NATIONAL 5 PHYSICS

ASTROPHYSICS

COSMOLOGY

There are some basic terms used in Cosmology that you need to be familiar with:

Celestial Body	Definition
Planet	An object, that is not undergoing fusion, orbiting a star and of sufficient size to be rounded by its own gravity.
Moon	A natural object orbiting a planet
Star	An object undergoing thermonuclear fusion
Solar System	A set of objects in orbit around a star (or star system)
Galaxy	A group of gravitationally bound stars, gas and dust clouds, and (we think) dark matter. The Milky Way galaxy is 100,000 light years across.
Universe	The totality of existence. The *observable universe* is everything we can see from Earth and is approximately 46 billion light years across.

The Light Year

Distances in space are so huge[1] that using numbers in conventional units such as metres and kilometres would become clumsy and incomprehensible. For example, the distance from the Sun to the Earth is 140,000,000,000 m (1.4×10^{11} m). If we look outside of our solar system, the numbers get far too big. For example, the distance to our nearest neighbouring star, Proxima Centauri is 4,100,000,000,000,000 m (4.1×10^{15} m). Instead we use the light-year (or ly for short). It is a unit of **distance** not time and is equal to the distance that light would travel in one year. So how far is that in meters?

$1 \text{ ly} = d = vt$

$1 \text{ ly} = 3\times10^{8} \times (1 \times 365.25 \times 24 \times 60 \times 60)$

$1 \text{ ly} = 9.4607\times10^{15} \text{ m}$

The other units you may come across when reading about cosmology and astrophysics are:

- The astronomical unit (au) — equal to the distance between the Earth and the Sun (8 light minutes, 15 light seconds).
- The parsec (pc) — equal to 3.26 ly.

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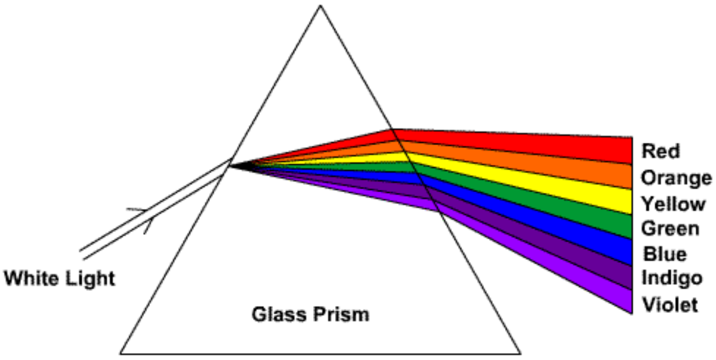
[1] http://scaleofuniverse.com

Exploring the Spectrum

By looking at the emissions (visible light and other parts of the electromagnetic spectrum) of a star, we can tell its temperature, mass, size and composition. Light can be gathered by telescopes and analysed by spectroscopes.

Visible light can be split into its component parts using 2 methods:

1. A Prism.
2. A diffraction grating.



Because white light is made up of seven other colours, we can show the separate colours using a prism. Each colour is refracted by a different angle depending on the wavelength of the light. This type of spectrum is known as a **continuous spectrum**.

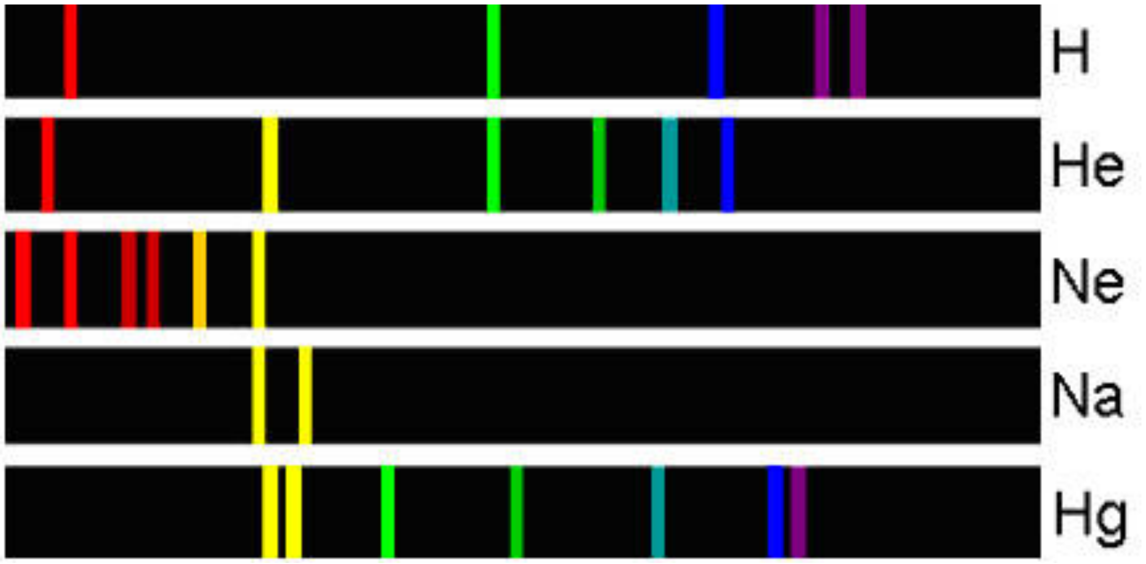
Looking at the single spectra produced, we can see that the white light is split into its component colours. Look carefully:

- Which colour is refracted the least?
- Is this a long or short wavelength?
- Which colour is refracted the most?
- Is this a long or short wavelength?

Line Spectra

When an electrical current is passed through a gas (or if it is extremely hot), energy is emitted from the gas in the form of light. The light produced has very specific frequencies for each element. This is called a **line** (emission) spectrum. This means that any gas can be identified by the light produced when burned, so we can identify the elements contained within a star just by looking at the starlight produced.

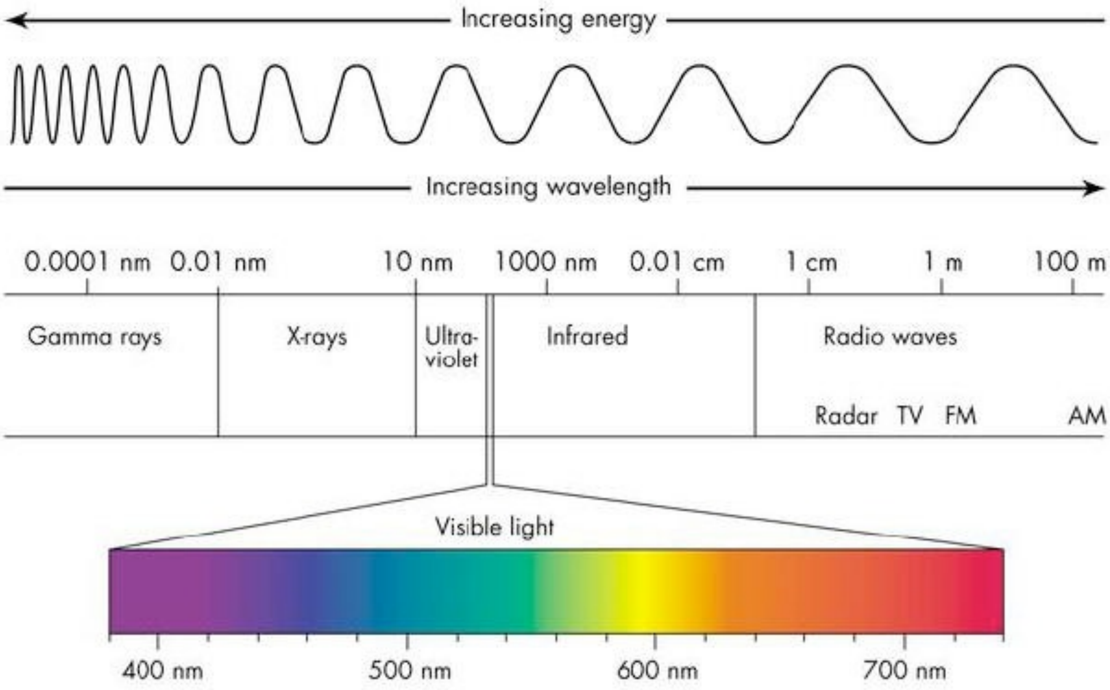
Below are some line spectra of various elements:



When light from a star is analysed in a spectrometer and compared to a database to find out what elements are contained in that star.

The Electromagnetic Spectrum

Remember that visible light is not the only part of the Electromagnetic Spectrum. There are many other wavelengths that we cannot see but we can detect.



Note that as wavelength decreases, the frequency of the wave increases and so the energy of the wave also increases.

All members of the spectrum travel at the same speed: the speed of light, $3 \times 10^8\,\mathrm{m\,s^{-1}}$.

Detecting Signals from Space

The stars in the night sky don't just give out the light that we see — they can also produce radio waves with very long wavelengths. The majority of the electromagnetic radiation hitting the Earth is absorbed by the Earth's atmosphere and its magnetic field. However, there is a "window" of wavelengths that allows radio waves to be travel through the atmosphere.

Radio waves from space can be detected by an aerial or receiver, the problem is that the radio waves are extremely weak. To combat this we can make curved reflectors that are either as large as possible or put together in an array. These receivers are called Radio Telescopes. They can be set to receive radio signals from a certain part of the sky, they do the same job that conventional telescopes do, but for radio waves.

Recently there has been an effort to look at other parts of the EM spectrum as well. This requires launching a telescope into orbit so that the Earth's atmosphere and magnetic field do not block the signals. Using satellites such as *Swift* and the planned *James Webb Space Telescope* we are able to look at the universe in every part of the EM spectrum.

In addition to light there are other things that we can detect from stars and galaxies:

Cosmic Rays — These are parts of atoms and other particles that are blasted across the universe by supernovae. The vast majority of these (99%) are Hydrogen and Helium nuclei. They travel at close to the speed of light and interact with magnetic fields making it very difficult for us to trace where they came from.

Neutrinos — A particle produced in massive numbers by the nuclear reactions in stars. They are very hard to detect because the vast majority of them pass completely through the Earth without interacting.

How old is the universe?

The universe is 13.8 billion years old. That is 13.8×10^9 years old.

How do we know this?

In simple terms, we know that the universe is still expanding — the galaxies that we can observe are accelerating away from us. Galaxies move further away the light coming from them is redder than what is should be. It is the same principle as when a police car drives past with the siren on, as it moves away from you, the sound changes to a lower pitch. It is called the Doppler Effect.

If we know the rate at which galaxies are accelerating we can reverse the process and see how long it would take to come to a single point — the Big Bang.

The Big Bang

Discoveries in astronomy and physics have shown beyond a reasonable doubt that our universe did in fact have a beginning. Prior to that moment there was nothing. During and after that moment there was something — our universe.

Though science is still unsure how or why this happened we do know what happened next. From 10^{-43} seconds after the Big Bang (the Planck Epoch) we know that the universe had a massive density (close to infinity), was expanding rapidly and all the fundamental forces acted as one. We know relatively little about this early stage of the universe's life and virtually nothing about what the universe was like before this.

By the time that the universe was 10^{-12} seconds old the four fundamental forces(electromagnetism, gravity and the strong and weak nuclear forces) have separated. The universe is filled with an extremely hot and dense quark-gluon plasma. The universe doesn't get cool enough for protons and neutrons to form until 1 second after the Big Bang. It is thought that neutrinos came into existance around this time as well. After about 10 seconds electrons start to appear in the universe.

When the universe is about 3 minutes old it is cool enough for the protons and neutrons to form into nuclei. This nuclear fusion lasts for about 17 minutes, producing a universe consisting of about 75% Hydrogen, 25% Helium with traces of a few heavier elements such as Lithium and Beryllium. Atoms still cannot form however, thanks to the vast numbers of high energy photons.

Atoms start to appear after the universe is about 377,000 years old but it isn't until the universe is 150 million years old that the first stars start to form. 8 billion years after the Big Bang the Milky Way galaxy was formed and a billion years later (4.6 billion years ago). Our own Solar System collapsed, forming the Sun. The dust and gas around the Sun would eventually form the planets, including our own.

Evidence for The Big Bang

Galaxies appear to be moving away from us at speeds proportional to their distance. The light from galaxies appears to be more red than it should be due to the Doppler Effect. The decreased frequency of the light tells us that the galaxies are moving away from us. This is called “Hubble’s Law”, named after Edwin Hubble (1889 – 1953) who discovered this phenomenon in 1929. This observation supports the expansion of the universe and suggests that the universe was once compacted.

If the universe was initially very, very hot as the Big Bang suggests, we should be able to find some remnant of this heat. In 1965, Arno Penzias and Robert Wilson discovered a 2.725 degree Kelvin (–270.425 °C) noise in their radiometer. After eliminating all other possibilities (including that pigeons had defecated inside the antenna) they realised they had found this remnant. The Cosmic Microwave Background radiation (CMB) pervades the observable universe and research continues into its properties. Penzias and Wilson shared in the 1978 Nobel Prize for Physics for their discovery.

The models of the Big Bang predict that the universe will have a certain ratio of elements (specifically Hydrogen to Helium, Deuterium to Hydrogen, Helium-3 to Hydrogen and Lithium-7 to Hydrogen). The measured ratios all fall well within the predicted values.

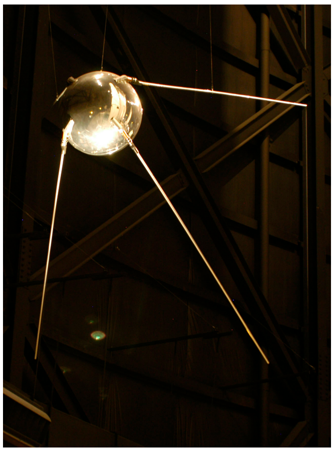
The Big Bang also influences how stars and galaxies form. Observations of the distribution of galaxies across the universe very closely match what would be expected from the Big Bang.

Stars produce heavy elements (such as Iron) in their cores and in supernovae explosions. When scientists discovered some gas clouds in 2011 they found that they contained nothing heavier than deuterium. This shows that there must have been a point in the universe when there were no stars or heavy elements.

SPACE EXPLORATION

Satellites

Since the first artificial satellite, the Soviet built *Sputnik 1*, launched in 1957 satellites have become so commonplace that nearly everyone uses one every day. Satellites can be built to do a wide variety of jobs:



- Communications (including the internet)
- Weather information capture
- Long term climate change monitoring
- Pollution monitoring (e.g. the Ozone layer)
- Navigation (GPS and GLONASS)
- Military observations — “spy satellites”
- Cartography (Google Earth and other similar satellite mapping tools)
- Entertainment — primarily satellite TV services (such as Sky or Freesat)
- Science — Hubble and James Webb space telescopes, the International Space Station and many others

Today there are over 3000 artificial satellites in orbit around Earth.

Geostationary Satellites

Geostaionary satellites are satellites that have been placed in a very particular orbit. They take 24 hours to orbit the Earth, meaning that they appear in a ‘fixed’ point in the sky when viewed from Earth. The orbital radius for an Earth geostationary orbit is (roughly) 36,000 km.

Space Technology

Satellites are not the only beneficial technology to arise from the exploration of space. To support manned missions into space — such as the first manned flight into space by Yuri Gagarin aboard *Vostok 1* in 1961 — many other technologies were developed and now see various applications back on the Earth's surface. For instance:

- Infrared thermometers were made possible by research into infrared telescopes
- Water purification systems developed for long term space missions are now used to help treat kidney disease
- Advances in robotic arms used in the Space Shuttle program were adapted to improve the functionality of prosthetic limbs
- Scratch resistant lenses were originally developed to prevent the visors on space suits becoming scratched by lunar dust and microscopic space debris. Enhanced UV protection in sunglasses was also originally developed for use in space suit visors
- The 'space blanket' was developed by NASA for the Apollo missions
- After helping to make tyres for rovers sent to Mars Goodyear developed a new type of radial tyre with a vastly improved tread life
- Extensive research into heat shielding and fire resistant materials (for re–entry) have been adapted into building and aircraft designs
- NASA's advanced fire fighting equipment is now standard issue
- Temper memory foam was developed as a crash protection material
- Enriched baby food is a result of fortifying astronaut's food for long missions
- Portable cordless vacuums were designed for the Apollo missions to allow astronauts to collect dust from drilling Moon rock
- Freeze dried food was also developed for the Apollo missions
- Development of solar cells to provide power to satellites is now used for electricity generation
- The NASA Structural Analysis Program (NASTRAN) software package is used the world over to model the stress, vibration and acoustic properties of all sorts of structures and vehicles

- Remotely operated ovens developed for the International Space Station are now commercially available
- A powdered non liquid lubricant — PS300 is now seeing widespread usage and was originally designed for moving parts of spacecraft exposed to vacuum
- MRI scanning has benefitted from advances in imaging software and technology developed for imaging the Moon and other celestial bodies

Velcro is commonly thought to have been invented by NASA for the Apollo missions — however NASA's use of the material merely popularised it — Velcro was in fact invented in 1948 and commercially available by the late 50's.

ORBITAL MECHANICS

Kepler's Third Law

One of the key concepts in space travel is Kepler's third law. This law describes how planets orbit the sun, but its concept can be applied to satellites, rockets and spacecraft. The law states that as the orbital radius increases so does the orbital period (the time taken to go around the sun). Thus planets close to the Sun will go around the Sun in a shorter time than planets further away from the Sun. The full relationship is shown below:

$$T^2 \propto r^3$$

This means that if you want to move from an orbit close to an body (like the Earth) to one further away you need to increase your orbital speed. You actually need to do this **twice** to move from a circular orbit to another circular orbit further away. This can be done in reverse, slow down when your are in orbit and your orbital radius will decrease.

Getting into Orbit

Getting a spacecraft into orbit is a challenging endeavour. One of the main issues that rockets are essentially controlled bombs, and a mistake in design or launch procedure can easily result in a total catastrophic failure of the rocket. To get from the surface Earth to a low Earth orbit you need to do two things:

1. Get high enough that your rocket will be above the Earth's atmosphere. If you do not manage this friction and drag will cause you to loose speed, and therefore orbital altitude. This means the rocket needs to get at least 160 km above the Earth's surface.

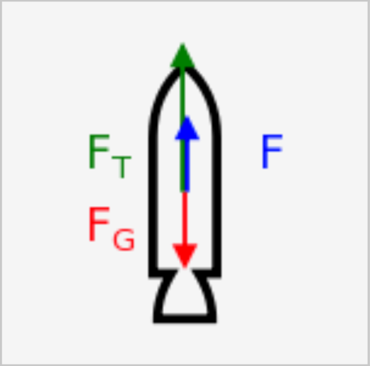
2. Go fast enough to 'miss' the Earth. We know from Newton's Cannon thought experiment that we need a significant amount of speed at right angles to the Earth's surface or our rocket will hit the Earth.

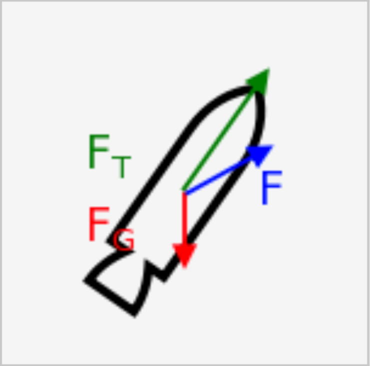
To achieve this you could simply send a rocket straight up to 160 km and then build orbital speed but this is very inefficient. Instead rocket scientists use a manoeuvre called a **gravity turn**.

Gravity Turns

Gravity turns work by fighting gravity the least amount possible — to gain enough altitude and horizontal speed for the desired orbit. Since the gravity of the local celestial body is always pulling on the craft, it will always accelerate most slowly when pointing directly away from that body and would accelerate faster in any other direction than straight up. If a launched craft followed a purely vertical flight path, then it would spend all of its thrust accelerating in the slowest direction, effectively spending the most fuel to gain the least speed without gaining any lateral speed necessary to orbit. In other words, a straight vertical launch is the least efficient launch. The gravity turn manoeuvre is accomplished as follows:

1. The manoeuvre begins as a vertical launch.
2. Once a certain altitude is reached, a slight turn is made, called the pitchover manoeuvre. By turning away from vertical slightly, gravity will pull the velocity vector of the craft down towards that direction and the craft has to tilt to follow it. The torque generated by the winglets placed on the bottom of the rocket will tilt the rocket to the right direction in the atmosphere, but out of atmosphere or without these winglets the operator of the craft has to control the tilt.
3. As this happens, the craft will gain more horizontal speed sooner since it is traveling in a vector that is not directly opposed to gravity.
4. The farther the vector tilts to the side, the percentage of thrust spent fighting gravity becomes smaller and the percentage of thrust spent gaining speed becomes larger. Since the majority of this vector change is done by gravity and not by the flight controls, another tiny amount of fuel is saved.
5. By the end of the gravity turn, no fuel is wasted fighting gravity. If the craft has gained enough lateral speed at an altitude above any mountains or atmosphere, it then begins a stable orbit.





Travelling in Space

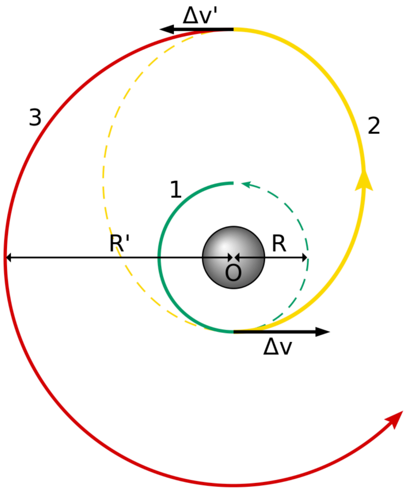
Once a spacecraft achieves orbit there are several challenges facing mission planners:

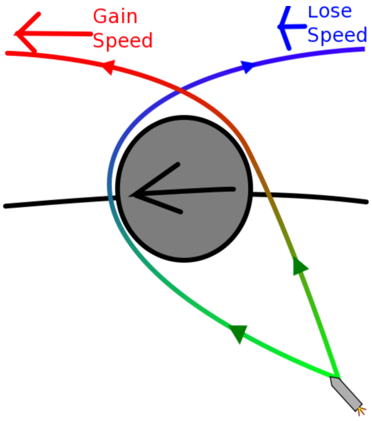
- Humans require food, water and oxygen. They also produce waste. Humans are vulnerable to exposure to radiation and the vacuum of space as well. This is why most space exploration is done by robots!
- All spacecraft require electricity. This can be done using solar panels, however missions that are planned for the outer solar system or beyond need power that does not depend on the Sun — typically a radiothermic generator (or RTG for short).
- Everything in space is really far apart. Missions need to bring all of their fuel and supplies with them.

Orbital Manoeuvres

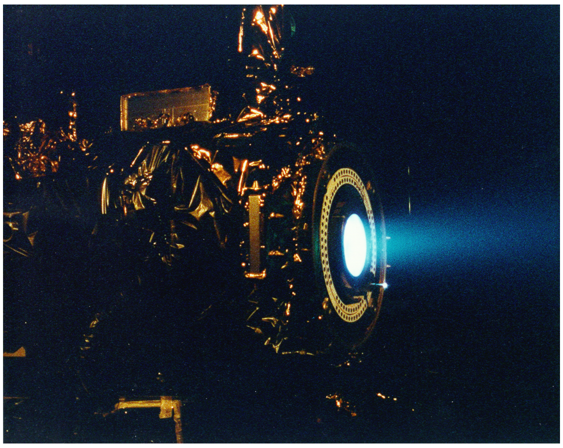
Moving around in space is not as simple as it is on Earth. Everything is moving and gravity is the dominant force. This means everything will be moving in circles and eclipses. There are many manoeuvre types but the basic ones are:

- Hohmann Transfer — by adding or removing orbital velocity this manoeuvre allows a craft to move from one circular orbit to another (see right).
- Docking — objects can be docked together in orbit. This is how the ISS was built. Docking requires a very precise Hohmann transfer from a phasing orbit to the target orbit. Docking is very counter intuitive, just going into the same orbit and then trying to ‘catch up’ will not work!
- Gravity Assist — rather than using fuel flight planners can use celestial object’s gravity to add or remove orbital velocity (see below). This is needed for any mission beyond Jupiter!





Ion Thrusters



These engines accelerate ions in a electric field to generate thrust rather than using combustion. There are a lot of different types of ion thruster (such as Hall effect thrusters) but they all have similar properties. Ion thrusters produce very little force compared to a chemical rocket but they can produce force for a long time and use very little mass of ‘fuel’ to do so. This means that they are convenient for sending small probes and spacecraft on long missions.

Landing

Landing spacecraft is also a very challenging part of space travel. Although it is fairly simple to reduce the orbital speed of a spacecraft so that it will hit a planet or moon, thanks to gravity, arriving in one piece is much harder.

Landing on a planet with an atmosphere is a double edged sword. Whilst the atmosphere provides a lot of drag, slowing the spacecraft down for free, this also tends to produce a lot of heat. If a spacecraft is not properly protected from the heat from passing through an atmosphere it can suffer a catastrophic failure. Spacecraft designed to land in an atmosphere therefor need heat shielding, but can use parachutes to slow to a safe speed, no fuel required.

Landing on a body without an atmosphere means that the spacecraft does not need any heat shielding. However nor can the spacecraft use parachutes to slow down. This means that the spacecraft must use fuel to slow down as it approaches the surface.

ASTROPHYSICS

You need to know:

	✓ ? ✘
How to explain orbital manoeuvres	
What evidence there is for the Big Bang	
The impact of space exploration	
The benefits of space exploration	
The challenges of space exploration	
What a light year is	
How to calculate the number of meters in a light year	
The age of the Universe	
How the Universe formed (The Big Bang)	
How different parts of the EM spectrum can be used to give information on astronomical objects and phenomena	
How to identify continuous and line spectra	
How to identify individual elements in the spectra of a star	