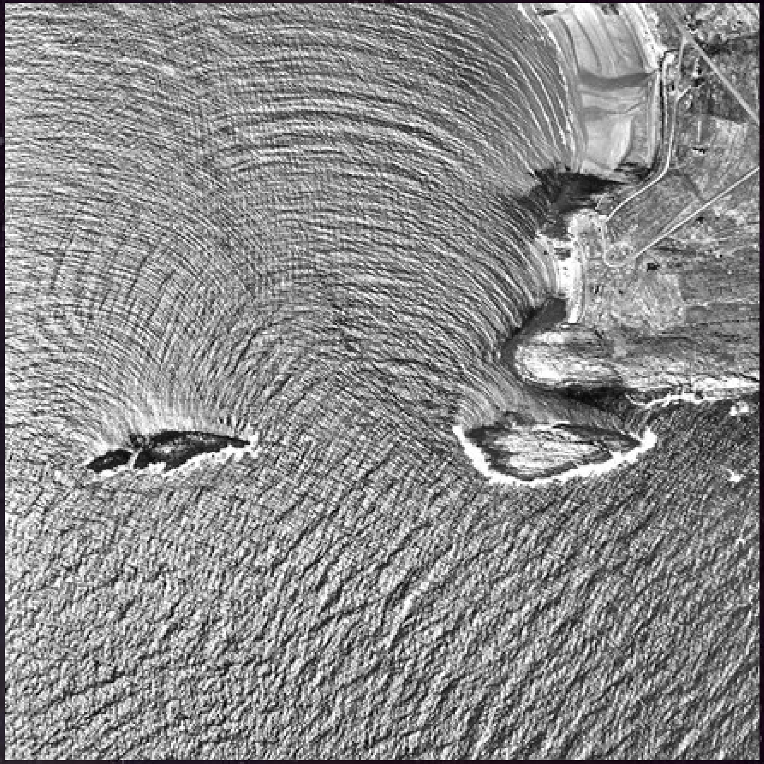
# Electromagnetic radiation

Recap from last time:

Light travels at 300,000 km/s. It is a form of *electromagnetic radiation*. Beyond the range of what the eye can perceive, you find other forms of electromagnetic radiation like X-rays, infrared and radio.

If you pass light through a narrow gap, it *diffracts* – just like waves entering a harbour. This shows that light behaves as a wave.



The 'classical' understanding of light is that it is composed of oscillating magnetic and electric fields.

# Wave/particle

But light also behaves as a particle, for example in the *photoelectric effect*, in which light striking a metal kicks off electrons, but only if the light has a wavelength shorter than a threshold.

So light behaves like a particle *and* like a wave. The 'particles' of light are called photons. The shorter the wavelength of a photon, the more energy it carries.

$$E = hf$$

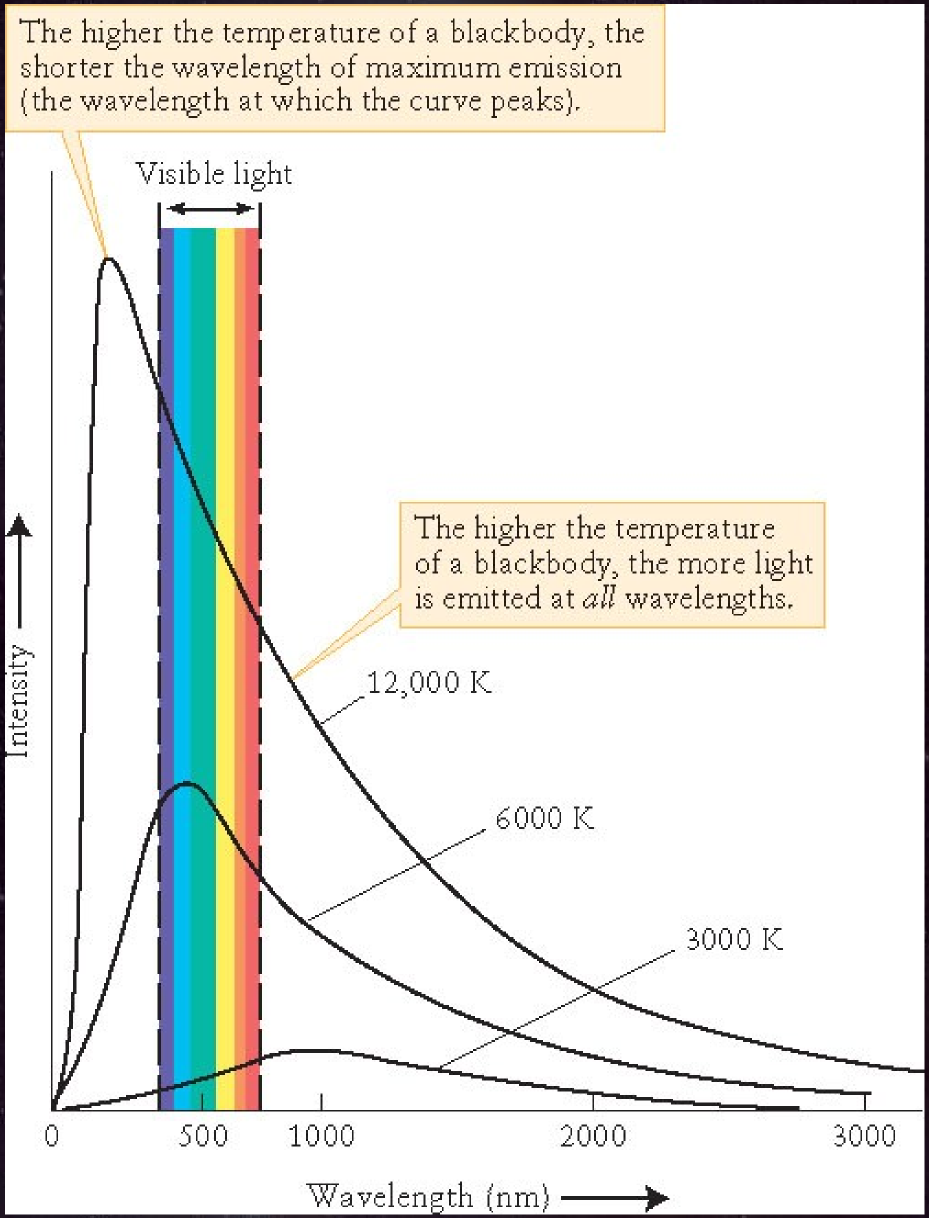
where h is the Planck Constant ($6.63 \times 10^{-34}$) and f is the frequency.

# Astronomical spectra

All matter in the universe emits electromagnetic radiation.

Dense opaque bodies emit continuous spectra, and the wavelength at which the continuous spectrum peaks is related to the temperature of the body.

So, the colours of stars can tell us something about the temperatures of stars.



# The electromagnetic spectrum and temperature

Albireo ($\beta$ Cygni) is a double star with an amazing colour contrast between the two stars. The orange one has a temperature of 4000K; the blue one is much hotter at about 30,000K

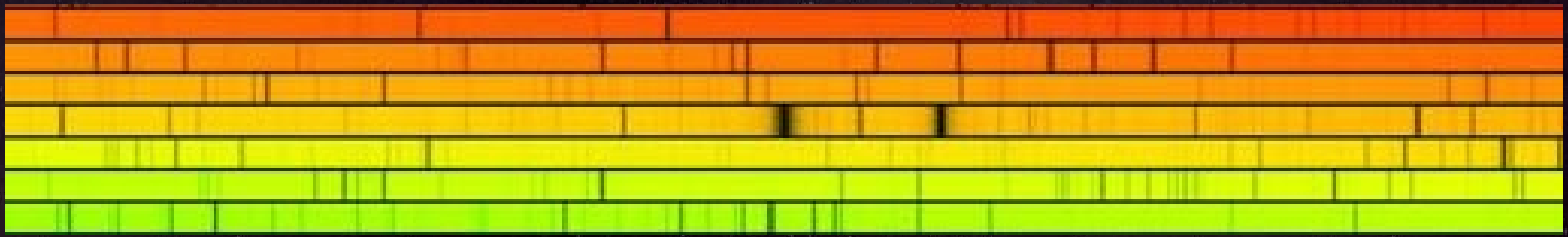
# Black bodies

A *black body* is one which absorbs all the radiation which falls on it. The radiation it then emits is defined only by its temperature. The emission from stars is quite similar to the emission from black bodies.

Generally, dense opaque objects behave approximately like black bodies.

# What EM radiation can tell us

Stars behave approximately like black bodies, but their continuous spectra generally contain a lot of narrow *absorption lines*. Here is a part of the Sun's spectrum.



The two dark yellow lines have exactly the same wavelength as the light you see if you burn salt. They tell us that there is sodium in the Sun's atmosphere.

The Sun's surface behaves roughly like a black body, but its outer gases are not dense and opaque, and they absorb light.

# Kirchhoff's laws

Clearly, there is a relation between the bright spectrum with dark lines emitted by the Sun, and the bright lines emitted by elements in the lab. Kirchhoff described this relation in the form of three 'laws':

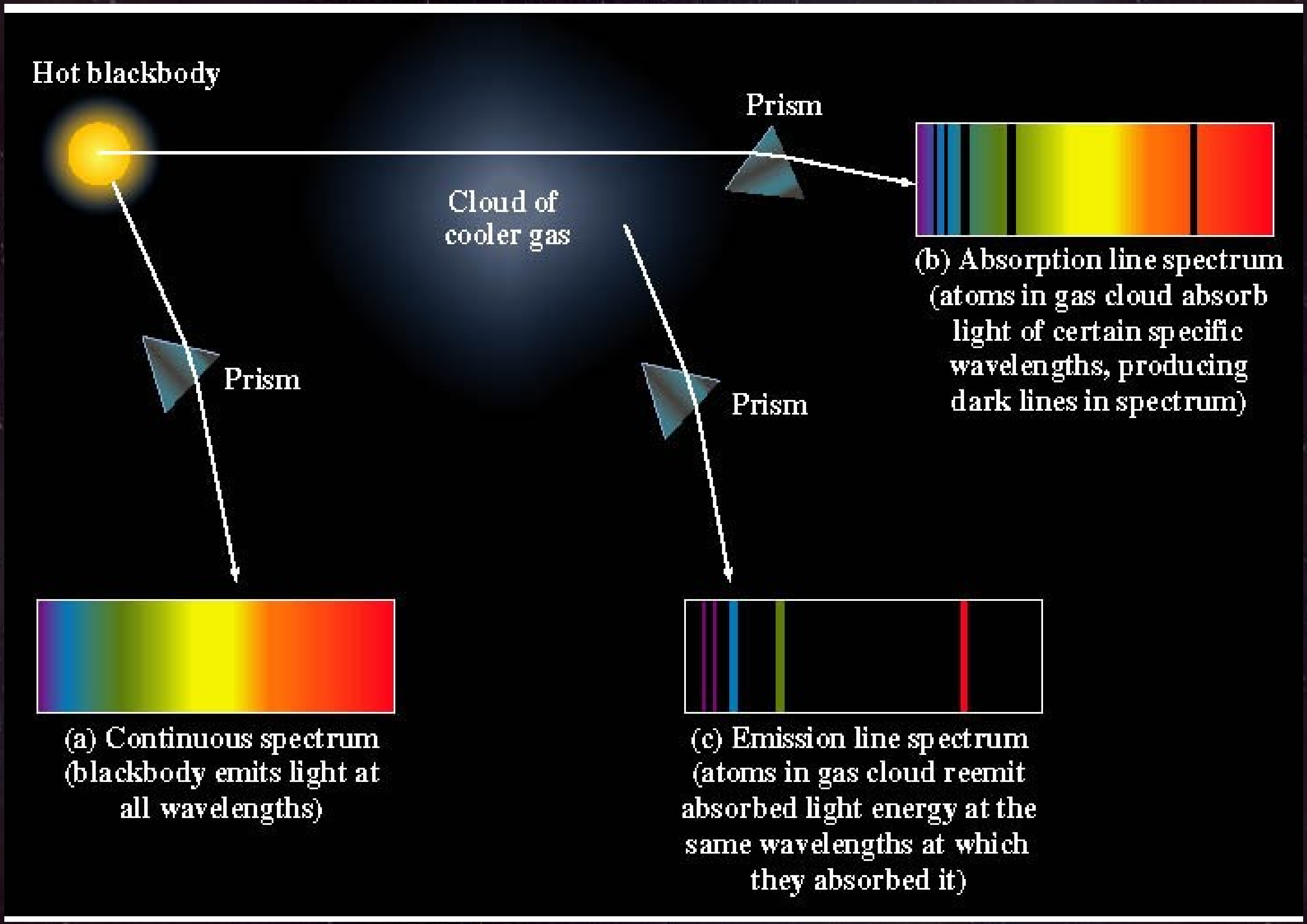
1. A hot opaque body, such as the ideal black body, or a star, emits a *continuous spectrum*.

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*.

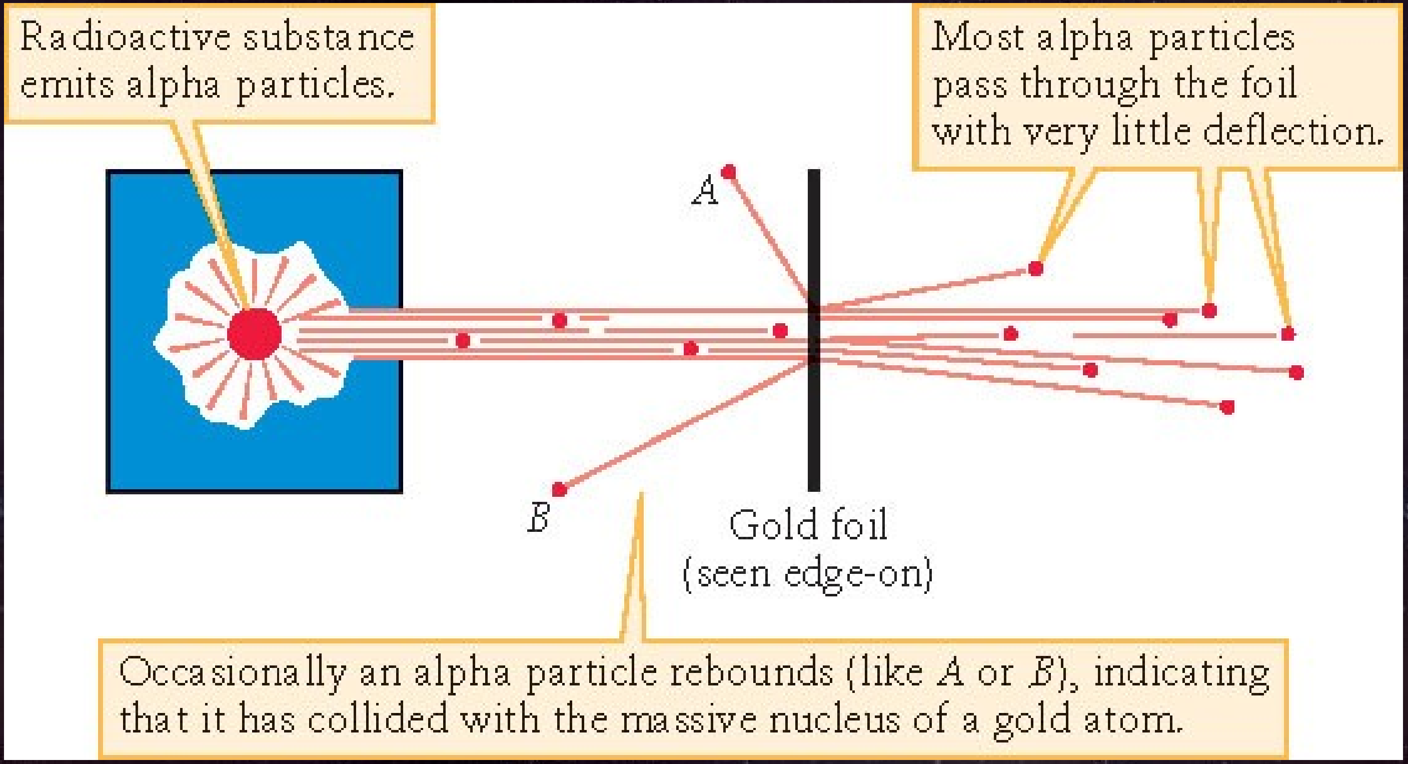
# Kirchhoff's laws

The Sun's spectrum can then be understood as being produced as light from the hot surface passes through the cooler atmosphere.

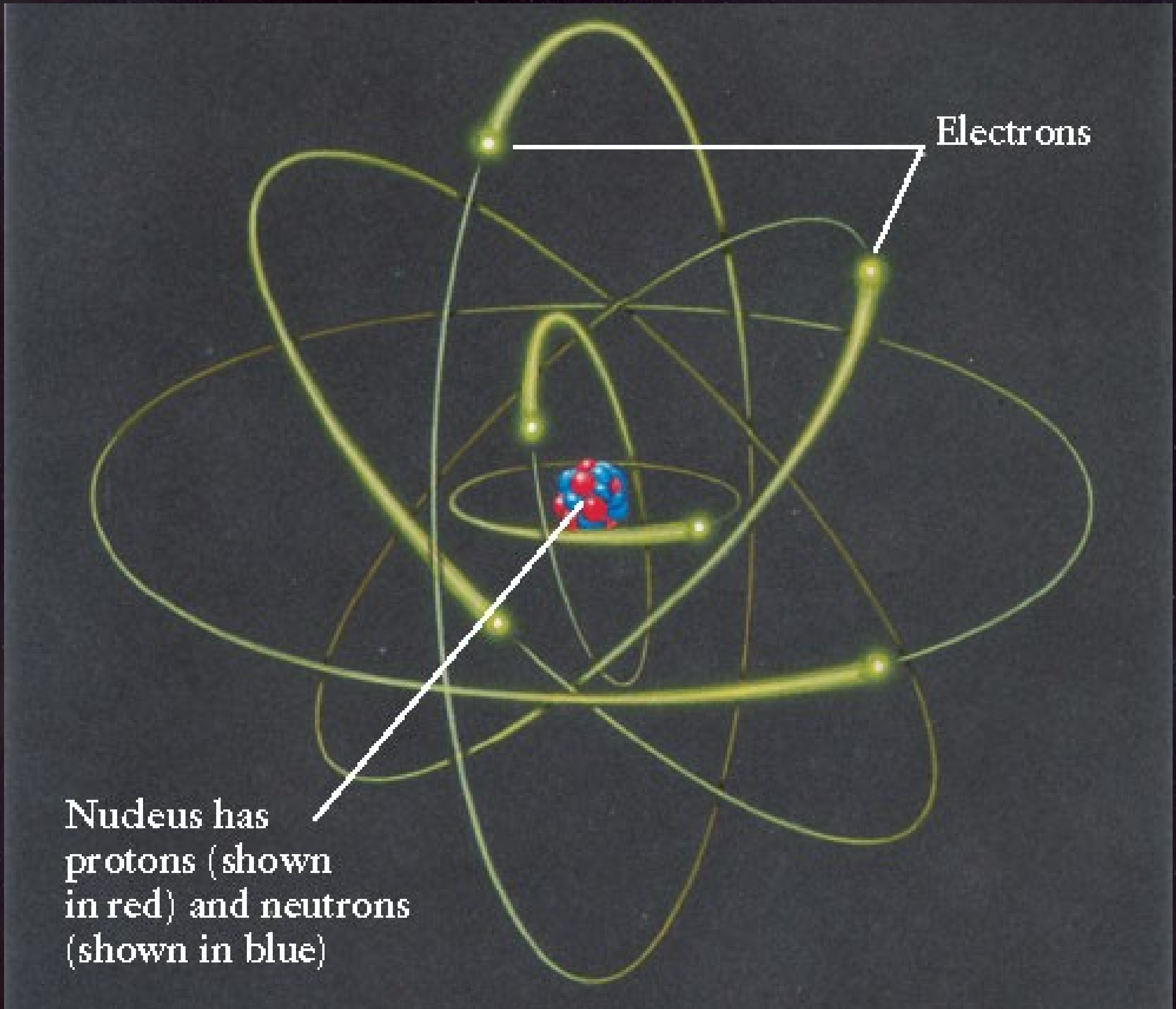


# The structure of matter

Rutherford fired alpha particles at a very thin sheet of gold, and found that gold atoms must consist of a very small nucleus containing most of the mass.



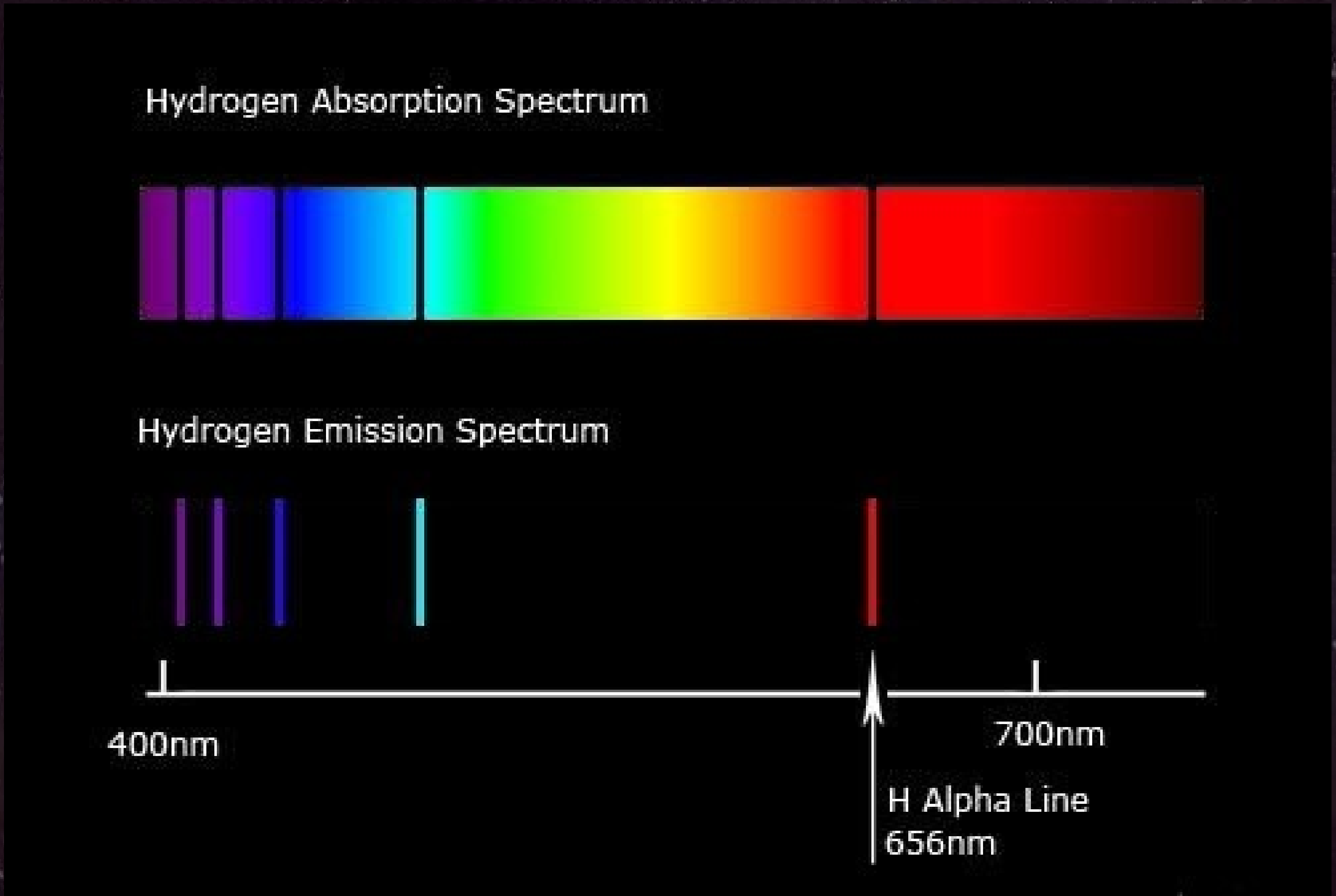
# The structure of matter



# Hydrogen

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

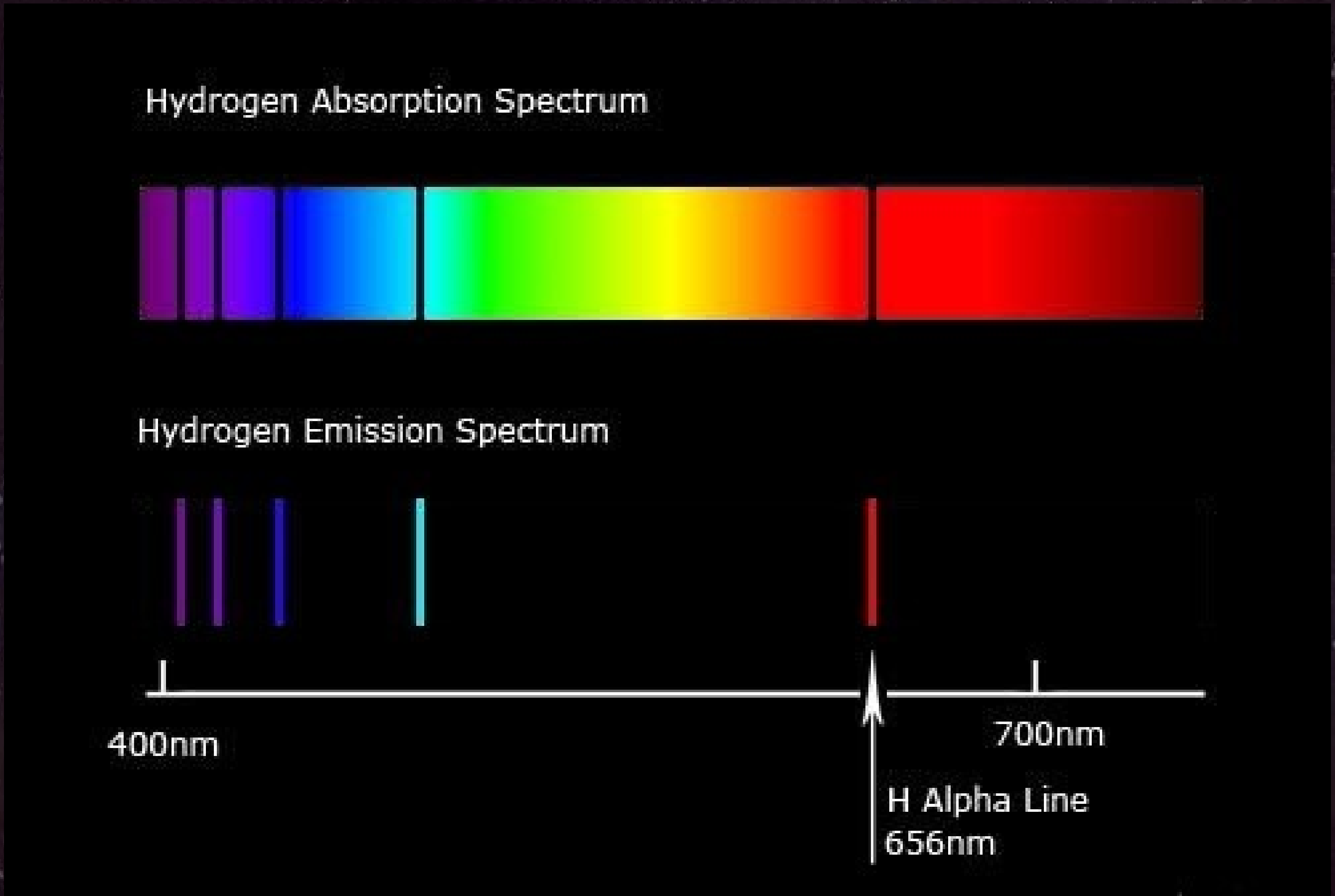
Hydrogen gas in space (and in the lab) has a spectrum like this:



# 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.*

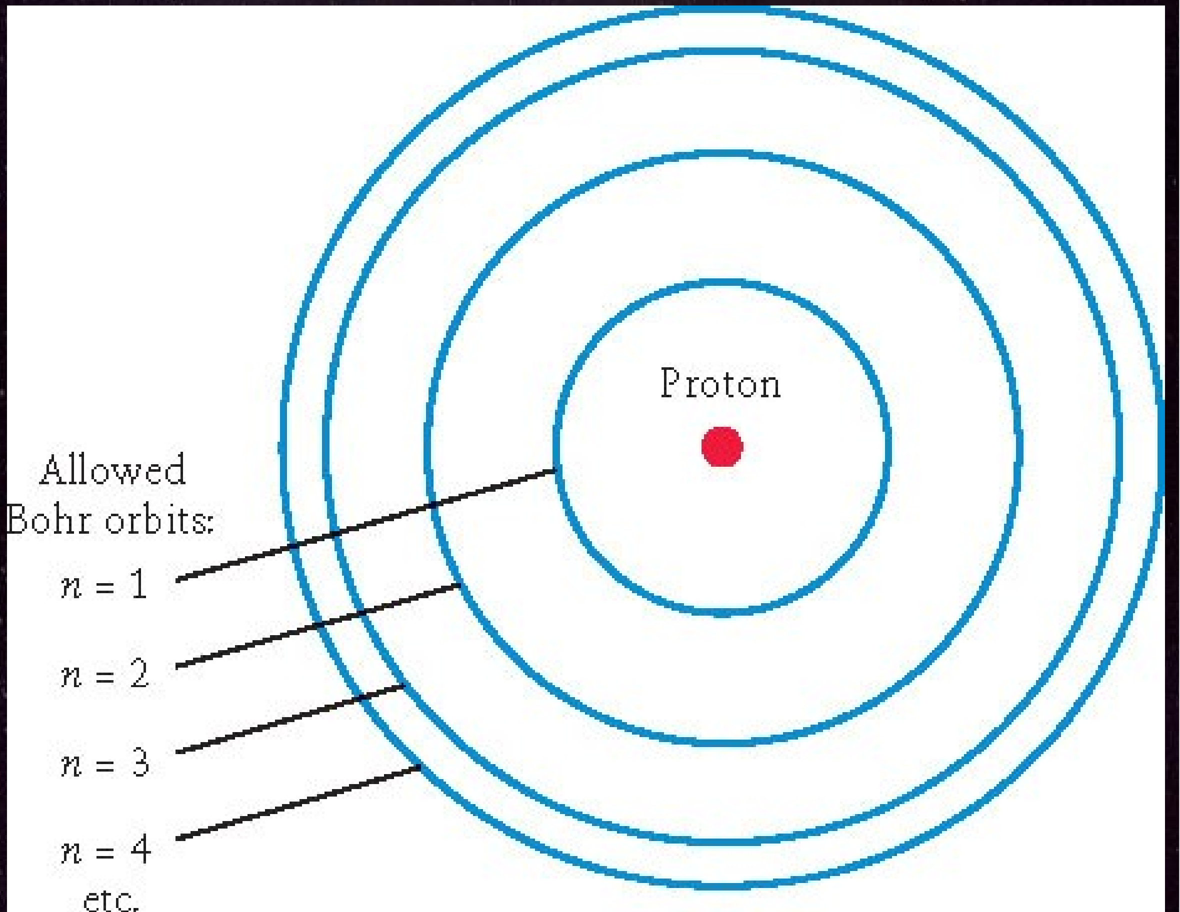


# Balmer lines

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.

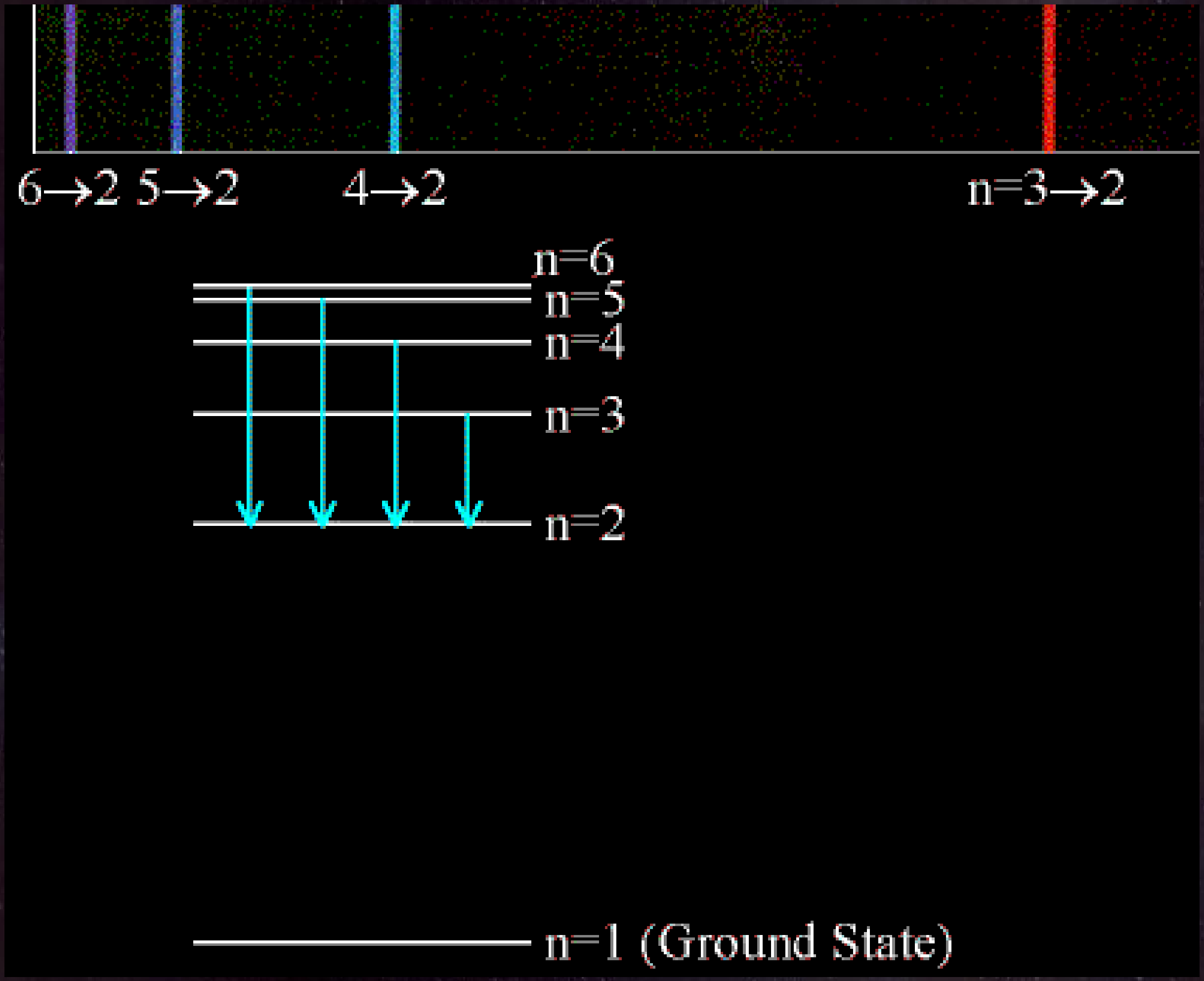
He proposed that electrons could only orbit the nucleus of the atom in certain fixed orbits, and not just at any distance. Then, when an electron drops into a lower orbit, it emits a photon with a particular wavelength.

The Balmer series is created by transitions of electrons into the second-lowest orbit in the hydrogen atom.



# Balmer lines

The orbits are normally referred to as *energy levels*. The lowest energy level is called the *ground state*.



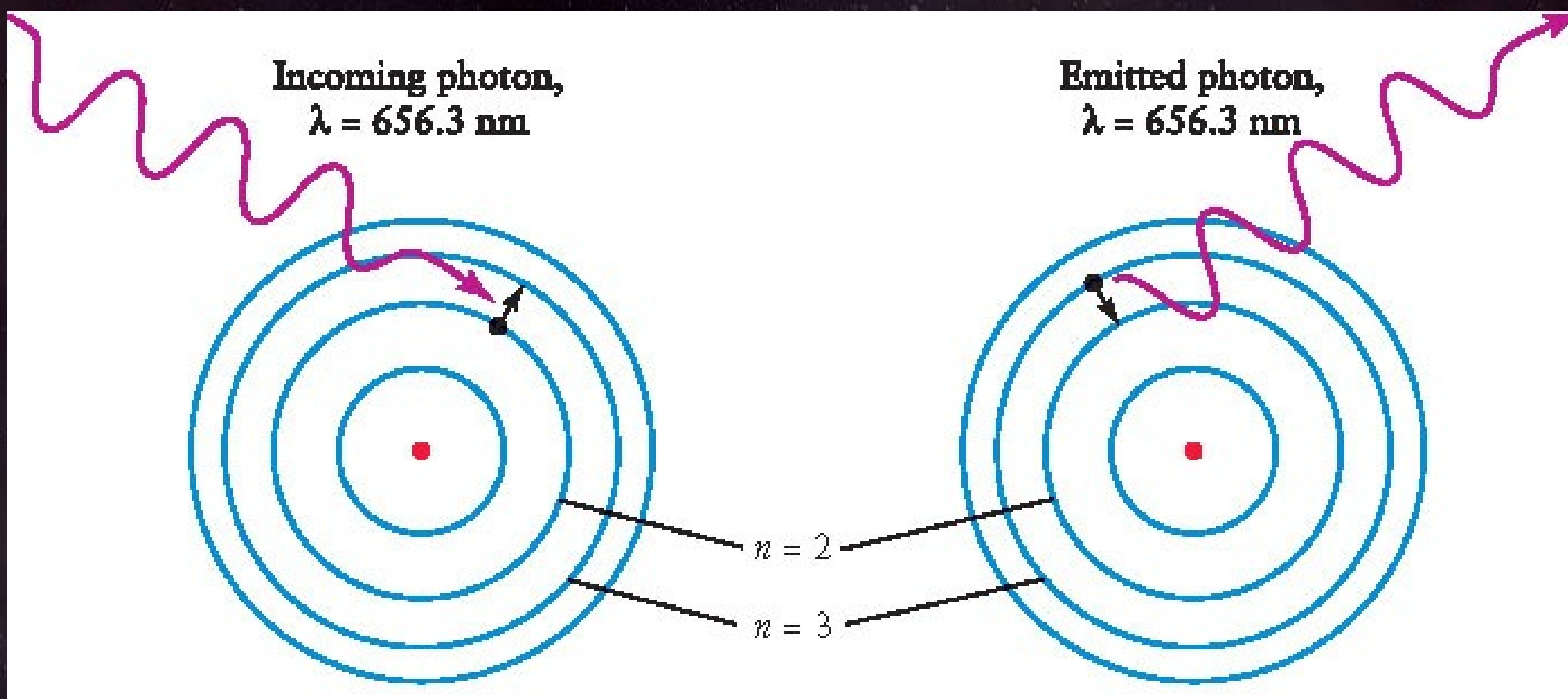
# Balmer lines

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.



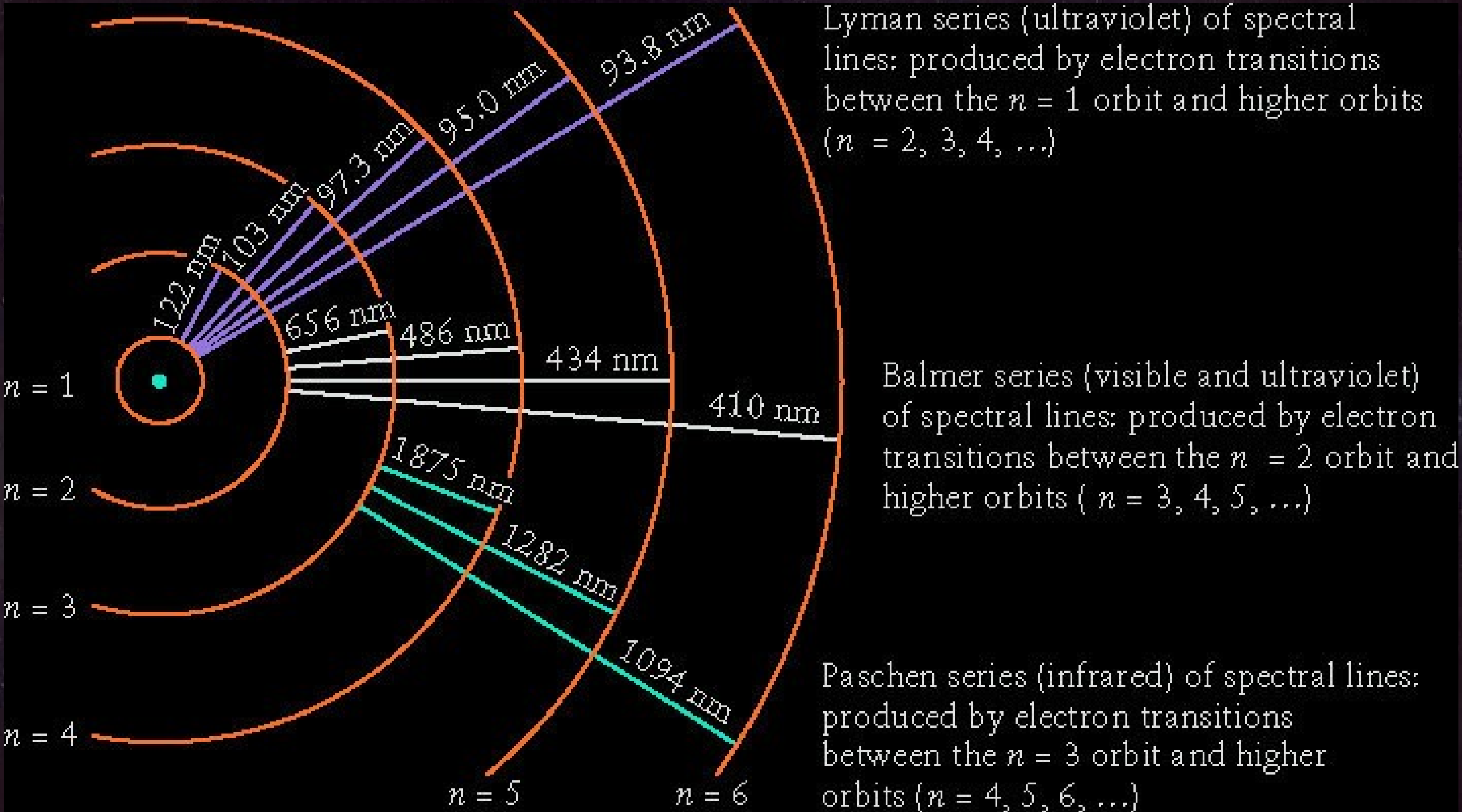

(a) Atom absorbs a 656.3-nm photon; absorbed energy causes electron to jump from the n = 2 orbit up the n = 3 orbit

(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*.

# 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:

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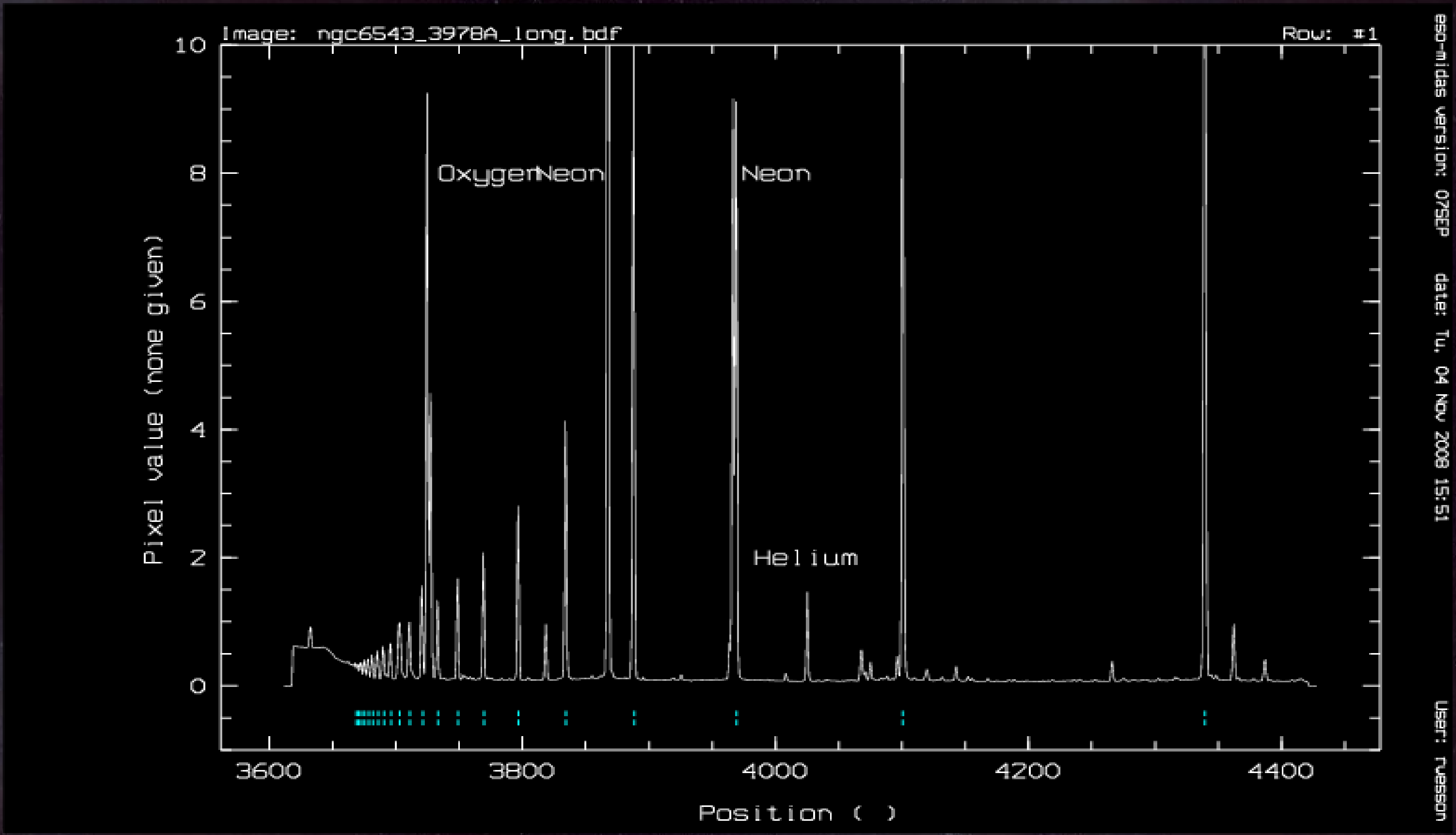


# Line spectra → continuous spectra

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.

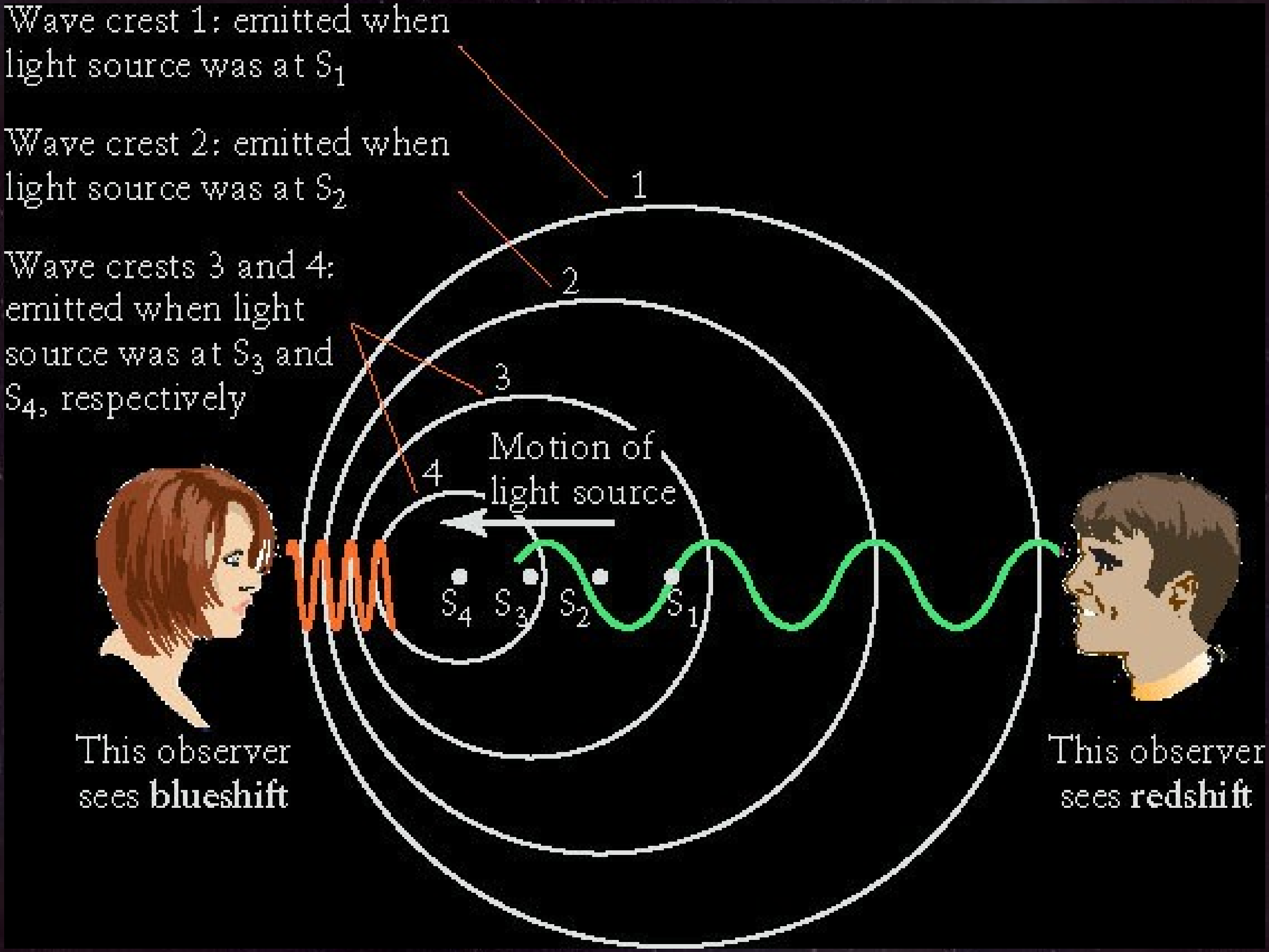
Another thing we can tell from spectroscopy is how fast things are moving, along our line of sight.

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.



# 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:

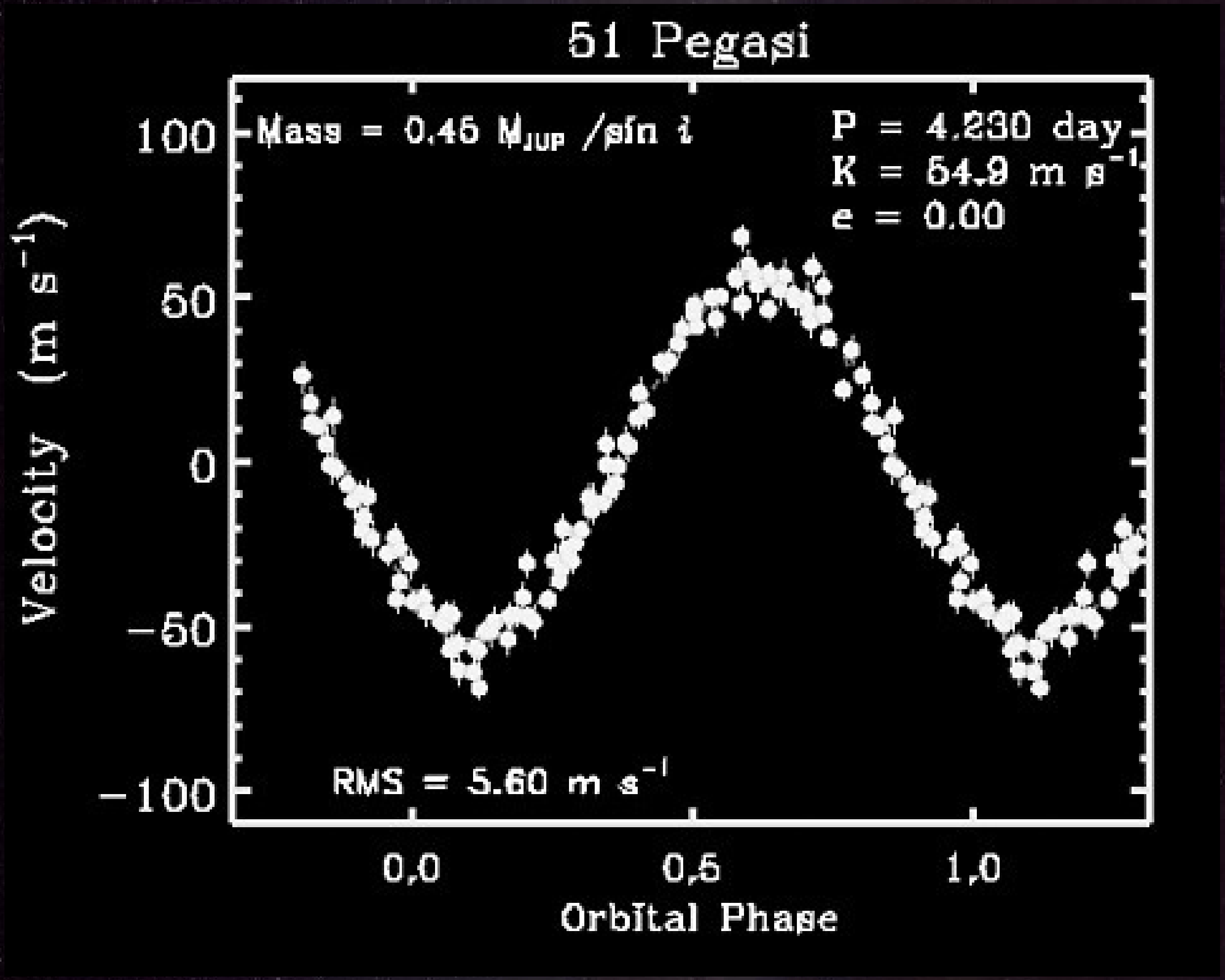
$$\Delta\lambda/\lambda = v/c$$

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

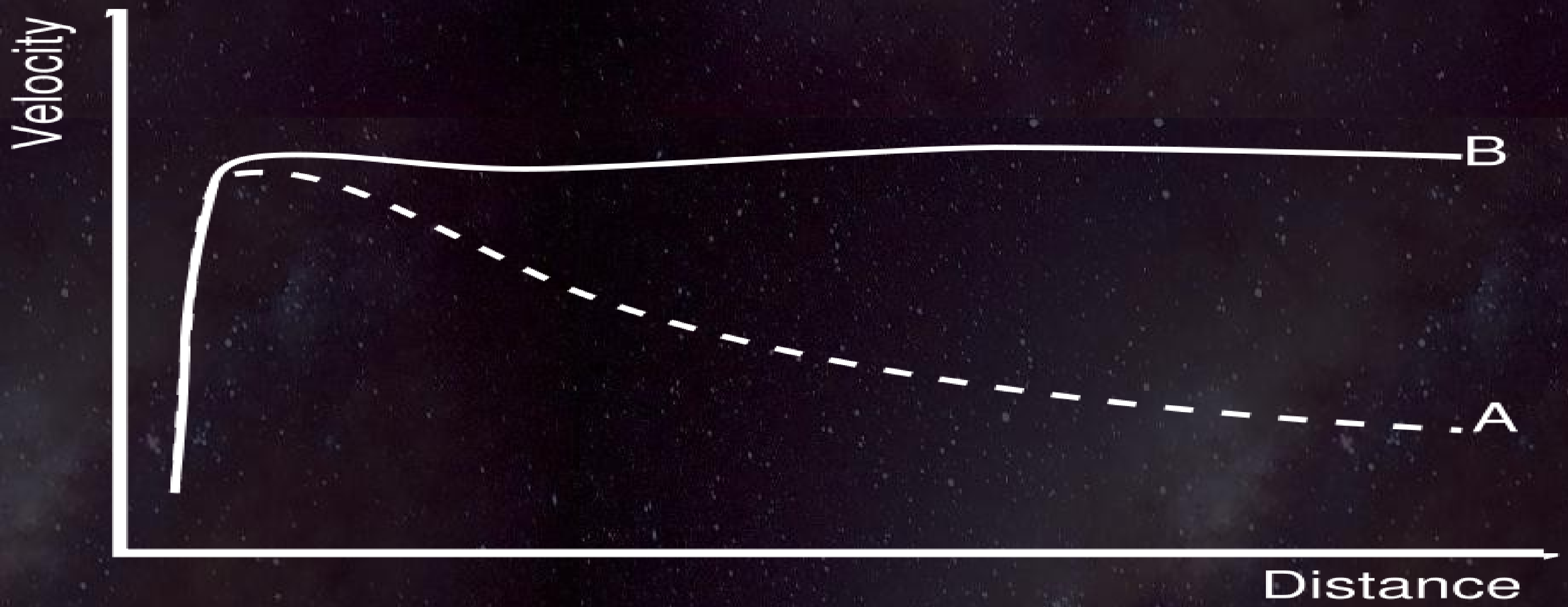
The first planets outside our solar system were detected by looking for tiny 'wobbles' in the motions of stars, caused by the gravitational tug of planets orbiting them.



# 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