

Fiat Lux




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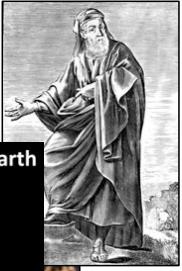

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What Is Light?


It's a warm summer evening in ancient Greece ...

Empedocles (~ 450 BC) postulated that everything was composed of four elements.

He believed that Aphrodite made the human eye from the four elements and that she lit the fire in the eye which shone out from the eye, making sight possible.



If you think the idea of eyes *emitting* light is rather weird, what about ...

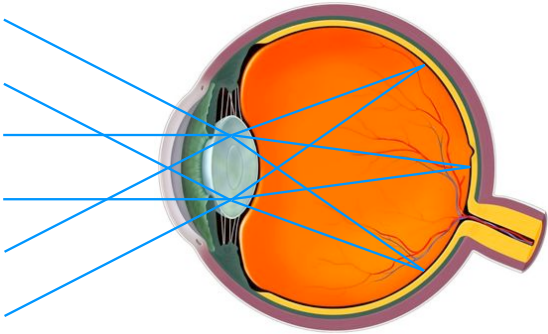


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How Do We See?

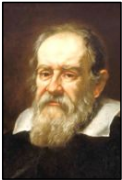


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Speed of Light



1638 Galileo Galilei
Lanterns on hilltops



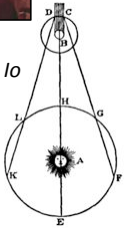
1676 Ole Rømer
Jupiter and Io



1728 James Bradley
Stellar aberration




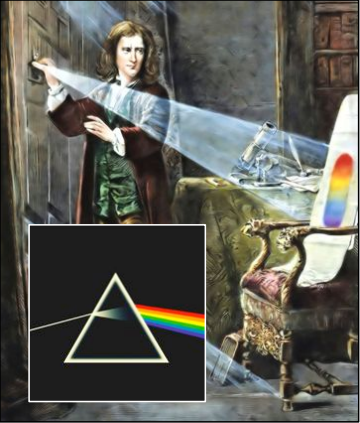
$c = 300,000 \text{ km/s}$



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Isaac Newton



Newton's work on optics in the 1660s established that white light is composed of many colours.



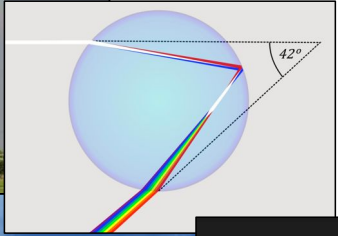

Arguments raged as to the nature of light – should it be considered as a stream of particles ('corpuscular') or as a wave?

(Curiously, modern physics developed centuries later gives the answer – both!)

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Making Rainbows



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Unwanted Rainbows

Chromatic Aberration

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Light as a Wave

When light passes through an aperture, such as an optical instrument like a telescope or a narrow slit, it reveals its wave nature.

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Electromagnetic Spectrum

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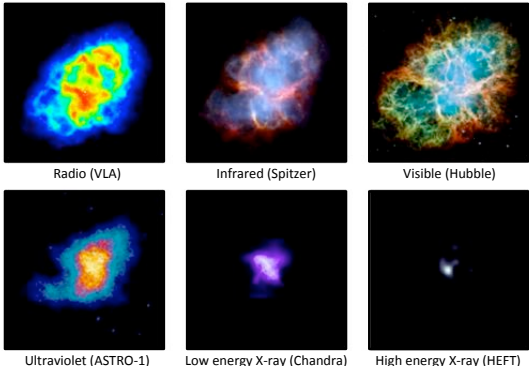
Electromagnetic Spectrum

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Electromagnetic Spectrum

Crab Nebula



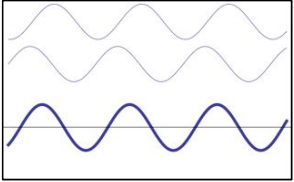
Radio (VLA) Infrared (Spitzer) Visible (Hubble)

Ultraviolet (ASTRO-1) Low energy X-ray (Chandra) High energy X-ray (HEFT)

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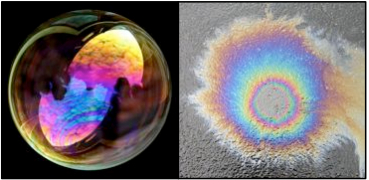
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Wave Interference



Just like waves on the surface of water, if two light waves meet and their crests and troughs fall on top of each other then they reinforce each other. However, if the crest of one wave meets the trough from another then they cancel each other out. We call this **interference**.

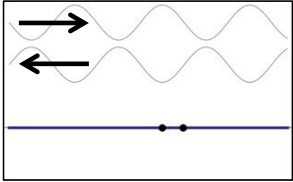
You will have seen some of the results of interference in soap bubbles or oil spills.



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Standing Waves



Waves that travel in one direction and meet similar waves travelling in the opposite direction will produce **standing waves**.

Some points ('hot spots' like the right dot) see big variations in the waves. Other points ('dead spots' like the left dot) see no waves at all.


Hence if we can create standing waves inside an object, some regions will feel the wave and some won't. Sending microwaves (radio-frequency light waves) into food will result in 'hot spots' being cooked and 'dead spots' remaining uncooked.

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Demonstration

Speed of Light




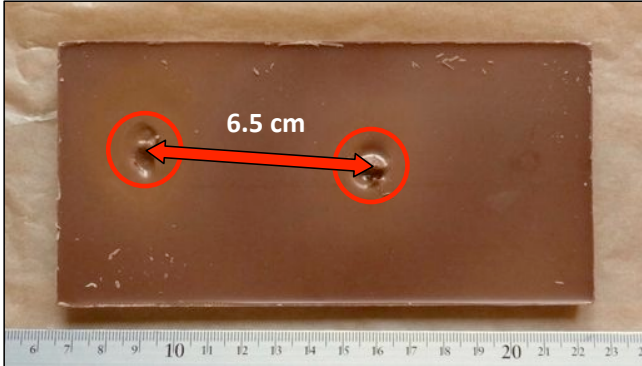
1. Take an ordinary microwave oven
2. Remove the rotating turntable
3. Put a chocolate bar into the oven (*it also works with cheese but it is (a) not as clear and (b) a waste of cheese*)
4. Cook for 15–20 seconds
5. Measure the distance between the melted regions

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 **Demonstration**



6.5 cm

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 **Demonstration**


Speed of Light

- The wavelength of the microwaves = 2 x this distance = 13 cm
- Note the frequency of the microwaves (on the back of the oven)
- Speed = frequency x wavelength (*wiggles per second* x *length of each wiggle*)
- Put in the numbers ...

Speed = 2450 MHz x 13 cm = **320,000** km/s

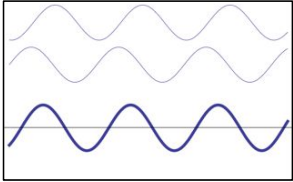
Actual value = **300,000** km/s



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Interference and Diffraction




Just like waves on the surface of water, if two light waves meet and their crests and troughs fall on top of each other then they reinforce each other. However, if the crest of one wave meets the trough from another then they cancel each other out. We call this **interference**.

Animation courtesy of Dr Dan Russell, Pennsylvania State University

When lots of waves interfere with each other we call this **diffraction**.

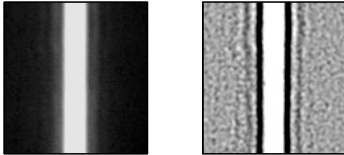
We don't usually notice diffraction effects unless we look very closely (for instance, with high magnification eyepieces in a telescope) or the light passes through very small apertures such as a slit of width of only a fraction of a millimetre.

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Diffraction

A wide slit produces diffraction 'fringes' that are closely spaced and a narrow slit produces wider (and more noticeable) diffraction fringes. This is why large telescope lenses or mirrors produce 'sharper' images.



↑↑↑ ↑↑↑

Enhancing the contrast makes the diffraction fringes easier to see*

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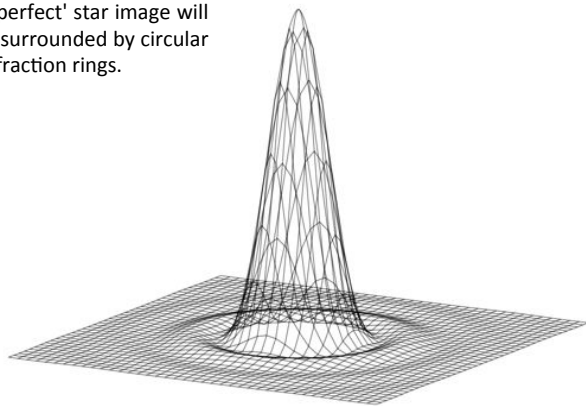
* www.liv.ac.uk/~sdb/ProcSyzSoc/Proc-Syz-Soc-2.pdf

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Diffraction

A 'perfect' star image will be surrounded by circular diffraction rings.



The diagram shows a central point source of light that has been focused to a point. The light rays are shown as a series of overlapping cones that form a central star-like shape. This central shape is surrounded by several concentric, circular rings of light, representing the diffraction pattern. The entire pattern is shown in a 3D perspective, with the light rays and rings appearing to rise from a flat surface.

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Demonstration

Wavelength of Light

- Shine a bright light through a narrow slit onto a screen
- Observe diffraction fringes either side of the slit

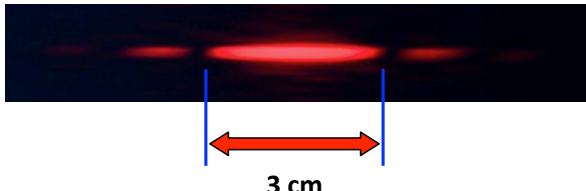
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Demonstration

Wavelength of Light

Measure the width of central bright region



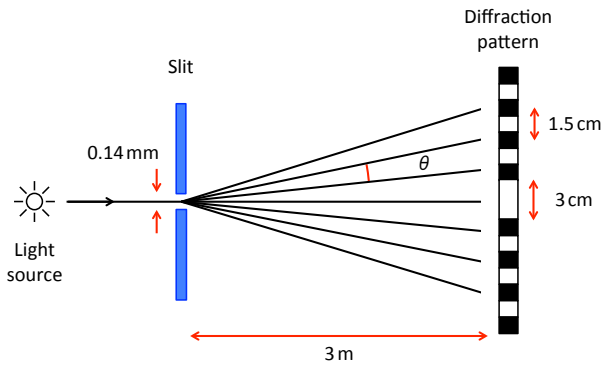
The photograph shows a horizontal diffraction pattern on a dark background. A central bright red region is flanked by several dimmer, secondary maxima. A red double-headed arrow below the central region indicates its width, which is labeled as 3 cm. Two vertical blue lines mark the boundaries of the central region.

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Demonstration

Wavelength of Light




The diagram illustrates the experimental setup for measuring the wavelength of light. A light source on the left emits a beam of light through a slit of width 0.14 mm. The light then spreads out and hits a vertical screen labeled 'Diffraction pattern' at a distance of 3 m. The screen shows a central bright spot and several dark fringes. The width of the central bright region is marked as 3 cm, and the distance from the central maximum to the first minimum is marked as 1.5 cm. The angle θ is shown between the central axis and the first minimum.

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 **Demonstration**


Wavelength of Light

The angular separation of the fringes ($\theta \approx 1.5/300$) is given by the ratio of the wavelength of light to the slit width.

The angular separation of the fringes = $\frac{1.5}{300} = \frac{\text{wavelength}}{\text{slit width}} = \frac{\lambda}{0.14 \text{ mm}}$

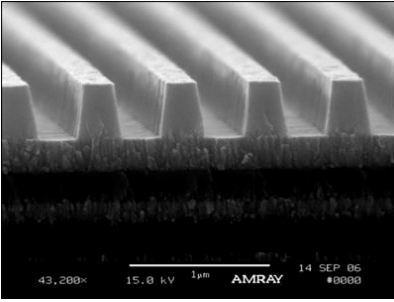
so the wavelength of light = $\frac{1.5}{300} \times 0.14 \text{ mm} = \mathbf{700 \text{ nm}}$

It ought to be about 650 nm, as the wavelengths of visible light span the range 400–700 nm (from blue to red) and a red laser was used in this demonstration.


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Diffraction Grating

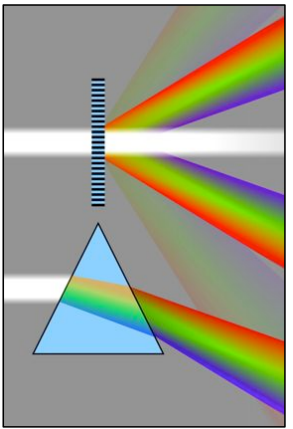
A diffraction grating, usually a piece of glass etched with closely-spaced parallel lines, uses the interference of light waves to make a spectrum.



43,200x 15.0 kV 1µm AMRAY 14 SEP 06 #0000


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Diffraction Grating



Some diffraction gratings are designed to make spectra by passing light through them, others are designed to make spectra by reflecting light.


Note that the colours with *smaller* wavelengths (at the blue end of the spectrum) are sent through *smaller* angles. This is the opposite to the way a prism works.

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Diffraction Grating

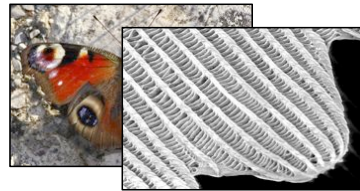
You have probably already seen a diffraction grating.


CDs and DVDs were not created because of the way they diffract light, but the closely-spaced tracks that are used to record the music or video data do diffract light just like a diffraction grating.



(This effect can be exploited by making a 'CD spectroscope' from a CD and an empty cereal box. *)

You have probably also seen diffraction effects in nature without realising it ...



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* www.liv.ac.uk/~sdb/ProcSyzSoc/Proc-Syz-Soc-3.pdf

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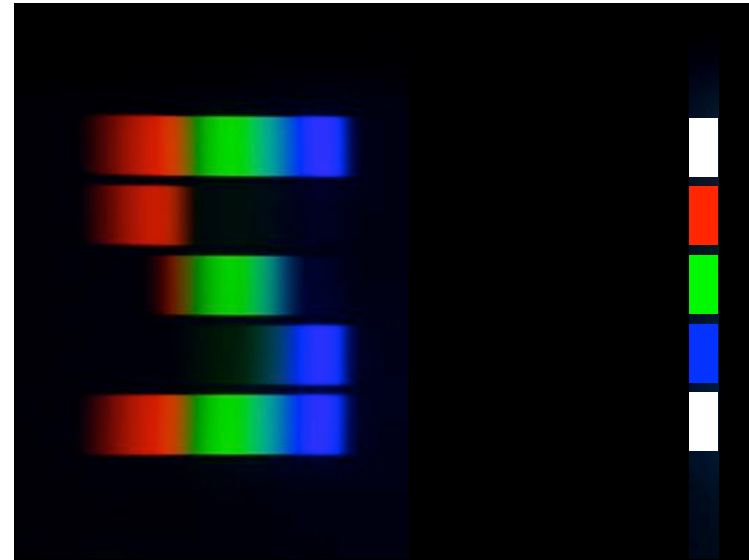
Demonstration

Spectrum of Light

- Make a spectrum using a prism
- Make a spectrum using a diffraction grating
- Look at different light sources using a diffraction grating

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Demonstration

Fluorescent Light Bulb

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Demonstration

Laser + 6" Ruler

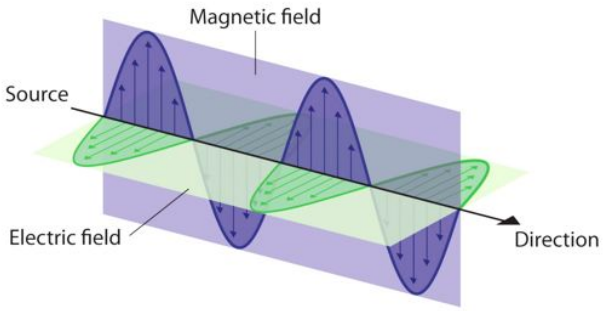
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Electromagnetic Wave

In 1865 James Clerk Maxwell showed that light is an electromagnetic wave. Electric fields and magnetic fields interact with each other and are interwoven to make a wave that can travel without a medium.



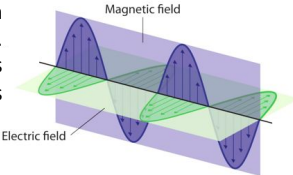
The diagram shows a wave traveling to the right. The electric field is represented by green loops in a vertical plane, and the magnetic field is represented by blue loops in a horizontal plane. Both fields oscillate perpendicular to the direction of travel. Labels include 'Source', 'Magnetic field', 'Electric field', and 'Direction'.

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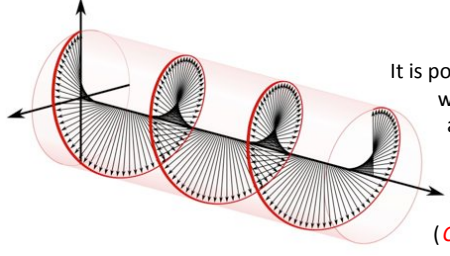
Polarisation

The electric and magnetic fields (green and blue arrows) stay in the same plane. For instance, the magnetic field varies 'up-down' and the electric field varies 'left-right'. (*Linear Polarisation*)



The diagram shows a wave with green arrows for the electric field and blue arrows for the magnetic field, both oscillating in the same vertical plane. Labels include 'Magnetic field' and 'Electric field'.

It is possible to create light waves that corkscrew around the direction in which they travel. (*Circular Polarisation*)



The diagram shows a wave where the electric field vectors rotate in a circle as the wave travels, forming a corkscrew shape. Labels include 'Circular Polarisation'.

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Polarisation of Light

Demonstration

- Pass light through linear polarising filters (aka Polaroid™)
- Pass light through a calcite crystal
- Pass light through circular polarising filters (aka 3D TV glasses)

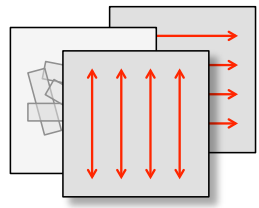
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Crossed Polarising Filters

Demonstration

Place two polarising filters together in perpendicular orientations so that no light is transmitted through them



The diagram shows two grey rectangular filters with red arrows indicating their polarisation directions. The arrows on the two filters are perpendicular to each other. A sheet of plastic is placed between them.

Place a sheet of plastic between them and see what happens. If the plastic has strips of sticky tape on it, they appear coloured dependent on the thicknesses of the tape.

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 **Demonstration**

Crossed Polarising Filters



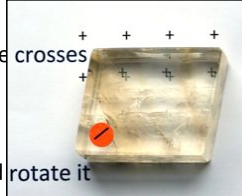
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 **Demonstration**

Calcite Crystal Double Refraction

Place the calcite crystal over this text or the crosses




You see two images of everything

Place a polarising filter over the crystal and rotate it

You see that each image has a different polarisation

This is because light takes two different paths through the crystal depending on its polarisation

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 **Demonstration**


Vampire Zebras




Zebras on the screen (left) have no reflection in the window (right)

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 **Demonstration**

Left-Handed Beetle



Left - Circular

Right - Circular

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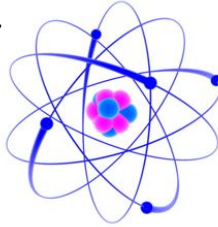
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Atoms and Light

Electromagnetic waves are created whenever charged particles are moved around.

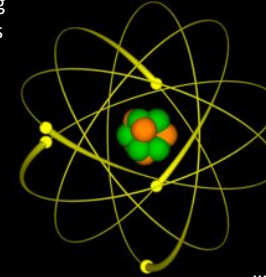
This can happen in a number of different ways, such as accelerating electrons or protons in a particle accelerator, but the smallest objects that involve moving charges are **atoms**.

Hence to understand how light is emitted or absorbed we should look at how atoms work.



Electrons in Atoms

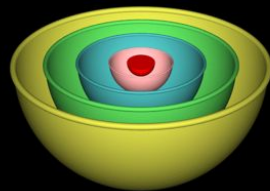
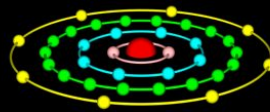
This might be how we imagine atoms with electrons buzzing around a nucleus like bees ...



... but it doesn't show us that all the electrons have different energies

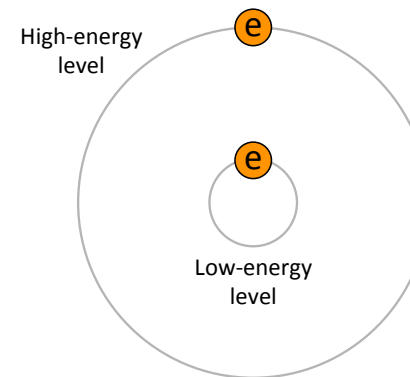
Electrons in Shells

It is better to think of the electrons in different sized orbits ...



... or concentric shells surrounding the nucleus

Quantum Jumps



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Absorption and Emission

The electron can only absorb the energy of the photon if the energies are an EXACT match

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Photon Energy and Colour

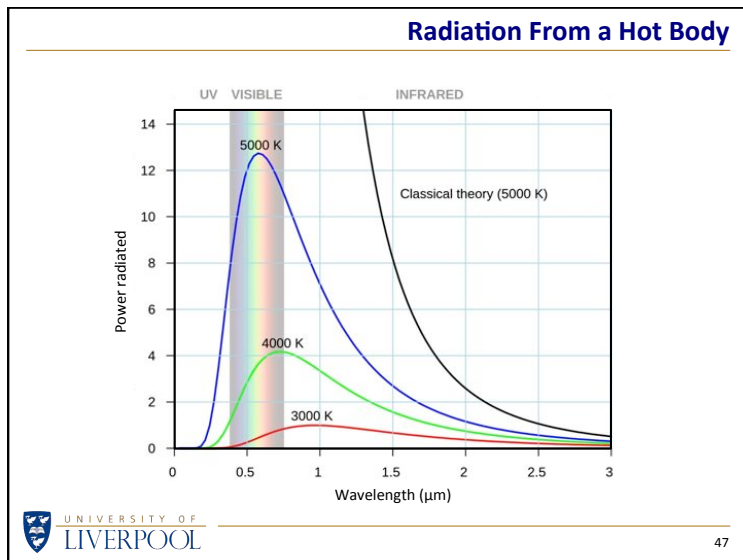
According to Quantum Mechanics – the laws of Physics that describe how things work on very small scales – a photon of light with a given energy has a particular wavelength, and hence a particular colour.

Lower ————— Energy —————> Higher

700 nm ←———— Wavelength ————— 400 nm

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Emission Spectrum

Every atom has many energy levels and so an electron can make quantum jumps with a number of specific energies that are characteristic of the atom.

Hence atoms emit or absorb photons with characteristic patterns of energies and hence colour spectra.

Emission

Absorption

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Spectrum of M57 Ring Nebula

Spectra of stars in the same field of view

M57 hydrogen

M57 oxygen

Direct image of M57
(enhanced as very faint)

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www.liv.ac.uk/~sdb/ProcSyzSoc/Proc-Syz-Soc-4.pdf 49

Spectroscope

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Star Analyser 100

PATON HAWKSLEY EDUCATION LTD
Manufacturer of diffraction gratings, spectroscopes and educational science

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The Star Analyser

With the Star Analyser... Turn this..Into this!

The STAR ANALYSER is used here with an 80mm reflector and an unmodified Philips Toucam Pro webcam, to reveal the telltale signature of molecules in the atmosphere of the magnitude +3.4 red giant Delta Virginis (spectral class M3 iii) (Graph plotted from spectrum image using Visual Spec software)

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www.patonhawksley.co.uk/staranalyser.html 51

Spectrum of Betelgeuse

Relative Intensity of Spectrum

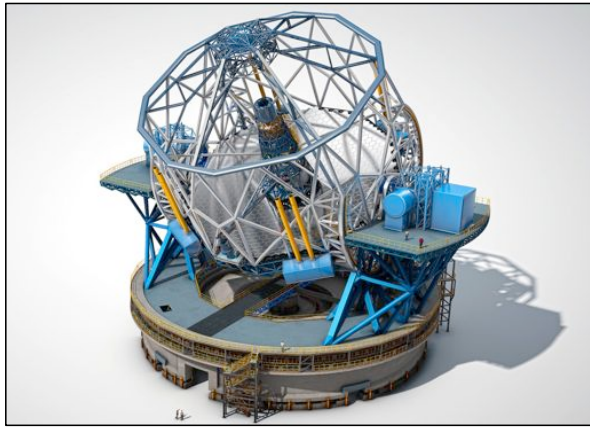
Wavelength (Å)

He TiO Fe VO Na TiO

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www.liv.ac.uk/~sdb/ProcSyzSoc/Proc-Syz-Soc-1.pdf 52

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European Extremely Large Telescope



Evolution of Telescopes

Telescopes have evolved with ever larger mirrors to collect the light.

Larger mirrors means better resolution, so **SHARPER** images.

Larger mirrors mean more light, so **BRIGHTER** images.

But remember that one of the most important instruments on these telescopes is the spectrograph, as without it we would not be able to understand what the light from these distant objects is telling us.

(For instance, note that the EELT has **3** cameras, but **7** spectrographs!)

Astronomy has come a long way since Auguste Comte (1798 – 1857):

"We will never know ... the composition of the stars"

Summary

You now have a better understanding of what light is.

You have seen demonstrations that have shown that ...

The speed of light is 300,000 km/s



The wavelength of light is 400–700 nm

Light can be split into its component colours



Light waves can be polarised in different ways

Now take a diffraction grating and go and experiment for yourself ...

