The nature of light

Speed of light Nature of light Light - a wave EM radiation Beyond the visible

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- Temperature

- 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.

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- 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.



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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.



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- 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.

- 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.



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- 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 = 3×10⁵ km/s
- c is a very important number in physics, and occurs in many equations: for example, E=mc²

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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.





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- 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'.

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



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



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- 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.

- 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 3x10⁸ m/s exactly equal to the observed value.

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- 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.



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- 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=10⁻⁹m)
- 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.



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

■ **C** = fλ



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.

Beyond the visible

Electromagnetic radiation beyond the visible

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- 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!

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- 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

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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

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

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- 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).

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- 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 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

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- 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

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- 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.
- OK = -273.15 C
- OC = 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!