rays** re 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.

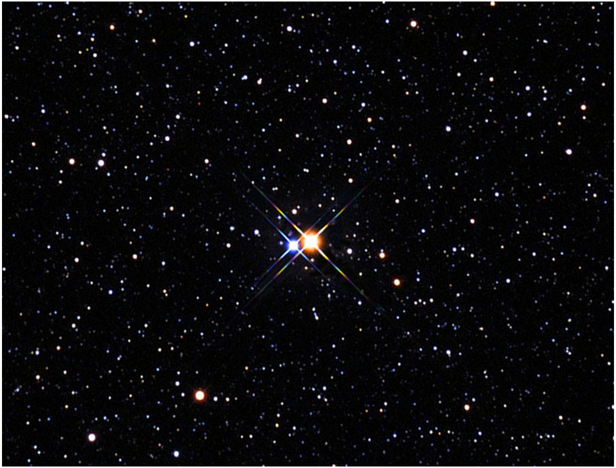
The galaxy at many wavelengths



Black body radiation

- 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



- β Cygni: the orange star has a temperature of 4000K; the blue one is much hotter at about 30,000K