

# Physics AS Level Astronomy 2018

Armagh Observatory and Planetarium

[www.armagh.ac.uk](http://www.armagh.ac.uk)



## **The Observatory and Planetarium**

Armagh has the remarkable distinction of having both the oldest astronomical research institute in the UK and Ireland in its Observatory, and also the oldest Planetarium as well. The Observatory was founded by Archbishop Robinson in 1790 and the Planetarium in 1968. On May 1 this year the Planetarium celebrates its 50<sup>th</sup> anniversary. The Observatory is internationally recognised for its astronomical research, particularly for its work on the Solar System, the Sun and the stars in our Galaxy. The Planetarium is the public face of astronomy in Northern Ireland conducted through its outreach programmes and in particular using its Digistar planetarium projector. We will use this projector in the course to illustrate how and where the planets, stars and galaxies fit into the universe and can they be connected together through the concept of redshift, central to the astronomy component of the A level physics syllabus.

## **Course Lecturers**

- Professor Michael Burton, Director of the Observatory and Planetarium, who studies how stars form from giant clouds of molecular gas in our Galaxy.
- Professor Simon Jeffery, who specialises in the study of the lives of exotic stars that reside in multiple stellar systems in our Galaxy.

## Course Content

The course covers section 2.7 “Astronomy” on the GCE Physics AS Level Syllabus:

- 2.7.1 Doppler Shift
- 2.7.2 Cosmological Redshift
- 2.7.3 Galaxy recession via redshift,  $z = \frac{v}{c} = \Delta\lambda/\lambda$
- 2.7.4 Hubble’s law,  $v = H_0 d$
- 2.7.5 Age of the Universe,  $T = 1/H_0$

*In more detail:*

2.7.1 recall, demonstrate an understanding of and apply the classical equations for Doppler shift to find the wavelength of the waves received by a stationary observer from a moving source.

2.7.2 demonstrate an understanding of the difference between cosmological red shift and Doppler red shift.

2.7.3 calculate the red shift parameter,  $z$ , of a receding galaxy using the equation  $z = \Delta\lambda/\lambda$  and use the equation  $z=v/c$  to find the recession speed  $v$ , where  $v \ll c$  (the speed of light).

2.7.4 use Hubble’s Law  $v=H_0 d$  to estimate the distance,  $d$ , to a distant galaxy, given the value of its speed of recession,  $v$ , and the Hubble constant,  $H_0 \approx 2.4 \times 10^{-18} \text{ s}^{-1}$ .

2.7.5 recall and use  $T=1/H_0$  to estimate the age of the universe.

## Outline Program

Week	Session 1: Classroom Theory	Session 2: Tutorial / Exercise	Session 3: Planetarium Demo
1	Doppler Redshift & Stars	Doppler redshift from the orbit of planet around a star	Our Solar System
2	Cosmological Redshift & Galaxies	Expansion of the Universe and the cosmological redshift	Our Galaxy
3	Cosmology & Age of the Universe	Age of the Universe	Galaxies and Large Scale Structure

## Lecture 1: Doppler Shift and the Stars

### Astronomical Basics – Distances

Distances used on the Earth, such as the “metre” and “kilometre”, are not suitable for astronomy as the distances involved are so large. Astronomers instead use several types of distance:

The Astronomical Unit: the average distance from the Earth to the Sun.

$$1 \text{ AU} = 1.496 \times 10^{11} \text{ m} \approx 1.5 \times 10^{11} \text{ m}$$

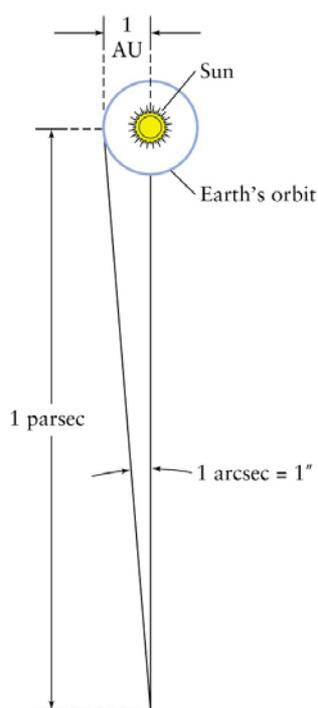
Generally used for distances in our Solar System.

The Light Year: the distance light travels in 1 year.

$$1 \text{ yr} = 9.461 \times 10^{15} \text{ m} \approx 9.5 \times 10^{15} \text{ m}$$

Generally used in popular descriptions of astronomy.

The Parsec:



The distance to a star that has a parallax angle of 1 arcsecond for a baseline of the Earth-Sun distance of 1 AU.

$$1 \text{ pc} = 3.086 \times 10^{16} \text{ m} \approx 3 \times 10^{16} \text{ m}$$

Generally used by astronomers for distances in our Galaxy.

Parsecs provide a convenient unit of measurement for astronomers because parallax angles can be measured over the course of 1 year as the Earth travels around the Sun.

Distances to other galaxies are often quoted in units of Mega-parsecs (Mpc) – which is 1 million ( $10^6$ ) parsecs.

#### Questions:

1. How long does it take light to travel from the Earth to the Sun?

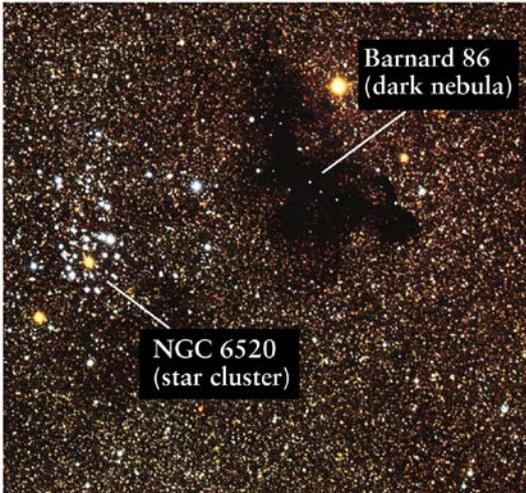
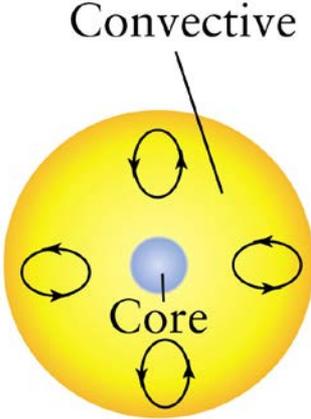
$$\text{Time} = \text{distance} / \text{speed}, \text{ so } t = \frac{D}{c} = \frac{1.496 \times 10^{11} \text{ m}}{3.0 \times 10^8 \text{ m/s}} = 499 \text{ s} \approx 8 \text{ min.}$$

2. How many light years are there in 1 parsec?  $= \frac{3.086 \times 10^{16}}{9.461 \times 10^{15}} = 3.26 \text{ yrs.}$

3. How many astronomical units are there in 1 parsec?  $= \frac{3.086 \times 10^{16}}{1.496 \times 10^{11}} = 206,000 \text{ AU.}$

## Stars

Stars are the basic components of the Universe. They are vast balls of gas undergoing nuclear fusion in their cores. In doing so, they convert hydrogen into helium, releasing energy in the process. This is the ultimate source of energy powering all life on the Earth!

 <p>Barnard 86 (dark nebula)</p> <p>NGC 6520 (star cluster)</p>	
<p>A star cluster (to left) and a dark cloud (to right), with a background starfield. Stars form within such clouds of gas.</p>	<p>A young star cluster known as the “Jewel Box” in the constellation of Crux – the Southern Cross.</p>
	 <p>Convective</p> <p>Core</p>
<p>The Sun, our local star. With a surface temperature of about 6,000°C, its emission peaks in the yellow portion of the spectrum. The dark blotches are “sunspots”, which are cooler regions where strong magnetic fields suppress the flow of energy to the surface.</p>	<p>Illustration showing the structure inside a typical low-mass star. The nuclear burning core in the centre is surrounded by a convective region, which brings the energy to the stellar surface.</p>

Mass of the Sun:  $2 \times 10^{30} \text{ kg} = 1 M_{\odot}$

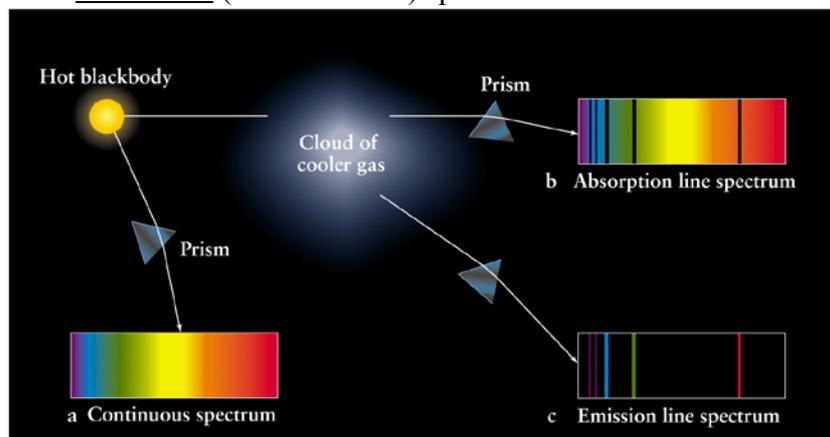
Mass of the Earth:  $6 \times 10^{24} \text{ kg}$ .

Hence the Sun is 300,000 times as massive as the Earth (*exercise: show this!*)

## Spectra

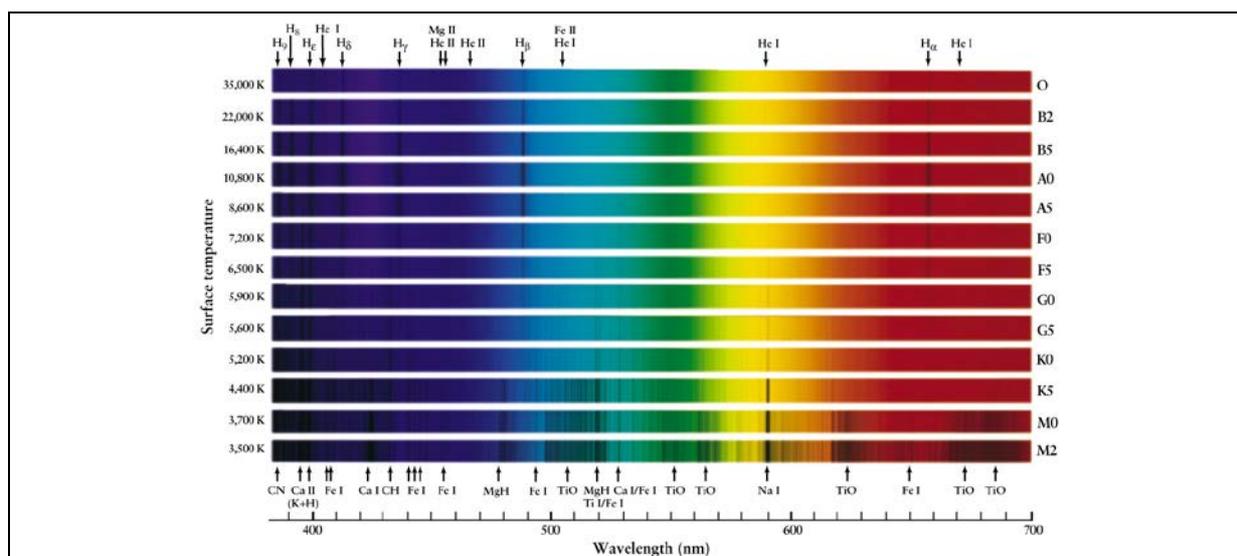
Stars emit light which is spread across the “electromagnetic spectrum”.

- ⇒ Contains colours such as red, green and blue.
- ⇒ Emitted in wavebands such as visible, ultraviolet, infrared and radio.
- ⇒ Results in a continuum (or continuous) spectrum of all the colours.



Elements in the surfaces of stars can absorb the light at specific wavelengths. These correspond to the differences in the energy levels of electrons in elements in the star.

- ⇒ Results in an absorption spectrum of dark lines set against the continuum spectrum.



*The spectra of different types of stars; i.e. the intensity of the light as a function of wavelength. The surface temperature is shown on the left-hand axis and the “spectral type” on the right-hand axis. The dark bands represent absorption lines, and the arrows indicate which elements they are caused by.*

Gases in interstellar clouds can emit radiation when their atoms are excited, as happens if the cloud is heated.

- ⇒ Results in an emission spectrum of bright lines.

We can precisely measure the wavelengths of the emission and absorption lines using spectrometers attached to telescopes. The most commonly observed spectral lines are caused by hydrogen. However, many lines are also seen, caused by elements such as carbon, oxygen and nitrogen.

We usually find that the wavelengths observed for these lines are different from those produced by the same elements when measured in a laboratory. This is due to the Doppler Effect arising from the relative motion of the stars with respect to us.

## The Doppler Effect

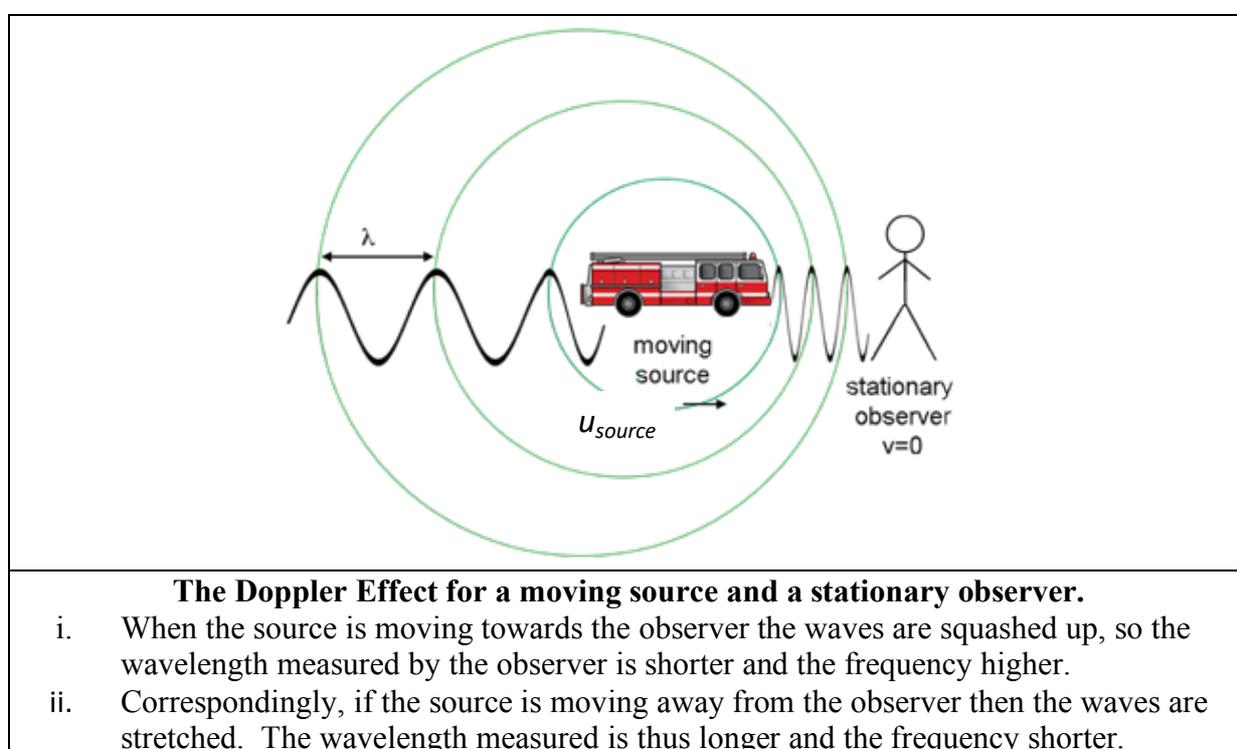
The change in frequency of a wave when there is relative motion between the source of the wave and the observer is called the *Doppler effect*.

Because wave speed = frequency x wavelength i.e.  $c = f\lambda$ , the Doppler effect applies to wavelength as well as frequency.

### The Doppler Effect for waves travelling in a medium

*Note: this is quite tricky. Fortunately, the Doppler Effect for light, which does not require a medium, is easier to understand and is the principal topic of the A Level physics syllabus here. We cover this in the next section.*

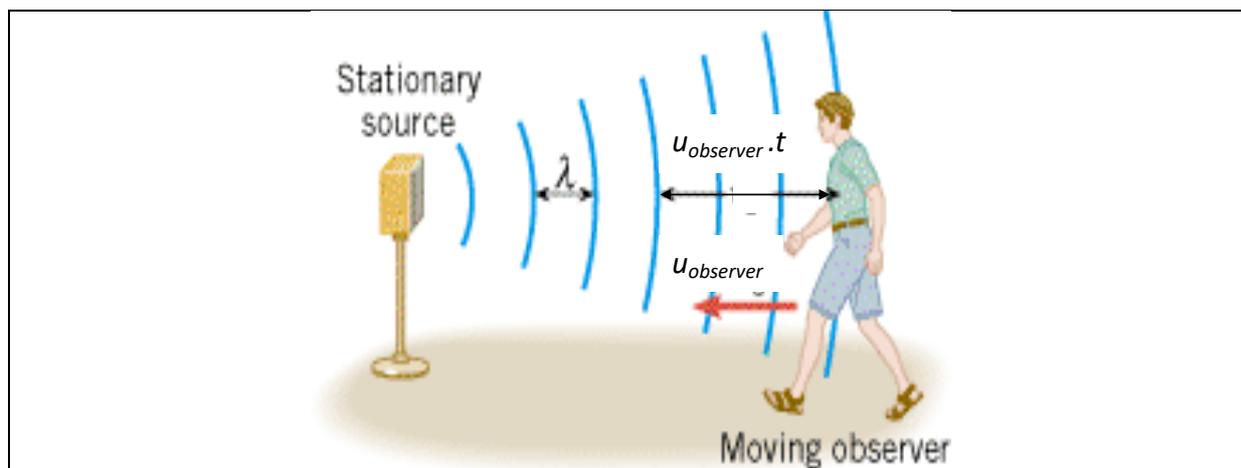
The magnitude of the Doppler effect depends on whether the source is moving, the observer is moving, or both.



It can be shown that (e.g. in a First Year University Physics course):

If the source is moving at speed  $u_{source}$  towards a stationary observer then the frequency observed,  $f'$ , is  $f' = \frac{c}{c - u_{source}} f$ . Here  $c$  is the wave speed and  $f$  is the frequency of the wave when there is no motion (i.e. at rest).

If the source is moving away from a stationary observer the frequency is  $f' = \frac{c}{c + u_{source}} f$ .



**The Doppler Effect for a stationary source and a moving observer.**

When the observer is moving towards the source at speed  $u_{observer}$  the waves are encountered more frequently. Hence, the wavelength measured is shorter and the frequency is correspondingly higher.

It can be shown that:

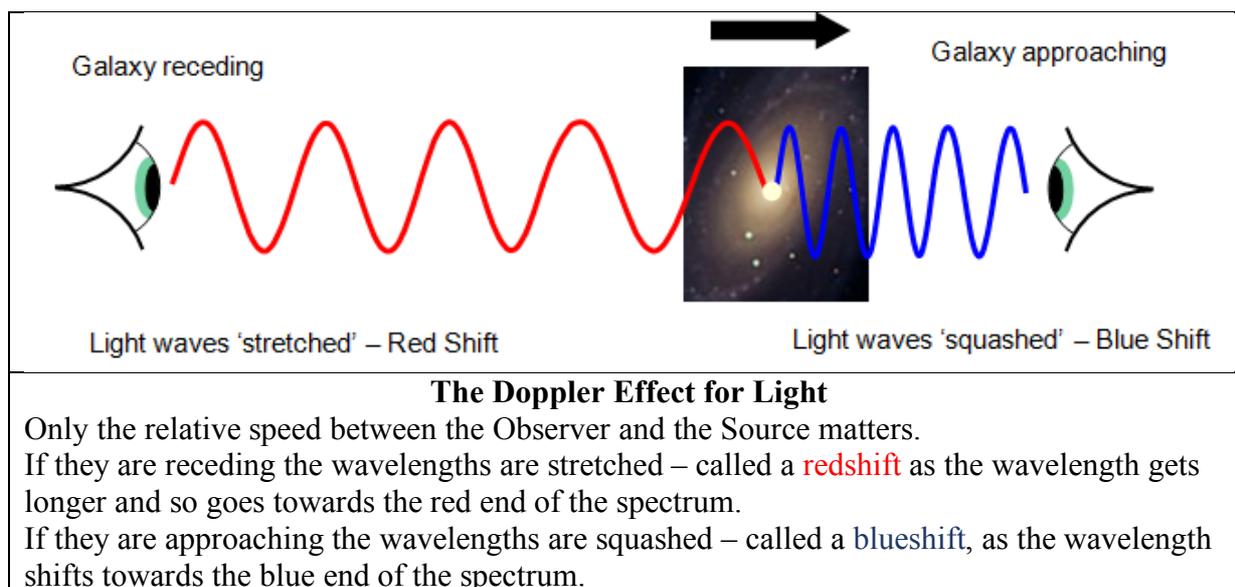
If the observer is moving towards a stationary source then  $f' = \frac{c+u_{observer}}{c} f$ .

If the observer is moving away from a stationary source then  $f' = \frac{c-u_{observer}}{c} f$ .

[i.e. we swap the + signs by – signs between moving away and moving towards.]

This applies for waves travelling in a medium, such as sound or water. For light the formula is different.

### Doppler Effect for Light (when there is no medium)



For light there is no medium, as light can travel in a vacuum. Only the relative speed between the source and the observer,  $v$ , matters. The Doppler effect formulae are then given by:

Source and observer receding: 
$$f' = \frac{c}{c+v} f$$

Source and observer approaching: 
$$f' = \frac{c}{c-v} f$$

Since  $c = f\lambda = f'\lambda'$  we obtain for the observed wavelength:

When receding: 
$$\lambda' = (1 + v/c)\lambda$$

When approaching: 
$$\lambda' = (1 - v/c)\lambda$$

#### Redshift

Thus, the change in wavelength is given by 
$$\Delta\lambda = \lambda' - \lambda = \frac{v}{c}\lambda$$

Here the two formulae above have been combined into a single formula by taking the sign of the velocity into account. If the source is moving away from the observer then  $v$  is taken to be *positive*. If the source is travelling towards the observer then  $v$  is taken to be *negative*.

Hence,

- (i) When the source is receding from the observer then  $v > 0$ , so that the change in wavelength  $\Delta\lambda$  is  $> 0$ , i.e. a longer wavelength, towards the red end of the spectrum, and
- (ii) When the source is approaching the observer then  $v < 0$ , so that the change in wavelength  $\Delta\lambda$  is  $< 0$ , i.e. a shorter wavelength, towards the blue end of the spectrum.

Since  $\Delta\lambda = \frac{v}{c}\lambda$  then 
$$\frac{\Delta\lambda}{\lambda} = \frac{v}{c}.$$

Let us define the Redshift parameter as  $z = \frac{\Delta\lambda}{\lambda}$ , the fractional change in wavelength. Thus

(i)  $z = \frac{v}{c} > 0$  when the source is receding; i.e. it is Doppler “redshifted” and

(ii)  $z = \frac{v}{c} < 0$  when the source is approaching; i.e. it is Doppler “blueshifted”.

### Example

A hydrogen line in a binary star system is measured to have a wavelength of 656.1nm (1 nm =  $10^{-9}$  m), while the same line when measured in the laboratory has a wavelength of 656.3nm. Is the star approaching or receding from us? At what speed?

$\Delta\lambda = 656.1 - 656.3 \text{ nm} = -0.2 \text{ nm}$ . This is negative so that the star is approaching us.

The velocity is then given by  $\frac{v}{c} = \frac{\Delta\lambda}{\lambda} = \frac{-0.2}{656.3}$  so that  $v = \frac{3 \times 10^5 \times -0.2}{656.3} = -91 \text{ km/s}$ .