INTERNATIONAL GCSE

Physics (2017)

TOPIC GUIDE:
Astrophysics

Pearson Edexcel International GCSE in Science

Pearson

Astrophysics

Contents

Introduction

Since the very beginning of human civilisation, we have tried to understand how our Universe works. Many of the greatest advances in physics have come from the solution of problems in astrophysics. Although the force of gravity attracts every particle in our Universe to every other particle, other factors can oppose it. The generation of nuclear energy can balance gravity to produce stars and the balance between gravity and the expansion of our Universe is the cosmological problem which holds the key to the future of the Universe itself.

The specification

The content of the specification for Topic 8: Astrophysics is arranged into 4 areas:

1. **Units**
   This section of the specification is the same as statement 1.1, covering the units needed for this area of the specification.

2. **Motion in the universe**
   Specification statements 8.2 – 8.6 are taken from Topic 1 of the old International GCSE Physics (2011) specification. They cover some basic terminology; the influence of *g* on the movement of satellites, comets and moons; and circular motion.

   The remaining statements in Topic 8 are new to the International GCSE Physics specification.

3. **Stellar evolution**
   The life cycle of stars and their classification by colour (and, therefore, by surface temperature) is covered by statements 8.7 – 8.10.
   Statements 8.11 – 8.12 consider the concept of absolute magnitude and introduced the Hertzsprung-Russell diagram. These statements are covered in Physics only, and not in Science (Double Award).

4. **Cosmology**
   Statements 8.13 – 8.18 consider evidence in favour of the Big Bang, as opposed to the steady state, theory for the evolution of the universe.
   As part of this, consideration is also given to red shift as an application of the Doppler effect. Again, these statements are covered in Physics only, and not in Science (Double Award).

Units

Specification coverage

Students should:

8.1 use the following units: kilogram (kg), metre (m), metre/second (m/s), metre/second^2 (m/s^2), newton (N), second (s), newton/kilogram (N/kg)

Key Physics Summary

As with any other area of physics, all the units required for the physical quantities in Astrophysics can be derived from the three base units of mass, length and time. The SI (Système International) system gives these there quantities the units of the kilogram, metre and second. The size of each of these three units have been agreed upon.

The units for all the other quantities in Astrophysics have been derived from these three base units, giving units such as the metre per second for speed and metre per second^2 for acceleration.

Combining the quantities of mass and acceleration allows us to derive the unit for Force – appropriately named the Newton, as the force needed to make a 1kg mass accelerate at 1m/s^2.

As a result of the enormous distances involved in astrophysics, an additional unit for distance – the light year – is regularly used. A light year is equal to the distance which light) or any other electromagnetic wave) would travel in one year. Since light travels at 3×10^8 m/s, a light year is equal to 9.5×10^{15} m.

Checkpoint questions

1. The Light-Year

A light-year is the distance travelled by a light wave in one year. If light travels at 3×10^8 m/s and there are 365¼ days in a year, calculate the number of kilometres in a light-year.

2. The Light-Minute

The average distance between the Earth and the Sun is 150 000 000 km. How many 'light-minutes' away is the Sun from the Earth?

Motion in the universe

Specification coverage

Students should:

8.2 know that:

- the universe is a large collection of billions of galaxies
- a galaxy is a large collection of billions of stars
- our solar system is in the Milky Way galaxy.

8.3 understand why gravitational field strength, g, varies and know that it is different on other planets and the Moon from that on the Earth

8.4 explain that gravitational force:

- causes moons to orbit planets
- causes the planets to orbit the Sun
- causes artificial satellites to orbit the Earth
- causes comets to orbit the Sun.

8.5 describe the differences in the orbits of comets, moons and planets

8.6 use the relationship between orbital speed, orbital radius and time period:

Orbital speed = orbital radius x 2π / time period

Key Physics Summary

The force of gravity can be seen at work on almost every scale within our Universe. From attracting falling objects to the surface of the Earth through the orbits of planets, moons, comets and stars to the shape of galaxies of billions of stars, to the evolution of the Universe itself.

Background Information

(a) Gravity and orbits

In the vacuum of space where there is no friction or air resistance, all objects would naturally move in a straight line at a constant speed, as explained by Newton's First Law of Motion. If an object also experienced a gravitational force then it would start to follow a curved path through space. If the sizes of their speed and the gravitational force were just right, then they would circle around another object, following a path called an orbit.

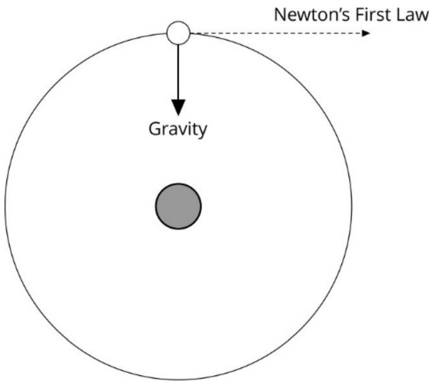


Figure 1: Orbital Motion. Objects naturally move in a straight line at a constant speed (Newton's First Law of Motion). The force of gravity from another body, pulling it to the side, can cause it to move in a repeating curved path called an orbit.

Although there are examples of orbits all around us in the Solar System and beyond, it took many thousands of years for physicists to understand fully the physics behind orbital motion.

One of the biggest difficulties is that the apparent movement of the Sun, Moon and stars in the sky would look exactly the same to us whether the Earth orbited the Sun or the Sun orbited the Earth[1]. With no 'fixed' background to check against, humans therefore believed the most obvious Earth-centred or 'geocentric' view of the universe for many thousands of years.

From the 16th century the work of astronomers like Nicolaus Copernicus and Galileo Galilei began to convince people that we actually live in a Sun-centred or 'heliocentric' Solar System. This allowed Johannes Kepler to explain the strange apparent motion of the planets in the sky. He showed that all the planets (including the Earth) must be moving in slightly oval or 'elliptical' orbits around the Sun.

[1] It's a very ancient idea in physics called 'relativity'.

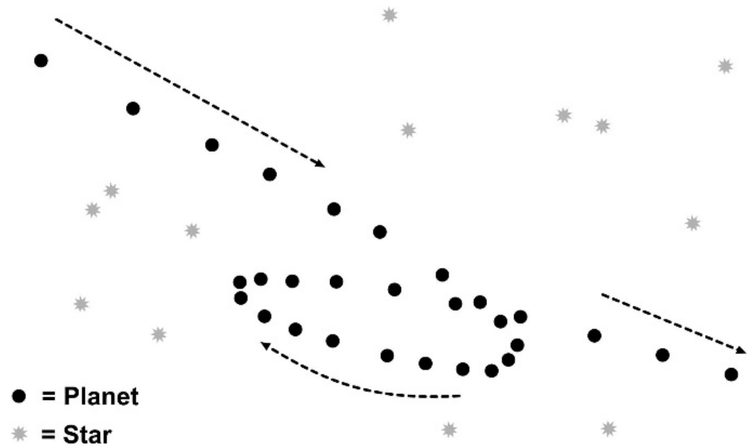


Figure 2: The Apparent Motion of the Planets. Although the Sun and Moon seem to move smoothly across the background of the stars, the planets appear to slow down, stop and even move backwards for short periods. Trying to explain this peculiar motion was the driving force which eventually led Johannes Kepler to uncover his three Laws of Planetary Motion which were one of the inspirations for Newton's idea of gravity.

Although it's fairly obvious that distant planets like Neptune take longer to orbit the Sun than closer planets like Mercury, Kepler found some complex mathematical patterns which only the great Isaac Newton was able to explain[2].

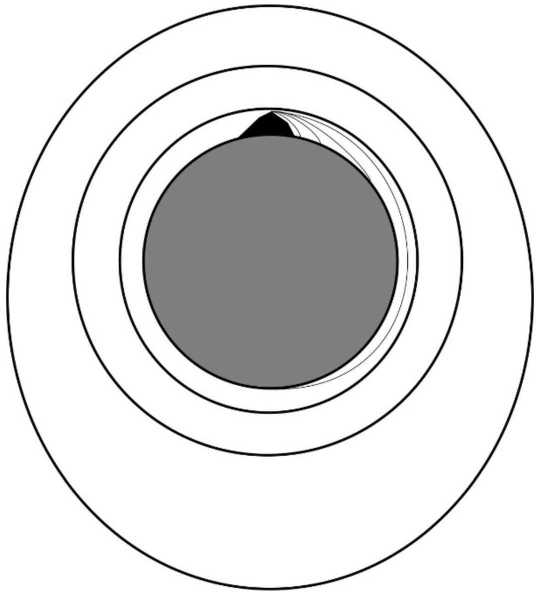


Figure 3: Orbiting the Earth. In his great book the 'Principia' of 1687, Isaac Newton imagined objects fired or 'projected' at great speed from the top of a very high mountain. The faster these 'projectiles' were fired, the further around the Earth's surface they would travel before hitting the ground. If they were fired at a speed of 11 km/s then the curve of their path would match the curve of the Earth's surface and they would go into orbit around the Earth. Objects fired in this way from very great heights above the Earth's surface would follow the orbital paths of objects like the Moon or an artificial satellite. All orbital paths are elliptical in shape although many, particularly those of the planets, are almost circular.

Newton's explanation claimed that there was a force attracting every particle in the Universe to every other particle. Because of this every planet has a gravitational force attracting it towards the Sun. Newton stated that the size of the gravitational force:

- got weaker as objects moved further apart
- was greater the more mass the objects had

[2] Incidentally, the idea of the falling apple being the inspiration for the theory of gravity was only mentioned by Newton many years later when he was an old man.

Figure 4: Woolsthorpe Manor. The farmhouse at Woolsthorpe Manor near Grantham in Lincolnshire was the birthplace and family home of the revolutionary physicist Isaac Newton. Showing little skill at farming, Newton spent many hours wondering about some of the most fundamental problems in physics such as how objects move and the nature of light. The farmhouse, along with the orchard containing the infamous apple tree are now owned by the National Trust and are open to the public.

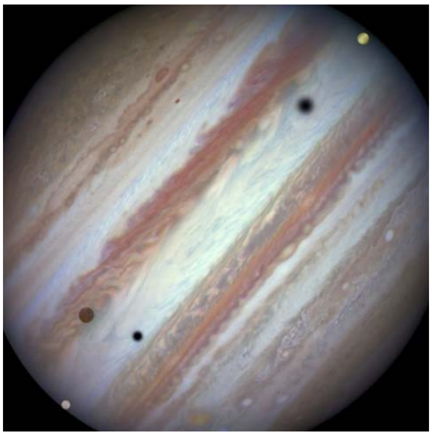


Figure 5: The Galilean Moons of Jupiter. First observed by Galileo in 1609, these are the four largest of the many natural satellites which orbit in Jupiter's vast gravitational field. Their discovery was a crucial piece of evidence in the seventeenth century debate over whether everything orbited the Earth. (Image © NASA/ESA & the Hubble Heritage Team (STScI/AURA))

This allowed Newton, with a single idea, to explain almost every motion which we see in our Solar System:

- the Earth follows a curved path around the Sun called its 'orbit', instead of following the straight path predicted for it by Newton's First Law of Motion
- the Moon orbits in a tight curve around the Earth because of the gravitational force between it and the Earth
- moons orbit around almost all other planets in the solar system
- other bodies such as planets and comets also follow elliptical paths around the Sun, each as a result of their gravitational force pulling them towards the Sun
- the Sun, despite its enormous mass[3], moves slightly from side to side as a result of the many gravitational forces[4] pulling on it due to the planets and comets of the Solar System.

[3] It's about 99.8% of the mass of the whole Solar System.
[4] An excellent example of Newton's Third Law of Motion in action.

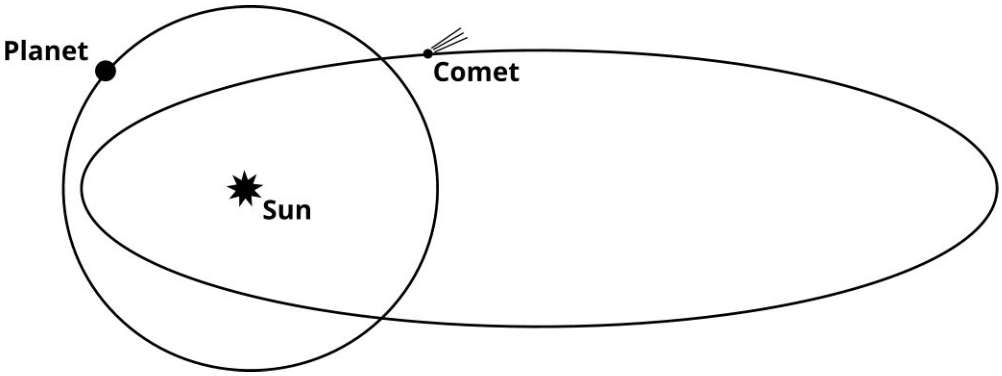


Figure 6: Elliptical Orbits. Kepler observed and Newton proved that all objects orbiting under the effect of gravity follow elliptical or oval paths. In some cases (planets) the ellipses can be hard to distinguish from circles while in others (comets) the ellipses are much longer than they are wide, i.e. very 'eccentric'.

In more recent times, we have used the same physical principles to place artificial satellites into orbit around the Earth, Moon, Sun and other planets.

Kepler identified that all orbits are elliptical or oval in shape, rather than circles as had been assumed for many centuries. Some orbits, such as those of the planets are very close to being circular whereas others, such as those of comets, are almost cigar-shaped.

Figure 7: The Voyager Probes. Launched in 1977, these two spacecraft used the gravity of the Earth, Sun and Jupiter to become the first probes to take photographs of the outer solar system. Their paths were not 'closed' orbits and so they have both now left the Solar System, never to return… (Image: ©NASA)

It turns out that we can see the force of gravity working in a very similar way on even larger scales than the orbits of the planets:

- the Sun orbits the centre of its large group of stars called the Milky Way galaxy, taking 230 million years to complete one orbit
- a number of small 'dwarf' galaxies are orbiting around our Milky Way galaxy
- the Milky Way and Andromeda galaxies are moving towards each other at around 300 km/s. Unfortunately their path is not that of an orbit and the two galaxies will start to collide and merge in around four billion years.
- the Milky Way and Andromeda galaxies, along with a handful of smaller galaxies are held together by the force of gravity into a group called the 'Local Group'.

Figure 8: The Andromeda Galaxy. At a distance of 'only' 2.5 million light years, the Andromeda galaxy is part of our Local Group of galaxies, all moving around each other as a result of the gravitational forces between them. (Image: © NASA/Daniel Lopez/IAC)

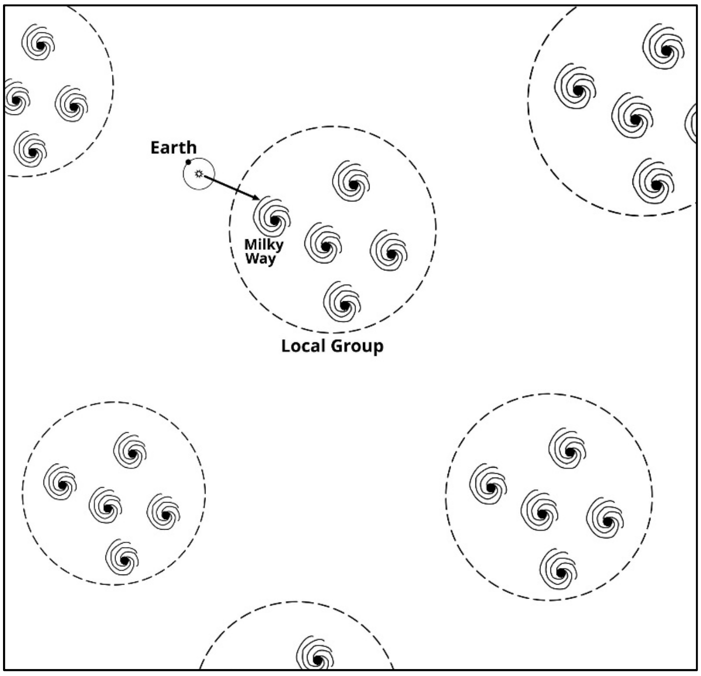


Figure 9: Our Place in the Universe. Although the Sun's gravity governs the orbit of the Earth and the other planets in our Solar System, the Sun is just one of billions of stars orbiting the centre of our galaxy, the Milky Way. The Milky Way in turn moves around the other galaxies in our Local Group of galaxies. Other galactic clusters complete our picture of the Universe as a whole.

(b) Orbital Speed

The speed at which an object is orbiting can be calculated in a similar way to that of any moving object, using the equation:

Speed = distance travelled / time taken

Since many orbits are approximately circular, the distance travelled will be equal to:

Distance travelled (circumference) = 2π x radius of orbit

Giving:

Orbital speed = orbital radius x 2π / time period

Example 1: The Earth's orbit around the Sun

Although it feels as though the Earth is not moving, it is in fact orbiting the Sun in a huge circle with a radius of approximately 150 000 000 km, once every year.

Using the above formula:

Orbital speed = orbital radius x 2π / time period

Gives:

Orbital speed = 150 000 000 x 2π / (365¼ x 24 x 60 x 60) [5]

= 942 000 000 / 31 557 600

= **30 km/s**

Example 2: The Orbit of Mars' moon, Phobos

Phobos is one of the two tiny moons which orbit the planet Mars. With an orbital radius of only 9377km it scoots around Mars in just 7.66 hours.

Using the Orbital Speed formula:

Orbital speed = orbital radius x 2π / time period

Gives:

Orbital speed = 9377 x 2π / (7.66 x 60 x 60)

= 58 888 / 27 576

= **2.1 km/s**

Example 3: Communications Satellites

Signals from satellites broadcasting television programmes are generally received by receivers which point in only one, fixed direction. A domestic satellite dish is a good example of this. This means that the satellite needs to be 'geostationary' so that it appears to stay in the same place in the sky to an observer on the Earth's surface.

[5] This is the number of seconds in a year of 365 ¼ days.

This means that it needs to have an orbital time period of 24 hours so that it turns at the same rate as the Earth.

A satellite is to be placed in a geostationary orbit with a radius of 42 200km. Calculate the orbital speed which the satellite will need in order to remain geostationary in this orbit.

Using the Orbital Speed formula:

Orbital speed = orbital radius x 2π / time period

Gives:

Orbital speed = 42 200 x 2π / (24 x 60 x 60)

= 265 016 / 86 400

= **3.1 km / s**

Checkpoint questions

1. Key Terms

Explain what is meant by each of the following terms:

i) ellipse,
ii) orbit,
iii) satellite,
iv) galaxy,
v) Local Group.

2. Sputnik 1

Launched by the Soviet Union in 1957, Sputnik 1 was the first artificial satellite of the Earth. The radius of its orbit was approximately 7000 km and it travelled at an orbital speed of around 29 300 km/h.

a) Calculate the circumference of Sputnik 1's orbit.
b) Show that Sputnik 1 orbited the Earth once every 90 minutes.
c) How many orbits of the Earth did Sputnik 1 complete each day?

3. The Martian Moons

The two tiny satellites of Mars are far from being 'geostationary' for any Martian watching them from the surface of the planet. Mars turns on its axis once every 24 hours and 40 minutes. The innermost satellite, Phobos, orbits Mars once every 7.7 hours and Deimos orbits once every 30.4 hours.

Use this information to describe how Phobos and Deimos would appear to move across the sky for an observer on the surface of Mars.

Stellar evolution

Specification coverage

Students should:

8.7 understand how stars can be classified according to their colour

8.8 know that a star's colour is related to its surface temperature

8.9 describe the evolution of stars of similar mass to the Sun through the following stages:

- nebula
- star (main sequence)
- red giant
- white dwarf.

8.10 describe the evolution of stars with a mass larger than the Sun

8.11P understand how the brightness of a star at a standard distance can be represented using absolute magnitude

8.12P draw the main components of the Hertzsprung–Russell diagram (HR diagram)

Key Physics Summary

The force of gravity causes clouds of hydrogen nuclei to form into nebulae. By releasing and radiating nuclear energy, stars are able to balance this gravitational collapse to form stable stars. Eventually their hydrogen 'fuel' runs out meaning that stars need to find other ways to balance the force of gravity in the later stages of their lives.

In some massive stars it is not possible to stop the gravitational collapse and a black hole is formed.

Background Information

(a) Classifying Stars

1. Colour

A fundamental concept in astrophysics is that the colour of a star is directly linked to its surface temperature. The coolest stars glow a dull red colour, medium temperature stars like the Sun are an orangey yellow whilst the very hottest stars are white or even blue-white in colour.

This link is so important that astrophysicists give each star a Spectral Class based on its colour, which links directly to its surface temperature, as shown below.

Colour	Surface Temperature (K)	Spectral Class[6]
Blue	30 000+	W
Blue	30 000+	O
Blue-white	10 000 – 30 000	B
White	7 500-10 000	A
Yellow-white	6 000 – 7 500	F
Yellow	5 200 – 6 000	G
Orange	3 700 – 5 200	K
Orange-red	2 400 – 3 700	M

Since we cannot visit any of the stars, being able to determine their surface temperature by classifying the light which we receive from them on Earth is an extremely useful tool in astrophysics.

2. Brightness

The range of brightness of stars is enormous, making it difficult to quantify without generating inconveniently large or small numbers. For this reason, the brightness of stars is measured using the Magnitude scale. Compared to most other quantities in physics such as mass, temperature or density, stellar magnitude has three unusual features:

- It is zero in the middle, having both positive and negative values
- Numbers on the magnitude scale go in the opposite direction to brightness, with bright objects having low or even negative values and dim objects having high values
- An increase of one on the magnitude scale represents a brightness increase of 2.5 TIMES. Each step on the scale therefore represents an increasingly large increase in brightness.

[6] This sequence of letters is easily remembered with the handy rhyme: 'Wow! Oh Be A Fine Girl/Guy, Kiss Me!'

In this way, fairly small steps on the magnitude scale can work cumulatively to represent extremely large increases in brightness, as shown below:

Magnitude Scale increase	Brightness increase	
1	x 2.5	x 2.5
2	x 2.5^2	x 6.25
3	x 2.5^3	x 16
4	x 2.5^4	x 40
5	x 2.5^5	x 100
6	x 2.5^6	x 250

For example, a star with a magnitude of 3 is 2.5 times brighter than a star with a magnitude of 4; a star with a magnitude of -3 is one hundred times brighter than a star of magnitude 2 and so on.

In addition, there are two kinds of magnitude – Apparent and Absolute.

(i) Apparent Magnitude – measures how bright a star looks when viewed from the Earth. Although it is easy to measure it is obviously affected by both the star's actual power output as well as its distance. Consequently some very powerful stars have a dim apparent magnitude because they are a long way from the Earth. The Sun obviously has the brightest apparent magnitude (-26.7) because it is so much closer than any other star, not because it is the most powerful star in the universe!

Sirius[7], the brightest star in the sky (after the Sun), has an apparent magnitude of -1.46 and the unaided human eye can see stars with an apparent magnitude as faint as 6.5 under perfect conditions. Using binoculars or a telescope allows the eye to see even fainter magnitudes. A telescope with a mirror 30cm in diameter, for example, allows the eye to see objects with apparent magnitudes as faint as 14, whilst those used by professional astronomers can image objects well below an apparent magnitude of 25.

(ii) Absolute Magnitude – this is effectively a 'fair test' for the true brightness or 'luminosity' of stars. It is their position on the magnitude scale not as viewed from Earth but as viewed from a common distance of 32.6[8] light years. Absolute magnitude is therefore extremely useful in astrophysics as it is directly related to the actual power output of a star, unaffected by its distance from the Earth. Obviously it cannot be measured from the Earth but must be calculated by other means.

If the Sun, which is a relatively low powered star, was moved away to a distance of 32.6 light years it would obviously appear much fainter, with an absolute magnitude of only 4.8. In contrast the blue supergiant star Rigel, with its absolute magnitude of -7.8, would appear brighter than the full Moon if viewed from just 32.6 light years. In reality it is around 860 light years from Earth and therefore appears only as a bright star with an apparent magnitude of 0.13.

[7] Sirius is actually a binary star – two stars very close to each other and it can be found by following the line of the belt of three stars in the constellation of Orion down to the left – see Figure 12.
[8] An important distance in astrophysics is the parsec which is 3.26 light years. This standard distance for measuring **absolute** magnitude is therefore ten parsecs.

(b) Stellar Evolution

All stars pass through the following stages of evolution:

- **Nebula**

Over very long periods of time the force of gravity begins to bring together clouds of hydrogen gas. As these clouds form and get steadily smaller, the force of gravity becomes stronger and accelerates the process. A collapsing cloud of gas like this represents the first stage in the evolution of a star and is called a Nebula.

As gravity makes the nebula smaller and denser, this increases the temperature and pressure at the centre. Eventually the temperature at the centre reaches a value of around 10 million degrees. At this temperature, the hydrogen nuclei within the nebula are moving so quickly that they can overcome the electrostatic repulsion between them, allowing them to fuse together.

Figure 10: The Orion Nebula. Situated just below the three stars of Orion's Belt, the Orion Nebula is an example of a nebula where new stars are being formed from a cloud of collapsing hydrogen nuclei. (Image: © NASA/Francesco Battistella)

When two nuclei of hydrogen fuse together, they form a nucleus of helium and a huge amount of energy is released. The energy released by this nuclear fusion reaction creates an outward force called 'radiation pressure' as it makes its way from the core to the surface of the star.

- **Stable (Main Sequence) Star**

When the radiation pressure is strong enough to balance the gravitational forces within the nebula, it will stop collapsing and a stable star is formed.

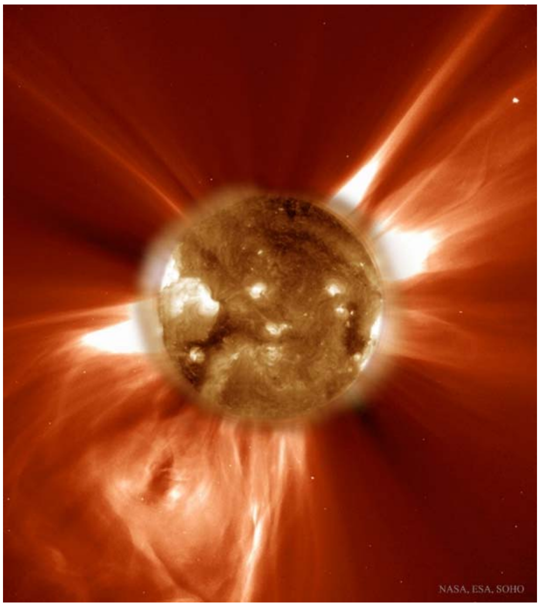


Figure 11: Our Nearest Star. The Sun is an example of a stable or 'Main Sequence' star, where the inward gravitational forces are balanced by the outward radiation pressure from the energy produced by the nuclear fusion at its core. In order to do this the Sun fuses four million tons of hydrogen nuclei into helium every second! (Image: © NASA/ESA/SOHO Consortium)

Stars which formed from larger nebulae will obviously form into more massive or 'giant' stars. The gravitational forces trying to compress these stars will be much larger than those of our Sun and they will require much larger radiation pressure to keep them stable. These stars will therefore be much more powerful and brighter than the Sun.

- **Red Giant Star**

Although the balance between the inward force of gravity and the outward force of radiation pressure in a Main Sequence star can allow the star to shine with a fairly constant output for several billion years, the hydrogen 'fuel' required for nuclear fusion will eventually run out[9]. When this happens the core of the star begins to collapse under the relentless pull of gravity. This increases the temperature and pressure at the core of the star, allowing it to start fusing the helium in its core to produce more energy and therefore radiation pressure.

This radiation pressure pushes out the outer layers of the star, causing it to swell up dramatically. It has been calculated that when the Sun runs out of hydrogen fuel, its outer layers will grow to a point where Mercury, Venus and the Earth will be swallowed up!

As the outer layers of the star are now much further from its core, they cool down and only glow with a red colour, thus forming a Red Giant star.

[9] Although you might expect larger stars to last longer, the lifetimes of the most massive stars are amongst the shortest. Although they were formed from a larger nebula, the inward gravitational forces are much stronger, forcing them to burn their hydrogen fuel much more quickly.

Figure 12: Orion. The constellation of Orion contains objects from across the range of stellar evolution. Just below the three stars of Orion's Belt is the Orion Nebula, where new stars are forming whereas the bright star to the top left of the rectangle of Orion's body is the red giant star Betelgeuse. The other two stars in Orion's body (Bellatrix and Saiph) have run out of their original hydrogen 'fuel' and are therefore leaving the Main Sequence. They now shine by fusing helium and other heavier elements in order to produce energy to stop collapsing under gravity. (Image: © NASA/Bill Dickinson)

- **White Dwarf star**

Eventually the thin outer layers of a Red Giant star will run out of energy and only the core of the star will remain. This is called a White Dwarf star – the hot dense core of a star which has passed through the Red Giant stage.

When the Sun becomes a White Dwarf star it is expected to be only about the size of the Earth. White Dwarf stars are obviously extremely dense as they represent the mass of a star which gravity has squeezed into a space about the size of a small planet!

Very slowly the white dwarf star will cool and dim to become a Black Dwarf star, marking the end of its evolution.

- **More Massive Stars**

In the 1930s the Indian astrophysicist Subramanyan Chandrasekhar calculated that only stars with a mass less than 1.4 times the mass of the Sun could end their lives as White Dwarf stars. The force of gravity in stars heavier than this would be so strong that it would continue to crush the star to even smaller sizes.

Stars with a mass greater than 1.4 solar masses[10] pass through other stages of stellar evolution, beyond the Red Giant stage. These include:

i) **Supernova** – stars much larger than the Sun form a Red Supergiant. As this star collapses, matter is compressed beyond the density of a white dwarf star. It becomes very unstable and this causes the star to explode as a supernova. This throws dust and gas into space, forming a new nebula. When this happens the star can become as bright as a galaxy for a few months.

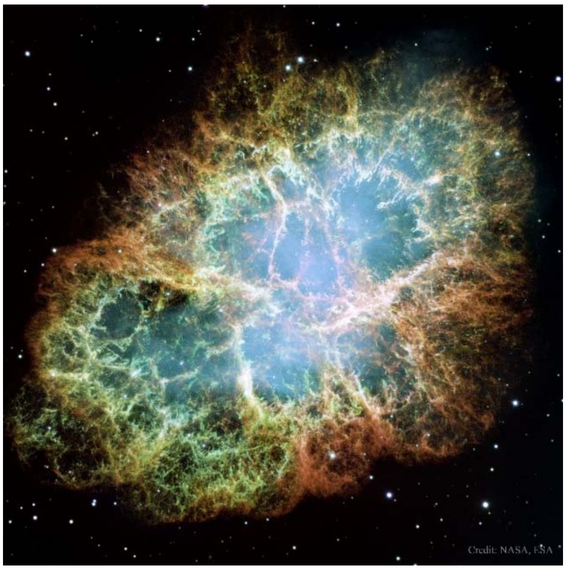


Figure 13: The Crab Nebula. In 1054 a star in our galaxy exploded as a supernova. For two years it shone more brightly than the Sun when viewed from Earth. All that can be seen now is the huge cloud of debris which is known as the Crab Nebula. At the centre of the nebula is a neutron star about 30km across, spinning at thirty times per second. (Image © NASA/ESA/J Hester/A Loll (ASU))

ii) **Neutron Star** – in the later stages of its evolution, the gravity of a large star can compress its core until it is only a few tens of kilometres across, sometimes as a result of a supernova explosion. This produces a tiny, rapidly-spinning star known as a neutron star.

iii) **Black Hole** – eventually some stars become so small and dense and their gravitational fields so strong that not even waves of light can escape. These stars are therefore called Black Holes. Although they emit no electromagnetic radiation, their gravitational fields can pull matter in from nearby stars. This material can glow very brightly as it falls into the black hole.

[10] Now known as the Chandrasekhar Limit.

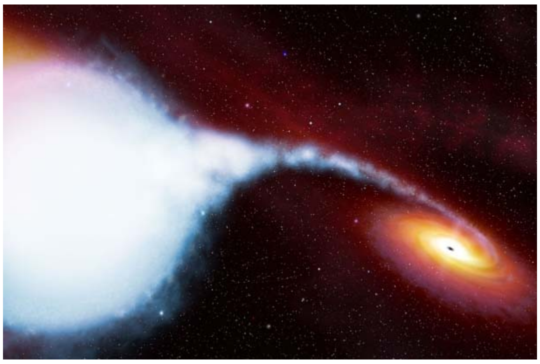


Figure 14: Cygnus X-1. This is an artist's impression of the Cygnus X-1 system which is believed to be a black hole orbited by a blue supergiant star. Material is constantly being pulled into the black hole by its enormous gravity, producing X-rays as it accelerates towards it. Cygnus X-1 is the brightest source of X-rays in the sky, after the Sun. (Image © ESA/Hubble)

Checkpoint questions

1. Key terms

Explain what is meant by each of the following terms:

i) nebula,
ii) Main Sequence star,
iii) red giant,
iv) white dwarf,
v) supernova,
vi) neutron star,
vii) black hole.

2. Key stages

Identify each of the following stages of stellar evolution from these descriptions:

i) a stable star like the Sun,
ii) a star compressed by gravity until it is only about 30km in diameter,
iii) a cloud of hydrogen nuclei collapsing under its own gravity,
iv) a large but cool star which has run out of hydrogen fuel.

Cosmology

Specification coverage

Students should:

8.13P describe the past evolution of the universe and the main arguments in favour of the Big Bang

8.14P describe evidence that supports the Big Bang theory (red-shift and cosmic microwave background (CMB) radiation)

8.15P describe that if a wave source is moving relative to an observer there will be a change in the observed frequency and wavelength

8.16P use the equation relating change in wavelength, wavelength, velocity of a galaxy and the speed of light:

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

8.17P describe the red-shift in light received from galaxies at different distances away from the Earth

8.18P explain why the red-shift of galaxies provides evidence for the expansion of the universe

Key Physics Summary

In the early twentieth century, astrophysicists discovered that the galaxies in our Universe are all moving away from each other at great speed. This is due to the fact that the space in our Universe is expanding. More recent evidence such as the discovery of cosmic microwave background radiation (CMBR) suggests that this is best explained by the Big Bang theory. This theory states that our Universe was in an incredibly small space about 13.8 billion years ago and supports a number of predictions for the future of our Universe.

Background Information

Since the 17th century, cosmologists had struggled with the problem that a universe governed by gravity alone would naturally collapse at a faster and faster rate. However, even a naked-eye glance at the night sky shows that our universe is mostly empty space[11].

The answer to this riddle came in 1929 when Edwin Hubble made a series of observations of some very distant galaxies – all of them well outside the Local Group. By splitting their light into its spectrum he found that its wavelengths had all been stretched or 'shifted' to the red (longer) end of the spectrum. Naming this effect 'red shift', Hubble realised that it must be caused by the galaxies all moving away from us at great speed.

He realised that the increase in wavelength was the result of the Doppler Effect. Here on Earth it is most commonly observed with the sound waves emitted by a fast-moving object such as a car or train. If the moving object sounds its horn as it passes us then

[11] Although it was written about by many scientists for many years, it has become known as Olber's Paradox.

the sound waves we receive appear to have a shorter wavelength and higher frequency as it approaches and a longer wavelength or lower frequency as it moves away. In the case of sound waves this means that they would have a higher frequency and pitch as the vehicle approached and a lower frequency or pitch as it moved away.

Since all the galaxies which he observed appeared to be moving away from us, with the more distant galaxies moving fastest of all, Hubble realised that these observations meant that the universe was expanding.

Hubble was able to use the Doppler Effect equation to calculate exactly how quickly each galaxy was moving away from us, as illustrated in the following example:

The different colours/wavelengths within the light from a distant galaxy are separated. A wavelength of 6×10^{-7} m is received on Earth at a wavelength of 6.3×10^{-7} m. Use this information to calculate the speed at which the galaxy is moving away from the Earth.

The Doppler Effect Equation is: $\Delta\lambda/\lambda = v/c$

λ is the wavelength at which the light would be received, if the galaxy was not moving

$\Delta\lambda$ is the amount by which the wavelength has 'shifted'.
In this case, it is $6.3 - 6 = 0.3 \times 10^{-7}$ m.

In this example, $\lambda = 6 \times 10^{-7}$ m, $\Delta\lambda = 0.3 \times 10^{-7}$ m; the speed of light, $c = 3 \times 10^{8}$ m/s.

This gives $v = c \times \Delta\lambda/\lambda$

$= 3 \times 10^{8} \times 0.3 \times 10^{-7} / 6 \times 10^{-7}$

$=$ **1.5×10^{7} m / s**

An alternative way of approaching calculations like these is to use the fact that:

Percentage Shift = Percentage of Speed of Light

In this example, the 'Percentage Shift' is simply $0.3/6 \times 100 = 5\%$

This means that the galaxy must be travelling at 5% of the speed of light

$= 0.05 \times (3 \times 10^{8}) = 0.15 \times 10^{8} =$ **1.5×10^{7} m / s**

This alternative method can be useful for checking red-shift calculations, particularly when completing examination questions.

Although at first glance the fact that every galaxy outside our Local Group is moving away from us might suggest that we are at the centre of the Universe, this is not the case. As shown in Figure 15, a better way of visualising the situation is to imagine all the galaxies in the Universe as dots marked on the surface of a balloon.

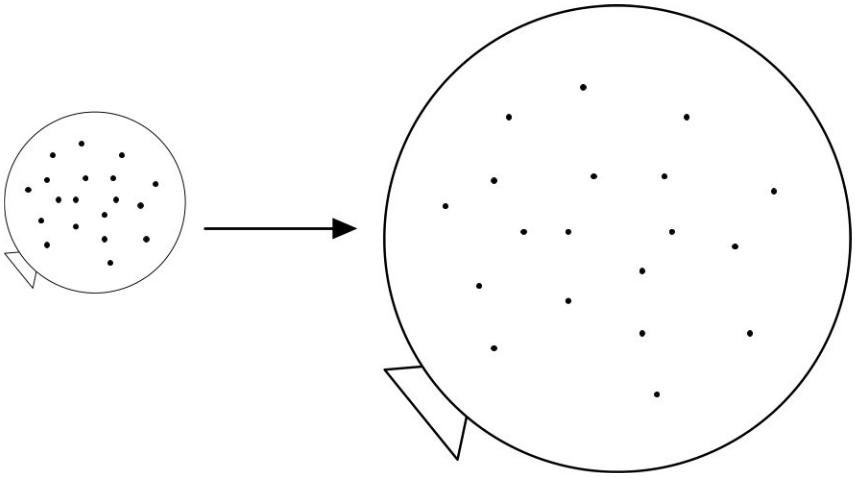


Figure 15: The Expansion of the Universe. A good way of picturing the expansion of the universe is to think of a balloon with galaxies drawn on its surface being inflated. As the balloon expands, every galaxy moves away from every other galaxy since it is the space between them which is expanding, not the galaxies themselves.

The key idea is that it is the space **between** the galaxies (the rubber of the balloon) which is getting bigger. In one sense the galaxies themselves are not moving around the Universe – they would be in exactly the same place on the balloon if it was let down again.

This also explains why more distant galaxies seem to be moving away from us more quickly. There is more space (balloon) between us and a distant galaxy so more space to expand (see '*You're the Astrophysicist #1: Our Expanding Universe*' on page 29).

Big Bang or Steady State?

Hubble's discovery that we live in an expanding universe led to the development of two competing theories – the Steady State and Big Bang theories.

The **Steady State** theory, developed by the cosmologist Fred Hoyle, proposed that the universe had always existed in a similar state to the way it appears nowadays. Although stars and galaxies are born, evolve and die, the average numbers of each has always remained the same. The average numbers of galaxies in our universe is the same no matter which direction we look from the Earth and the Steady State theory was suggesting that this symmetry extended to time itself, implying that our universe had no beginning and would have no end.

The **Big Bang** theory proposed that around 13.8 billion years ago our universe existed in an incredibly tiny space. It then began to expand very quickly – an event known as the Big Bang and we can still see this expansion taking place today, although gravity has brought matter together to create stars and galaxies in certain areas.

Through the 1950s there was a fierce debate amongst cosmologists as to which of these two theories was the better explanation for the expanding universe. However, during the 1950s and 1960s there were two major discoveries which tipped the balance firmly in favour of the Big Bang theory.

Cosmic Microwave Background Radiation (CMBR)

In 1965 two radio astronomers Arno Penzias and Robert Wilson detected a mysterious 'background' of radio waves with a wavelength of around 1mm (microwaves) which appeared to be coming with equal strength from every direction in the universe. This Cosmic Microwave Background radiation was quickly suggested to be left over from the Big Bang[12] itself. The strength and wavelength of the CMBR was also shown to be consistent with a Big Bang which took place 13.8 billion years ago.

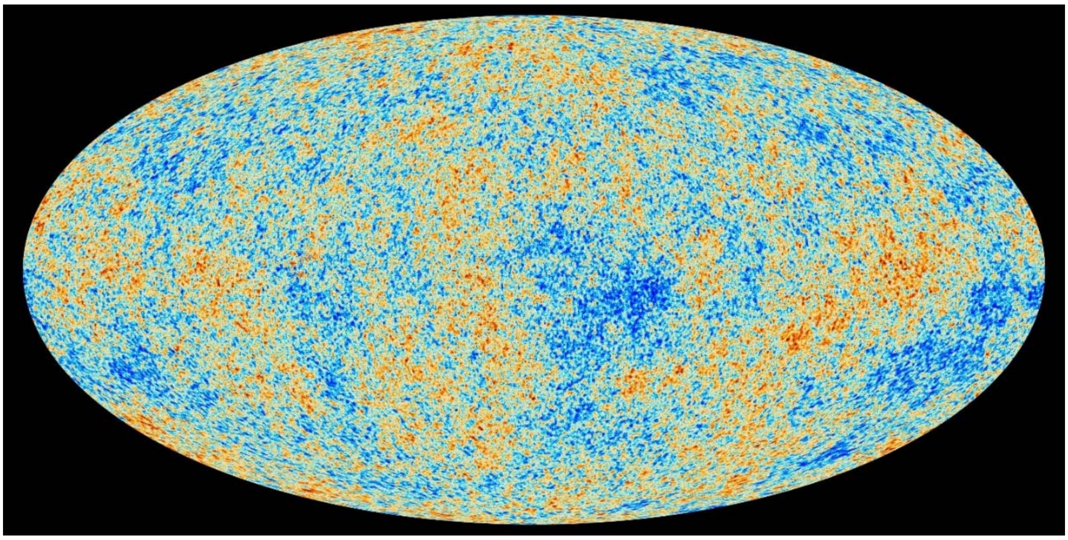


Figure 16: Map of the CMBR. This image shows the tiny variations in the intensity of the Cosmic Microwave Background Radiation, as measured by the European Space Agency's Planck satellite in 2013. The tiny variations in the CMBR were the product of fluctuations which took place close to the very beginning of our universe. (Image: © NASA/European Space Agency, Planck Collaboration)

Quasi-Stellar Objects (QSOs)

In the late 1950s, as the power of telescopes increased, a number of extremely compact objects with very large luminosities were discovered. They all had exceptionally high red-shifts, suggesting that they were at enormous distances from the Earth and receding at speeds close to the speed of light. Their exact nature was not clear and so they were called QSOs or Quasi-Stellar Objects.

[12] Sometimes rather misleadingly called the 'echo' of the Big Bang.

Figure 17: Quasars. This Hubble Space Telescope image shows QSO1229+204 – a massive black hole at the centre of a galaxy. Even though it is one of the most distant objects visible from Earth it still appears to shine brightly, indicating the tremendous power output of this quasar. (Image: © J. Hutchings (DAO)/NASA)

They are now known to be the nuclei of galaxies or Active Galactic Nuclei (AGNs). The importance of QSOs for the debate between the Big Bang and Steady State theories of the universe is that they are only found at very great distances from the Earth – almost at the edge of the observable universe. Whenever astrophysicists look out across great distances in space they are effectively looking back in time. For example, when looking at a galaxy at a distance of five million light years, astrophysicists are seeing it as it appeared five million years ago, since its light will have taken five million years to reach the Earth.

The nearest quasar is at a distance of 1.5 billion light years which means that they only existed up until 1.5 billion years ago. This means that the Steady State theory's idea that the universe has always looked broadly the same cannot be true.

Consequently, the Big Bang theory is now the dominant theory in cosmology.

Checkpoint questions

1. Key terms

Explain what is meant by each of the following terms:

i) Doppler Effect,
ii) red-shift,
iii) CMBR,
iv) Big Bang theory.

2. Andromeda's Blue Shift

The wavelengths of light from the Andromeda Galaxy are found to be **shorter** than expected by 0.1%. This effect is known as 'blue-shift'.

a) What does blue-shift tell us about the direction of Andromeda's movement relative to us?
b) Calculate the speed at which Andromeda appears to be moving.
c) What is the cause of this movement?

You're the Astrophysicist…

Motion in the Universe

1. Gravity and the Orbits of the Planets

The orbital periods of the planets can show us how the strength of the Sun's gravity changes with their distance from the Sun. The table below shows some data about the 'naked-eye[13]' planets of our Solar System:

	Distance from Sun (AU)	Orbital Period (years)
Mercury	0.4	0.24
Venus	0.7	0.62
Earth	**1.0**	**1.0**
Mars	1.5	1.99
Jupiter	5.2	11.9
Saturn	9.5	29.5

a) Plot a graph of these data, with Distance from the Sun along the horizontal axis and Orbital Period on the vertical axis.
b) Draw a smooth curve through your points.
c) A student suggests that Orbital Period and Distance from the Sun are directly proportional. Draw a straight line on your graph through the origin and the point representing the Earth (1,1), showing how the results would appear if this was true.
d) Which planets are orbiting more quickly than the Orbital Period predicted by the 'proportional' straight line?
e) Which planets are orbiting more slowly than the Orbital Period predicted by the 'proportional' straight line?
f) What do the answers to d) and e) tell you about the strength of the Sun's gravity close to and far away from the Sun?

Extension Research Question

Although you might expect Mercury to be the hottest planet, it is in fact Venus which has the highest surface temperature. In addition, although Neptune is farthest from the Sun, Uranus is the coldest! Can you find out the reasons for these two curious facts?

Figure 18: Uranus. Despite being closer to the Sun than Neptune, its average surface temperature is the lowest in the solar system. (Image: © Voyager 2 Team/NASA)

[13] These are the planets which can be seen by the human eye on its own, without any optical aid such as binoculars or a telescope. They have therefore been observed and their motion recorded since the very earliest times.

2. Objects in the Solar System

The details of an object's orbit can help to identify the object. The table below shows some data about a range of objects in our Solar System.

	Average distance from Sun (AU)	Eccentricity of orbit (-)	Orbital Angle (°)	Orbital Period (years)
A	68	0.44	44	558
B	186	1.0	89	2530
C	1	0.02	0	1
D	17.8	0.97	163	75
E	5.2	0.05	1.3	11.9
F	2.7	0.26	13	4.4

AU = Astronomical Units. One Astronomical unit (AU) is the average distance between the Earth and the Sun

Eccentricity = how elliptical an orbit is. Zero would be a perfectly circular orbit.

Orbital Angle = the angle between the object's orbit and the orbit of the Earth.

Orbital Period = time taken to complete one orbit of the Sun.

a) Use the orbital data in the table to identify which of the objects A-F is:
   i. Eris, a Trans-Neptunian Object,
   ii. Earth,
   iii. Jupiter,
   iv. Halley's Comet, which was visible from Earth in 1910 and 1986,
   v. Comet Hale Bopp,
   vi. an object from the Asteroid Belt, between Mars and Jupiter.

b) Which of the above objects is most likely to pass close to the Earth?

Stellar evolution

1. Identifying Stars

The light from a star can be analysed to allow astrophysicists to work out many of the star's physical properties, such as its mass, radius, temperature etc. In this way we can find out which type of star it is.

The table below gives some data about some stars in our galaxy.

	Radius (Sun =1)	Spectral Class	Brightness (Sun=1)
A	100	O	60 000
B	0.01	A	1/1600
C	1	G	1
D	900	M	10 000
E	0.3	R	1/6000
F	0.9	F	1.1

Use these data to identify which star (A-F) is a:

i. Star similar to the Sun
ii. Red Giant star
iii. White Dwarf star
iv. Blue Supergiant star
v. Red Dwarf star

2. Balancing the Sun

All Main Sequence stars are a balance between the force of gravity (trying to make them smaller) and radiation pressure (trying to make them bigger). The table below shows the strength of these two forces for several different sizes of a star.

Radius of Star (x 10^3 km)	Gravitational Field Strength, g (MN/kg)	Radiation Pressure (MN/kg)
400	838	1490
500	536	763
600	372	442
700	273	278
800	209	186
900	165	130
1000	134	95
1100	111	72
1200	81	55

a) Draw a graph of Radiation Pressure against Radius, using the data in the table above.
b) Draw a graph of Gravitational Field Strength against Radius, using the data in the table above.
c) A star is stable when the forces of gravity and radiation pressure are equal. Use your graph to estimate the radius at which this star would be stable.
d) Compare your answer to c) with the Sun's radius of 700 000 km and use this to decide whether this star is more or less massive than the Sun.

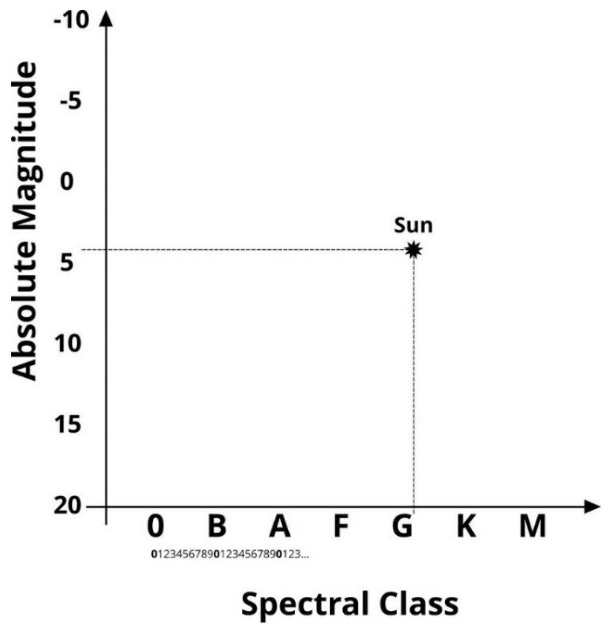
3. The Hertzsprung –Russell Diagram (SEPARATE PHYSICS)

The Hertzsprung-Russell (H-R) Diagram is effectively a graph of brightness (measured by absolute magnitude) against temperature (or Spectral Class) for stars. Each star has its own unique position on this graph.

The table below gives Spectral Class and Absolute Magnitude data for a range of stars.

Star	**Spectral Class**	**Absolute Magnitude**
61 Cygni	K5	7.5
α Centauri	G2	4.4
Barnard's Star	M4	13.2
Bellatrix	B2	-2.8
Betelgeuse	M1	-5.9
Deneb	A2	-8.4
Procyon B	F5	13
Proxima Centauri	M6	15.6
Rigel	B8	-7.8
Sirius B	A2	11.2
Spica	B1	-3.6
Sun	G2	4.8
Vega	A0	0.6
Wolf 359	M7	16.7

a) Use these data to plot a graph of Absolute Magnitude (vertical axis) against Spectral Class (horizontal axis), as shown below. Notice that each Spectral Class is split up into ten divisions, numbered 0 to 9.



b) Draw a smooth curve to show the Main Sequence on your H-R Diagram.

c) Can you identify the following groups of stars on your H-R Diagram?
   i. White Dwarf stars
   ii. Blue Supergiant stars
   iii. Red Giant stars

Cosmology

1. Our Expanding Universe

The diagram below shows some of Edwin Hubble's results from his measurements of the speeds of distant galaxies. By looking at the spectra from the light from each galaxy he could see that their spectral lines had all moved towards the red end of the spectrum. In other words they had been 'red-shifted'. He also saw that the amount of red-shift was greater for the more distant galaxies.

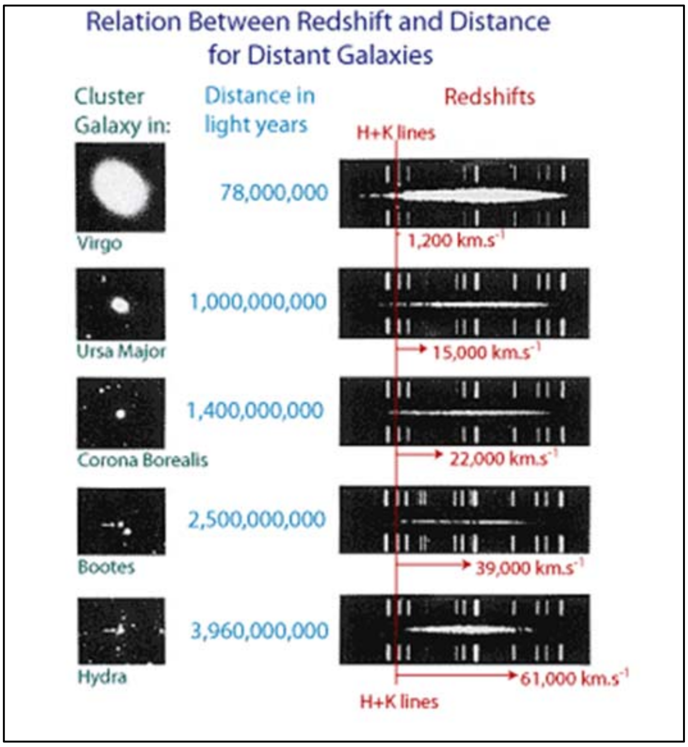


Figure 19: Hubble's Results. Measurements of the speeds of galaxies outside the Local Group, made by Edwin Hubble. Adapted from http://www.atnf.csiro.au/outreach/education/senior/cosmicengine/hubble.html

His measurements are summarised in the table below:

Galaxy	Distance from Earth (Mly)	Speed of Recession (km / s)
Virgo	78	1 200
Ursa Major	1000	15 000
Corona Borealis	1400	22 000
Boötes	2500	39 000
Hydra	3960	61 000

a) Use these data to plot a graph of Speed of Recession against Distance from Earth.
b) Draw a smooth line or curve through your points.
c) The speed at which a galaxy at 1 Mpc (3.26 Mly) would be moving away from the Earth is called the Hubble Constant (H). Use your graph to calculate a value for H.
d) In recent years, astrophysicists have made observations which suggest that the value of H is increasing. What does this tell us about the behaviour of our Universe?

Figure 20: The Cluster of Galaxies in the Constellation of Hydra. This was one of the most distant sets of galaxies observed and measured by Edwin Hubble. At 724 million light years away from the Earth they appear to be receding from us at 16500 km/s. The two bright stars to the lower left and upper right of centre are stars in the Milky Way which happen to lie close to the 'line of sight' to this galactic cluster. (Image: © Angus Lea/NASA)

2. Big Bang or Steady State Universe?

When the expansion of the Universe was first discovered, two main theories were proposed to explain it – the Steady State and Big Bang theories.

The following is a list of observations about our Universe.

- The Cosmic Microwave Background Radiation (CMBR)
- Quasars
- The red-shift of distant galaxies
- The existence of black holes
- The Milky Way and Andromeda galaxies are moving towards each other
- The proportions of hydrogen and helium in the universe
- The fact that the numbers of galaxies is the same no matter which direction you look in the Universe

a) Arrange these pieces of evidence into the following table:

Supports the Big Bang Theory	Supports the Steady State Theory	Not relevant to either theory

b) Use your completed table to explain why astrophysicists currently believe the Big Bang Theory.

Extension Research Question

The simple model of a universe expanding rapidly from a Big Bang, with gravity pulling material together to form stars and galaxies in some areas has undergone some significant changes in recent years. The most notable have been the suggestion of Dark Matter and Dark Energy, along with some observational evidence for them.

a) What effect does each of these ideas have on our expanding universe?
b) How might the ultimate future of our universe be affected by each one?

Appendix 1: Nuclear Fusion in Stars

Specification coverage

This guide covers the following specification points (7.24-7.26), related to the nuclear fusion reaction within stars:

Students should:

7.24 describe nuclear fusion as the creation of larger nuclei resulting in a loss of mass from smaller nuclei, accompanied by a release of energy

7.25 know that fusion is the energy source for stars

7.26 explain why nuclear fusion does not happen at low temperatures and pressures, due to electrostatic repulsion of protons

Introduction

The rays of sunlight which reach us on Earth every day are the result of reactions between nuclei deep in the core of the Sun. The cores of stars are the only places in the universe where temperatures, pressures and densities are high enough to overcome the electrostatic repulsion between protons, allowing them to fuse and generate the colossal amounts of energy required to balance a star's constant gravitational collapse. Since its discovery in the 1930s physicists have been working to produce a reactor which will allow this process to happen in a controlled way on the Earth, thus providing large amounts of sustainable energy.

Background Information

How old is the Sun?

In 1862 the physicist William Thomson (later Lord Kelvin) made an estimate of the maximum possible age of the Sun and therefore the Solar System and the Earth[14]. Using the idea of a chemical fuel for the Sun, he calculated that the Sun could not last for more than a few thousand years.

We now know that the Sun is actually millions of times older than this estimate – around 4.5 billion years old. Lord Kelvin obviously assumed that the Sun's internal energy source was based on a chemical reaction whereas we know nowadays that the Sun is powered by nuclear reactions which generate millions of times more energy from every kilogram of fuel.

[14] Kelvin was firmly opposed to Charles Darwin's proposal of his theory of evolution and used these short estimates for the age of the Sun and Earth as strong evidence to the contrary.

Checkpoint question: Kelvin's Calculation

In the 19th century, Lord Kelvin had estimates of the size of the Sun and the rate at which it was radiating energy. He used these to estimate the possible lifetime of the Sun.

Kelvin was unsure of the Sun's energy source and could not have known anything about nuclear energy. He assumed that the Sun was using a chemical reaction like the combustion of coal, which can generate 32.5 MJ/kg.

a) If the Sun has a mass of 2×10^{30} kg, estimate the total amount of chemical energy which could be contained in the Sun.

The Sun radiates energy at the rate of 4×10^{26} W, which means that it radiates around 4×10^{26} joules of energy every second.

b) Use this figure to obtain a value for the number of seconds which the Sun could last for.
c) Convert this into years (1 year = 31 600 000 s).

Some chemical reactions can produce more energy than the combustion of coal. One example is the reaction of hydrogen and oxygen to form water, which generates 143 MJ/kg.

d) Use this increased figure for the energy generated by each kilogram of the Sun to calculate a longer estimate tor its lifetime.

The energy density of the nuclear fusion reaction is around 337 000 000 MJ/kg.

e) Does this result in a more realistic figure for the lifetime of the Sun?

The Nuclear Fusion Reaction

Humans have been releasing the chemical energy stored by the electrons orbiting at the edge of atoms for millions of years through chemical reactions such as combustion. In the 1930s physicists discovered how to release the nuclear energy stored in the nucleus of an atom. Two methods were discovered:

1) **Fission.** This involves making large nuclei such as Uranium split into smaller nuclei.
2) **Fusion.** This involves forcing light nuclei such as Hydrogen together to form heavier ones.

The amount of energy released from each kilogram of a material undergoing these nuclear reactions is many millions of times larger than that released by even the most violent chemical reaction. This explains how the Sun is able to maintain its enormous energy output for such an unimaginably long time.

In simple terms the process involves fusing two isotopes of hydrogen together. These two isotopes are:

- Hydrogen-1 – the most common form of hydrogen. This nucleus simply contains a single proton

- Hydrogen-2 – this is a less common isotope of hydrogen called deuterium[15]. Its nucleus contains one proton and one neutron

As shown below, when nuclei of these two isotopes of hydrogen meet under the right conditions, they can fuse together to form a nucleus containing two protons and one neutron which is an isotope of helium. This reaction releases enormous amounts of energy.

The Conditions for Nuclear Fusion

Nuclear fusion only occurs when hydrogen is at very high temperatures and pressures. The main reason for this is that the protons in a hydrogen-1 and deuterium nucleus are both positively charged. Their like charges will therefore repel each other as a result of the electrostatic force.

When two protons are extremely close together, such as in a nucleus, they are tightly held together by the Strong Nuclear Force which attracts all protons and neutrons together. However, the Strong Nuclear Force only acts over extremely short distances and so, up until the point where the two nuclei are almost touching, the Electrostatic force is much stronger.

The solution to this problem is to ensure that the hydrogen is at a very high temperature so that the nuclei are moving extremely fast. In this situation the electrostatic repulsion does not have time to push them away from each other before they bump into each other and are locked together by the Strong Nuclear Force.

Unfortunately this requires a temperature of at least 10 000 000K, which is why creating the conditions for fusion to occur on the Earth continues to be a very difficult technological problem.

Nuclear Fusion in Stars

One obvious place in nature where temperatures and pressures are high enough for the nuclear fusion reaction is at the centre of stars. Here enormous gravitational forces compress the star to the point where nuclear fusion can take place in its core. This allows the star to produce the vast quantities of energy needed to balance the gravitational collapse and form a stable or 'Main Sequence' stars.

It is obviously possible to fuse helium to form heavier elements such as lithium and so on but this requires even greater temperatures which are only found in more massive stars.

[15] This is one area where physicists trying to create nuclear fusion on the Earth have a slight advantage over stars. About 0.02% of sea water uses deuterium atoms instead of Hydrogen-1 whereas stars take many thousands of years to make deuterium by first fusing a proton and a neutron.

However, even the largest stars can only fuse nuclei together to form elements up to Iron, which contains 26 protons. Fusing elements heavier than this will not release any nuclear energy to support the star.

Amazingly, this means that all the natural elements on the Periodic Table with an atomic number greater than 26 were formed in the immense explosion when a star becomes a supernova. This explains why their abundances in the universe are so very low compared with hydrogen and helium.

Nuclear Fusion on Earth

The enormous amounts of energy which can be released from plentiful materials such as hydrogen have meant that physicists and engineers have been trying to produce a reactor which can produce and sustain a controllable fusion reaction for many decades now.

Some reactors have successfully fused small amounts of hydrogen into helium but to date this has always involved putting in much more energy than has been released by the fusion reaction. A working power station generating electricity from the fusion of hydrogen nuclei may still be many years in the future.

Checkpoint question: Fusion power

a) Make a list of the advantages and disadvantages of generating electricity from nuclear fusion, compared to using non-renewable resources such as coal.
b) Make a list of the advantages and disadvantages of generating electricity from nuclear fusion, compared to using nuclear fission – the splitting of heavy nuclei such as uranium.
c) There are two main approaches to the problem of producing controlled nuclear fusion on Earth. Which of them is currently closest to producing a working fusion reactor?

Checkpoint question: Cold Fusion

In 1989 two scientists thought that they had found a way to make a nuclear fusion reaction happen at close to room temperature. Their equipment simply involved some pieces of metal in a test tube, connected to a battery.

Although their 'discovery' of 'Cold' Fusion created great excitement around the world it was soon discovered to be incorrect.

a) Research the topic of cold fusion.
b) Compare the way in which cold fusion was investigated with the usual way in which scientists check a new discovery.

Appendix 2: Further Support

Association for Astronomy Education

The AAE website contains downloadable resources to support the teaching of astronomical topics within a number of GCSE and A Level courses - www.aae.org.uk/

NASA

The 'For Educators' section of the NASA website contains a wide range of resources to support the teaching of the astrophysical concepts within this topic.
www.nasa.gov/audience/foreducators/index.html

RAS website and leaflets

The 'Information for Schools & Teachers' page of the RAS website provides access to a range of resources to support the teaching of many astrophysical topics. In particular the RAS's downloadable leaflet on Gravity relates directly to this topic.
www.ras.org.uk/education-and-careers/for-schools-and-teachers

Royal Greenwich Observatory

This historic site contains exhibits and activities related to the astrophysical topics covered in this guide. Further details at: www.rmg.co.uk/royal-observatory

Science & Technology Facilities Council

The STFC provides a number of activities and resources to support the teaching of many of the concepts covered in this topic. Further details can be found at:
www.stfc.ac.uk/public-engagement/activities-for-schools/

Woolsthorpe Manor

The Lincolnshire farmhouse where Isaac Newton was born and grew up is open to the public and includes a Visitors' Centre with many displays and demonstrations relating to his work on motion and gravity. Further details are available on the National Trust website: www.nationaltrust.org.uk/woolsthorpe-manor