CHAPTER 06

Astrophysics

From the very earliest days, humans have looked into the sky and wondered what it's all about. Thousands of years ago priests in Babylon (now present-day Iraq) stood gazing into the night sky, not realising just how big it was. All sorts of theories, all sorts of myths and legends have grown out of attempts to understand how the universe works.

The big questions on everyone's mind concerned the solar system (Sun and planets) and the universe in general. The old **geocentric** view of our solar system said that the Sun went around the Earth (Greek *geo* from *gaia* = 'Earth' and *centro* = 'centre'). The modern view belongs to the Polish astronomer and priest Nicolas Koppernigk (**Copernicus**, as he was better known in Latin), who published his **heliocentric** or Sun-centred theory in 1540. Not that it was a new concept, for the Greek philosophers Heraclides and Aristarchus put forward a similar view in 300 BC, but after they were threatened with death they kept quiet.

The modern view of the entire universe came much later. The general opinion up until the 1920s suggested that the universe was infinite in size and in a steady unchanging 'static' state, made up of fixed stars that had always shone and would continue to shine forever. This view was well entrenched — even Einstein believed it! But in 1929 an astronomer made a finding that was to shake the foundations of this steady state model forever. His name was Edwin Hubble and his story follows later. The **steady-state** theory clung on until the 1970s when it died and was buried.

Like those before us, do you ever wonder about these:

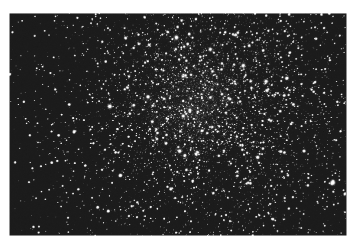
- What makes the Universe tick? How do the four forces work together?
- What is the Universe made of? We don't know what's out there.
- Was Einstein's anti-gravity theory really a great mistake or ahead of its time?
- Why do we live in a three-dimensional world; is it just a fluke?
- Can we travel in time and could we come back?
- Can black holes collapse to infinite density? How would you know?
- Where does consciousness come from; where does life come from?
- Are we alone?

6.1 THE NATURE OF THE UNIVERSE

Here's what *The Hitch Hiker's Guide to the Galaxy* has to say about the size of the universe:

> Space is big. Really big. You just won't believe how vastly hugely mindbogglingly big it is. I mean you may think it's a long way down the road to the chemist, but that's peanuts to space ... It's just so big that by comparison, bigness itself looks small.

Photo 6.1
The sky at night is almost black — but so what?



Astrophysicists agree. They can also answer some of the other questions above.

- The universe is between 10 and 15 billion years old, with most scientists agreeing on 13.4 billion years (a billion is 10^9).
- The remotest object from us is the quasar PC 1247+3406 at 13 200 million light years (1.25×10^{23} km). One light year is the distance light travels in one year or 9.46×10^{12} km. Hence, the edge of the universe is believed to be 15 000 million light years from us.

Some of the other questions will be answered later in this chapter. Some may never be answered but physicists will keep on trying. Many laws have been developed in this quest.

To appreciate the size of the universe, imagine the Earth is the size of a pinhead. The Sun would be the size of a grape about $1\frac{1}{2}$ metres away. Jupiter would be a pea 8 metres away, and Pluto a grain of dust 70 m in the distance. That's our solar system. Whew!

Now imagine the whole solar system shrunk down so that the Sun is now a pinhead. The Earth would orbit a few centimetres away, and Pluto about 60 cm away. On this scale our nearest star system — containing Proxima Centauri — is 3 km away and the size of a tiny sand grain. Other stars are also like sand grains and they reach out a distance equal to the distance from us to the moon. That's our galaxy. Big in anyone's language!

Lastly, imagine our galaxy shrunk down to the size of a dinner plate. Our nearest neighbouring galaxy is Andromeda — another dinner plate just a few metres away. The edge of the visible universe is many kilometres in every direction. But extending past that are more galaxies that we can't see because light has yet to reach us. Scientists believe that there are approximately 100 billion galaxies, with each galaxy containing between 100 and 200 billion star systems. That's our universe. To better understand the universe as it is today, you have to appreciate three fundamental observations: Olbers's paradox, Hubble's law, and the Cosmic Microwave Background Radiation, of which more later.

Astronomical distances

It takes light about 10 billion years to get from the edge of the observable universe to us. That's a huge distance and the units metre and kilometre seem inadequate. Astronomers use the unit megaparsec (Mpc) for distance. A parsec (pc) is a distance based on how far away a star would be if it appeared to change position by an angle of one second when viewed from the Earth at 6-month intervals. It sounds complex but astronomers assure us it is eminently suitable for their work. They also use light-years (ly) for distance: the distance light travels in a year. They use km s^{-1} for velocity or express it as a fraction of the speed of light (c).

1 light-year (ly)	9.47×10^{15} m
1 parsec (pc)	3.262 ly
	3.09×10^{16} m
1 megaparsec (Mpc)	1 million parsec
	3.262×10^{6} ly = 3.262 Mly
	3.09×10^{19} km
Speed of light (c)	3×10^{8} m s^{-1}
Temperature (T)	K = °C + 273

Example

The Hydra galaxy is 1960 million light-years (Mly) away and has a radial velocity of 60 500 km s^{-1}. Convert the distance to Mpc and the speed to units of c.

Solution

Mpc = Mly/3.262, hence Mpc = 1960/3.262 = 600 Mpc

$$\boldsymbol{v} \text{ in units of } c = \frac{\text{m s}^{-1}}{3 \times 10^{8}} = \frac{60\,500 \times 1000}{3 \times 10^{8}} = 0.20\ \text{c}$$

Olbers's paradox

In 1823, a German astronomer Heinrich Olbers stumbled on a contradiction that could not be easily explained. The following activity poses this contradiction.

SR Activity 6.1 THE NIGHT SKY

You don't really need to carry out this experiment — a *gedanken* (thinking) experiment will do!

Have a look at the sky at night. Is it black or white? Of course it is mostly black (see Photo 6.1), with about 4000 tiny stars twinkling away; but why doesn't the night sky look uniformly bright? If there were an infinite number of stars which had been glowing for an infinite time, no matter where you looked you'd see a star and so the night sky should be ablaze with light. But it's not!

We now know that the old-fashioned idea of an infinite, static universe is simply wrong. The universe has a finite age, and is not just three-dimensional as we perceive things on Earth. Because only 10 billion years have elapsed thus far, we can only observe stars out to a large, but strictly finite, distance of 10 billion light-years or so. This 'observable universe' contains a large but finite number of stars, about 1000 billion (10^{12}). These stars contribute to the observed brightness of the night sky, which glows very faintly.

SR Activity 6.2 LIGHT AT A DISTANCE

Here's a good experiment you could try using a computer-based laboratory such as the TI graphing calculator and the CBL. There are plenty of other ways to do it as well.

Set up equipment as shown in the Figure 6.1.

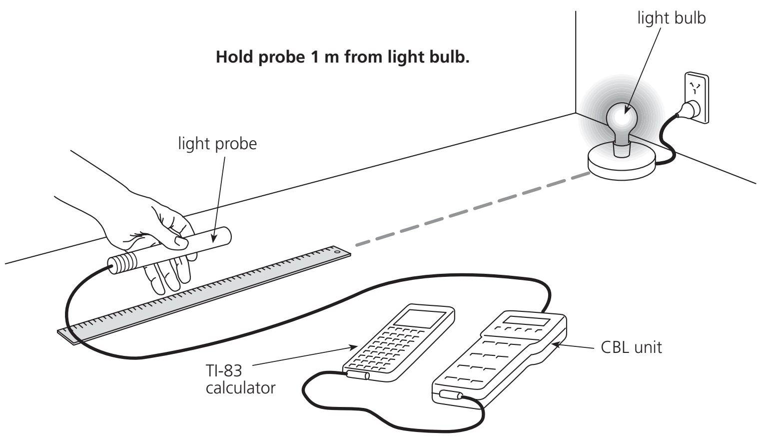


Figure 6.1
Apparatus to measure how light intensity varies with distance.

1. Mark off distances of 1 m and 2 m from the light socket. Then divide the distance into 10-centimetre intervals between the one-metre and two-metre marks.
2. While you are taking intensity readings during the activity, the light sensor should be pointed directly at the illuminated bulb with the end of the sensor held a certain distance from the bulb, as specified in the calculator program.
3. Darken the room, with the exception of the light source.
4. Collect light intensity data for different distances.
5. The data you collected will be modelled with a power relation of the form $y = ax^b$. First, you will need to find the values of A and B. The rest is up to you and your graphing calculator. Good luck.
6. According to scientific theory, the correct model for light intensity against distance is an inverse square relationship. This relation is expressed mathematically as: $y = a/x^2$ (inverse square law).

   If this equation is expressed in the form $y = ax^b$, what would be the value of b? Is this consistent with the models you found earlier?

Hubble's law

During the 1920s astronomers looked at starlight through spectrometers and noticed that the spectral lines of elements such as hydrogen and helium seemed to be occurring at longer wavelengths than normal (more on this in Chapter 29). If you look at the centre colour photos in this book you will see the normal spectra of many elements. The shift in wavelength was towards the red end of the spectra and so the term '**red shift**' was coined for this phenomenon. Physicists deduced that the shift in wavelength meant that the star was moving relative to the observer on Earth, similarly to the way the sound of an ambulance siren seems to change as it moves towards or away from you. This is called the **Doppler effect** and is discussed fully in Chapter 16 (section 16.3). Red shift is also treated comprehensively in Chapter 29.

In 1929, US astronomer Edwin Hubble used his 100 inch (2.5 m) diameter telescope to show that the universe is expanding. This was a monumental breakthrough. And if galaxies are moving away from each other, there must have been a time when they were all together. This was about 10 billion years ago — the time of the Big Bang — when the whole universe was the size of a dot (.).

Hubble combined his knowledge of galaxy red shifts with an estimate of the distance to these galaxies, and determined that galaxies more distant from us were moving away from us more rapidly than closer galaxies. This relationship has become known as **Hubble's law**.

Mathematically the law is written as $v = H_0 D$, where v is the **radial velocity** — that is, how fast the galaxy is moving directly away from us; D is the distance to the galaxy; and H_0 is the **Hubble constant**. The radial velocity is sometimes called the ***recession velocity*** (Latin *recessio* = 'recede' or 'withdraw').

SR Activity 6.3 HOW OLD IS THE UNIVERSE?

A plot of distance and radial velocity gives the Hubble constant, which is a measure of the rate of the expansion of the universe. It can be used to calculate the age of the universe.

1. Use the data in Table 6.1 to plot distance (Mpc) on the x-axis and radial velocity (km s^{-1}) on the y-axis. The table also shows the laboratory values for the three common spectral lines (e.g. H_α is 656.3 nm).

TABLE 6.1

GALACTIC CLUSTER	SPECTRAL LINES (nm)			RADIAL VELOCITY (km s^{-1})	DISTANCE (Mly)	DISTANCE (Mpc)
	Ca-K (393.4)	Ca-H (396.9)	$H\alpha$ (656.3)			
Virgo	394.9	397.0	656.3	1 140	38	12
Perseus	400.5	397.1	656.4	5 430	179	55
Hercules	407.0	397.4	656.5	10 400	360	110
Pegasus II	410.2	397.5	656.6	12 800	490	150
Ursa Major 1	413.1	397.9	656.8	15 000	750	230
Gemini	424.1	398.2	657.0	23 400	980	300
Ursa Major 2	446.4	398.9	657.3	40 400	1 500	460
Hydra	472.7	399.5	657.6	60 500	1 960	601
3C295	574.4	404.4	660.1	138 000	5 700	1 747

2 Calculate the slope of the line produced by these points (= Hubble constant, H_0). It should be given in (km/s)/Mpc. Most modern estimates put it somewhere between 70 (km/s)/Mpc and 75 (km/s)/Mpc. Show your calculations.

3 We can use this to determine the age of the universe. At the instant of the Big Bang, all the matter in the universe was together. It has had all of the intervening time to fly apart to its present positions. A galaxy that is more distant from us is so because we have been separating from it at a faster rate in that time. (Remember, Hubble's law states that the farther a galaxy is from us, the more rapidly it is receding from us.) Choose a point on the line in your graph that you used to find Hubble's constant. This point represents the distance and recession velocity of a galaxy following Hubble's law. The only problem is that Mpc and km are different units, and seconds aren't terribly good units for measuring the age of the universe. Convert Mpc to km (1 Mpc = 3.09×10^{19} km).

Use the relationship $\boldsymbol{v} = d/t$ or $t = d/\boldsymbol{v}$ to calculate the time taken for the galaxy to cover the distance at the given velocity. Convert seconds to years. It should be about 10 billion years. Alternatively, take the reciprocal of the Hubble constant and multiply by 3.09×10^{19} km to get the age in seconds. Convert to years.

Example

Using the data for the cluster Virgo, calculate **(a)** the Hubble constant; **(b)** the age of the universe.

Solution

(a) $H_0 = \dfrac{\boldsymbol{v}}{D} = \dfrac{23\,400 \text{ km/s}}{300 \text{ Mpc}} = 78 \text{ km/s/Mpc}$

(b) $300 \text{ Mpc} = 300 \times 3.09 \times 10^{19} = 9.27 \times 10^{21} \text{ km}$

$$t = \frac{9.27 \times 10^{21} \text{ km}}{23\,400 \text{ km/s}} = 3.96 \times 10^{17} \text{ s} = 1.256 \times 10^{10} \text{ years} = 12.56 \text{ billion years.}$$

Alternatively: $t = \dfrac{1}{H_0} \times 3.09 \times 10^{19} \text{ km} = 3.96 \times 10^{17} \text{ s} = 1.256 \times 10^{10}$ years.

Some people say that the Earth was created 6000 to 8000 years ago, because that's what they get when they add up all of the 'begats' in the genealogy of the Old Testament. However, many people agree that the 'days' of creation are not literal 24-hour days but could be translated from the Hebrew as billion-year 'eras'. You decide — but be aware that scientists reject anything less that about 10 billion years for the age of the universe and $4\frac{1}{2}$ billion years for the age of the Earth.

Cosmic microwave background radiation

The entire universe exists in a sea of background radiation. During the early days of creation, a great deal of radiation was present. As the universe continues to expand and cool, this radiation should still be present, although at a stretched wavelength due to the expansion. The presence of this 'microwave' radiation is unmistakable evidence of the Big Bang fireball of creation. In 1955, astronomer George Gamow predicted background radiation of 5 K, which was subsequently confirmed by Arno Penzias and Robert Wilson at Bell Laboratories in New Jersey USA in 1965. The Cosmic Background Explorer (COBE) satellite measured the radiation more accurately in 1989 — to a wavelength of 1 mm, equating to a temperature of 2.3 K. (See Photo 6.5, page 151.)

ACTIVITY 6.4 THE TEMPERATURE OF DEEP SPACE

SR

In the early 1900s, German scientist Max Planck found that the peak wavelength of black-body radiation was related to temperature by the formula: $\lambda = 0.2\ hc/kT$ where h = Planck's constant = 6.63×10^{-34} Js, k = Boltzmann's constant = 1.38×10^{-23} J K^{-1} (see Section 11.4), c = speed of light = 3×10^{8} m s^{-1}, and T = Kelvin temperature.

Example

Calculate the peak wavelength of light emitted by the brightest visible star in the sky (Sirius) with a temperature of 9000 K.

Solution

$$\lambda = \frac{0.2 \times h \times c}{k \times T} = \frac{0.2 \times 6.63 \times 10^{-34} \times 3 \times 10^{8}}{1.38 \times 10^{-23} \times 9000} = 3.20 \times 10^{-7}\text{ m} = 320\text{ nm}$$

(a) Use the formula to confirm that the background temperature of outer space is 2.73 K, given that the Cosmic Background Explorer (COBE) satellite measured the cosmic background radiation to have a wavelength of 1 mm. This provided dramatic evidence in 1989 to support the prediction of the Big Bang theory.

(b) Show, by dimensional analysis (cancellation), that the unit for the right-hand side of the equation is metres.

(c) A simplification of Planck's law is known as Wein's law. Wein expressed it as $\lambda = 0.0029/T$. Show that it is the same as the original formula.

(d) In 1992, COBE detected *fluctuations* in the background radiation, and this sent tingles of excitement down astronomers' backs. Why was this, and where does the 'recombination' of 300 000 years ago fit in? Off to the library.

Questions

1. The Leo cluster is 251 Mpc away. Prove that this is equal to a distance of 7.8×10^{24} m.
2. Hercules has a radial velocity of $0.035c$. What is this in km/s?
3. The Bootes cluster is 457 Mpc away from us. Based on an average Hubble constant of 75 km/s/Mpc, calculate the recession speed of Bootes.
4. If the Hubble constant was found to be 100 km/s/Mpc, what would the age of the universe be?
5. Calculate the wavelength of maximum intensity of the red star Proxima Centauri, which is 4.3 times the diameter of the Sun and has a temperature of 2870 K.
6. The Stefan–Boltzmann law can be used to calculate the power output (luminosity, L) of a star based on its radius (R) and temperature (T): $L = (7.125 \times 10^{-7})\ R^2\ T^4$, where L is in watts, R in metres and T in kelvins.
   (a) Our star, the Sun, has a temperature of 5775 K and a radius of 1.39×10^{6} km. Calculate its luminosity.
   (b) The star Rigel has a temperature three times that of the Sun, and a luminosity 64 000 times that of the Sun (one very bright star). If the Sun's temperature is 5775 K, calculate Rigel's radius.
7. Some stars are red and some are blue. Which are hotter? Why?
8. Comment critically: 'A star with a temperature of 0°C will not give off any radiation.'
9. Does a star at 6000 K emit twice as much radiation as it does when it drops to 3000 K? Explain.

6.2 HISTORY OF THE UNIVERSE

'This is the way the world ends
Not with a bang but a whimper' — T. S. Eliot

The best picture we have at present suggests that the past, present and future of the universe can be arranged into the five 'ages' proposed by creative American astrophysicists Fred Adams and Greg Laughlin. It starts with the Big Bang and ends up expanding forever 'like a whimper', as poet T. S. Eliot put it. Like all scientific theories, it could be wrong, but it does explain why the universe is like it is today. Many people opposed to these theories say 'You can't re-create the Big Bang so how can it be scientific?' However, the theory is consistent with all known laws and principles of physics, and many parts of the theory can be tested experimentally. It also offers testable predictions about what we should find as time goes by. All that makes it scientific.

Admittedly, we can't tell what is happening beyond a certain distance (>10 billion light-years away) because light has not had time to reach us. We call this the 'visible horizon'. As we get older this horizon will get further away. Maybe it's where the wild things are.

The Primordial Era: t = 0 to 3 minutes

The very beginning

About 13 billion years ago, the universe was just a point in space with infinite density and temperature. This was the beginning of time ($t = 0$) as we know it. We have no understanding yet of what the universe was like inside this point. The four fundamental forces that we know today (gravity, electromagnetic, weak and strong nuclear) were rolled up into one 'super force' known as the Grand Unified Theory (GUT) force.

The Big Bang and inflation

An enormous explosion ('the Big Bang') occurred at $t = 0$, and after 10^{-43} s had elapsed the universe began to expand and cool at a fantastic rate. Adjacent points in space rushed away from each other at speeds greater than that of light, and the small dot (.) that was the universe inflated about 10^{30} times — all within a period of about 10^{-35} s (see Figure 6.2).

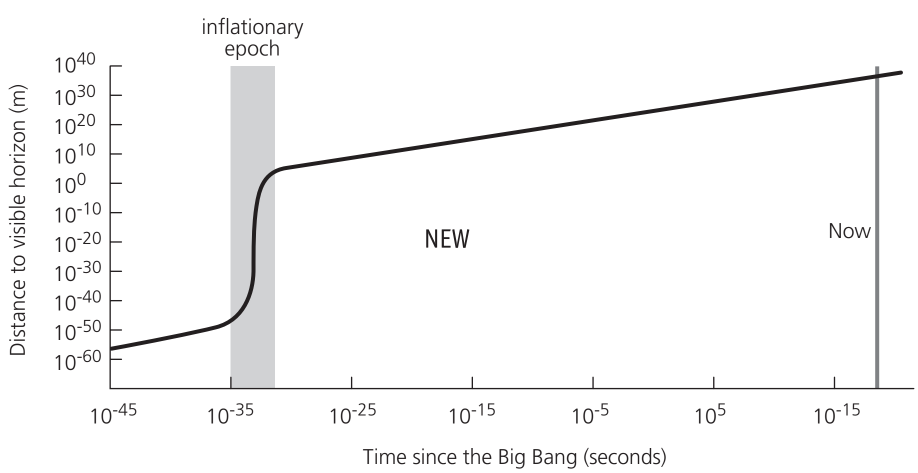


Figure 6.2
The expansion of the universe throughout time. Note the exponential scale (powers of 10) on the *x*-axis.

In this very short time the temperature fell from 10^{32} K to 10^{20} K. Most of the energy of the universe at the time of **inflation** was in the form of electromagnetic radiation because it was like a blast furnace — too hot for atoms and molecules. It was too hot for even protons and neutrons. During this period the GUT forces began to decouple (separate out) into the four fundamental forces (Table 6.2). Chapter 29 deals with these forces in more detail.

Table 6.2

FUNDAMENTAL FORCE	TIME OF SEPARATION (S)	STRENGTH	TEMPERATURE (K)	PARTICLE THAT CARRIES THE FORCE
Gravitation	10^{-43}	10^{-38}	10^{32}	graviton
Strong nuclear	10^{-35}	10^{0}	10^{27}	gluon
Weak nuclear	10^{-12}	10^{-13}	10^{15}	W and Z
Electromagnetic	10^{-12}	10^{-2}	10^{15}	photon

Figure 6.3 shows the decoupling graphically.

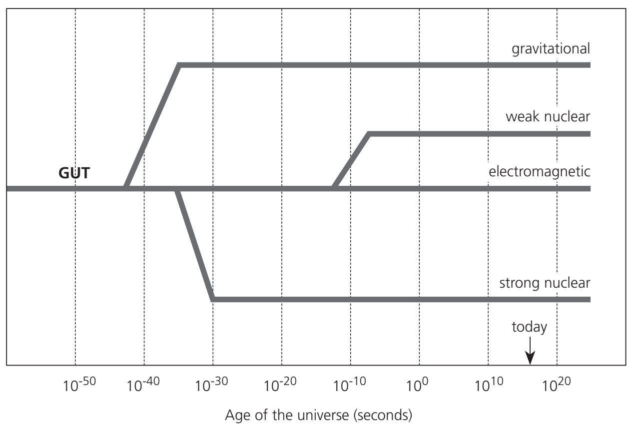


Figure 6.3
Decoupling of the GUT forces into the four forces we know today.

Baryogenesis

The universe was now a vast sea of radiation with a small mixture of **quarks** and other particles called **gluons** which acted between these quarks. This froth of quarks and gluons is known as the Quark Gluon Plasma (QGP). Quarks consist of both ordinary matter and antimatter, with a slight excess of the former. For every 30 million antimatter quarks there were 30 million and one quarks made of matter. As the universe cooled, the matter and antimatter quarks annihilated each other, leaving the excess fraction of matter quarks to survive. This process is called **baryogenesis** (Greek *baros* = 'weight', *genesis* = 'origin'); the general name given to particles that form matter is *baryons*.

Physicists have speculated that in other universes there must be an equivalent excess of antiquarks so that the total amount of matter and antimatter are equal, as stipulated by the conservation law. During this period any quarks that came together were unable to combine to form larger particles (protons and neutrons) as the high-energy gamma rays blasted them apart. By the time the universe was 10^{-12} s old the temperature was down to 10^{15} K and the GUT forces had completely decoupled. It was now sufficiently cool for all quarks to condense (in groups of three) to form **hadrons** (such as protons and neutrons). Because there was an excess of quarks over antiquarks, more protons and neutrons formed than antiprotons and antineutrons. These particles and antiparticles continued to annihilate each other, but as the temperature dropped fewer and fewer particles and their antiparticles were created, which just left an excess of protons and neutrons.

These basic building blocks of matter, synthesised in the first microsecond of the universe's history, live not only to the present time, some ten billion years later, but will endure for another 10^{32} years — give or take a few years. You are made up of quarks from the Big Bang.

PHYSICS FACT

During 'inflation' the universe expanded at a rate faster than the speed of light. How can this be, if nothing can go faster than light? The answer is that it is space that is expanding without any objects moving. In the Big Bang model the distance between galaxies increases, but the galaxies don't move. Since nothing is moving, there is no violation of the restriction that nothing can move faster than light. Hence, it is quite possible that the distance between two objects is so great that the distance between them expands faster than the speed of light.

Nucleosynthesis

The next major achievement of the early universe was the production of small compound nuclei. About one second after the Big Bang, when the temperature had dropped to 10 billion kelvin, the universe was cool enough to allow the fusing of protons and neutrons to synthesise (Greek *syn* = 'together', *tithenai* = 'to place') light atomic nuclei, mainly helium (${}^{4}_{2}\text{He}$) with some traces of deuterium (${}^{2}_{1}\text{H}$), and lithium (${}^{7}_{3}\text{Li}$). This **nucleosynthesis** continued for about three minutes until the temperature of the ever-expanding universe dropped to a mere 1 billion kelvin. Nuclear reactions abruptly stopped and nucleosynthesis thus came to an end. Although huge amounts of helium and the other light nuclei were produced, about 75% of the observable mass of the universe remained as hydrogen nuclei (protons, ${}^{1}_{1}\text{H}$). This was a busy three minutes.

The Stelliferous Era: $t = 3$ minutes to 10^{14} years

Stelliferous comes from the Latin and means 'star-producing' (*stella* = 'star', *fero* = 'bring forth' or 'produce'). We are in the middle of this era right now. Our Sun ignited some 4.5 billion years ago (4.5×10^9 years) and has enough hydrogen to last another 6 billion years. We are all children of the stars because ten billion years ago every atom in our bodies was once near the centre of a star.

Once the explosive first three minutes ended, the universe settled into a much calmer phase. For the next 300 000 years, the universe consisted of a sea of hydrogen and helium nuclei, photons, free electrons and the mysterious **dark matter**. The universe kept expanding and cooling but the intense radiation caused the disintegration of any atoms. After further expansion and cooling, this period eventually ended when the sea of photons was not energetic enough to keep electrons from joining with nuclei to form atoms.

The universe had cooled down to about 3000 K by now. Atoms — mostly hydrogen and some helium — began forming. The photons no longer had much to do, so they travelled unhindered through space. It was as if the universe became transparent to photons. Gravity started pulling the hydrogen and helium together and this collapse produced the vast aggregations of gas and other matter we now call galaxies. Scattered within these galaxies were sub-condensations of gas. As this gas continued to condense inwards, magnetic fields provided a pressure acting outwards which slowed the collapse. Enormous heat was generated as gravitational energy was transferred to heat energy and this caused them to glow with infrared radiation. As the swirling and rotating gases collapsed, the speed of rotation increased (we see this principle stated in the law of conservation of angular momentum; that is, as the radius decreases, the speed increases). Jets of material blew outwards and stopped any more material condensing on the newly created star (the 'protostar') and this outflow separated the young solar system from its parental core.

These protostars give off huge amount of heat, but not all ignite to become true visible stars. Depending on their mass, they can go one of several ways: The low-mass protostars (<0.08 solar masses) will fail to ignite and just glow dull red. These 'failed' stars are called 'brown dwarfs' and lock up enormous amounts of hydrogen for billions of years. Ones that are more than 8% of the mass of our Sun (>0.08 solar masses) will sustain nuclear reactions. Low-mass stars (0.08–0.5 solar masses) fuse hydrogen into helium but at a fairly slow rate. These are called 'red dwarfs' and will last for an extraordinarily long time — possibly a trillion (10^{12}) years.

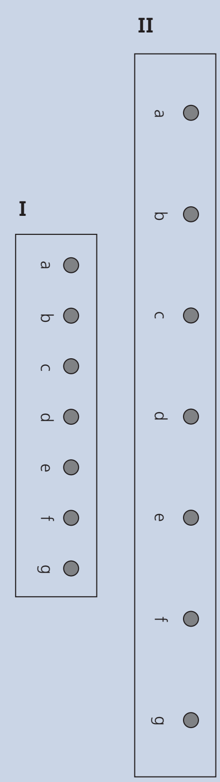
Stars with masses in the range from 0.5 to 8 solar masses will burn like our Sun. The core temperature of our Sun is currently about 16 million K, but when the hydrogen becomes depleted in its centre the core will lack an energy source and will cool. There will not be enough heat to support its overlying bulk. The core will shrink to become a white dwarf but the outer layers will evaporate as a massive solar wind of energetic particles — and become a red giant. The central core will continue to shrink and heat up, and when it reaches

NOVEL CHALLENGE

The figure below shows the relative positions of some ink dots on the surface of a balloon as it is inflated. If you keep dot 'd' directly in front of you, all the other dots appear to be moving away from 'd' as the balloon gets bigger. Imagine diagram II shows the positions 1 second after diagram I.

A Calculate the speed of dots 'e', 'f' and 'g' by measuring the distances with a ruler. Plot a graph of speed (y-axis) versus distance from 'd'. Relate this graph to Hubble's law.

B Imagine we are object 'd' in the Milky Way galaxy and object 'g' is the Hydra galaxy. If Hydra is moving at a speed of 60 500 km s^{-1}, calculate the time elapsed between diagrams I and II.



PHYSICS FACT

The shortest 'day' in our solar system has just been discovered by NASA. The asteroid 1998KY26 (about 30 m across) spins at 1 revolution every 10.7 second. That means its day is 0.09 seconds long. KY26 consists of 4 tonnes of water which must be frozen otherwise it would fly apart.

100 million K a new series of nuclear reactions will occur. Helium will fuse into carbon and release more energy. The core of the giant will become an enormous helium bomb and for a time will produce more energy than all the stars in the universe combined. The resulting helium flash will be followed by a quiet burning for about 100 million years.

Stars that are superheavy (>8 solar masses) will burn up their central stores of hydrogen in about 10 million years (recall that lighter ones like our Sun will last for about 10 *billion* years from ignition). The helium quickly fuses into carbon and the star begins to collapse under its own weight. The core reaches 100 billion K and huge numbers of neutrinos are produced, leaking away energy and allowing the collapse to accelerate. Temperatures rise and carbon fuses into magnesium, and by a complex maze of nuclear reactions neon, oxygen, silicon, sulfur and iron form. Once the chain reaches iron no further fusion is possible as iron is so stable. A star with an iron core is doomed as it cannot squeeze any more energy out by fusion. The star cannot support itself any longer. In a single second the star collapses, compressing the central regions to a density of 10^{14} g cm^{-3} (and that is dense — water is only 1 g cm^{-3}). If Earth were this dense it would be about 400 m in diameter. Electrons and protons are squashed up to form neutrons and the whole star resembles one big nucleus. A shock wave ensues and the outer layers are fused into heavy elements such as gold, lead and uranium and blown away, leaving a dense core of neutrons behind. This explosion is a **supernova** and the dense core of neutrons remaining becomes a **neutron star**. For some very massive stars (8–50 solar masses), the neutron cores cannot support their own weight and collapse to become a **black hole**. Black holes are strange beasts, with gravitational fields so strong that light itself cannot escape. They are so fascinating that we have devoted a whole section to them later on. (See section 6.9.) The matter produced by the supernova is thrown back into the interstellar medium, where it eventually condenses to form stars like our own Sun and its planets like our Earth. The heavy elements on Earth (e.g. uranium) originated in a supernova.

Superheavy stars of more than 100 solar masses are likely to blow themselves apart instantly so that nothing is left.

Many stars will continue to be born, but after a few trillion years even the hardiest of stars will have died and returned much of their mass back to the interstellar medium. The universe will all of a sudden be a dark place.

The Degenerate Era: $t = 10^{15}$ to 10^{39} years

At the beginning of the Degenerate Era, a thousand trillion years will have elapsed since the Big Bang. The universe will be a pretty boring place with just the remnants of the Stelliferous Era scattered all over the place. There will be brown, red and white dwarfs, neutron stars and black holes. Galaxies will drift around but the mutual force of attraction will cause them to combine and form mega-galaxies. Our Milky Way will combine with the Andromeda galaxy to form a sort of thick-shake. However, stellar collisions will be rare because space is so big (remember?). About once every billion years two stars will collide, and this will be a big event in the Degenerate Era. The most boring will be two brown dwarfs in collision. They won't light up but will just form some planets which are likely to have the conditions necessary to support life. White dwarf collisions will be more spectacular. Their combined mass will enable them to ignite and burn for a million years before depleting their nuclear fuel and turning off. Black holes will grow larger and more massive throughout this era as they capture stars and gas that have come too close.

Proton decay

Up until the 1980s it was thought that protons were infinitely stable. Now we know that protons do not last forever; in fact they last for only about 10^{37} years. In the final stages of the Degenerate Era protons will start to decay. In a white dwarf for instance, the protons decay into pions and positrons; the pions decay into high-energy gamma rays and the positrons pair up with stray electrons to form more gamma rays. The net result is that the white dwarf slowly evaporates and finally nothing is left. Kaput! Neutron stars suffer the same fate. Neutrons decay into protons, electrons and antineutrinos, which all end up as gamma radiation. By the end of the era, 10^{40} years will have passed since the Big Bang. All that will remain will be a vast sea of radiation, mostly photons and neutrinos with a smaller admixture of electrons and positrons. And Black Holes — millions of big Black Holes.

The Black Hole Era: $t = 10^{40}$ to 10^{100} years

Now the black holes reign supreme. The universe has reached a volume of 10^{100} cubic metres and is inhabited by 10^{46} black holes in an otherwise almost empty universe (see Figure 6.4). These holes grew larger and larger during the previous two eras — sweeping up everything in sight. But black holes radiate energy, and slowly — very slowly — evaporate. Their last moments are dramatic. After shedding 95% of their mass through evaporation, their surface will be as hot as our Sun. During the last second the black hole explodes, giving off 10^{22} J in gamma-ray energy and a blast of electrons, positrons, protons, antiprotons and other exotic particles such as the dark matter WIMPS. The protons and antiprotons annihilate themselves immediately to produce more gamma photons. By 10^{100} years the black holes have all evaporated and a final enveloping night moves in. This is getting creepy!

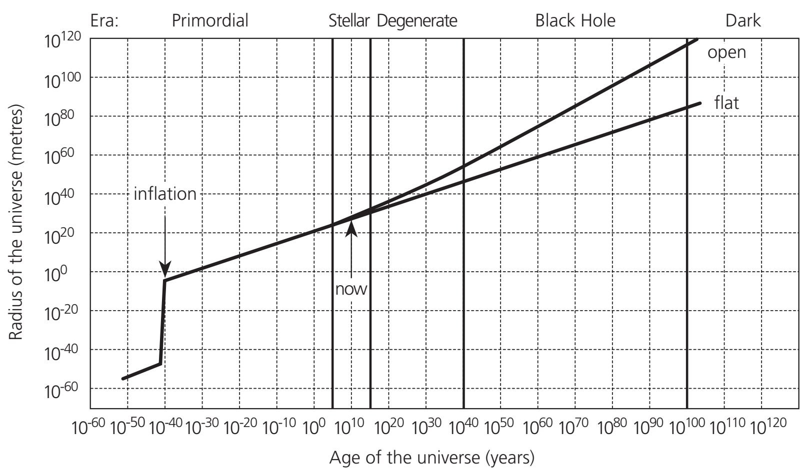


Figure 6.4
Changes to the radius of the observed universe over the five eras. Note the exponential scales.

The Dark Era: $t = 10^{100}$ years to eternity

In this cold and distant future, activity in the universe has almost stopped. Energy levels are low and the expanses of time and space are almost beyond belief. Much depends on whether the universe will continue to expand at the same rate (an 'open' universe — the most favoured model) or slow down to an almost negligible expansion (a 'flat' universe). The third alternative — the 'closed' universe — now seems most unlikely, as there appears to be insufficient mass in the universe to stop expansion and begin a contraction phase. (See Figure 6.5.) This possibility has the universe expanding to a maximum volume in about 20 billion years and then contracting back to a point in another 20 billion years — the Big Crunch. Not much is mentioned of the Big Crunch these days. If it does happen, there is speculation that another Big Bang could ensue and another cycle begins. Physicists say that if this happens, the cycles will get bigger and bigger as each one occurs. Some say that maybe there was a cycle before the present one. They say that if there was there could have been up to 100 previous cycles (but no more). They are adamant that there was a definite start to the cycles if they occurred – that is, the universe hasn't been going for an infinite time.

At the start of the Dark Era the volume of the universe will be 10^{182} m^3 if the 'flat' scenario happens or 10^{272} m^3 if it is 'open'. Either way, space will be occupied by about one electron and positron in every 10^{192} m^3 or so. With no protons left, electrons cannot form

NOVEL CHALLENGE

A marathon runner starts off at the same time as a radar signal leaves the earth for Jupiter. He stops when the echo is received back on Earth. How many kilometres does he run?

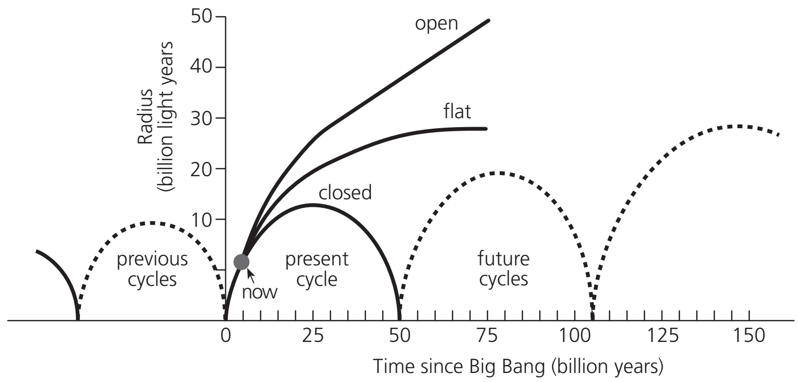


Figure 6.5
Three models of the future of the universe. The 'open' model is the current favourite.

normal atoms. Instead they form **positronium** atoms in which the electron and positron spiral around each other in orbits trillions of light-years across. By the time 10^{145} years have passed since the Big Bang, even these atoms will have decayed. The temperature is now exceedingly low — just billionths of a degree above absolute zero. The photons of light that inhabit the universe are so lacking in energy that their wavelength is 10^{41} light-years — bigger than the observable universe today. The universe has run down and now heads for heat death but never quite dies; it hangs on in eternal death throes. But wait — bizarre things could happen. Physicists say that processes could happen where new 'child universes' are created spontaneously within our universe and then undergo inflation just like ours did at the Big Bang. Who knows?

Questions

10 By what factor did the universe expand in the 'inflation' phase?
11 What was the cause of the universe cooling?
12 Comment critically: 'The Big Crunch is the favoured theory of the future of the universe.'
13 Discuss the longevity of protons.
14 Discuss critically: 'All stars containing hydrogen will undergo fusion at a rate dependent on their mass.'
15 Inward and outward forces maintain a star in a state of equilibrium. Explain what happens to the forces as a star turns into **(a)** a brown dwarf; **(b)** a white dwarf; **(c)** a neutron star; **(d)** a black hole.

Let's now look at our own Solar System in more detail.

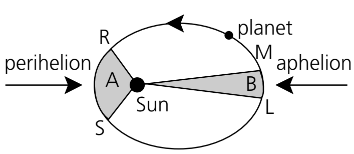
KEPLER'S LAWS 6.3

German astronomer **Johannes Kepler** (1571–1630) spent years working on data provided by Tycho Brahe, his predecessor as Imperial Mathematician to Emperor Rudolph in Prague. However, in 1614, Galileo described Kepler's writing as 'so obscure that apparently the author did not know what he was talking about'. In 1618 Kepler published the first two of his three laws and was hailed as a hero by those who wanted to do away with the old geocentric (Earth-centred) universe of Aristotle and Ptolemy. Kepler's laws were these:

First law: the law of orbits All planets move in elliptical paths, the Sun being at one focus.

Second law: the law of areas The speed of a planet along this path is not uniform, but varies with its distance from the Sun in such a way that a line drawn from the planet to the Sun would sweep out equal areas in equal times; or, in other words, the area swept out in a given time by the radius vector is always constant (Figure 6.6).

Figure 6.6
Planets move in elliptical orbits, with varying speeds around the Sun. The planet takes the same time to move from L to M as it does from R to S. The shaded areas A and B are equal (Kepler's law).



Both these laws were in contradiction to conventional wisdom of the time. The view of the universe being taught in universities in the 1500s and early 1600s was based on the ideas of Greek philosophers Pythagoras, Aristotle and Plato, who declared that the Earth was at the centre of the universe and the path of planets must be circular and the speed uniform. The second-century Arab astronomer Ptolemy produced a comprehensive theory of planetary motion based on these ideas (the Ptolemaic theory), which held sway for 1400 years. In fact, all Christian astronomers held this view, using a literal interpretation of the Bible for support ('Joshua commanded the Sun to stand still, not the Earth'). As a result, the Catholic Church in 1616 put Copernicus's works on the forbidden list. Galileo and Tycho refused to accept elliptical motion, preferring to believe in Copernicus's Sun-centred model but with uniform circular orbits. Copernicus too said that his 'mind shuddered' at the idea of elliptical orbits. Kepler had earlier agreed, saying that non-circular orbits were 'a cartful of dung', but was eventually won over by the beauty and simplicity of elliptical orbits. Kepler was truly the first astrophysicist.

Third law: the harmonic law or the law of periods In 1619, a more remarkable hypothesis followed. Galileo couldn't cope with this one either. The law stated:

For orbiting satellites or planets of any system, the ratio of the radius of orbit cubed, r^3, to period squared, T^2, is constant for all satellites of that system. (Table 6.3)

$$\frac{r^3}{T^2} = \text{constant, or } \frac{r_a^{\,3}}{T_a^{\,2}} = \frac{r_b^{\,3}}{T_b^{\,2}}$$

The table below shows the r^3/T^2 values for the Earth and its neighbouring planets. Note how constant the ratio is (average = 3.36×10^{18} m^3/s^2).

Table 6.3

PLANET	AVERAGE RADIUS OF ORBIT (m)	PERIOD OF REVOLUTION (s)	r^3/T^2 (m^3/s^2)
Mercury	5.97×10^{10}	7.60×10^6	3.68×10^{18}
Venus	1.08×10^{11}	1.94×10^7	3.35×10^{18}
Earth	1.49×10^{11}	3.16×10^7	3.31×10^{18}
Mars	2.28×10^{11}	5.94×10^7	3.35×10^{18}
Jupiter	7.78×10^{11}	3.74×10^8	3.36×10^{18}
Saturn	1.43×10^{12}	9.30×10^8	3.38×10^{18}

Example 1

Triton and Nereid are the two moons of Neptune. Triton is 353 000 km from Neptune and has a period of 5.87 Earth days. Nereid is 5 560 000 km from Neptune and its period is 359.9 Earth days. Find out if these data are consistent with Kepler's third law. Neptune has a radius of 24 750 km.

Solution

For Triton: $$\frac{r^3}{T^2} = \frac{(353\ 000 + 24\ 750)^3}{5.87^2} = 1.56 \times 10^{15}.$$

For Nereid: $$\frac{r^3}{T^2} = \frac{(5\ 560\ 000 + 24\ 750)^3}{359.9^2} = 1.34 \times 10^{15}.$$

Conclusion: values are close — Kepler's Law confirmed.

NOVEL CHALLENGE

Another new planet outside our solar system has recently been discovered. It lies within the Oort Cloud with an orbital radius of 0.4 ly. It has a mass 1.5 to 6 times of Jupiter and a period of 6 million years. How does it r^3/T^2 ratio compare to that of our solar system?

Example 2

Consider a satellite launched from Earth to have a geosynchronous orbit (period = 1 day) around the Earth. Knowing that the natural satellite of Earth (the Moon) has a period of 28 days and an orbiting radius of 3.8×10^8 m, calculate the desired radius for the artificial satellite so that it has a period of 1 day.

Solution

$$\frac{r_m^3}{T_m^2} = \frac{r_s^3}{T_s^2}$$

$$r_s^3 = \frac{r_m^3 \times T_s^2}{T_m^2} = \frac{(3.8 \times 10^8)^3 \times 1^2}{28^2} = 7.0 \times 10^{22}$$

$$r_s = 4.1 \times 10^7 \text{ m } (41\,000 \text{ km})$$

Questions

16 The average radius of the orbit of Uranus is 2.87×10^{12} m. Use the average value for r^3/T^2 from Table 6.3 to calculate the period of Uranus in **(a)** seconds; **(b)** years.

17 Neptune takes 164.8 y to orbit the Sun. Use the average value of r^3/T^2 from Table 6.3 to find the average radius of its orbit.

18 It was once thought that the planet Vulcan existed between Mercury and the Sun. What would its period have been if it was at a mean radius of 40 million km from the Sun?

NEI Activity 6.5 FACTS AND FIGURES

Use a dictionary or encyclopaedia to answer the following:

1. **Planet** means 'wanderer' but what exactly was meant by wandering and what is **retrograde** motion?
2. **Galaxy** comes from the Greek *galas* meaning 'milk'. What has our galaxy got to do with milk?
3. What is the difference between a **pulsar** and a **quasar**? Name one of each and state their distance from Earth.
4. Locate r and T values for Pluto and determine its r^3/T^2 value as in Table 6.3.

NEI Activity 6.6 COMPETING THEORIES

Select one of the following topics for library research and write a short (one page) response.

- The Ptolemaic system used circular motion but still allowed planets to move in non-circular orbits. Show how **Ptolemy** used 'epicycles' to contrive his system.
- Why was **Copernicus** so reluctant to publish his theory but finally relented on his deathbed? What was he scared of?
- Why was the Church so annoyed with **Galileo**? Describe how he was treated. Was he better off than fellow astronomer Bruno in the hands of the Inquisition?

6.4 NEWTON'S LAW OF GRAVITATION

Kepler had shown that the Sun was the centre of our solar system but the question remained: what was the nature of the force that the Sun exerted? Kepler believed that the Sun moved the planets by sending out rays like wheel-spokes, which carried the planets around.

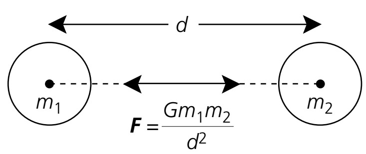
In 1666, **Newton** united the ideas of Copernicus and Kepler with the laws of falling bodies, developed by Galileo. Newton provided a new worldview, based on a new physics, uniting heaven and Earth in one mathematical structure. A revolution in thought had begun.

Newton used the word **gravity** to describe the force between the Sun and the planets. It came from the Latin *gravitas*, meaning 'weight'. In his most famous work, *Philosophiae Naturalis Principia Mathematica*, published in Latin in 1687, he wrote: 'I deduced that the forces which keep the planets in their orbs must vary reciprocally as the squares of their distances from the centres about which they revolve and in direct proportion to their masses'. In the form of an equation, this becomes:

$$\mathbf{F}_g = \frac{Gm_1m_2}{d^2}$$

where $\mathbf{F}_g$ is the force of gravitational attraction, m_1 and m_2 are the masses of the attracting objects, d is the distance between the objects' centres and G is a proportionality constant called the **universal gravitational constant** or more commonly known by astrophysicists as *Big G* to distinguish it from 'little' g — the acceleration due to gravity. In SI units, G has the value 6.67×10^{-11} N m^2 kg^{-2}. (See Figure 6.7.)

Figure 6.7



Example

Determine the force of attraction between the Earth (mass = 5.98×10^{24} kg) and the Moon (mass of the Moon is 7.35×10^{22} kg), given that the Earth–Moon distance is 3.8×10^8 m.

Solution

$$\mathbf{F}_g = \frac{Gm_1m_2}{d^2} = \frac{6.67 \times 10^{-11} \times 7.35 \times 10^{22} \times 5.98 \times 10^{24}}{(3.8 \times 10^8)^2} = 2.07 \times 10^{20}\ \text{N}$$

Questions

19 Calculate the force between the Sun ($m = 2.0 \times 10^{30}$ kg) and the Earth ($m = 5.98 \times 10^{24}$ kg) assuming they are about 1.5×10^8 km apart.

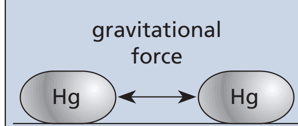
20 Black holes are super-massive collapsed stars. The closest anything can get to one and still escape the gravitational force is called the 'event horizon'. Calculate the force acting on a 15 t spacecraft at the event horizon of 30 km from a black hole that has a mass equal to 10 times that of the Sun. Mass of Sun = 2×10^{30} kg; 1 t = 1000 kg.

NOVEL CHALLENGE

Newton said *rationem vero harum Gravitatis propietartum ex phenomenis nondrum potui decucere* ('But I have not been able to discover the reason for this property of gravitation from the phenomena').
What did he mean?

NOVEL CHALLENGE

Two spherical drops of mercury are resting on a frictionless surface. The only force between them is that of gravitation. *What would you need to know to be able to calculate how much time it would take for them to touch?*



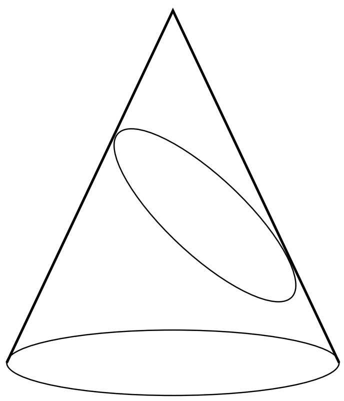
PHYSICS UPDATE

In 1998, the International Panel on Physical Constants deemed G to be $6.672\ 59 \pm 0.008 \times 10^{-11}$ N m^2 kg^{-2}.

CIRCULAR MOTION 6.5

The two main types of periodic motion in space are:
- **elliptical motion** — planets about the Sun and some artificial satellites
- **circular motion** — moons about their planets and some artificial satellites.

Figure 6.8
An ellipse is an angled segment through a cone.



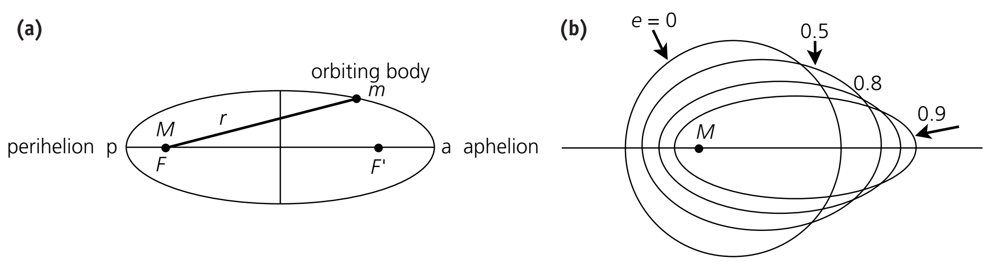
Elliptical motion

An ellipse is produced if you make a sloping cut through a conical pyramid (Figure 6.8).

A planet of mass *m* moves in an elliptical orbit around the Sun. The Sun, of mass *M*, is at one focus F of the ellipse (Figure 6.9**(a)**). The other, or 'empty' focus is F′. The point closest to the Sun is called the **perihelion** and the opposite point farthest from the Sun is called the **aphelion**. When referring to an elliptical orbit in general, these points are called the **perigee** and **apogee** respectively. The words come from the Greek *peri* meaning 'around'; *apo* meaning 'away'; *helios* meaning 'Sun'. The suffix 'gee' is derived from the Greek *geo*, the Earth. You should be able to deduce where words like perimeter, geometry and apology come from.

The **eccentricity** is a measure of how much out-of-round the ellipse is (Figure 6.9**(b)**). The eccentricity, e, is the difference between the distance from focal point to aphelion, F_a, and focal point to perihelion, F_p, divided by the total perihelion to aphelion distance, ap: $e = \dfrac{F_a - F_p}{ap}$. An eccentricity of zero means the ellipse is circular. At perihelion, the Earth is 147 097 800 km from the Sun; at aphelion it is 152 098 200 km, a difference of 5 million km. The eccentricity of the Earth's orbit about the Sun is 0.0167, which means it is almost circular. In a circle of diameter 100 cm, this difference corresponds to the centre being 0.8 cm off-centre. Not much! In the drawings below, the shape of the ellipse has been distorted for clarity. It should look more like a circle.

Figure 6.9
Planets move in elliptical orbits.

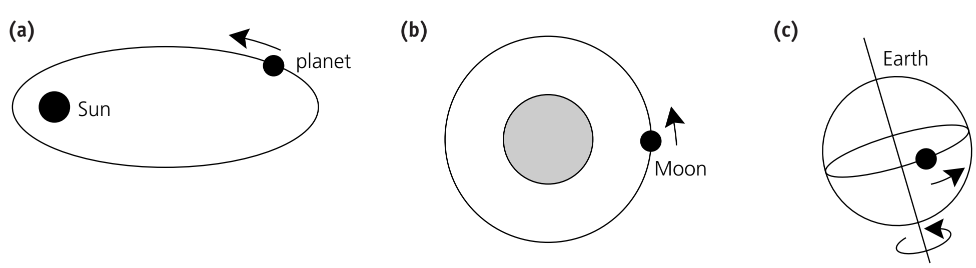


Circular motion

Planets may have elliptical orbits about the Sun, but satellites that orbit the planets mostly have **circular** paths.
- The natural satellite of the Earth (the Moon) has a circular path.
- Most artificial Earth-orbiting satellites have circular paths, thus keeping their speed constant.
- The Earth rotates on its own axis, so a point on its surface travels in a circular path too.

In order to understand surface and satellite motion, it is necessary to revise the physics of circular motion.

Figure 6.10
(a) Planets travel around the Sun in elliptical orbits. **(b)** The moon and most artificial satellites have circular orbits about the Earth. **(c)** Points on the Earth's surface have circular paths as the Earth turns on its own axis.



Centripetal acceleration

In the previous chapter it was shown that objects travelling in circular orbits at constant speed had an acceleration directed toward the centre of the circular path. This acceleration was called **centripetal acceleration:**

$$\boldsymbol{a}_c = \frac{v^2}{r}$$

Centripetal force

Because of this centripetal acceleration, an object of mass m experiences a **centripetal force** $\boldsymbol{F}_c$ also directed toward the centre of the circular path:

$$\boldsymbol{F}_c = m\boldsymbol{a}_c = \frac{mv^2}{r}$$

Period of circular motion

If the object travels at uniform speed $\boldsymbol{v}$ in a circle of radius r, the distance travelled during one full revolution $s = 2\pi r$. The time taken to complete one full revolution (the period, T) is:

$$T = \frac{\boldsymbol{s}}{\boldsymbol{v}} = \frac{2\pi r}{\boldsymbol{v}} \quad \text{or} \quad \boldsymbol{v} = \frac{2\pi r}{T}$$

Since $\boldsymbol{a}_c = \frac{v^2}{r}$, we obtain $\boldsymbol{a}_c = \frac{4\pi^2 r}{T^2}$ and $\boldsymbol{F}_c = \frac{4\pi^2 rm}{T^2}$.

Example

The radius of the Earth at the equator is 6.4×10^6 m and its mass is 6.0×10^{24} kg. Calculate **(a)** the centripetal acceleration of a point at the equator; **(b)** the centripetal force acting on this point; **(c)** the linear velocity of this point.

Solution

- T = 24 hours = 86 400 s

  (a) $\boldsymbol{a}_c = \frac{4\pi^2 r}{T^2} = \frac{4\pi^2 \times 6.4 \times 10^6}{86\ 400^2} = 0.034\ \text{m s}^{-2}$.

  (b) $\boldsymbol{F}_c = m\boldsymbol{a}_c = 6.0 \times 10^{24} \times 0.034 = 2.04 \times 10^{23}$ N.

  (c) $\boldsymbol{v} = \frac{2\pi r}{T} = \frac{2\pi \times 6.4 \times 10^6}{86\ 400} = 465\ \text{m s}^{-1}$.

Questions

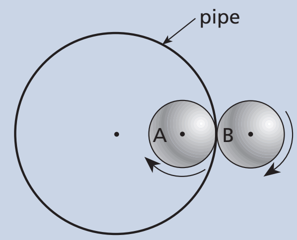
21 A 750 kg spacecraft is in a circular orbit of radius 700 km and is travelling at 6500 m s^{-1}. Calculate **(a)** the centripetal acceleration; **(b)** the centripetal force; **(c)** the period.

22 A person living on the equator of the Earth makes one complete revolution around the Earth's axis in 24 hours. For a 65 kg person, find **(a)** their centripetal acceleration; **(b)** the centripetal force; **(c)** the linear velocity. The radius of the Earth is 6.4×10^6 m.

NOVEL CHALLENGE

Two balls are rolled around the inside surface and outside surface of a pipe whose diameter is 3 times the diameter of the balls.

How many times will the outside ball turn to complete one rotation of the pipe compared with the inside one?



6.6 SATELLITES

Satellite means 'neighbour' or 'companion'. Town planners talk about satellite cities. To an astrophysicist, satellites can either be natural (moons) or artificial (e.g. communications satellites). Artificial satellites are generally used for:

- science — research, weather, mapping
- industry — agriculture, mining
- communications — radio, TV, phone and computer networks; position coordinates
- military and political — defence planning, spying.

Photo 6.2
The Hubble telescope.

Photo 6.3
Einstein's Cross.

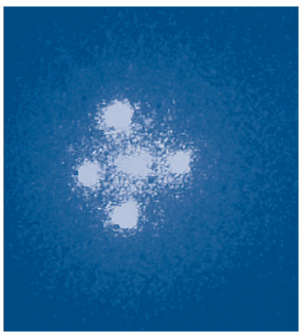
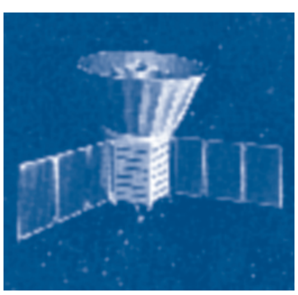


Photo 6.4
The ERS-1 satellite.

Photo 6.5
NASA's Cosmic Background Explorer (COBE). What a success!



Examples of satellites

A big new eye in the sky

A new era in astronomy began in 1990 when the **Hubble space telescope** went into orbit around the Earth (see Photo 6.2). The telescope initially had blurred vision due to a faulty main mirror and also had problems with shaking solar panels. These were eventually fixed in 1993 and it now sends back a rich harvest of observations including compelling clues to the existence of some super-heavy massive black holes and amazing close-ups of the Orion nebula, where new stars are being born from clouds of gas. Hubble also beamed back details of a new type of cosmic object — a gigantic concentration of stars produced by two colliding galaxies 200 million light years away called the 'Starburst galaxy'. Probably the most spectacular Hubble image shows the famous 'Einstein cross' (see Photo 6.3). As light from a quasar 8000 million light years away grazes a galaxy at only 400 million light years away, it is bent in new directions. From Earth we see four images of the distant quasar, with the foreground galaxy in the middle. This effect, called 'gravitational lensing', was predicted by Albert Einstein 70 years ago and is a remarkable confirmation of his theory of gravity.

The Hubble space telescope has a mass of 11 t and is in a circular Earth orbit 610 km above the surface. With its unrivalled ability to measure cosmic distances, it could help to answer one of the biggest questions of all: how big and how old is the universe? If Hubble could see 15 billion light years away then it would see the moment of creation.

ERS-2 This satellite was launched in April 1995 after the huge success of ERS-1 (see Photo 6.4). CSIRO placed a temperature sensor aboard to gather data about global warming. The sensor also measures sunlight reflected from the ground, providing better estimates of bushfire risk and crop yields.

Scientists have a new tool to search for the 'fossil record' of the Big Bang and uncover clues about the evolution of the universe. Launched in 1999, NASA's **Far Ultraviolet Spectroscopic Explorer** (FUSE) observes nearby planets and the farthest reaches of the universe to provide a detailed picture of the immense structure of our own Milky Way galaxy. The FUSE mission's primary scientific focus is the study of hydrogen and deuterium ($^{2}_{1}H$), which were created shortly after the Big Bang. With this information, astronomers in effect will be able to look back in time at the infant universe.

By examining these earliest relics of the birth of the universe, astronomers hope to gain a better understanding of the processes that led to the formation and evolution of stars, including our solar system. Ultimately, scientists hope data from FUSE will allow them to make a huge leap of understanding about how the primordial elements were created and have been distributed since the beginning of time.

The **Cosmic Background Explorer** (COBE) spacecraft has been engaged in some of the most exciting work ever done in the study of the universe. It has peered back in time some 10 billion years, very nearly the point of creation. Launched in 1989 and managed by NASA's Goddard Space Flight Center, COBE has uncovered landmark evidence to support the Big Bang theory of an expanding universe. Science researchers continue to analyse data received from the spacecraft.

SR Activity 6.7 UPDATE ON SATELLITE PROGRAMS

The problem in writing about satellite programs in textbooks like this is that progress is so rapid and developments unfolding so fast that information dates very quickly. The only way to keep up is with newspaper and magazine articles or by direct communication with the satellite agencies themselves. Alternatively, you could always see what answers you can get on the Internet (start with NASA's Home Page on the Worldwide Web or join some of the Astronomy newsgroups).

Using the Internet, try to get an update on one of the following programs:

- CSIRO's involvement in **ERS-2** and when its program is likely to finish.
- **Cape York space port** — will it ever launch a satellite?
- How does the **Global positioning system** (GPS) work?
- Sailors often have an **EPIRB** on their boats. What is it and how does it work?

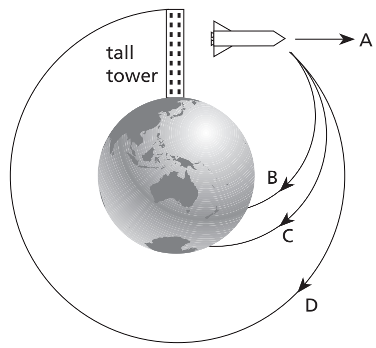
Satellite motion

For any object to orbit the Earth, it must have sufficient velocity to overcome the Earth's gravitational pull. Figure 6.11 shows the path of four objects projected horizontally from a high tower. Path A would happen if gravity did not act; Path B if the speed was low; Path C if it was higher than B but still too slow; and Path D if the speed was just right.

In a **circular orbit**, a satellite always travels at the same speed and stays the same distance from Earth. The earliest measurement of the Moon's period shows that it hasn't changed over the past few thousand years — all we've been able to do is measure it more accurately. It is known to be 27.321 661 days.

The 'right' speed for a satellite is such that the centripetal force needed to keep it in a circular path exactly equals the force of gravity or its weight. This velocity is called its **critical velocity** ($\boldsymbol{v}_{crit}$)

Figure 6.11



$$\text{Centripetal force} = \text{satellite's weight}$$
$$\boldsymbol{F}_c = m\boldsymbol{g}$$
$$\frac{m\boldsymbol{v}_{crit}^2}{r} = m\boldsymbol{g}$$
$$\boldsymbol{v}_{crit} = \sqrt{\boldsymbol{g}r}$$

If the velocity is less than critical the satellite will fall back towards Earth. If it is more than critical it will rise to a bigger orbit. Note that the value of the critical velocity is independent of mass. It just depends on the radius of the orbit and the acceleration due to gravity ($\boldsymbol{a}_g$ or $\boldsymbol{g}$) at that radius. The value of $\boldsymbol{g}$ is not 9.8 m s^{-2} — it is a lower value further away from the Earth.

NOVEL CHALLENGE

A simple formula for calculating the distance to the horizon is:

miles to horizon = $\sqrt{\text{eyeheight in feet} \times 1.5}$.

Show that this formula can be converted to:

kilometres = $\sqrt{\dfrac{\text{eyeheight in cm}}{8}}$.

Example

Calculate **(a)** the gravitational force; **(b)** the critical velocity; **(c)** the period of the orbit of a 5000 kg satellite moving uniformly in a circular path 400 km above the Earth. The radius of the Earth = 6.38×10^6 m.

Solution

(a) $m_s = 5000$ kg; $m_e = 5.98 \times 10^{24}$ kg.

$$\text{Radius of orbit, } d = 400 \times 10^3 \text{ m} + 6.38 \times 10^6 \text{ m} = 6.78 \times 10^6 \text{ m}$$
$$\boldsymbol{F} = \frac{Gm_1m_2}{d^2} = \frac{6.67 \times 10^{-11} \times 5000 \times 5.98 \times 10^{24}}{(6.78 \times 10^6)^2} = 43\ 385 \text{ N}$$

(b) The force of attraction (43 385 N) equals the centripetal force.
Using the centripetal force law:

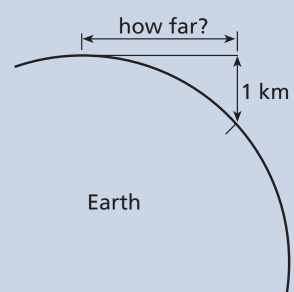
$$\boldsymbol{F}_c = \frac{m\boldsymbol{v}^2}{r};\ \boldsymbol{v}^2 = \frac{\boldsymbol{F}_c r}{m} = \frac{43\ 385 \times 6.78 \times 10^6}{5000} = 5.88 \times 10^7$$
$$\boldsymbol{v} = \sqrt{5.88 \times 10^7} = 7670 \text{ m s}^{-1}$$

(c)

$$T = \frac{2\pi r}{\boldsymbol{v}} = \frac{2\pi \times 6.78 \times 10^6}{7670} = 5554 \text{ s (1.54 hours)}$$

NOVEL CHALLENGE

How far would you have to travel horizontally out from the Earth for your altitude to be 1 km?



Escape velocity

If you fire an arrow upward, usually it will slow, stop momentarily, and return to Earth. There is, however, a certain initial speed that will cause it to move upward and escape the Earth's pull. This is called its **escape velocity** and for Earth it is 11.2 km/s. Physicists have derived a formula:

NOVEL CHALLENGE

In 1971 Apollo 15 astronauts David Scott and James Irwin drove the 4WD lunar vehicle around for 30 km on the Moon. Would they have used as much fuel as on Earth?

NOVEL CHALLENGE

During a lunar eclipse, the shadow of the Moon on the Earth consists of a black region 100 km wide which travels at 3000 km h^{-1}. Scientists and thrill seekers try to stay in the shadow zone as long as possible to make observations. *What is the maximum time you could stay in the shadow zone if you were in a plane that could travel at 1000 km h^{-1}?*

$$v_{esc} = \sqrt{\frac{2Gm}{r}}$$

where m is the mass of the planet or moon and r is the radius.

Example

Verify the escape velocity for the Earth as 11.2 km s^{-1}. Ignore the effects of air drag and Earth's rotation. $G = 6.67 \times 10^{-11}$ N m^2 kg^{-2}.

Solution

$$v = \sqrt{\frac{2Gm}{r}} = \sqrt{\frac{2 \times 6.67 \times 10^{-11} \times 5.98 \times 10^{24}}{6.37 \times 10^{6}}}$$
$$= 1.12 \times 10^{4} \text{ m s}^{-1} \text{ (= 11.2 km/s)}$$

Questions

Use the data supplied in Table 6.3 on page 146 where necessary.

23 Calculate **(a)** the force between the Earth and an artificial satellite of mass 2500 kg, which is in a 6400 km orbit above the surface of the Earth; **(b)** its velocity; **(c)** its period.

24 A communications satellite is shifted from an orbit of one Earth radius above the surface of the Earth to three Earth radii above the surface. What effect does this have on the satellite's **(a)** gravitational force; **(b)** velocity; **(c)** period?

25 Calculate **(a)** the minimum orbiting speed; **(b)** the period of the orbit of a satellite moving uniformly in a circular path 1170 km above the Earth, where $\boldsymbol{g}$ = 7.0 m s^{-2}. The radius of the Earth = 6.4 × 10^6 m.

26 Calculate the escape velocity from **(a)** the Moon; **(b)** Pluto; **(c)** Jupiter; **(d)** the Sun.

WEIGHT, GRAVITY AND CENTRIPETAL FORCE 6.7

The weight of a body is a measure of the force acting on it due to a nearby astronomical object such as a planet. To us on Earth, the astronomical object is the Earth. Your true weight ($\boldsymbol{F}_W$) is the product of mass and the free-fall acceleration at the surface of the planet (= $m\boldsymbol{g}$). For us, $\boldsymbol{g}$ = 9.8 m s^{-2} or approximately 10 m s^{-2}. Your apparent weight may change depending on whether the planet rotates or not.

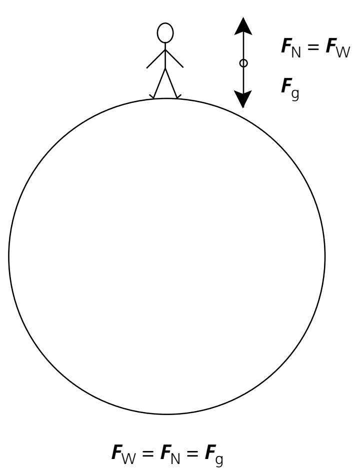


Figure 6.12
A non-rotating planet.

On a non-rotating planet

In such a case (see Figure 6.12), the weight of an object, $\boldsymbol{F}_w$, is equal to the force due to gravity, $\boldsymbol{F}_g$. The symbol $\boldsymbol{g}$ is called the acceleration due to gravity but is more correctly referred to as **free-fall** acceleration. It is the net acceleration.

$$\boldsymbol{F}_g = \frac{Gm_1m_2}{d^2}, \text{ which equals } \boldsymbol{F}_w = m\boldsymbol{g}$$

Example

A 1.00 kg block of wood is at rest on the surface of a non-rotating planet of mass 3.0 × 10^{24} kg and radius 3.4 × 10^6 m. Calculate **(a)** its weight; **(b)** acceleration due to gravity (i.e. free-fall).

Solution

(a) $F_g = \frac{Gm_1m_2}{d^2} = \frac{6.67 \times 10^{-11} \times 3.0 \times 10^{24} \times 1.00}{(3.4 \times 10^6)^2} = 17.3$ N.

(b) $F_g = F_w = mg$, so $g = \frac{F_w}{m} = \frac{17.3}{1.00} = 17.3$ m s^{-2}.

On a rotating planet

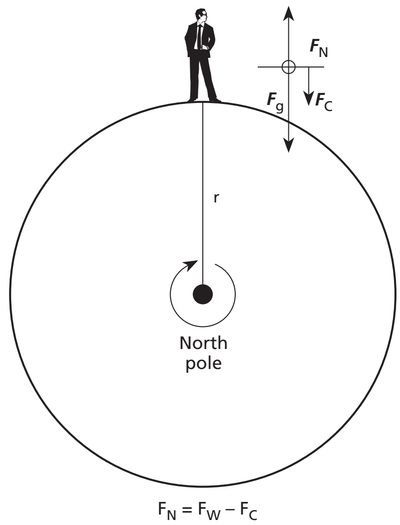


Figure 6.13
A rotating planet.

Consider an object resting on the surface of the Earth at the equator (see Figure 6.13). As in the non-rotating case, the object is acted on by the weight (F_W, which equals F_g) causing the Earth to exert an opposite normal reaction force (F_N) back on the object. If the Earth was not rotating, $F_N = F_W$ and so the resultant force (the difference between the two) is zero; there is no acceleration.

However, the Earth and all objects on its surface rotate. An object will undergo uniform circular motion, which is to say the object is accelerating (centripetal acceleration a_c). As it is accelerating, there must be a resultant force — this is the centripetal force (F_c) acting towards the centre of the Earth. This means that F_N must be smaller than F_W, consistent with Newton's second law.

$$F_C = F_W - F_N$$
$$\text{Hence } F_N = F_W - F_C$$
$$\text{Apparent weight} = \text{weight} - \text{centripetal force}$$

The free-fall acceleration (g) is equal to the acceleration due to the gravitational force (a_g) minus the centripetal acceleration (a_c): $g = a_g - a_c$

Note: you'll find that centripetal acceleration is very small (about 0.3%) compared with free-fall acceleration and can be generally omitted without concern.

Note: for points not on the equator, the centripetal acceleration is not normal to the surface but is normal to the Earth's axis. It is not correct to use the formulas above as the forces are no longer in line. For this reason, the symbol F_N would be better replaced by F_R, the reaction force.

NOVEL CHALLENGE

If the Earth stopped rotating, how much would a 60 kg (590 N) person weigh? What would his bathroom scales read?

Example

A 1.00 kg brick rests on the surface of the Earth at the equator. Given that the radius of the Earth at the equator is 6.4×10^6 m and its mass is 6.0×10^{24} kg, calculate **(a)** the gravitational force on the brick; **(b)** the centripetal force on the brick; **(c)** the weight of the brick; **(d)** acceleration due to gravity; **(e)** centripetal acceleration; **(f)** free-fall acceleration; **(g)** centripetal acceleration as a percentage of free-fall acceleration.

Solution

- T = 24 hours = 86 400 s, m_o (mass of object) = 1 kg.

(a) $F_g = \frac{Gm_em_o}{r^2} = \frac{6.67 \times 10^{-11} \times 5.98 \times 10^{24} \times 1.00}{(6.38 \times 10^6)^2} = 9.83$ N.

(b) $F_c = \frac{4\pi^2 rm_o}{T^2} = \frac{4\pi^2 \times 6.4 \times 10^6 \times 1.00}{86\,400^2} = 0.0338$ N.

(c) $F_N = F_W - F_c = 9.83 \text{ N} - 0.0338 \text{ N} = 9.80$ N.

(d) Acceleration due to gravity, $a_g = \frac{F_g}{m} = \frac{9.83}{1.00} = 9.83$ m s^{-2}.

(e) Centripetal acceleration, $a_c = \frac{F_c}{m} = \frac{0.0338}{1.00} = 0.0338$ m s^{-2}.

(f) Free-fall or net acceleration, $g = 9.83 - 0.0338 = 9.80$ m s^{-2} (or could use $F_w = mg$).

(g) $\frac{a_c \times 100}{g} = \frac{0.0338 \times 100}{9.80} = 0.3\%$.

Hence, as centripetal acceleration, a_c, is so small, it is convenient to approximate the net or free-fall acceleration, g, by the acceleration due to gravity, a_g, and still call it g. This is what we did in previous chapters.

Questions

27 A 5.00 kg rock is at rest on the surface of a non-rotating planet of mass 1.5×10^{24} kg and radius 2.4×10^{6} m. Calculate **(a)** its weight; **(b)** acceleration due to gravity (i.e. free-fall).

28 A 750 kg space probe rests on the surface of the Earth near the equator. Given that the radius of the Earth at the equator is 6.4×10^{6} m and its mass is 6.0×10^{24} kg, calculate **(a)** the gravitational force on the vehicle; **(b)** the centripetal force on the vehicle; **(c)** the weight of the vehicle at that point; **(d)** the mass of the vehicle.

THE GRAVITATIONAL FIELD 6.8

All objects are pulled toward Earth by gravity. We could represent the force of gravity by arrows as shown in Figure 6.14. The arrows are called its **gravitational field**. It is because the Earth has mass that it has gravity, so any object with mass could have a gravitational field as represented in Figure 6.15. The more massive an object is, the stronger its gravitational field.

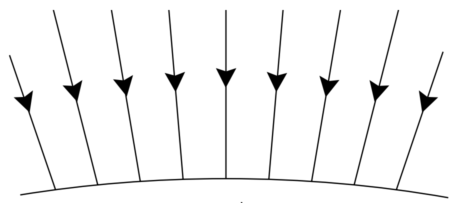


Figure 6.14
The gravitational field is downward, perpendicular to the surface.

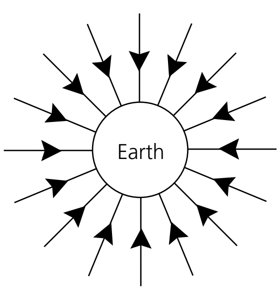


Figure 6.15
The shape of the gravitational field surrounding Earth or any isolated point mass.

Can the arrows point the other way? In other words, can we have **antigravity** — a force that pushes two objects apart? The answer for the moment is no. Unlike electrostatic and magnetic forces (like charges repel, unlike attract), physicists have never observed a repulsive gravitational force, only an attractive one. **Einstein** produced a comprehensive theory of gravity in 1915 — his **general theory of relativity** (see Chapter 30). In it, he argues that gravitational force is different from forces like magnetism and electrostatics even though the mathematical relationships are identical. He said that gravity is not so much something that happens in space but is a distortion or a warp in space itself. His theory encompasses all of Newton's laws but takes them much further and because they have been confirmed by independent research thousands of times, physicists accept his theories as being the best current model for the forces in the universe. Einstein's theories won't be dealt with here but you should have several books in the library on the topic. **Special relativity** is also covered in Chapter 30.

Gravitational field strength

A gravitational field is a region of space where an object experiences a force due to its mass. A measure of the strength of this field is given by the symbol $\boldsymbol{g}$ — the same $\boldsymbol{g}$ you used in acceleration due to gravity. When you think about it, the stronger the field, the faster the acceleration (Newton's second law, $\boldsymbol{F} = m\boldsymbol{a} = m\boldsymbol{g}$):

$$\boldsymbol{g} = \frac{\text{gravitational force}}{\text{mass}} = \frac{\boldsymbol{F}}{m}$$

The Earth has a gravitational field and so does the Moon. Objects placed in the Earth's gravitational field experience a force of attraction given by:

$$\boldsymbol{F} = \frac{Gm_1m_2}{d^2} = m\boldsymbol{g}$$

Hence, the **gravitational field strength** of Earth, $g = \frac{Gm_e}{d^2}$.

Substituting in this formula gives: $g = \frac{6.67 \times 10^{-11} \times 6 \times 10^{24}}{(6.4 \times 10^6)^2} = 9.8 \text{ m s}^{-2}$.

Hence, at the surface of the Earth, $g = 9.8 \text{ m s}^{-2}$, but this value decreases following an inverse square law. At two Earth radii from the *centre* of the Earth, g would be one-quarter of 9.8 m s^{-2} (2.45 m s^{-2}) and at three Earth radii from the centre would be one-ninth of 9.8 m s^{-2} (1.1 m s^{-2}). Further values are shown in Table 6.4.

NOVEL CHALLENGE

'Zero G' is good for producing genetically engineered crops. Bacteria move more easily in space and it helps the pathogen (bacteria) attach to the surface of the plant and alter it. It is a good way to make soy sauce. What are some other good uses for Zero G?

Table 6.4

ACCELERATION DUE TO GRAVITY (m s^{-2})	DISTANCE FROM EARTH'S SURFACE (km)	DISTANCE FROM EARTH'S CENTRE (km)
9.8	0	6 400
9.0	270	6 670
8.0	670	7 050
7.0	1 160	7 560
5.0	2 540	8 940
3.0	5 150	11 550
2.0	7 740	14 140
1.0	13 590	19 990

Example

Calculate the gravitational field strength in the region of a satellite orbiting 8000 km above the Earth's surface.

Solution

$$m_e = 6 \times 10^{24} \text{ kg}$$

$$d = \text{radius of Earth} + \text{orbiting height} = 6.4 \times 10^6 \text{ m} + 8000 \times 10^3 \text{ m} = 1.44 \times 10^7 \text{ m}$$

$$g = \frac{Gm_e}{d^2} = \frac{6.67 \times 10^{-11} \times 6 \times 10^{24} \text{ kg}}{(1.44 \times 10^7)^2} = 1.93 \text{ m s}^{-2}$$

Questions

29 What is the gravitational field strength at a point whose distance from the Earth's surface is equal to three Earth radii?

30 At what altitude above the Earth's surface must you go for the gravitational field strength to be one-sixteenth the value on Earth?

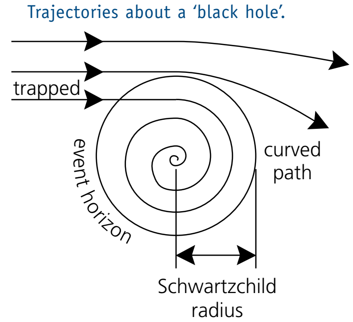
31 Plot a graph of g versus distance from the Earth's centre, using the data from Table 6.4 above. Comment on the relationship. Plot a second graph to prove your prediction.

6.9 BLACK HOLES

A **black hole** is a term used to describe a region of space that contains matter so dense that even light cannot escape its grip. It was coined by John Wheeler of Princeton University (USA) in 1967. A black hole is thought to come about from the **gravitational collapse** of a star. The first tentative identification of a black hole was announced in December 1972 in the binary-star X-ray source Cygnus X-1. The best black hole candidate at the moment is the central star of the triple star system V404, which is 5000 light years (ly) from Earth in the constellation Cygnus. In the case of our galaxy, the Milky Way, there appears to be a two million **solar mass** black hole in the region of Sagittarius A. (One solar mass = mass of the Sun.)

For a black hole with a mass ten times that of our Sun, the point at which light cannot escape (i.e. the point at which it becomes 'black') is within 30 km of the centre. This is called the **Schwartzchild radius**.

Figure 6.12
Trajectories about a 'black hole'.



NOVEL CHALLENGE

Try these Fermi questions:

A How long would a beanstalk (elevated to geosynchronous orbit) have to be? What tensile strength would it require? How does this compare to steel, kelvar, spider silk, the maximum theoretical material strength?

B According to one hypothesis, 20% of the mass of the asteroid that killed the dinosaurs was uniformly deposited over the surface of the Earth at a density of 0.02 g/cm^{-3}. What was the mass of this asteroid?

Falling into a black hole

If a black hole were to exist near some other stellar object such as a **quasar** (quasi-stellar radio source) the gravitational attraction would drag matter from the quasar into the black hole. Atomic particles would accelerate to near the speed of light as they approached. Rather than falling straight in, they would swirl in like a whirlpool, becoming compressed and heated and giving off enormous amounts of energy. It is this radiant energy that astrophysicists detect as they try to identify the location of black holes.

If you tried to travel into a black hole would you survive? It's hardly likely! You'd be stretched, compressed and heated. Hardly the romantic stuff of science fiction novels. If you could avoid getting too close then you wouldn't get sucked in. The minimum distance from which it is still just possible to escape (Schwartzchild radius) marks the boundary called the **event horizon**.

The dilation of time caused by gravity

One of the consequences of Einstein's general theory of relativity is that the passage of time is affected by gravity. To an astronaut falling into a black hole time would pass normally. But to outside observers, for example us on Earth, time would appear to slow down because of the immense gravity near a black hole. It would seem to take ages for the astronaut to disappear into the hole. This is called the **dilation** of time (Latin *dilato* = 'expand').

What's it like inside a black hole?

You can't escape from a black hole — it's sort of like our universe. You can't travel off into space and leave our universe so some scientists have said that our universe is like a black hole in someone else's universe. And their universe is a black hole in some higher universe. Perhaps within black holes in our universe are smaller universes. Who knows? It's all speculation but makes an intriguing thought. Books by Steven Hawking, Carl Sagan, Paul Davies and Kip Thorne examine the possibilities and consequences of such theories. Magazines such as *Scientific American* and *New Scientist* tell of the latest research. There's no room for it here.

What is the fate of a black hole?

Stephen Hawking was the theoretical physicist who showed that black holes eventually evaporate. That's right — evaporate. His technical paper had the unusual title of 'Black holes ain't so black!!' Hawking's calculations confirmed that a spinning black hole loses energy by emitting radiation (the so-called 'Hawking radiation') and as it does it becomes smaller and hotter, eventually becoming so small and hot that it simply evaporates. In fact, today, physicists applying the laws of thermodynamics and quantum gravity require black holes to eventually evaporate in about 10^{67} years. The smaller the black hole, the faster it will evaporate. An interesting theory but who'll be around to see if it's true?

ASTRONOMY VERSUS ASTROLOGY 6.10

Astronomy is the scientific study of heavenly bodies — stars, planets, comets, quasars etc. **Astrology** is a pseudo-science (i.e. non-scientific) that claims to foretell the future by studying the supposed influence of the relative positions of the Moon, Sun and stars on human affairs. Up to the time of Kepler (1600) only astrology existed. Observations and experiments by Galileo, Kepler and Newton produced universal laws and the new science of astronomy began. Astrology slowly became the mumbo-jumbo side of sky watching and was relegated to the irrational, non-scientific and hoaxers club together with pyramid power, clairvoyance, ESP, water divining, flat earth theory, numerology, faxes from the dead, Feng Shui, Tarot Cards, Bermuda Triangle, runes, UFOs, levitation, Philadelphia experiment, faces on the Moon and Elvis sightings, to name just a few.

Astrology has stagnated in the pre-scientific theories of thousands of years ago. It has no testable hypotheses, no statistically reliable evidence of past successes, no research program, no predictive power that can be tested by experiment. Astrologers make many extravagant claims of success but they have never stood up to rigorous scientific scrutiny. In short — astrology is an article of faith, of pseudo-scientific hocus-pocus and rightly belongs in the comic section of the newspaper. There is a group, the *Australian Skeptics*, which examines pseudo-scientific claims and publishes a bi-monthly journal. Visit their Web page at http://www.skeptics.com.au for more information.

SR Activity 6.8 A SIMPLE TEST

Astrologers believe that the positions of planets at the time of birth influence the newborn. Scientists deride this belief and claim that the gravitational force exerted on a baby by the obstetrician or midwife is greater than that exerted by the planets.

1. To check this claim, calculate and compare the gravitational force exerted on a 4 kg baby by **(a)** a 70 kg obstetrician who is 1 m away; **(b)** the massive planet Jupiter ($m = 2 \times 10^{27}$ kg) at its closest approach to Earth ($= 6 \times 10^{11}$ m); **(c)** by Jupiter at its greatest distance from Earth ($= 9 \times 10^{11}$ m). What is your conclusion?
2. Are there any planets that may be lighter but closer that could have some effect? What about the Moon?
3. What new planets have been discovered in the past 2000 years that astrologers conveniently forget about? Where would you look?

6.11 UNANSWERED QUESTIONS

Many of the questions people ask about the structure, history and future of the universe can't be answered with a lot of certainty, but there is consensus among scientists about most of the main theories. There is a lot of debate within the scientific community about many aspects, though. You'll find plenty of books in the library and bookstores in which the authors speculate on the story of the universe. Happy hunting!

Questions you could ask:

- Did the universe create itself?
- Could we possibly know about past cycles of creation if there were any?
- Can we have parallel universes made of antimatter?
- Could astrology work by undiscovered forces?
- Do quantum fluctuations enable the creation of something out of nothing? Yeah right!
- Is there life out there, and what is the SETI project on about?

NOVEL CHALLENGE

If you happened to be a kilometre from the 'Big Bang' when it occurred, what would you hear? We bet you miss the critical problem with this scenario. Good luck!

Practice questions

The relative difficulty of these questions is indicated by the number of stars beside each question number: * = low; ** = medium; *** = high.

For questions that follow, use the following data:

- $\boldsymbol{g}$ (on Earth) = 10 m s^{-2}.
- $G = 6.67 \times 10^{-11}$ N m^2 kg^{-2}.
- r_{mo} (radius of Moon's orbit around Earth) = 3.8×10^8 m.
- r_{eo} (mean radius of Earth's orbit around Sun) = 1.5×10^{11} m.

Table 6.5

BODY	MASS (kg)	RADIUS (m)
Earth	$m_e = 6 \times 10^{24}$ kg	$r_e = 6.38 \times 10^6$ m
Moon	$m_m = 7.34 \times 10^{22}$ kg	$r_m = 1.74 \times 10^6$ m
Sun	$m_s = 2.0 \times 10^{30}$ kg	$r_s = 6.96 \times 10^8$ m

Review — applying principles and problem solving

***32** The *Gemini* cluster is 300 Mpc away. Convert this distance to metres.

***33** *Pegasus II* has a radial velocity of 12 800 km/s. What is this in units of 'c'?

***34** The *Coma* cluster is 60 Mpc away from us and has a recession speed of 6600 km/s. Calculate the Hubble constant for this galaxy.

***35** Some early estimates of the Hubble Constant put it at 50 km/s/Mpc.

(a) Would this make the universe older or younger than if a value of 75 km/s/Mpc was used?

(b) What would the age of the universe be if H_0 was 50 km/s/Mpc?

***36** Calculate the wavelength of maximum radiation emitted by the red star Barnard's Star, which has a temperature of 3090 K.

****37** The mean radius of the orbit of planet X in another solar system is 4×10^{12} m. If the average value for r^3/T^2 for this system is 3.5×10^{-18} m^3/s^2, calculate the period of planet Y, which has an orbital radius of 3×10^{10} m.

***38** What is the gravitational force of attraction between:

(a) two apples, of mass 100 g each, placed 30 cm apart on a table

(b) the Earth and the Sun

(c) an electron and a nucleus 1.5 µm apart? The mass of the electron (m_{e-}) is 9.11×10^{-31} kg. Consider the nucleus to be made up of two protons each with a mass (m_{p+}) of 1.67×10^{-27} kg.

***39** How far apart would you have to place two masses each of 1 million kg in order that the force between them was 1.0 N?

***40** The 2270 kg Cosmic Background Explorer (COBE) spacecraft is in a circular polar orbit of radius 900 km and is travelling at 530 m s^{-1}. Calculate

(a) the centripetal acceleration; **(b)** the centripetal force; **(c)** the period.

***41** Ignoring the rotation of the Earth, what is the weight of a 1.5 kg mass

(a) on the surface of the Earth; **(b)** 100 km above the Earth's surface;

(c) in free space?

***42** A satellite of mass 1850 kg is in a orbit 4500 km above the Earth's surface. Calculate **(a)** the gravitational force on the satellite; **(b)** the velocity of the satellite; **(c)** the period of the satellite.

***43** An Apollo spacecraft is orbiting the Earth in a circular orbit 180 km above the surface. If its mass is 3890 kg, calculate **(a)** the force on the satellite; **(b)** the velocity of the satellite; **(c)** the period of the satellite.

***44** Calculate the escape velocity from Ceres, the most massive of the asteroids — mass 1.17×10^{21} kg, radius 3.8×10^5 m.

***45** **(a)** Calculate the acceleration due to gravity on the surface of the Moon.
(b) What time would it take a spanner to fall (from rest) from a height of 1.5 m to the ground on the Moon?

***46** What is the gravitational field strength at a point **(a)** on the Earth's surface; **(b)** 1.5 Earth radii above the Earth's surface; **(c)** 3.0 Earth radii above the Earth's surface; **(d)** 1000 m above the surface of the Moon; **(e)** on the surface of the Sun?

****47** The constant G can be found by measuring the gravitational force between two spheres of known mass, separated by a known distance. The first person to do this was Henry Cavendish, in 1798, more than a century after Newton proposed his law.

Figure 6.17 shows Cavendish's apparatus. Two small lead spheres, each of mass m, were fastened to the ends of a rod that was suspended from its mid-point by a fine fibre. Large lead balls were brought up close to the small ones. The lead balls attracted each other and caused the fibre to twist. The amount of twist was proportional to the force between the spheres. Cavendish standardised the device beforehand by determining how much force was needed to twist the fibre by certain amounts.

Cavendish used two large lead spheres, each of mass 12.7 kg and two smaller spheres, each of mass 9.85 g. Table 6.6 gives the results for the total force on the fibre with the masses at various distances.

Figure 6.17
Cavendish's apparatus.

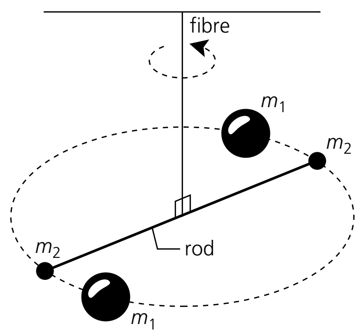


Table 6.6

d (cm)	TOTAL FORCE (N)
5.0	66.8×10^{-10}
8.0	26.6×10^{-10}
10.0	16.6×10^{-10}
12.0	11.6×10^{-10}
13.0	9.9×10^{-10}
15.0	7.4×10^{-10}

(a) Calculate the force between one pair of spheres (divide the total force by 2).
(b) Plot $\boldsymbol{F}$ (y-axis) vs distance. Make sure the distance is in metres.
(c) What relationship does this graph suggest?
(d) Plot another graph to confirm your prediction.
(e) Measure the slope of the graph. This gives the value $\boldsymbol{F}d^2$. Divide it by the product of the masses to get the value for G. How does it compare with the accepted value?
(f) From the graph, determine what force there would be for a distance of 9.5 cm.

PHYSICS FACT

Cavendish didn't actually make the apparatus he used for measuring electrostatic forces (shown above). He inherited it from John Mitchell who died in 1793 before he could try the experiment himself.

**48 The following is based on an excerpt from an article written by Sally Ride. She is a NASA space shuttle astronaut who is Professor of physics and Director of the California Space Institute at the University of California, San Diego. Read the article and answer the questions that follow.

Photo 6.6
Challenger launch.

Adapting to outer space

Astronauts have to adapt to an environment that can't be simulated on Earth. Things in weightlessness seem to be subject to a different set of physical laws. The laws are of course the same but sometimes the implications of those laws are much more apparent. For example, on Earth, frictional effects make it difficult to study Newton's laws of motion. Friction is hard to avoid because of gravity. Gravity holds things in contact with the floor. Newton's laws take some getting used to. A peanut shell set in motion will remain in motion until it hits a wall, a ceiling or somebody's mouth. And a sharp tap on the shoulder can give sufficient impulse to send an astronaut drifting across the room.

When an unanchored astronaut pulls on a drawer the result is frustrating, but predictable. The drawer doesn't open, but the astronaut moves toward the drawer. And if that astronaut uses a screwdriver, the result will be a spinning astronaut, not a turning screw.

Surface tension tends to pull liquids into spheres. On Earth this isn't as obvious: spilled milk lies in a puddle on the floor; in weightlessness, the same milk doesn't splatter on the floor but forms a sphere floating in the middle of the room.

Astronauts eat out of open cartons and use spoons to get the food to their mouths. The trick of course is to use sticky foods. Most of the food is dehydrated and vacuum-packed in plastic cartons with thin plastic tops. It's rehydrated by poking the needle of a water gun through the plastic top and injecting water. Surface tension also causes liquids to creep up drinking straws. Space shuttle straws come with a small clamp to keep the drinks from climbing out. In orbit, a column of liquid has no buoyant effect and no sedimentation. A cork does not bob in water, a bubble would not rise to the surface of a liquid (which means dissolved gases stay in carbonated soft drinks, so they aren't very good to drink), and there would be no layer of chocolate at the bottom of a glass of chocolate milk. As you can imagine, it's a unique living environment.

(from Halliday & Resnick *Fundamentals of Physics*, 3rd edn, 1988)

(a) Which of Newton's laws was the author referring to in her discussion about the drawer?
(b) What would happen to the gases in a soft drink when you drank it?
(c) Milk mightn't splatter but would a tennis ball bounce?
(d) Describe some way astronauts could anchor themselves to the floor.
(e) Friction with the floor is a problem, but does this mean all friction is reduced?

Extension — complex, challenging and novel

***49 How far above the surface of the Earth would you have to be so that a dollar coin (mass 7.4 g) took twice as long to fall 1.5 m when compared with a similar fall on the surface of the Earth?

***50 Describe a planet in terms of its mass and radius that could give **(a)** an acceleration due to gravity half that for g on the surface of Earth; **(b)** a time of flight twice that compared with Earth for a stone dropped from 2.0 m; **(c)** a time of flight twice that on Earth for a stone projected vertically upward at 10 m s^{-1}.

***51 On a spherical non-rotating planet with a radius of 5.1×10^3 km, what is the value of $\boldsymbol{g}$ for an object when it is at a height of 150 km, expressed as a fraction of its value at the surface?

***52 In 1610, Galileo used his telescope to discover the four most prominent moons of Jupiter (the Galilean moons). Their mean orbital radii and periods are given in Table 6.7.

Table 6.7

NAME	r ($\times 10^8$ m)	T (DAYS)
Io	4.22	1.77
Europa	6.71	3.55
Ganymede	10.70	7.16
Callisto	18.80	16.70

Plot a graph of r^3 (y-axis) against T^2 (x-axis) and comment on what this graph shows about the relationship between r and T.

***53 **(a)** At what distance from the Earth would a spacecraft experience zero net gravitational force due to the opposing pulls of the Earth and the Moon?
(b) Express this as a fraction of the total Earth–Moon distance.
(c) Is this the only place you would feel weightless? (See Figure 6.18.)

***54 **(a)** What is the acceleration due to gravity inside an aeroplane cruising at 10 000 m above the ground? Assume $\boldsymbol{g}$ at ground level is 9.810 m s^{-2}.
(b) How much more time would it take for a coin to fall a metre when inside the plane compared with on the ground?

***55 Consider a pulsar, a collapsed star of extremely high density, with a mass equal to that of the Sun but with a radius of only 12 km.
(a) Calculate the value of gravitational acceleration.
(b) If the period of rotation is 0.041 s, calculate the value of centripetal acceleration at the equator.

***56 One clock uses an oscillating spring; a second clock uses a pendulum. Both are taken to Mars. Will they keep the same time there that they kept on Earth? Will they agree with each other? (The mass of Mars is one-tenth that of the Earth and its radius is half that of Earth.)

***57 Brisbane has a latitude of 28° south, which means that the angle between lines from the centre of the Earth to Brisbane and from the centre to the equator is 28°. (See Figure 6.19.) People in Brisbane still make 1 revolution in 24 hours but travel a smaller distance than someone at the equator.

For a 60 kg person in Brisbane, calculate:
(a) the distance travelled in one day due to the Earth's rotation on its own axis
(b) the linear velocity
(c) the centripetal acceleration
(d) the centripetal force.
(e) In which direction would the following forces be directed:
(i) gravitational force; **(ii)** centripetal force; **(iii)** weight?

Figure 6.18
For question 53**(c)**.

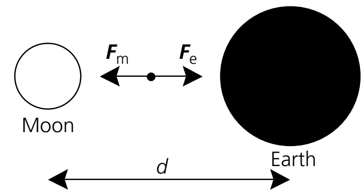
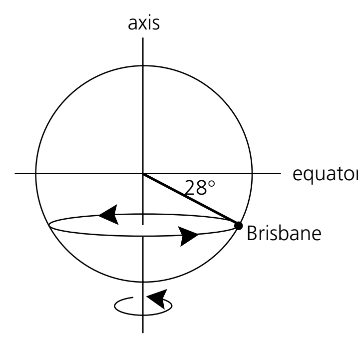


Figure 6.19
For question 57.



✔ TEST YOUR UNDERSTANDING

(Answer true or false)
- The moon is not falling.
- There is no gravity in space.
- Weightlessness means that there is no gravity.
- The Earth's spinning motion produces gravity.
- Planetary orbits are circles.
- Summer is when the Earth is closest to the sun.
- Spacecraft travel in straight lines from one planet to another.
- Black holes are big.
- Light travels in straight lines.

***58 A spaceship is idling at the fringes of our galaxy, 80 000 light years from the galactic centre. What is the ship's escape velocity from the galaxy? The mass of the galaxy is 1.4×10^{11} solar masses. A light year is the distance light travels in one year at a speed of 3×10^8 m s^{-1}.

***59 The planet Mars has a satellite, Phobos, which travels in an orbit of radius 9.4×10^6 m with a period of 7 hours 39 minutes. Calculate the mass of Mars from this information.

***60 The blue stars Procycon and Formalhaut have the same temperature of 7600 K but have radii of 848 000 and 750 600 km respectively.

(a) Determine the wavelength of maximum energy emission of the stars using Wein's law.

(b) Which star would be emitting radiation at the greater rate?

(c) Which star would be emitting the more radiation from an area 1 m^2 in size?