OCR A Physics A-level

Topic 5.6: Astrophysics and Cosmology

Notes

Stars

Definitions

- Planets – objects with mass sufficient for their own gravity to force them to take a **spherical** shape, where **no nuclear fusion** occurs, and the object has **cleared its orbit** of other objects.
- Dwarf planets – planets where the **orbit has not been cleared** of other objects.
- Planetary satellites – bodies that orbit a planet.
- Asteroids – objects which are too **small and uneven** in shape to be planets, with a near circular orbit around the sun.
- Comets – small, **irregularly sized** balls of rock, dust, and ice. They orbit the sun in **eccentric elliptical** orbits.
- Solar systems – the systems containing stars and orbiting objects like planets.
- Galaxies – a collection of stars, dust, and gas. Each galaxy contains around 100 billion stars.

Formation of stars

Nebulae are gigantic clouds of dust and gas, and are the birthplace of all stars. Over millions of years, the **gravitational attraction** between dust and gas particles pulls them together to form clouds. As they come closer together, the gravitational collapse accelerates, and some regions become **denser** and pull in more dust and gas. The gravitational energy of the particles is converted to thermal energy.

The resultant sphere of very hot, dense dust and gas is a **protostar**. For a star to form, the temperature and pressure must be high enough for hydrogen gas nuclei in the protostar to **overcome** the **electrostatic forces of repulsion** and undergo **nuclear fusion**. This nuclear fusion produces helium nuclei, producing a star.

Initially, the star remains in **stable equilibrium**. The gravitational forces of the particles act to compress the star, but radiation pressure from photons emitted in fusion and gas pressure from nuclei in the core counteract this, keeping the size of the star almost constant. This equilibrium is known as the **main phase** of the star. Larger stars are hotter, and so undergo fusion faster, using up available hydrogen nuclei more quickly. This means they have a shorter main phase than smaller stars. What happens after the main phase depends on the **mass** of the **star's core** (the central region of the star where fusion occurs).

Evolution of a low mass star

$M_\odot$ is the solar mass = 1.99×10^{30} kg. It is the mass of our sun's core. **Low mass stars** are classed as having a core mass between $0.5M_\odot$ and $10M_\odot$. As these stars have a smaller, cooler core, they remain in the main sequence for longer. Once the hydrogen supplies are low, the gravitational forces inwards overcome the radiation and gas pressures, so the star begins to

collapse inwards. It evolves in to a **red giant**. The core of the red giant is too cool for helium to fuse, but the pressure in the outer shell is great enough for fusion to occur there.

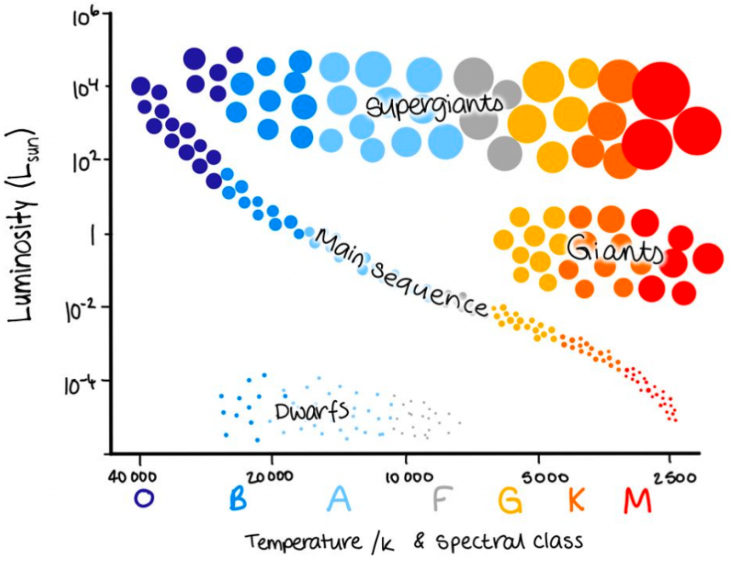
As helium nuclei run low, the red giant evolves in to a **white dwarf**. The **outer shells** begin to drift off in to space as a **planetary nebula**, and the core remains as a very dense white dwarf. The white dwarf has a temperature of around 3000K, and no fusion occurs. Photons which were produced earlier in the evolution leak out, dissipating heat. As the star core collapses, **electron degeneracy pressure** (caused as two electrons cannot exist in the same state) prevents the core from collapsing. As long as the core mass is below $1.44M_\odot$, then the white dwarf star is stable – this is the **Chandrasekhar limit**.

Evolution of a massive star

Where a star's mass in is excess of $10\ M_\odot$, its evolution takes a different path. As hydrogen supplies deplete, the temperature is high enough for **helium fusion** in to heavier elements to take place, forming a **red supergiant**. The red supergiant has **layers** of increasingly heavy elements produced from fusion, with an **inert iron core** (as iron fusion does not release energy, it is unable to fuse further).

Once the iron core is produced, the star becomes **unstable**. A **type 2 supernova** occurs where there is a shockwave which ejects the materials in the outer shells out in to space, and the **core collapses**. Any elements heavier than iron are formed in supernovas. If the remaining core mass is greater than $1.44M_\odot$, protons and electrons combine to form neutrons. This produces an extremely small, dense **neutron star**. If the remaining core mass is greater than $3M_\odot$, the gravitational forces are so strong that the escape velocity of the core is greater than the speed of light. This is a **black hole**, which even photons cannot escape.

The **Hertzsprung-Russell (HR) diagram** shows the stellar luminosity of a star against its temperature. By looking at the position of a star on the HR diagram, you will likely be able to tell what spectral class that star belongs to.



Electromagnetic radiation from stars

Energy levels of electrons

Electrons bound to an atom can only exist in certain **discrete energy levels**. The electrons cannot have an energy value that is between two levels. Each element has its own set of energy levels.

When an electron moves from a lower energy state to a higher energy state, it is ‘excited’. This requires the input of external energy e.g. heat, absorption of a photon. When an electron is de-excited, it moves towards the ground state. It releases energy in the form of a photon with a specific wavelength. Electrons can only be excited to the other discrete energy levels for that element.

All energy level values are **negative**, with the ground state being the most negative. An electron that is completely free from an atom has energy equal to 0. This negative sign is used to represent the **energy required** to be inputted to remove the electron from the atom.

Spectra definitions

- Emission line spectra – each element produces a **unique** emission line spectrum because of the unique set of energy levels associated with its electrons. It appears as a series of coloured lines on a black background
- Continuous line spectra – **all visible wavelengths** of light are present. They are produced by atoms of solid heated metals.
- Absorption line spectra – a series of **dark spectral lines** against the background of the continuous spectrum, with each line corresponding to a wavelength of light used to excite atoms of that element. The dark lines are at the same wavelengths as the coloured lines produced when the atoms are de-excited.

Emission spectral lines

When an electron is de-excited, it **releases energy** as a **photon** with a specific wavelength. The energy of a photon is given by the formula $E = hc/\lambda$, where h is the Planck constant, c is the speed of light, and λ is the wavelength of the photon. The energy released is the difference between the initial energy level of the electron, and the final energy level of the photon. This means that transitions between different energy levels produce photons with different wavelengths.

As each element has a unique set of discrete energy levels, the **wavelengths of light** produced by the de-exciting of electrons are **different for each element**. Spectroscopy is the technique used to identify elements based on the wavelengths of light emitted when atoms in a gas are exited. The characteristic emission line spectrum is produced – the spectral line is black, apart from emission line spectra at specific wavelengths.

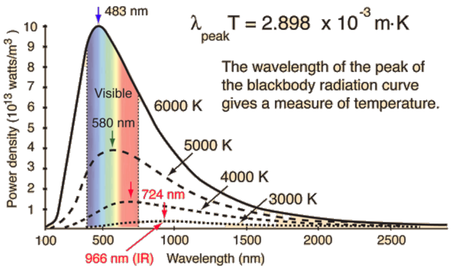
Diffraction gratings

Diffraction gratings are components with **regularly spaced slits** that can diffract light. Different colours of light have different wavelengths, and so will be diffracted at **different angles**. The equation

$$d sin\theta \ = n\lambda$$

Can be used to determine the wavelength of the light, where d is the diffraction slit separation, θ is the angle of diffraction, and n is the order of maxima.

Wein's displacement law



The **surface temperature** of a star affects its colour. At any temperature above 0K, objects emit electromagnetic radiation of varying wavelength and intensity. Stars can be modelled as **idealised black bodies** that emit radiation across a range of wavelengths, with a **peak** in intensity at a specific wavelength, corresponding to the colour of the star.

Wein's law is used to relate the temperature of the star with the peak wavelength of the electromagnetic radiation emitted by the star. It states that *the black body radiation curve for different temperatures peaks at a wavelength inversely proportional to the temperature of the object.* This gives the formula

$$\lambda_{max} \propto \frac{1}{T} \ so \ \lambda_{max} T = \text{Wein's Constant } (2.9 \ x10^{-3} mK)$$

Where λ_{max} is the wavelength of light produced with the maximum intensity (the peak wavelength) and T is the absolute surface temperature of the object.

Stefan's law

Stefan's law is used to relate the temperature of a star with its luminosity, L. The luminosity is the **radiant power output** of the star, and is also proportional to the **surface area** of the star. It states that *for a black body, the total radiant heat energy emitted from a surface is proportional to the fourth power of its absolute temperature.* This gives us the formula

$$L \ \propto \ 4\pi r^2 T^4 \rightarrow L = \ 4\pi r^2 T^4 \sigma \ (where \ \sigma \ is \ Stefan's \ Constaant \ 5.67x10^{-8} \ Wm^{-2} k^{-4})$$

If the colour, and hence peak wavelength of the star is known, then Wein's law can be used to calculate the absolute temperature of the star. If the luminosity is also known, then the radius of the star can be determined.

In exams, it is important to remember that these temperatures must be the **absolute values**, measured in Kelvin. Often the temperatures will be given in Centigrade to try and catch you out, so don't forget to convert them.

Cosmological Distances and Measurements

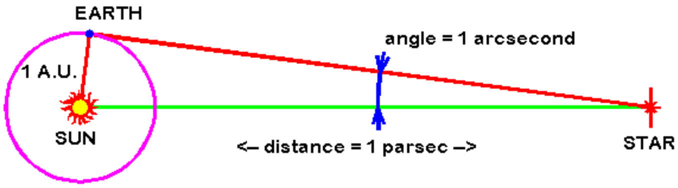
Distances

When considering the distances between planets and stars, **different measurement units** are used, as a metre is very small compared to these distances.

1 Astronomical Unit (AU) = 1.5 x10^{11}m – It is the **average distance** from the Earth to the sun, and is mostly used to express the distance of planets from the sun.

1 Light year (ly) is the distance **light travels** in **one year**. It is given using the speed of light x time of 1 year (in seconds) = 9.46 x 10^{15}m – It is used to express the distances to stars and other galaxies.

Angles can be measured in units of **arcminutes** and **arcseconds**, for angles which are only a small fraction of a degree. In one degree there are 60 arcminutes, and 3600 arcseconds (so one arcsecond is 1/3600th of a degree.

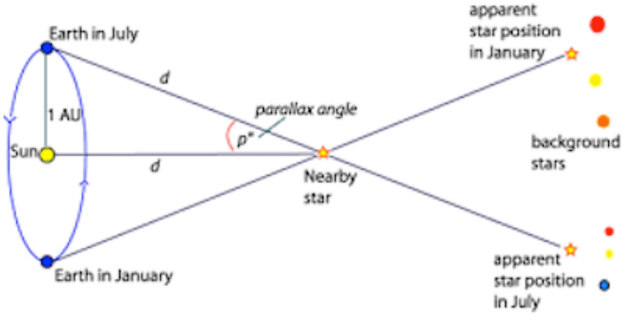


A Parsec (pc) is defined as the distance at which a radius of 1 AU subtends an angle of 1 arcsecond. In metres, 1 pc is 3.1x10^{16}m, but it can also be written as 1 AU / arcsecond.

$$\tan\left(\frac{1}{3600}\right) = \frac{1AU}{1pc}$$

$$\tan(\theta) = \theta;\ pc = \frac{1AU}{\theta}$$

Stellar parallax



Parallax of nearby star

Stellar parallax can be used to measure the distance to nearby stars. Parallax is the **apparent shift** in positon of an object against a backdrop of distance objects (that don't appear to move). It is accurate for distances of up to 100pc. Beyond this point, the angles involved are so small they are hard to accurately measure.

To use parallax to calculate distance, the formula

$$d = \frac{1}{p}$$

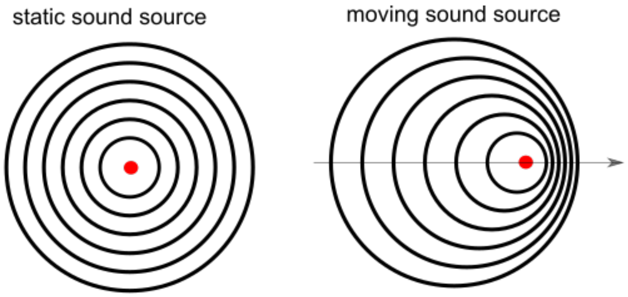
can be used, where *d* is the distance between the observer and the object, and *p* is the parallax angle. This relationship is only true where *d* is measured in **parsecs** and *p* is measured in **arcseconds**.

Cosmological principle

The **cosmological principle** defines the formation of the universe on a large scale. It states that *the universe is isotropic and homogenous, and the laws of physics are universal.* Isotropic means that the universe is the **same in all directions** to every observer, and it has no centre or edge. Homogenous means that matter is **uniformly distributed** – for a large volume of the universe the density is the same.

The Doppler Effect

The Doppler Effect



The Doppler Effect is the **apparent shift** in **wavelength** occurring when the source of the waves is moving. If the source is moving towards the detector then the wavelength appears to decrease. If the source is moving away from the detector, the wavelength appears in increase.

It is important to note that the **actual wavelength** emitted by the source **remains the same** – it is only the wavelength that is **received** by the observer or detector that appears to have changed.

The Doppler Effect and stars

In star light, the Doppler Effect shifts the **position** of **spectral lines**. We can determine the absorption spectra of an element in the lab, and compare it to what is detected in the light from a star. The Doppler equation can be used to determine the **relative speed** of a star using the shift in wavelength from a hydrogen emission spectrum.

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

Where v is the velocity of the star relative to Earth, λ is the original wavelength of the hydrogen spectral line, and $\Delta\lambda$ is the change in wavelength of the hydrogen spectral line from light emitted by the star.

Hubble's law and the expanding universe

Hubble's law

Hubble's law states that *the recessional velocity v of a galaxy is proportional to its distance from earth.* This means that the **further away** a star is from the Earth, the **faster** it is moving away from us. As a formula, $V = H_0 d$, where H_0 is the Hubble constant, 67.8 $\text{kms}^{-1}\text{Mpc}^{-1}$.

Model of an expanding universe

Hubble's law provides key evidence for the model that states that the **universe is expanding**. Almost all light from distance galaxies is **red shifted**, showing that the galaxies are moving **away from Earth**. This suggests that the fabric of space and time is expanding, and any point in the universe is moving away from any other point.

Estimating the age of the universe

Hubble's law can be used to estimate the age of the universe. If initially all points in the universe were together, then the distance of a galaxy from Earth, and its speed, are related to the time taken for the galaxy to reach this distance away from Earth. The time is given by d/v, which is equal to $1/H_0$, with the Hubble constant measured in seconds. It is difficult to get an accurate measurement for this value, but it is approximately 14 billion years.

The Big Bang theory

The Big Bang theory

The Big Bang theory attempts to describe the origins and development of the early universe. All objects were initially **contained in a singularity**, which suddenly expanded outwards. The universe has not stopped expanding since then.

Evidence for the Big Bang theory

There are 2 key pieces of evidence to support the Big Bang theory. Hubble's Law shows the universe is expanding, through the red shift of light from distant galaxies. There is also **microwave background radiation**. Scientists were first measuring the radiation in space, and found a constant interference. There was no justification for this except the Big Bang theory. Originally there were **high energy gamma photons**, but as the universe expanded, the **wavelength** of these photons was **stretched** into the **microwave region** – this provides a constant signal now. However this theory is not reliable because there is no experimental evidence – we can't recreate the initial conditions of the Big Bang.

The evolution of the universe

- The Big Bang: Time and space are created; the universe is a dense, hot singularity.
- 10^{-35} s: The universe expands rapidly, in a period of incredible acceleration known as "inflation". There is no matter, only high energy gamma photons and electromagnetic radiation.

- 10^{-6} s: The first fundamental particles gain mass. The mechanism behind this is not fully understood but it involves the Higgs Boson.
- 10^{-3} s: Most of the mass is created using pair production. The first hadrons come from quarks.
- 1s: Production of mass is halted.
- 100s: Protons and neutrons fuse to form deuterium, helium, lithium and beryllium nuclei, but nothing heavier. Rapid expansion continues. 25% of matter is helium nuclei.
- 380 thousand years: It is now cool enough for the first atoms to form.
- 30 million years: The first stars form, and fusion creates heavier elements.
- 200 million years: Our galaxy forms as gravitational forces pull together clouds of hydrogen and existing stars.
- 9 billion years: The solar system forms by a nebula from a supernova. This is followed by the formation of our sun, and then the Earth almost 1billion years later.
- 11 billion years: Primitive life begins on Earth.
- 13.7 billion years: The first modern humans evolve.

Current theories on the universe

We only understand 5% of our universe. It is expanding at an **increasing rate**, but this acceleration is not fully understood. **Dark Energy** is a hypothetical form which fills all of space and accelerates expansion. It is used to explain the accelerating expansion, and should make up 68% of the total energy in the universe but so far experiments have not been able to find the form of the energy.

During observations of galaxies, it was found that the velocity did not always behave as predicted. It was assumed that as an object moved away from the centre of a galaxy, its velocity would decrease (due to a lower gravitational field). This is what happens in smaller mass systems, like the solar system, or the moons of Jupiter. However, some observations suggested the mass is **not concentrated** in the **centre** of the galaxy, but instead is spread out. All of the observable mass in galaxies is concentrated in the centre, so there must be another type of matter we can't see, called '**Dark Matter**'. It should make up 27% of the mass in the universe. We don't know much about it, as it is not seen through telescopes and doesn't interact with light, but several particles have been suggested, such as gravitinos and axions.

The future of the universe could be 'open' – where it would **continue expanding** for all of time. Alternatively, it could be 'closed' – at one point it will stop expanding, contract and **collapse on itself**. It may be 'flat' – there might be an **end to the expansion** and the universe will remain a fixed size. The outcome that takes place depends on the **density** of the universe, but what will happen in our universe is not currently known.