Wallace Hall Academy

CfE Higher Physics

Unit 1 - Universe
Notes

Name ____________________

Newton and Gravity

Newton's Thought Experiment – Satellite's orbit as an Application of Projectiles

Isaac Newton, as well as giving us the three laws, came up with an ingenious thought experiment for satellite motion that predated the first artificial satellite by over 300 years.

Essentially Newton suggested that if a cannon fired a cannonball it would fall towards the Earth. If it was fired at ever higher speeds then at some speed it would fall towards the Earth but never land since the curvature of the Earth would be the same as the flight path of the cannonball. This would then be a satellite. You would need a high mountain and an enormous cannon, but it would work.

Gravity

There is much confusion in Physics of the difference between mass and weight. This could be because the word weight is used, wrongly, in everyday life. People are always talking about their 'weight'.

What they are really talking about is their mass. **Mass is a measure of how much matter an object contains.** This will only change if matter is added to or taken from the object. We can see this on a person as their body shape changes as matter is added or taken away. **Weight is a measure of the gravitational pull on an object.**

What is Gravity?
Gravity is caused by mass. Any object that has mass will have its own gravitational field. We already know that the strength of gravity varies from planet to planet around our solar system and this is called gravitational field strength. **Gravitational field strength is the weight per unit mass.**

You will recall the following equation from National 5

$$W = mg$$

This equation still has its uses in Higher Physics but Newton created a more useful equation which means we don't need to remember the gravitational field strength on each planet.

Newton's Universal Law of Gravitation

Newton produced what is known as the Universal Law of Gravitation

$$F = \frac{Gm_1m_2}{r^2}$$

G is the universal constant of gravitation = $6{\cdot}67 \times 10^{-11}$ m^3 kg^{-1} s^{-2}. Newton's Law of gravitation states that the gravitational attraction between two objects (m_1 and m_2) is directly proportional to the mass of each object and is inversely proportional to the square of their distance (r) apart. Gravitational force is always attractive, unlike electrostatic or magnetic forces.

The distance r between the two objects is the distance between their **centres of mass**. This is especially important when considering planetary bodies. For example, the radius of the orbit of the moon is only the distance from the surface of the Earth to the surface of the Moon, not the distance between their centres of mass. Do not worry too much about this, it will be obvious from the question if you need to consider this.

Example

Consider a folder, of mass 0.3 kg and a pen, of mass 0.05 kg, sitting on a desk, 0.25 m apart.
Calculate the magnitude of the gravitational force between the two masses. (Assume they can be approximated to spherical objects).

Solution

Example

The mass of the Earth is 6×10^{24} kg and it has a radius of 6.4×10^6 m. A satellite of mass 5600 kg orbits 34 km above its surface.
Calculate the magnitude of the gravitational force between the Earth and the satellite.

Solution

Special Relativity

Introduction to Relativity

Einstein originally proposed his theory of special relativity in 1905 and it is often taken as the beginning of modern Physics. It was one of four world changing theories published by Einstein that year, known as the Annus Mirabilis (miracle year) papers. Einstein was 26.

Relativity has allowed us to examine the mechanics of the universe far beyond that of Newtonian mechanics, especially the more extreme phenomena such as black holes, dark matter and the expansion of the universe, where the usual laws of motion and gravity appear to break down.

Special Relativity was the first theory of relativity Einstein proposed. It was termed as 'special' as it only considers the 'special' case of reference frames moving at **constant** speed. Later he developed the theory of general relativity which considers accelerating frames of reference.

We will only consider special relativity in the Higher Physics course.

Reference Frames

Relativity is all about observing events and measuring physical quantities, such as distance and time, from different reference frames. Here is an example of the same event seen by three different observers, each in their own frame of reference:

Event 1: You are reading your Kindle on the train. The train is travelling at 20 ms^{-1}.

Observer	Location	Observation
1	Passenger sitting next to you	You are moving at
2	Person standing on the platform	You are moving at
3	Passenger on train travelling at 20 ms^{-1} in opposite direction	You are moving at

This example works well as it only involves objects travelling at relatively low speeds. The comparison between reference frames does not work in quite the same way, however, if objects are moving close to the speed of light.

Event 2: You are reading your Kindle on an interstellar train. The train is travelling at 2×10^8 ms^{-1}.

Observer	Location	Observation
1	Passenger sitting next to you	You are moving at
2	Person standing on the platform	You are moving at
3	Passenger on train travelling at 2×10^8 ms^{-1} in opposite direction	You are moving at

This is obviously impossible as nothing can travel faster than the speed of light.

The Principles of Relativity

The Principles of Relativity - Introduction

Using his imagination and performing thought experiments like those on the previous page, Einstein came up with two principles, or postulates, to explain the problem of fast moving reference frames. These were later proved with a vast array of data from many different experiments and became very clear once we started communicating with satellites, in orbit. GPS satellites, for example, must calculate relativistic effects.

The postulates of Special Relativity:

1. **When two observers are moving at constant speeds relative to one another, they will observe the same laws of physics.**
2. **The speed of light (in a vacuum) is the same for all observers.**

This means that no matter how fast you go, you can never catch up with a beam of light, since it always travels at $3{\cdot}0 \times 10^8$ ms^{-1} **relative** *to you*.

If you (or anything made of matter) were able to travel as fast as light, light would still move away or towards you at $3{\cdot}0 \times 10^8$ ms^{-1}, as you are stationary in your own reference frame.

Example: If a car ship is travelling through space at 90% of the speed of light and then switches on its headlights. The passenger of the car will see the beams of the headlights travel away from them at 3×10^8 ms^{-1}.
An observer on Earth will also observe light of the beams travelling at 3×10^8 ms^{-1}.

The speed of light, **c**, is constant in and between all reference frames and for all observers.
These principles have strange consequences for the measurement of distance and time between reference frames.

Einstein created equations to describe time dilation and length contraction which occur at velocities close to the speed of light.

Time Dilation

Time Dilation

For all of the complex Physics involved with special relativity one of the two main things you need to understand is the time dilates for stationary observers who are observing objects moving close to the speed of light. This means time appears to dilate when a moving object is observed by a stationary observer.

$$t' = \frac{t}{\sqrt{1-\left(\frac{v}{c}\right)^2}}$$

Where:

t' = time observed (experienced) by stationary observer (s) – can also be in minutes, hours, days or years

t = time experienced by moving object (s) – can also be in minutes, hours, days or years

v = speed of moving object (ms^{-1})

c = speed of light (3×10^8 ms^{-1})

<u>Example</u>

A rocket is travelling past Earth at a constant speed of 2.7×10^8 ms^{-1}. The **pilot** measures the journey as taking 240 minutes. Calculate how long the journey would take when measured by an **observer** on Earth.

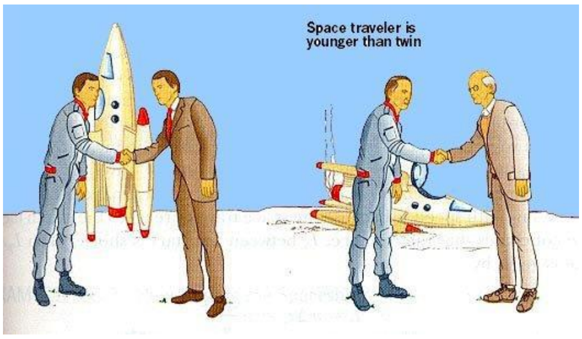
<u>Solution</u>

<u>**Time observed (experienced) by a stationary observer is always bigger**</u>

A good way to remember what is going on here is to think of the twins paradox.

Twins paradox

You leave Earth and your twin to go on a mission in a spaceship travelling at 90% of the speed of light on a return journey that lasts 20 years. When you get back you find that 46 years will have elapsed on Earth. Your clock will have run slowly compared to one on Earth, however as far as you were concerned the clock would have been working correctly on your spaceship. **You will look 26 years younger than your twin.**



Application of Time Dilation

Further evidence in support of special relativity comes from the field of particle physics, in the form of the detection of a particle called a muon at the surface of the Earth. Muons are produced in the upper layers of the atmosphere by cosmic rays (high-energy protons from space). The speed of muons high in the atmosphere is 99·9653% of the speed of light.

<u>Example</u>

The half-life of muons when measured in a laboratory is about 2·2 μs.

(a) Calculate how far a muon would travel in 2·2 μs.
(b) Calculate the relativistic lifetime of a muon as seen by an observer on Earth due to time dilation.

<u>Solution</u>

Length Contraction

For all of the complex Physics involved with special relativity the second of the two main things you need to understand is the length contracts for stationary observers who are observing objects moving close to the speed of light. This means length appears to contract when a moving object is observed by a stationary observer.

$$l' = l\sqrt{1 - \left(\frac{v}{c}\right)^2}$$

Where:

l' = length observed by stationary observer (m) – can also be in km or light years

l = length observed by moving object (m) – can also be in km or light years

v = speed of moving object (ms^{-1})

c = speed of light ($3 \times 10^8\ ms^{-1}$)

<u>Example</u>

A rocket is travelling past Earth at a constant speed of $2.8 \times 10^8\ ms^{-1}$. The **pilot** measures the length of the rocket to be 80 m. Calculate how long the moving rocket appears when measured by an **observer** on Earth.

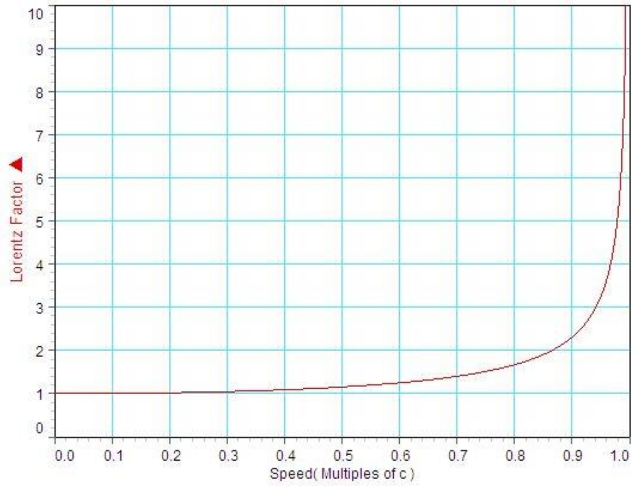
<u>Solution</u>

<u>Length observed of a moving object by a stationary observer is always smaller</u>

The Lorentz Factor

The Lorentz factor is contained in both the time dilation and length contraction equations. The Lorentz factor is shown below alongside a graph of how it varies with the velocity of an object.

$$\gamma = \frac{1}{\sqrt{1 - \left(\frac{v}{c}\right)^2}}$$



The graph clearly shows that relativistic effects only really have an effect when we get to within 10% of the speed of light which is 2.7×10^8 ms^{-1} and above.

Special relativity – A summary

The physics behind special relativity can be complex but it is important to remember that the level of understanding required to answer questions in a Higher Physics exam is not. You will be expected to be able to perform calculations on time dilation and length contraction. You could be asked for t, t', l or l' but it is very, very, very unlikely you will be asked to determine v.

You should remember the following:

Time dilation is when moving and stationary observers measure different time intervals. Time appears to move slower for moving observers (stationary objects age more – time dilation).

Length contraction is when moving and stationary observers measure different lengths. Length appears to be shorter for stationary observers (moving objects appear shorter – length contraction).

The Expanding Universe

The Doppler Effect – For Sound

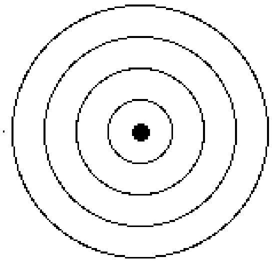
The Doppler Effect is the change in the observed frequency of a wave, when the source or observer is moving. In this course we will concentrate on a wave source moving at **constant speed** relative to a stationary observer.

You have already experienced the Doppler Effect many times. The most noticeable is when a police car, ambulance or fire engine passes you. You hear the pitch of their siren increase as they come towards you and then decrease as they move away.

The Doppler Effect applies to all waves, including light, although we will initially discuss the Doppler effect in terms of sound..

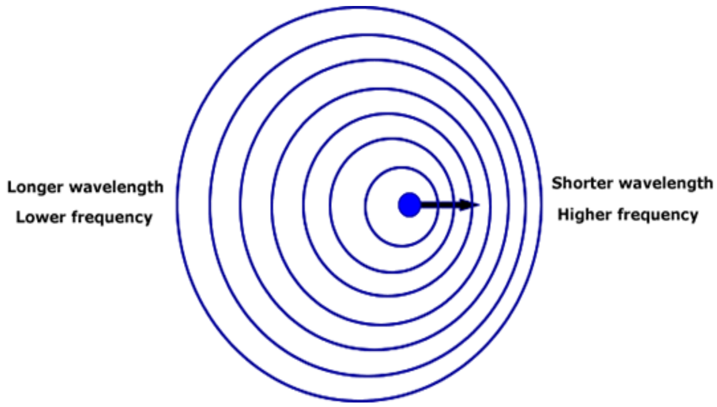
Stationary Source

A stationary sound source produces sound waves at a constant frequency **f**, and the wavefronts propagate symmetrically away from the source at a constant speed, which is the speed of sound in the medium. The distance between wave-fronts is the wavelength. All observers will hear the same frequency, which will be equal to the actual frequency of the source: $\mathbf{f = f_0}$.



Moving Source

The sound source now moves to the right with a speed $\mathbf{v_s}$. The wavefronts are produced with the same frequency as before, therefore the period of each wave is the same as before. However, in the time taken for the production of each new wave the source has moved some distance to the right. This means that the wavefronts on the left are created further apart and the wavefronts on the right are created closer together. This leads to the spreading out and bunching up of waves you can see to the right and hence the change in frequency.



The frequency of the source will remain constant, it is the observed frequency that changes.

The observed frequency of a source of sound moving towards an observer increases because more wavefronts are observed per second.

The observed frequency of a source of sound moving away from an observer decreases because less wavefronts are observed per second.

The Doppler Effect Equations – For Sound

For a stationary observer with a wave source **moving towards them**, the relationship between the frequency, $\mathbf{f_s}$, of the source and the observed frequency, $\mathbf{f_o}$, is:

$$\mathbf{f_o = f_s\left(\frac{v}{v - v_s}\right)}$$

v = speed of sound (340 ms^{-1})
v_s = speed of source (ms^{-1})
f_s = frequency source (Hz)
f_o = observed frequency (Hz)

For a stationary observer with a wave source **moving away from them**, the relationship between the frequency, $\mathbf{f_s}$, of the source and the observed frequency, $\mathbf{f_o}$, is:

$$\mathbf{f_o = f_s\left(\frac{v}{v + v_s}\right)}$$

v = speed of sound (340 ms^{-1})
v_s = speed of source (ms^{-1})
f_s = frequency source (Hz)
f_o = observed frequency (Hz)

Example

A fire engine is travelling at 20 ms^{-1} with a 500 Hz siren sounding.

(a) Calculate what frequency would be heard when the fire engine travels towards you.
(b) Calculate what frequency would be heard when the fire engine travels away from you.

Solution

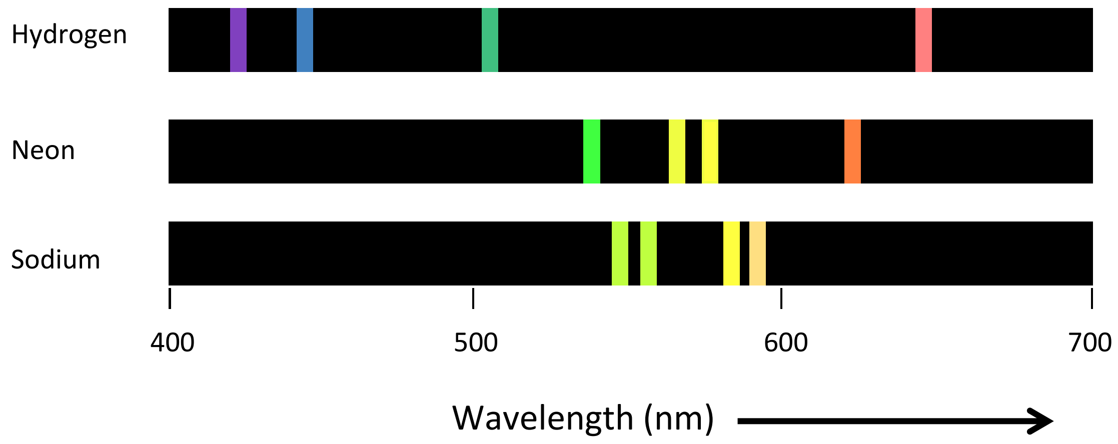
The Doppler Effect – For Light

Redshift is an example of the Doppler Effect. **The light from stars, as observed from Earth, is always reduced in frequency and shifted towards the red (longer wavelengths) end of the spectrum. This is because the stars and galaxies are sources of light which are moving away from us.**

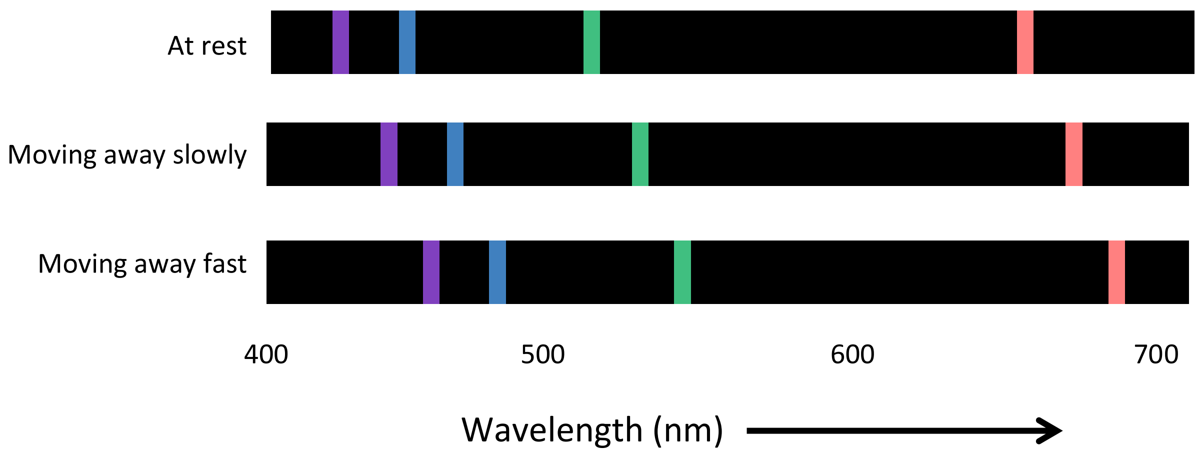
The light emitted by a star is made up of the line spectra emitted by the different elements present in that star. Each of these line spectra is an identifying signature for an element and these spectra are constant throughout the universe. You will learn a lot more about spectra in the Particles and Waves unit of this course.

Since these line spectra are so recognisable, we can compare the spectra produced by these elements, on Earth, with the spectra emitted by a distant star or galaxy.

Examples of line spectra of different elements



Edwin Hubble examined the spectral lines from various elements and found that the spectra emitted by each galaxy were shifted towards the red by a specific amount. This shift was due to the **galaxy moving away from the Earth** at speed, causing the Doppler Effect to be observed. The **bigger the magnitude of the shift the faster the galaxy** was moving.



Redshift of a Galaxy Equation – For Light

Redshift, **z**, of a galaxy is given by:

$$z = \frac{\lambda_{observed} - \lambda_{rest}}{\lambda_{rest}} = \frac{\Delta\lambda}{\lambda_{rest}}$$

z = redshift
$\lambda_{observed}$ = observed wavelength of light (m)
λ_{rest} = rest wavelength of light (m)

Redshift of galaxies, travelling at non-relativistic speeds, can also be shown to be the ratio of the velocity of the galaxy to the velocity of light:

$$z = \frac{v_{galaxy}}{c}$$

z = redshift
v_{galaxy} = speed of galaxy (ms^{-1})
c = speed of light (3×10^8 ms^{-1})

As redshift is always calculated from the ratio of quantities with the same unit, it has **no unit of its own**.

<u>Example</u>

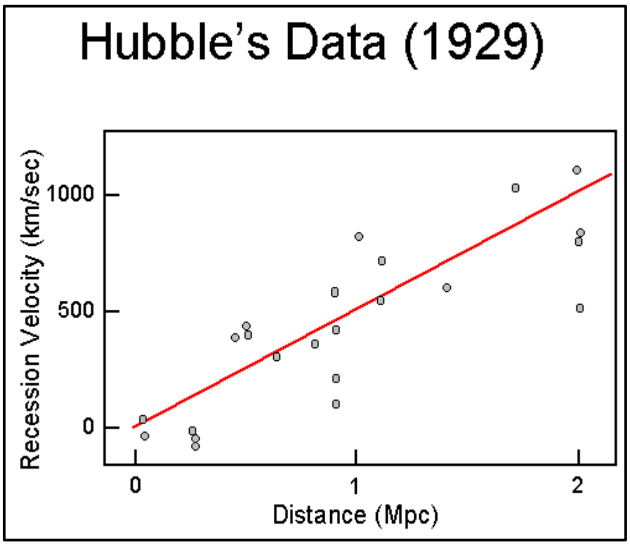
Light from a distant galaxy is observed to have a wavelength of 620 nm while at rest on Earth it would have a wavelength of 590 nm.

(a) Calculate the redshift of the distant galaxy.
(b) Calculate how fast the distant galaxy is moving away from us.

<u>Solution</u>

Hubble's Law

Edwin Hubble was able to show that the further away from us that a galaxy was, the faster it was moving. He plotted these results on the graph shown. The gradient of the line is known as the Hubble constant H_o.



$$\mathbf{v = H_o\, d}$$

where

v = velocity of galaxy (ms^{-1})
H_o = Hubble constant ($2.3 \times 10^{-18}\ s^{-1}$)
d = distance to galaxy (m)

<u>Example</u>

Light from a distant galaxy is observed to have a wavelength of 580 nm while at rest on Earth it would have a wavelength of 563 nm.

(a) Calculate the redshift of the distant galaxy.
(b) Calculate how fast the distant galaxy is moving away from us.
(c) Calculate how far away the galaxy is.

<u>Solution</u>

Calculating the Age of the Universe

Hubble's observations show that galaxies are moving away from the Earth and each other in all directions, which suggests that the universe is expanding. This means that in the past the galaxies were closer to each other than they are today. By working back in time it is possible to calculate a time when all the galaxies were at the same point in space. This allows the age of the universe to be calculated.

Example

Calculate the age of the Universe using Hubble's constant.

Solution

Evidence for the Expanding Universe

We know the Universe is expanding because the redshift of galaxies shows that all galaxies are moving away from us and each other.

When we observe these distant galaxies they appear to be spinning faster than we would expect or be able to explain. This is because of Dark Matter. **Dark Matter is mass that we cannot see but we know is there.**

As well as the Universe expanding the rate at which it is expanding is also increasing. This means that galaxies are actually accelerating away from us. In order to do this energy must be provided to give galaxies energy to overcome the gravitational force and it is called Dark Energy. **Dark Energy is energy galaxies have to overcome the gravitational force.** The gravitational force is working to slow down the rate of expansion of the Universe but Dark Energy is working to increase the rate of expansion of the Universe.

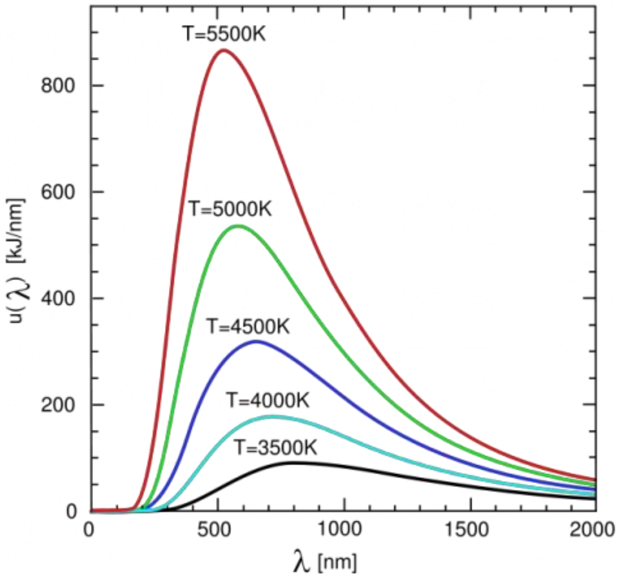
Big Bang Theory

The Big Bang theory indicates that 13.7 Billion years ago all matter in the Universe was concentrated into a tiny point. There was then a hot explosion which expanded the mass outwards and it is still expanding today. Redshift and the expansion of the Universe support the idea of a 'Big Bang' but they are not conclusive. They only show the current movement of the galaxies and not the evidence of the aftermath of any 'Big Bang' itself. There are 4 examples of evidence for the Big Bang and the expanding Universe,

- **Temperature of distant stars varying through their life cycle**
- **Cosmic Microwave Background Radiation (CMBR)**
- **The abundance of elements in the Universe**
- **The dark sky at night**

Temperature of distant stars varying through their life cycle

It is possible to determine the temperature of distant stars and galaxies. You will have seen what happens to a piece of iron as it is heated, as it gets hotter its colour changes from dull red to bright red to orange then yellow.



The temperature of an object determines the frequency of light it emits. This is also true of distant stars which vary in temperature through their life cycle.

What this means is that by examining the spectrum of a distant star, its temperature can effectively be determined.

The graph shows that as the temperature of a star <u>increases</u> its peak emission wavelength <u>decreases</u>.

The graph shows that as the temperature of a star <u>increases</u> its peak intensity (height of graph) <u>increases</u>.

The graph shows that as the temperature of a star <u>increases</u> its total energy emitted (area under graph) <u>increases</u>.

Cosmic Microwave Background Radiation (CMBR)

If the Big Bang had actually taken place then there would be a residual background EM radiation, in the microwave region, in every direction in the sky representing a temperature of around 2.7K as the Universe cooled from its original high temperature. This value for the wavelength of the light and its consequent equivalent temperature was arrived at by considering how the light produced at the Big Bang would have changed as the universe expanded.

This CMBR is observed wherever you look in the Universe indicating that it all started from a common point at a common temperature.

The abundance of elements in the Universe

Evidence to support the Big Bang theory includes the relative abundances of hydrogen and helium in the Universe. Scientists predicted that there should be a significantly greater proportion of hydrogen in the universe. The next most abundant should be helium.

The latest proportions are given in the table shown. These observations conform to the predicted proportions.

Element	Relative Abundance
Hydrogen	10 000
Helium	1 000
Oxygen	6
Carbon	1
All others	1

The dark sky at night

The sky is light during the day because of our sun. There are so many stars in the sky that the sky should also be light at night but because of the expanding Universe only stars within the distance of 15 000 light years will be observed. Not all stars will be within that range and so the dark sky can be explained.

Universe

State what is meant by gravitational field strength.

Weight per unit mass.

State what happens to the gravitational field strength as you move away from a planet.

It decreases.

Describe what effect the mass of objects and distance between objects has on the gravitational attraction between them.

As the masses increase the gravitational force increases and as the distance increases the gravitational force decreases ($F = Gm_1m_2/r^2$).

Describe how the speed of light is affected when viewed by stationary or moving observers.

It is not affected. The speed of light is constant (3×10^8 ms^{-1}) for all observers regardless of their own speed.

Explain what is meant by time dilation.

Moving and stationary observers measure different time intervals. Time appears to move slower for moving observers (stationary objects age more – time dilation).

Explain what is meant by length contraction.

Moving and stationary observers measure different lengths. Length appears to be shorter for stationary observers (moving objects appear shorter – length contraction).

Explain using wavefronts why a sound moving **towards** a stationary observer appears higher in frequency.

The stationary observer hears **more** wavefronts per second.

Explain using wavefronts why a sound **moving away** from a stationary observer appears lower in frequency.

The stationary observer hears **less** wavefronts per second.

Describe what redshift is.

Light from galaxies appear shifted to a higher wavelength (red end of the spectrum) because they are moving away from us.

Describe how the distance to far away galaxies and their velocity is related.

They vary linearly. The further away a galaxy, the faster it is moving.

Describe how the temperature of a star affects its peak wavelength of emission.

As temperature increases peak wavelength decreases.

Describe how the temperature of a star affects the amount of energy it emits.

As temperature increases the amount of energy it emits also increases.

Describe how the temperature of a star affects the level of peak intensity it emits.

As temperature increases the level of peak intensity it emits also increases.

Explain 3 examples of evidence which support the Big Bang theory.

1. Cosmic microwave background radiation, at the same temperature everywhere in the universe as it cooled from one single point.
2. The dark sky at night, most stars so far away light hasn't reached us yet.
3. Redshift, all galaxies moving away from us.

Describe what dark matter is and explain how we know it exists.

Dark matter is matter we cannot observe which was created during the big bang and causes galaxies to rotate faster than they should based on the observable matter in them.

Describe what dark energy is and explain how we know it exists.

Dark energy is energy we cannot observe which was created during the big bang and provides energy to allow galaxies to accelerate away from us.