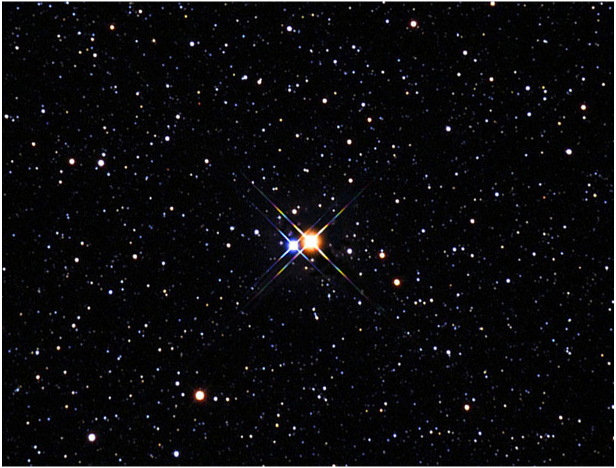
Black body radiation

- Another fact about black bodies is that the hotter they are, the more energy they emit.
- How much more? Jožef Stefan and Ludwig Boltzmann discovered that if you double the temperature of a black body, it emits 16 times as much energy.

$$F = \sigma T^4$$

- F is the energy emitted per square metre of surface area. σ is a constant.
- This equation is called the **Stefan-Boltzmann Law**

Wien and Stefan-Boltzmann - example



- β Cygni: the *cooler* star is also *brighter* - it must therefore be *larger*

Wien and Stefan-Boltzmann - example

- Sirius is the brightest star in the sky. Its spectrum peaks at a wavelength of 290nm. So, what is its temperature?

$$\lambda = 0.0029 / T$$

- So,

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

Wien and Stefan-Boltzmann - example

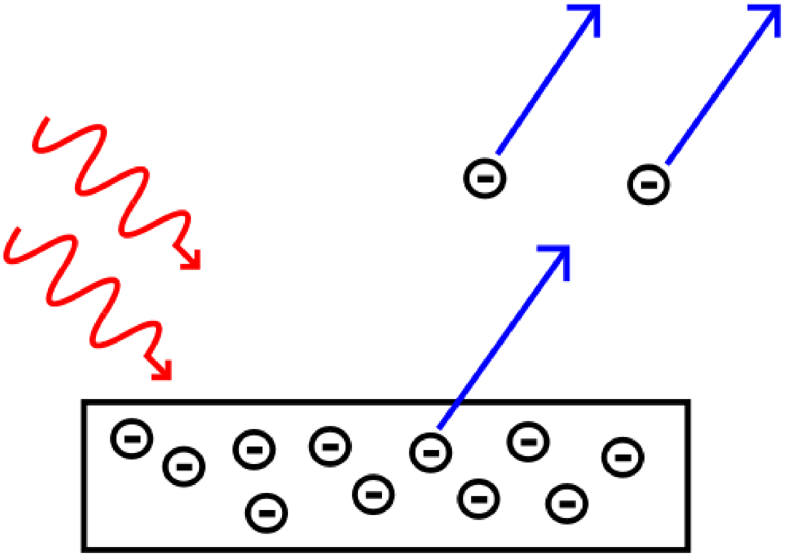
- How much more energy does Sirius emit per square metre of its surface than the Sun does?

$$
\begin{aligned}
\frac{F(Sirius)}{F(Sun)} &= \frac{T(Sirius)^4}{T(Sun)^4} \\
&= (10,000/5,800)^4 \\
&= 8.8
\end{aligned}
$$

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 nature of light – Part II

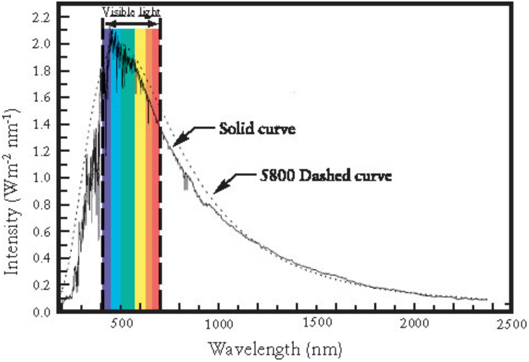
- If you increase the *brightness* of the light, the energy of the electrons stays the same. But if you increase the *frequency* of the light, the electrons move faster.
- This doesn't make sense, if light is a wave. But it makes perfect sense if light is made of particles.
- The photoelectric effect proves that light is made of particles (called **photons**. 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. The higher the *frequency*, the more *energy* the light particles (photons) are carrying:

$$E = hf$$

- (h = Planck's constant = 6.634×10^{-34}J/Hz)

What EM radiation can tell us

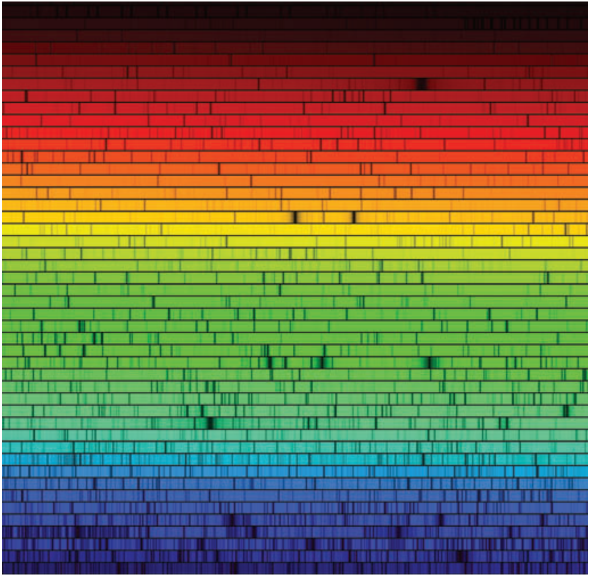
- Using Wien's law, we can use the fact that stars are quite like black bodies to estimate their temperatures. But so far we don't know anything about their composition.
- Stars are not exactly like BBs:



What EM radiation can tell us

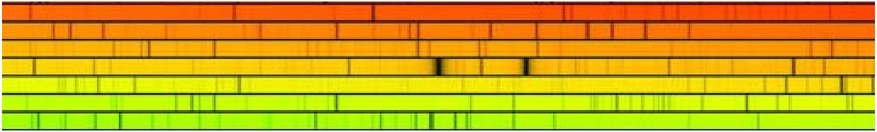
- The difference between a stellar spectrum and a black body can tell us about what the star is made of.
- Joseph von Fraunhofer made a major advance in astronomy by examining the spectrum of the Sun at very high magnification. He found that it was full of dark lines.

What EM radiation can tell us



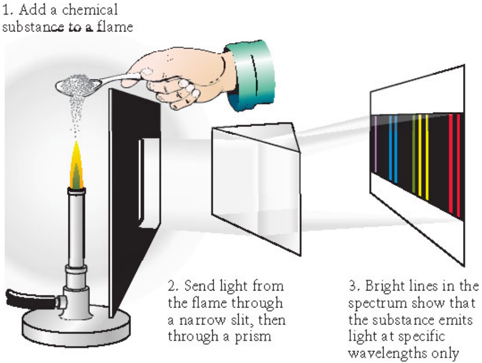
What EM radiation can tell us

- 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.



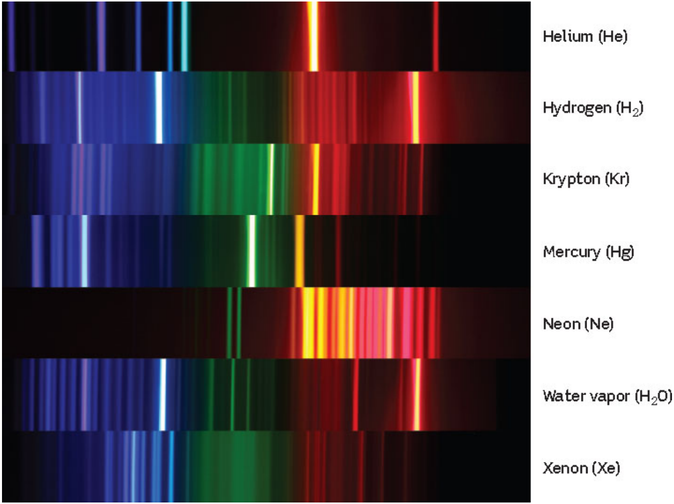
What EM radiation can tell us

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



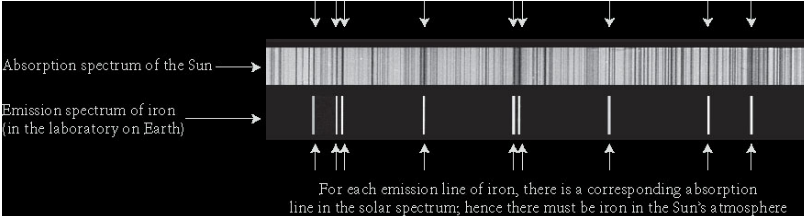
What EM radiation can tell us

- 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.

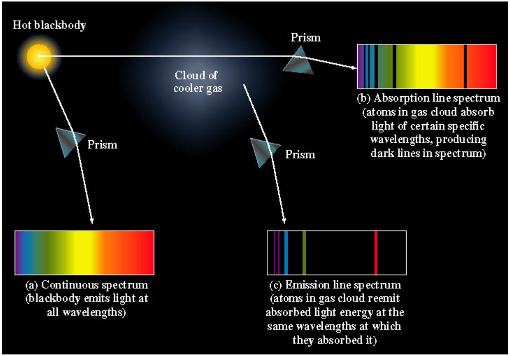
- He proposed that the line was due to a new element, which he called helium (from the Greek Helios: Sun).
- He was proved right: helium was discovered on Earth in 1895 (it is given off by the radioactive decay of Uranium)

Kirchhoff's laws

- You can see bright sodium spectral lines if you drop salt in a flame. And you can see dark sodium spectral lines if you look at the Sun's light. They are definitely sodium lines in each case. So why is it sometimes dark (absorbing light) and sometimes light (emitting light)?
- Gustav Kirchhoff was the first to describe why:
  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

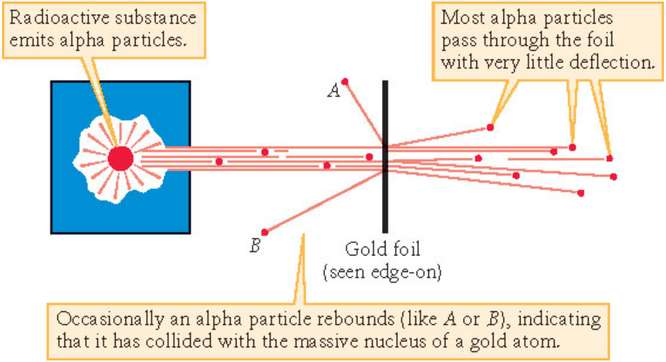
- The fact that different atoms absorb and emit radiation only at particular wavelengths tells us a great deal about extremely distant astronomical objects.
- Much closer to home, it also tells us about the fundamental structure of matter. It cannot be explained by the wave theory of light, and the reasons why matter behaves in this way did not become clear until the 20th 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

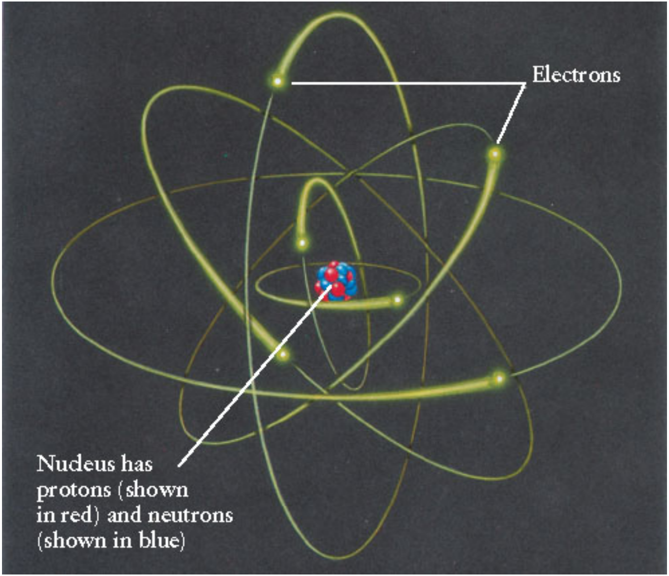
- In fact, most of the helium atoms passed through with almost no deflection at all. A very small number were deflected by a large amount.
- This showed that the atoms in the gold had the vast majority of their mass concentrated in a very small volume.



The structure of matter

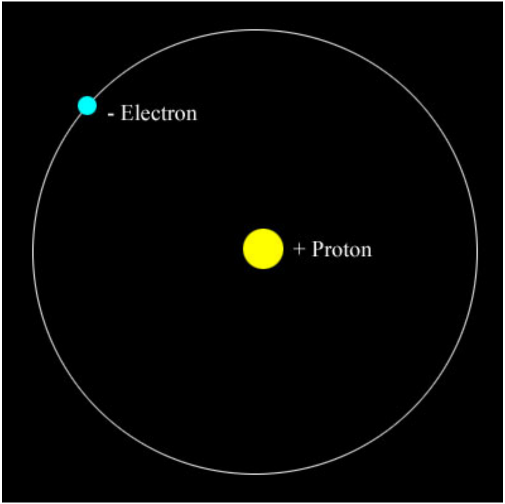
- Rutherford said he was as surprised as if he'd fired a cannonball at a piece of tissue paper and seen it rebound.
- His result led to the understanding of an atom as consisting of a very small and dense nucleus, containing almost all of the mass of the atom, surrounded by a shell of electrons.
- If an atom were the size of a football field, its nucleus would be about 1cm across.

The structure of matter



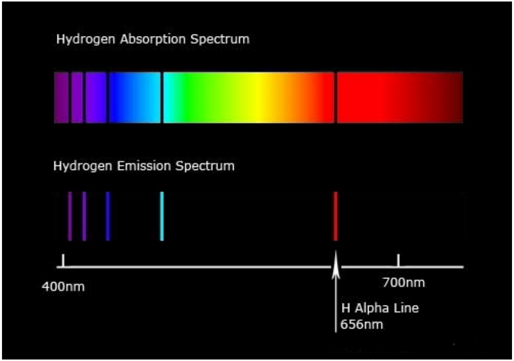
Hydrogen

- The easiest atom to understand is hydrogen. It consists of one proton and one electron.



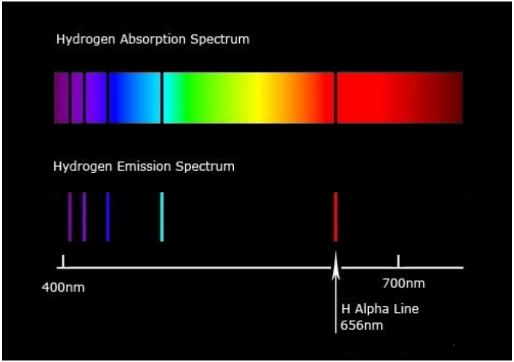
Hydrogen

- Hydrogen gas in space (and in the lab) has a spectrum like this:



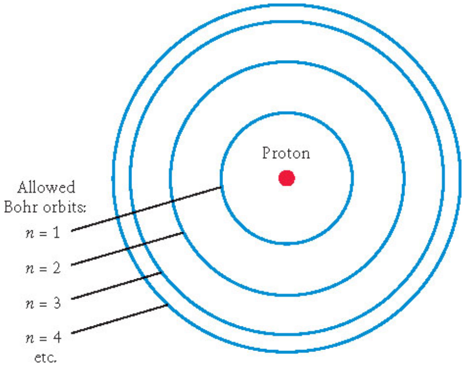
Balmer lines

- The visible lines have wavelengths ranging from 656.3nm to 364.6nm, getting more closely spaced at shorter wavelengths.
- This was first noticed by Swiss school teacher Johann Jakob Balmer, and so the lines are now called Balmer lines or the Balmer series.



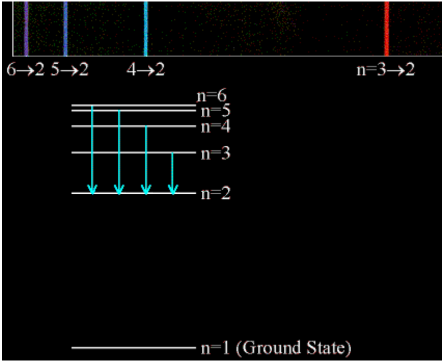
Balmer lines

- The wavelengths of the Balmer lines follow a very simple mathematical relation. Niels Bohr was the first to work out what this meant about the structure of the hydrogen atom.
- He proposed that electrons could only orbit the nucleus of the atom in certain fixed orbits, and not just at any distance.



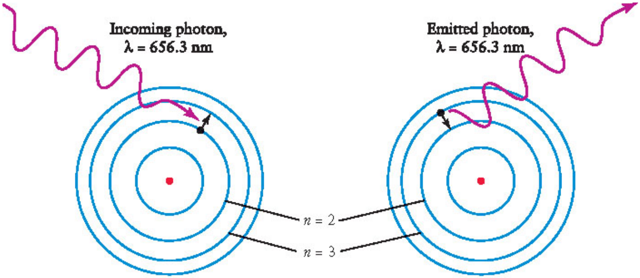
Balmer lines

- Then, when an electron drops into a lower orbit, it emits a photon with a particular wavelength.
- The orbits are normally referred to as energy levels. The lowest energy level is called the ground state.



Balmer lines

- When an electron drops into a lower energy level, a photon is emitted. The wavelength of the photon depends on the gap between the energy levels.
- And vice versa - when a photon strikes an atom, it can make an electron jump up to a higher energy level - but **only** if the energy of the photon is **exactly** right.

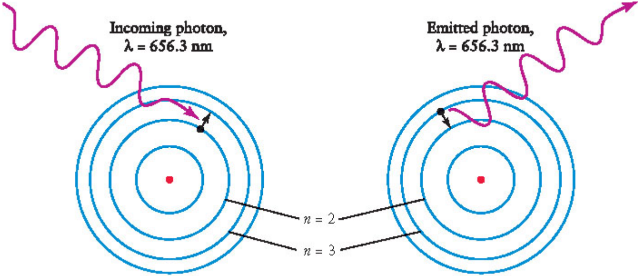


(a) Atom absorbs a 656.3-nm photon; absorbed energy causes electron to jump from the n = 2 orbit up the n = 3 orbit

(b) Electron falls from the n = 3 orbit to the n = 2 orbit; energy lost by atom goes into emitting a 656.3-nm photon

Balmer lines

- This picture of the atom explains why hot gases display an emission line spectrum, while cold gases in front of hot opaque bodies like stars cause an absorption spectrum – we see where Kirchhoff's laws come from.

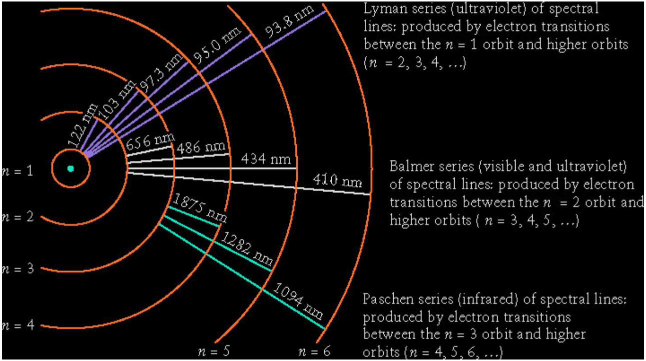


(a) Atom absorbs a 656.3-nm photon; absorbed energy causes electron to jump from the n = 2 orbit up the n = 3 orbit

(b) Electron falls from the n = 3 orbit to the n = 2 orbit; energy lost by atom goes into emitting a 656.3-nm photon

Other hydrogen series

- The Balmer series arises from transitions into the second-lowest energy level in the hydrogen atom.
- Other series exist that are formed by transitions into other energy levels.



Ionisation

- The Balmer series ends at 364.6nm. This corresponds to a transition from an infinitely high energy level into the second-from-bottom energy level.
- The Lyman series (transitions into the ground state) ends at 91.2nm, deep in the ultraviolet.
- If a photon with a wavelength less than 91.2nm strikes a hydrogen atom, it will remove the electron completely. This process is called ionisation.

The hydrogen atom

Animation - available in screen version

Other elements

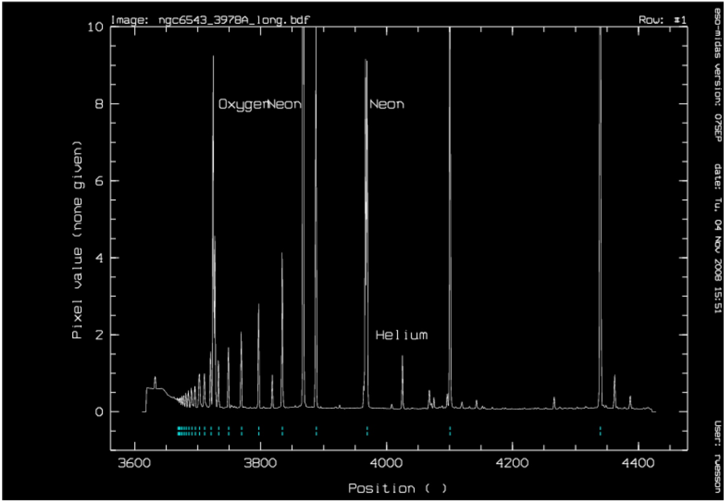
- The same principles apply to all elements. We can calculate from atomic physics where we expect to see spectral lines, for each element.
- Then, when we see those lines in astronomical objects, we can work out the composition of the objects.

Other elements

- For example – the Cat's Eye Nebula:

Other elements

- For example – the Cat’s Eye Nebula:



Line spectra and continuous spectra

- Our understanding of atoms as being composed of electrons orbiting a nucleus explains Kirchoff's second and third laws. But what about the first? Why do dense opaque bodies emit continuous spectra?
- Street lamps containing low pressure sodium gas give off the classic, monochromatic yellow sodium light. But if you put the gas under pressure, the two bright yellow lines become broader.
- The higher the pressure, the broader the line emission. For solids, the interaction between all the closely spaced atoms results in a continuous spectrum.

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.
- When a car approaches, the pitch of its engine sounds higher. As it recedes, the pitch of its engine sounds lower.

Light and motion

- The same effect also happens with EM radiation.

Animation - available in screen version