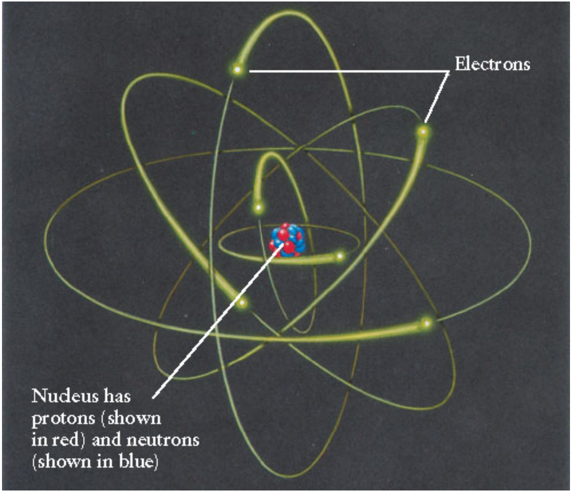
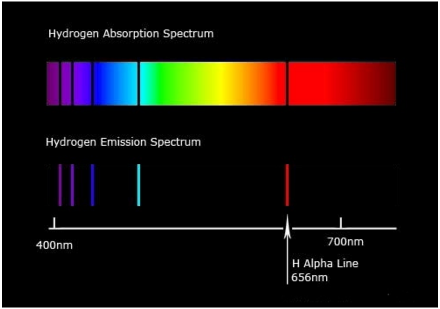
The structure of matter



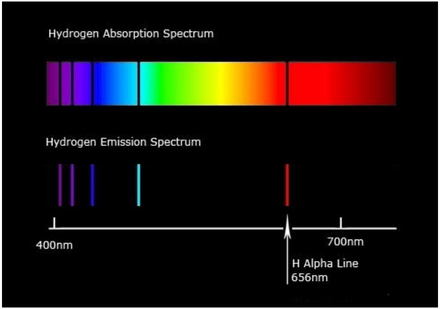
Hydrogen

- The easiest atom to understand is hydrogen. It consists of one proton and one electron.
- Hydrogen gas in space (and in the lab) has a spectrum like this:



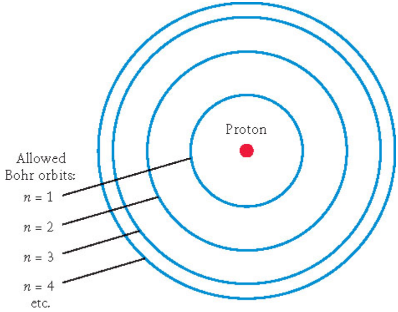
Balmer lines

- 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.



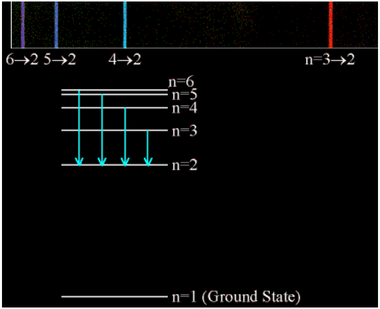
Balmer lines

- 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.

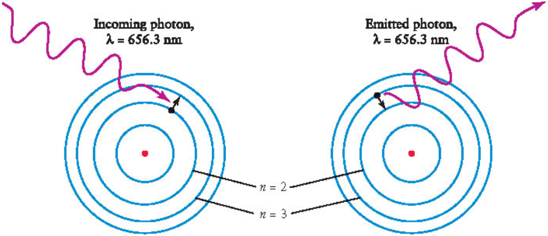


Balmer lines

- When an electron orbiting an atomic nucleus from a high energy level to a lower one, a photon is emitted. The larger the difference between the energy levels, the shorter the wavelength of the photon that is emitted.
- Similarly, if a photon with the same energy as the difference between two energy levels strikes an atom, an electron in the lower energy level may be boosted into the higher energy level and the photon will be absorbed.

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.

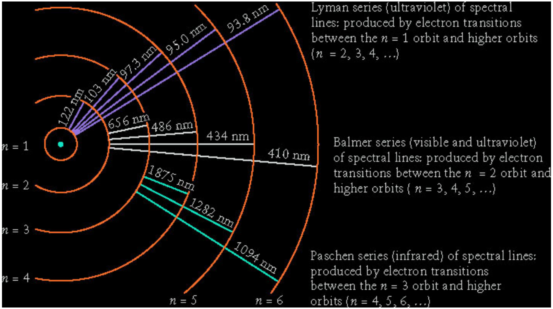


(a) Atom absorbs a 656.3-nm photon; absorbed energy causes electron to jump from the n = 2 orbit up the n = 3 orbit

(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

Click to start

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

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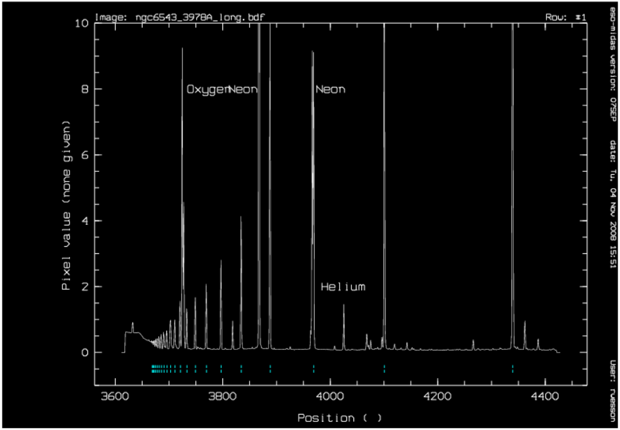


Line spectra and continuous spectra

- 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.

Click to start

Light and motion

- This means that if you know what wavelength some radiation was emitted at (as you would for, say, a hydrogen Balmer line), then the observed wavelength tells you the velocity of the object along the line of sight.
- The change in wavelength is related to the velocity by a simple equation:

$$\frac{\Delta\lambda}{\lambda} = \frac{v}{c}$$

Light and motion

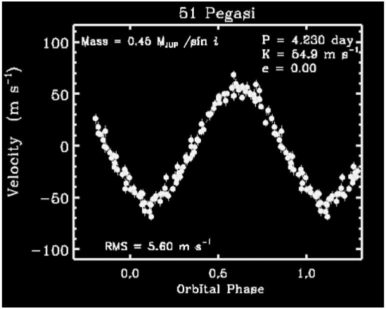
- So, for example, in the spectrum of Sirius, you see the Balmer alpha absorption line at 656.260 instead of 656.277 nm.

$$\begin{aligned} \frac{0.017}{656.277} &= \frac{v}{c} \\ v &= c \times \frac{0.017}{656.277} \\ &= 3 \times 10^8 \times \frac{0.017}{656.277} \end{aligned}$$

- This means that Sirius is moving towards us at 7.7km/s

Light and motion

- The Doppler effect is very important in astronomy. Some examples:
- The first planets outside our solar system were detected by looking for tiny 'wobbles' in the motions of stars, caused by the gravitational tug of planets orbiting them.



Light and motion

- If you look at a spiral galaxy, you can see that stars on one side are approaching us while stars on the other side are receding.
- The velocity of the stars far out is much larger than you would expect, from the amount of visible matter you see. This implies that there is dark matter.

Light and motion

- If you look at any galaxy beyond the Local Group, you find that it is receding from Earth. The Universe is expanding.
- Looking in more detail, you find that the more distant it is, the faster it is receding. Edwin Hubble discovered this, and the phenomenon is called the Hubble Flow.

Light and motion

- We learned earlier that the Lyman series of hydrogen terminates at 91.2 nm. Any photon with a wavelength smaller than this ionises the hydrogen. Galaxies are full of hydrogen so they absorb very strongly below 91.2 nm.
- This can be used in a handy technique for finding very distant galaxies. The Hubble Deep Field consisted of images taken at wavelengths of 300, 450, 606 and 814nm.
- If a galaxy is far away enough, the Lyman limit may be redshifted into the visible part of the spectrum. A galaxy like this will be visible in the 450, 606 and 814nm images, but not the 300nm one.

Light and motion