FACTFILE:
GCE PHYSICS AS2

2.7 ASTRONOMY

This fact file seeks to provide information relating to the following section of the AS Specification; it does not seek to give any guidance on teaching methodology or classroom practice.

Astronomy

Learning outcomes

Students should be able to:

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 cosmological 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 $v << c$;

2.7.4 use Hubble's Law $v = H_o d$ to estimate the distance d to a distant galaxy given the value of the speed pf recession, v, and the Hubble constant,
$H_o \approx 2.4 \times 10^{-18}\ s^{-1}$; and

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

Material in the Appendices is for teachers who would like to delve a little further into the subject than is required by the specification

Astronomical measurements

A light year is the distance light travels in one year.
1 ly = $3 \times 10^8 \times 365 \times 24 \times 60^2 = 9.46 \times 10^{15}$ m.

Our Milky Way galaxy is approximately 100 000 ly across and our solar system is about 27 000 ly from the centre of the galaxy.

The astronomical unit AU is the mean distance from the centre of the earth to the centre of the sun.

1 AU = 1.5×10^{11} m

Pluto is about 57 AU from the sun. Our nearest star-system, outside our solar system, Alpha Centauri is 300 000 AU or 4.3 ly away.

The Hubble telescope can see galaxies 10^{10} ly away. Our nearest galaxy the Andromeda Nebula, is about 200 000 ly away.

For nearby stars, distances are measured in units called parsecs.

A parsec is approximately

2.06×10^5 AU or
3.26 ly or
3.09×10^{16} m

For more information on parsecs and measuring inter-stellar distances, see **Appendix 1**

Emission and absorption spectra

A gas can be stimulated by applying energy in the form of heat, electrical energy, light, particles, or a chemical reaction. Before applying energy, the electrons in the gas molecules are in a lower energy state, which we call the ground state. After applying energy, some of the electrons will move to a higher energy states called **excited states**. Excited states are unstable. Electrons in excited states return to the lower energy states in one or more steps, in a process called **relaxation**. As they do so they emit light of discrete wavelengths. This light is called an **emission spectrum**.

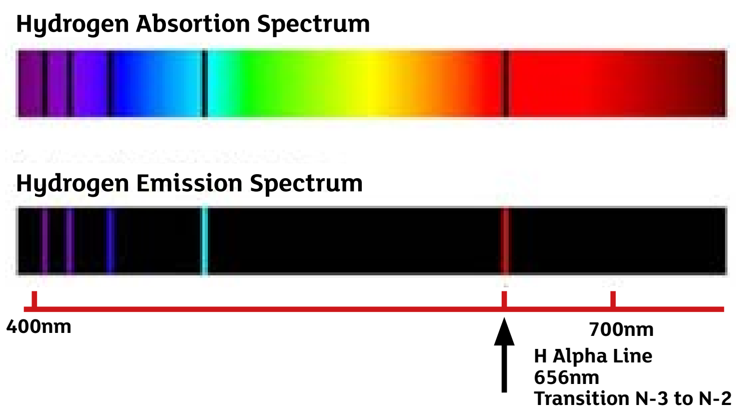
Each element has a unique emission spectrum. The wavelengths present depend on the energy gaps between the ground state and the excited states, which change from one element to another.

An element illuminated with radiation containing all the wavelengths of the visible spectrum (white light) will selectively absorb only those wavelengths needed to excite electrons to a higher energy level. This produces an **absorption spectrum**.

The difference between energy levels is unique to each element and so absorbed wavelengths are different for different atoms. When the transmitted radiation is observed, the spectrum consists of a number of very narrow absorption lines.

Therefore, **an absorption spectrum shows the wavelengths absorbed by the element**, whereas **an emission spectrum shows wavelengths emitted by the element**, which have been stimulated by energy before. Compared to the continuous visible spectrum, both emission and absorption spectra are line spectra because they only contain certain wavelengths.

In an emission spectrum there'll be only few coloured lines in a dark back ground. But in an absorption spectrum there'll be few dark bands within the continuous spectrum. The dark lines in the absorption spectrum and the coloured lines in the emitted spectrum of the same element have identical wavelengths.



Red shift and Blue shift

When we view the spectrum of an element coming from stars from neighbouring galaxies, the spectral lines appear to be shifted from their usual observed positions.

Red shift is when the spectral lines appear to have shifted towards the red end of the spectrum and thus have a longer wavelength than the same wavelengths observed in the laboratory or from nearby stars like our sun. This is due to the galaxy moving away from us and the speed of recession can be calculated using the Doppler equations for frequency or wavelength. The light coming from most neighbouring galaxies is red shifted. When light is observed from the stars of distant galaxies, it always appears red shifted.

Blue shift is when the spectral lines appear to have shifted towards the blue end of the spectrum and thus the light has a shorter wavelength than expected. This suggests these galaxies must be moving towards us and the speed of these galaxies can also be explained using the Doppler equations. Only a few local galaxies, such as the Andromeda Nebula, exhibit blue shift. This is because galaxies have their own (ordinary) velocity superimposed on their recessional velocity. The ordinary velocity and recessional velocity combine to give a velocity which astrophysicists call the galaxy's peculiar velocity. For Andromeda, the peculiar velocity is towards the Milky Way, so its light is blue-shifted.

Hubble's Law shows that the most distant galaxies are moving away from us at the greatest speed. The spectra from the most distant galaxies therefore have the greatest red-shift.

The Doppler Effect

The pitch of a note from a siren noticeably drops as it passes by a stationary observer. This apparent change in frequency of a wave when there is relative motion between the source and an observer is called the Doppler Effect. It occurs with electromagnetic waves as well as with sound waves and the microwave Doppler Effect can be used by police to check the speed of passing motorists.

The equations summarised below also apply to electromagnetic waves when the relative speed of the source and observer is small, however, when an object is travelling at a speed appreciable to the speed of light then relativistic effects have to be considered. **The derivation of these equations is not required** by the CCEA specification. However, it is required that students can recall, understand and apply the equations summarised in the table at the end of this section for a moving source. The Doppler shift for a moving observer is not required.

For details on the derivation of the classical Doppler equations for both a moving source and a moving observer, see **Appendix 2**.

A source emitting sound of speed v, frequency f and wavelength λ^1 and ..	Frequency f^1 detected by observer	Wavelength λ^1 detected by observer
Moving **away** from a stationary observer with speed u_{source}	$f^1 = \frac{v}{v + u_{source}} f$	$\lambda^1 = \frac{v + u_{source}}{v} \lambda$
Moving **towards** a stationary observer with a speed u_{source}	$f^1 = \frac{v}{v - u_{source}} f$	$\lambda^1 = \frac{v - u_{source}}{v} \lambda$

Cosmological Red Shift

The red shift from distant galaxies is not due primarily to the movement of these galaxies themselves. Space itself is expanding, so the separation of the galaxies is increasing and the light transmitted across this expanding gap is being stretched. The red shift we observe from these galaxies, the cosmological red shift, is mainly due to this expansion of the universe, rather than the classical Doppler effect.

Doppler Effect in Light

Red shift indicates recession of the star from the earth and from its size the speed can by calculated. Redshift is usually stated in terms of a z parameter. If the speed of the galaxy relative to Earth is v (where v <<c) then:

The derivation of this equation is not required; however, for the benefit of teachers, the derivation is provided in **Appendix 3.**

$$z = \frac{v}{c} = \frac{\Delta\lambda}{\lambda} = \frac{\lambda_{observed} - \lambda_{emitted}}{\lambda_{emitted}}$$

Hubble's law

In the 1920's Edwin Hubble analysed data collected from a large number of galaxies and discovered that the speed of recession of a galaxy was proportional to its distance from earth. This can be written as

$$v = H_o d$$

where v is the recessional speed, d is the distance of a galaxy from earth and Ho is the constant of proportionality, Hubble's constant, which represents the rate at which the universe is expanding.
A graph of v against d would produce a straight line graph through the origin of gradient H_o

Observations of distant galaxies also suggested that each galaxy was moving away from other galaxies at the same rate. There is no preferred direction of expansion and observers in any galaxy would observe the same recessional speeds for galaxies the same distance away.

The value of 70kms^{-1} Mpc^{-1} is often used (Mpc = mega parsec).

This means that the velocity of recession of a galaxy increases by 70 kms^{-1} for every 1 Mpc increase in distance.

(The uncertainty in H_o is high because of the difficulty in obtaining measuring data for distant galaxies.)

Value of H_o in SI units

You can convert the value of Ho to SI units as follows. Take the Hubble constant Ho to be 70 kms^{-1} Mpc^{-1} and one light year to be 9.46 x 10^{15} m.

One Parsec = 3.26 light years = 3.09 x 10^{16} m
therefore 1 Mpc = 3.09x10^{22} m

So 70 kms^{-1}Mpc^{-1} = 70x10^{3}/ 3.09x10^{22} = 2.27 x 10^{-18} s^{-1}

Example
Find the distance of the galaxy with a recession velocity of 1200 kms-1 if the Hubble constant is 2.27 x 10^{-18} s^{-1}

Using $v = H_o d$

d = v/H_o = 1.2 x 10^{6}/2.27 x 10^{-18} = 5.29x10^{23} m
= 5.6 x 10^{7} light years.

The galaxy is therefore 56 million light years away.

The Age of the Universe

Imagine the Universe running backwards. How long would it take a distant galaxy to reach you? Answering this question tells you how long ago it is since all the galaxies were together in the same place, i.e. how long ago the Big Bang occurred. The time, T, taken for a galaxy travelling at speed v to travel a distance d is:

$$T = \frac{d}{v} = \frac{1}{H}$$

Therefore, the value of 1 / H gives us an estimate of the age of the Universe.

T = 1/2.27 x 10^{-18} = 4.43 x10^{17} s = 1.40 x 10^{10} years

The reciprocal of the Hubble constant thus enables an estimate to be made of the age of the universe; it is only an approximation since the recessional speed of galaxies and hence the Hubble constant are thought to have changed with time.

However, this value for the age of the universe is consistent with calculations of stellar evolution which suggest the age of the oldest stars to be around 12 billion years.

Questions on Astronomy AS 2 Sections 2.7.1 – 2.7.5

1. 1. An express train, travelling at a steady speed of 30 ms^{-1}, approaches and passes a station. The train sounds its whistle at a frequency of 500 Hz. The speed of sound in air is 330 ms^{-1}.
   - (a) Calculate the wavelength of the waves being emitted by the train.
   - (b) Calculate the wavelength of the waves detected by an observer on the station platform as the train approaches.
   - (c) Calculate the wavelength and frequency of the waves detected by the observer when the train is moving away from the station.
   - (d) A faster train passes the same station travelling at a constant speed. This train also sounds its whistle at a frequency of 500 Hz.
     However, the observer on the station platform detects a sound wave of wavelength 0.78 m.
     - (i) In what direction was the train travelling relative to the station when the observer measured the wavelength? Give a reason for your answer.
     - (ii) Find the speed of the train.

Solution

(a) λ_o = v/f = 330/500 = 0.66 m

(b) $\lambda = (1 - v/v_s).\lambda_o$ = (1 – 30/330). 0.66 = 0.60 m

(c) $\lambda = (1 + v/v_s).\lambda_o$ = (1 + 30/330). 0.66 = 0.72 m
f = v/λ = 330/0.72 = 458.3 Hz

(d) (i) Since the observed wavelength was bigger than 0.66 m, the train was moving away from the station.

(ii) $\lambda = (1 + v/v_s).\lambda_o$

0.84 = (1 + v/330).0.78
v = 60 ms^{-1}

2. The apparent change in the wavelength of light coming from very distant galaxies is explained by cosmological red shift.
   - (a) What is the difference between cosmological red shift and Doppler shift?
   - (b) The Ursa Major cluster has a redshift z of 0.05.
   - (i) Calculate the speed of recession of this cluster.
   - (ii) Estimate the distance between Ursa Major and Earth.
   - (c) Professional astrophysicists measure the Hubble constant in units of kms^{-1} Mpc^{-1}. The Mpc (megaparsec) is a unit of distance and corresponds to 3.08×10^{22} m

Express the Hubble constant in of kms^{-1} Mpc^{-1}.

Solution

(a) Doppler shift is due to the relative speed between the observer and the source. Cosmological redshift is due to the expansion of the space between the observer and the source.

(b) (i) v = zc = 0.05 x 3 x 10^8 = 1.5 x 10^7 ms^{-1}

(ii) By Hubble's Law, d = v/H_o = 1.5 x 10^7 / 2.4 x 10^{-18} = 6.25 x 10^{24} m

(c) H_o = v/d = 2.4 × 10^{-18} s^{-1} = 2.4 × 10^{-18} ms^{-1} / 1 m
= 2.4 x 10^{-21} kms^{-1} / (3.08 x 10^{22})-1 Mpc^{-1}
≈74 kms^{-1} Mpc^{-1}

Questions on Astronomy AS 2 Sections 2.7.1 – 2.7.5

3. Quasars are enormous bodies often found at the centre of some large galaxies. A particular quasar known as 3C 273 has a prominent emission line in the hydrogen spectrum, H_D at 475 nm. When the normal hydrogen spectrum is viewed in the laboratory the H_D line has a wavelength of 410 nm.
   - (a) Is this a redshift or a blueshift? Give a reason for your answer.
   - (b) Suggest a reason why the lines in the hydrogen spectrum play an important role in determining redshifts.
   - (c) Calculate the speed of 3C 273 and say in what direction it is moving relative to Earth.

Solution

- (a) Redshift – the observed wavelength from 3C 273 is greater than the normal wavelength.
- (b) Hydrogen is the most common element in any galaxy, so hydrogen spectra are readily observed.
- (c) $z = \Delta\lambda/\lambda = 65/410 = 0.1585$
  $v = zc = 0.1585 \times 3 \times 10^8 = 4.76 \times 10^7$ ms^{-1}, away from the Earth

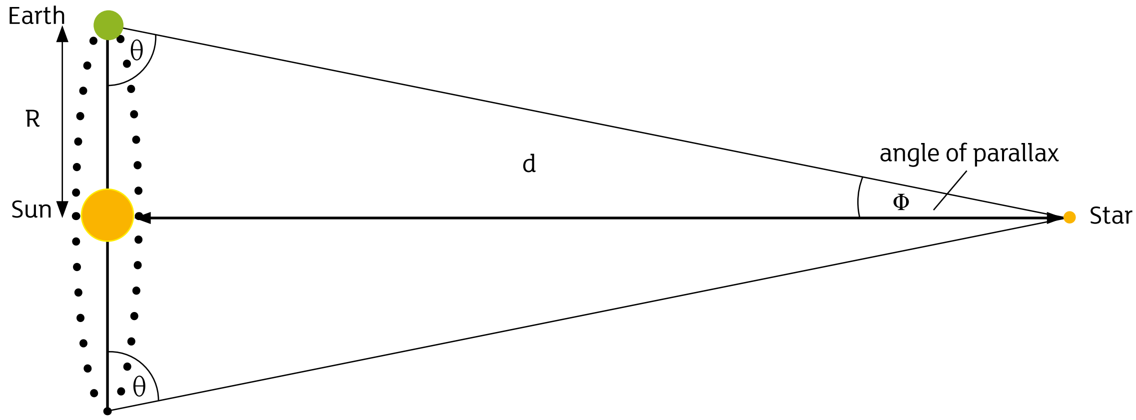
4 According to the European Space Agency's Planck Spacecraft Team, the approximate age of the universe is 13.8×10^9 years.
   - (i) Use this information to estimate the size of the Hubble constant.
     Take 1 year to be 3.16×10^7 seconds.
   - (ii) What assumption have you made in your calculation of H_o?

Solution

- (i) Age of universe, $t = 13.8 \times 10^9 \times 3.16 \times 10^7 = 4.3608 \times 10^{17}$ s
  $H_o = 1/t = 1/4.3608 \times 10^{17} = 2.29 \times 10^{-18}$ s^{-1}
- (ii) It is assumed that the rate of expansion of the universe (or H_o) is constant.

Appendix 1 – Inter-Stellar Distances

The distances between the Earth and nearby stars (<100 ly) are measured using trigonometric parallax.



Astrophysicists quote these distances in parsecs (pc). One parsec corresponds to the distance at which the mean radius of the earth's orbit subtends an angle of one second of arc. One minute of an arc is equal to 1/60th of one degree. As one degree is 1/360 th of a circle, one minute of arc is 1/21600th of a circle (or, in radians, $\frac{2\pi}{21600}$).

One second of an arc is equal to 1/60 th of one arcminute and so 1/3,600th of a degree, 1/1,296,000th of a circle,

so, 1 second of arc = $\frac{2\pi}{1296000}$ radians

$\tan \Phi = \frac{R}{d}$ and, for very small angles, measured in radians, $\tan\Phi \approx \Phi$

So $\Phi = \frac{R}{d}$ and therefore $d = \frac{R}{\Phi}$

Substituting for R, the distance from the earth to the sun (R = 1.5 x 1011 m) and

for Φ (1 second of arc = $\frac{2\pi}{1296000}$)

we can see 1 pc = $\frac{(1.5 \times 10^{11}) \times 1296000}{2\pi} = 3.09 \times 10^{16}$ m

which is $\frac{3.09 \times 10^{16}}{9.46 \times 10^{15}} \approx 3.26\ ly$

Appendix 2 – The Classical Doppler Effect

Consider a source of waves of frequency f and velocity v. A stationary observer would notice waves of wavelength $\lambda = \frac{v}{f}$, however as the source moves towards the observer with velocity u_{source}, the wavelength would be compressed. The time between each wave is $\frac{1}{f}$ and so, distance travelled by the wave in this time is $v \times \frac{1}{f} = \frac{v}{f}$

and distance travelled by the source in this time is $\frac{u_{source}}{f}$

Therefore, the new wavelength of the wave $\lambda' = \frac{u}{f} - \frac{u_{source}}{f} = \frac{v - u_{source}}{f}$

and new frequency $f' = \frac{v}{\lambda'} = \frac{v}{v - u_{source}} f$

Similarly, for an object moving away from an observer, the wavelength and frequency are described by the equations

wavelength λ′ = (v+u_source)/f

and new frequency $f' = \frac{v}{\lambda'} = \frac{v}{v + u_{source}} f$

What if the source is stationary and the observer is moving?

This time the wavelength is fixed and given by $\frac{v}{f}$ If an observer has a speed $u_{observer}$ towards the source, then the velocity of the waves relative to the observer is $v+u_{observer}$, and so the apparent frequency f' is given by

$$f' = \frac{v + u_{observer}}{\lambda} = \frac{v + u_{observer}}{v} f = \left(1 + \frac{u_{observer}}{v}\right) f$$

If the source is stationary and the observer is moving away from the source then the apparent frequency f' is given by

$$f' = \frac{v - u_{observer}}{\lambda} = \frac{v - u_{observer}}{v} f$$

Appendix 1 – Red Shift

If a galaxy is moving with a speed v with respect to the Earth (where v << c) and emitting radiation of frequency f, then the frequency observed by an observer on Earth, f' is given by the classical Doppler equation:

$$f' = f(1 + \frac{v}{c})$$

So

$$f' - f \pm f\frac{v}{c}\ )$$

Therefore if Δf = f^1– f then the magnitude of frequency shift $\Delta f = f\frac{v}{c}$ and so Δf/f=v/c

Also in terms of wavelength $\frac{\Delta\lambda}{\lambda} = \frac{v}{c}$

Recessional speed is then $v = \frac{c\Delta f}{f} = \frac{c\Delta\lambda}{\lambda}$

These equations can only be used when v « c as at higher recessional velocities, equations must be derived from Einstein's special theory of relativity.

Redshift of nearby galaxies is usually stated in terms of a dimensionless parameter, z, which is ratio of the relative difference between the observed wavelength and emitted wavelength and the emitted wavelength.

$$z = \frac{v}{c} = \frac{\Delta\lambda}{\lambda} = \frac{\lambda_{observed} - \lambda_{emitted}}{\lambda_{emitted}}$$