3.3 Man-made Satellites

Orbit of Satellite

Figure 3.33 shows the International Space Station, ISS, and MEASAT satellite. ISS can be seen from the Earth because of its large size and orbits at a height of 408 km. MEASAT satellite is difficult to be seen because of its small size and orbits at a height of 35 786 km. Satellites move in orbits at specific heights and suitable linear speeds.

Formulae for **centripetal force** and **Newton's Universal Law of Gravitation** are used to establish and determine the linear speed of satellites. Figure 3.34 shows the orbit of a satellite around the Earth.

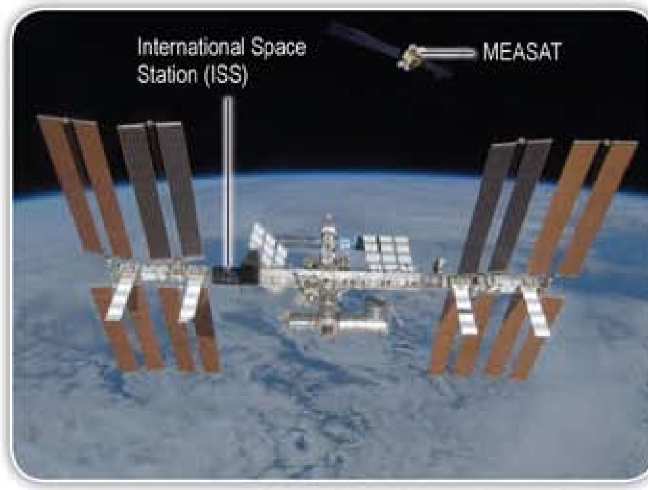
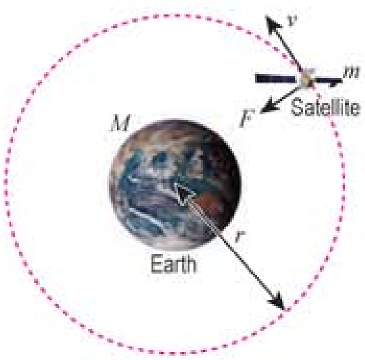


Figure 3.33 *Man-made satellite orbiting the Earth*



Mass of the Earth = M
Mass of satellite = m
Radius of orbit of satellite = r
Linear speed of satellite = v
Orbital period = T

Figure 3.34 *Orbit of a satellite*

Position and path of ISS

http://bt.sasbadi.com/p4103

A satellite moving in a circular orbit around the Earth experiences centripetal force, which is gravitational force.

Gravitational force between satellite and the Earth, $F = \frac{GMm}{r^2}$

Centripetal force on satellite, $F = \frac{mv^2}{r}$

Centripetal force = Gravitational force

$$\frac{mv^2}{r} = \frac{GMm}{r^2}$$

$$v^2 = \frac{GM}{r}$$

$$v = \sqrt{\frac{GM}{r}}$$

CAREER INFO

Astronautical engineering involves the field of Physics on orbital mechanics, outer space environment, guidance and control of height, telecommunications, aerospace structure and rocket propulsion.

3.3.1

As GM is constant, linear speed of the satellite only depends on the radius of its orbit. If a satellite is at a height, h above the surface of the Earth,

Radius of its orbit, $r = R + h$
that is R = radius of the Earth
Therefore, linear speed of the satellite, $v = \sqrt{\dfrac{GM}{R + h}}$

Man-made satellites can be launched to keep orbiting at specific heights around the Earth at radius of orbit, r if the satellite is given linear speed, $v = \sqrt{\dfrac{GM}{r}}$. Figure 3.35 shows a Global Positioning System (GPS) satellite at an altitude of 20 200 km from the Earth.

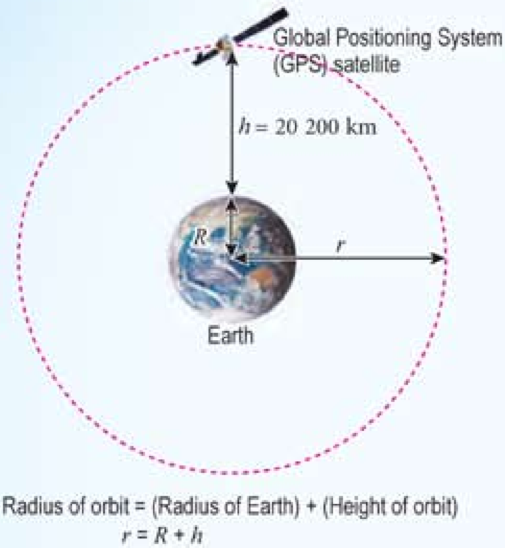


Figure 3.35 *GPS satellite orbits the Earth*

How does GPS work?

http://bt.sasbadi.com/p4104

Height, $h = 20\ 200 \times 1000$ m
$= 2.02 \times 10^7$ m

Radius of orbit, $r = (6.37 \times 10^6) + (2.02 \times 10^7)$
$= 2.657 \times 10^7$ m

Linear speed of satellite, $v = \sqrt{\dfrac{GM}{r}}$
$= \sqrt{\dfrac{(6.67 \times 10^{-11}) \times (5.97 \times 10^{24})}{2.657 \times 10^7}}$
$= 3.87 \times 10^3$ m s^{-1}

In a stable orbit, linear speed of satellite is $v = \sqrt{\dfrac{GM}{r}}$. This linear speed is high enough for the satellite to move in a circular orbit around the Earth. Centripetal acceleration is the same as gravitational acceleration.

If the linear speed of the satellite becomes less than the required linear speed, the satellite will fall to a lower orbit and continue to revolve towards the Earth until it enters the atmosphere. The movement of the satellite at a high linear speed against air resistance will generate heat and eventually causes the satellite to burn.

Geostationary and Non-Geostationary Satellites

Figure 3.36 shows two types of satellites orbiting the Earth, which is geostationary satellite and non-geostationary satellite. Study the features of the satellites.

Geostationary satellite

- In a special orbit named the Geostationary Earth Orbit
- Moves around the Earth in the same direction as the direction of the Earth's rotation on its axis
- Orbital period T = 24 hours, that is the same as the period of rotation of the Earth
- Always above the same geographical location

Geostationary satellite

http://bt.sasbadi.com/p4105a

Non-geostationary satellite

http://bt.sasbadi.com/p4105b

Non-geostationary satellite

- Normally in a lower or higher orbit than the Geostationary Earth Orbit
- Orbital period is shorter or longer than 24 hours
- Above different geographical locations at different times

Figure 3.36 *Geostationary and non-geostationary satellites*

Activity 3.12

ICS

Aim: To gather information on geostationary and non-geostationary satellites in terms of functions and lifespans

Instructions:

1. Work in groups.
2. Surf the internet to gather information on functions and lifespans for one geostationary satellite and one non-geostationary satellite.
3. Present your findings in the form of a folio and display it at the Resource Centre of your school.

Discussion:

1. What are the advantages of a non-geostationary satellite?
2. Why do communication satellites need to be in geostationary orbits?

Figure 3.37 shows the comparison between geostationary and non-geostationary satellites as well as examples of the satellites.

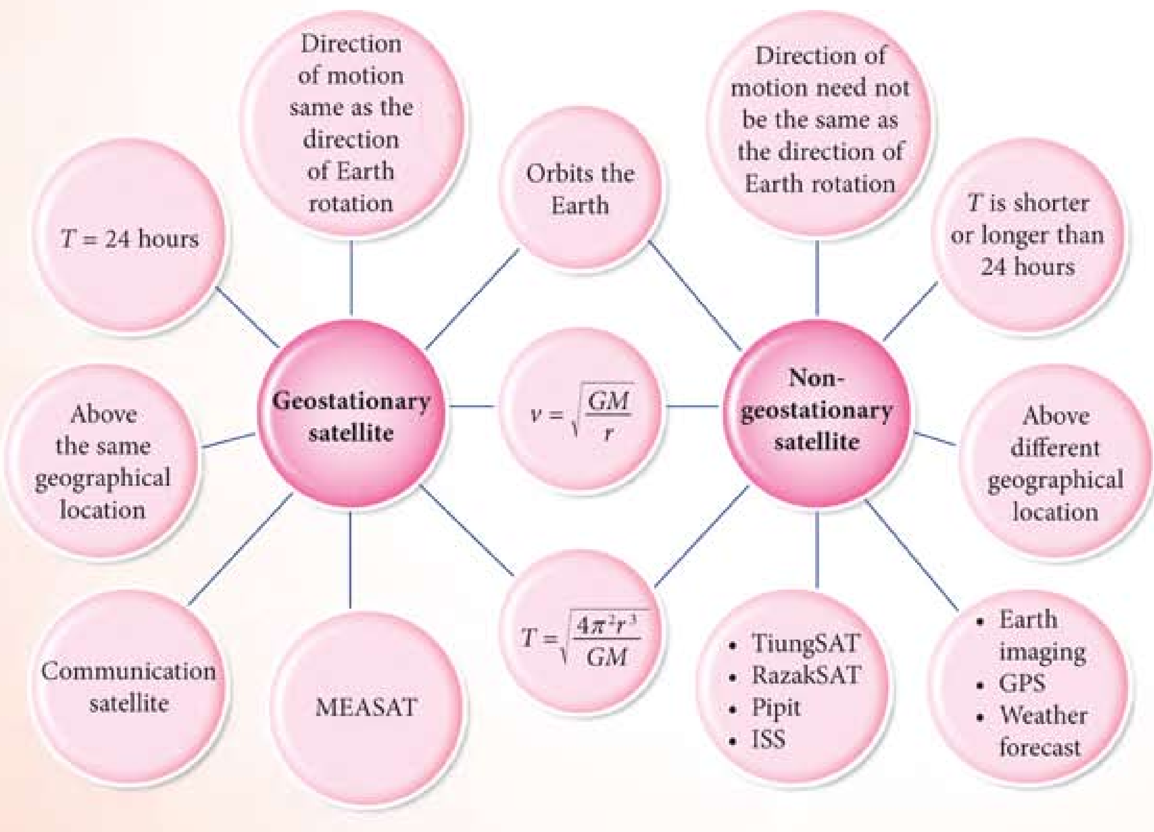


***Figure 3.37** Comparison between geostationary and non-geostationary satellites*

Escape Velocity

Escape velocity, v is the minimum velocity needed by an object on the surface of the Earth to overcome the gravitational force and escape to outer space.

If the distance of an object from the centre of the Earth is r, the mass of the object is m, and the mass of the Earth is M, then the object possesses gravitational potential energy, $U = -\frac{GMm}{r}$.

Figure 3.38 shows an object launched at escape velocity, v. This object can overcome gravitational force and move an infinite distance from the Earth.

Escape velocity

http://bt.sasbadi.com/p4107a

http://bt.sasbadi.com/p4107b

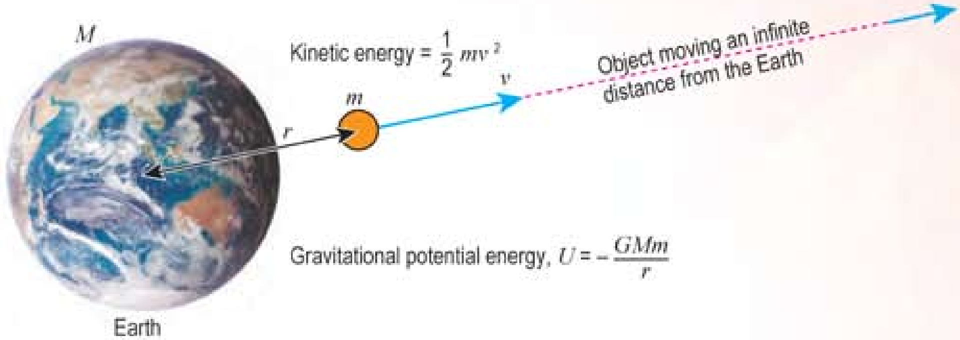


***Figure 3.38** Object launched at escape velocity*

Escape velocity is achieved when the minimum kinetic energy of an object is able to overcome its gravitational potential energy. As such:

Minimum kinetic energy + Gravitational potential energy = 0

that is, $\frac{1}{2}mv^2 + \left(-\frac{GMm}{r}\right) = 0$

$$v^2 = \frac{2GM}{r}$$

Escape velocity, $v = \sqrt{\frac{2GM}{r}}$

Info File

For an object on the surface of the Earth, its distance from the centre is the same as the radius of the Earth, R.

Escape velocity of the object is

$v = \sqrt{\frac{2GM}{R}}$

Mass of the Earth, $M = 5.97 \times 10^{24}$ kg
Radius of the Earth, $R = 6.37 \times 10^{6}$ m

Escape velocity from the Earth, $v = \sqrt{\frac{2GM}{R}}$

$$= \sqrt{\frac{2 \times (6.67 \times 10^{-11}) \times (5.97 \times 10^{24})}{(6.37 \times 10^{6})}}$$

$$= 1.12 \times 10^{4} \text{ m s}^{-1}$$
$$= 11.2 \times 10^{3} \text{ m s}^{-1}$$
$$= 11.2 \text{ km s}^{-1}$$

Info File

As the Earth has a large mass, escape velocity from the Earth has a high value, 11 200 m s^{-1} or 40 300 km h^{-1}.

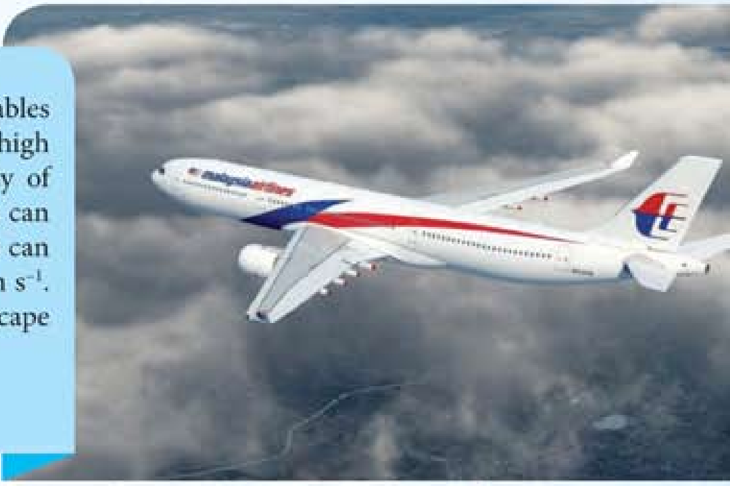
Escape velocity, v of an object depends on the mass of the Earth, M and distance, r of the object from the centre of the Earth. Escape velocity does not depend on mass of the object, m.

Benefits and Implications of Escape Velocity

High escape velocity of the Earth, that is 11 200 m s^{-1} has benefits and implications on humans. One of the benefits is the Earth is able to maintain a layer of atmosphere around it. Molecules in the atmosphere move at average linear speed of 500 m s^{-1}, that is lower than the escape velocity from the Earth. As such, air molecules that are moving randomly will not be able to escape from the Earth into outer space.

Figure 3.39 *Earth's atmosphere*

High escape velocity of the Earth also enables commercial aircrafts or fighter jets to fly to high levels in the atmosphere without the possibility of escaping into outer space. Commercial aircrafts can fly at linear speed of 250 m s^{-1} while fighter jets can achieve supersonic linear speed of up to 2 200 m s^{-1}. Both their linear speeds are lower than the escape velocity from the Earth.



Photograph 3.1 *Commercial aircraft*

The launching of rockets requires large quantities of fuel to produce high thrust that enables the rocket to achieve escape velocity of the Earth. Hence, it can send the spacecraft into outer space.

Photograph 3.2 *Rocket launching*

Solving Problems Involving Escape Velocity

You have calculated escape velocity from the Earth using the formula $v = \sqrt{\frac{2GM}{R}}$. In fact, this formula can also be used to calculate escape velocity from other bodies such as the Moon, Mars and the Sun.

Activity 3.13

Logical Reasoning CPS

Aim: To discuss escape velocity from planets

Instructions:

1. Work in pairs.
2. Copy and complete Table 3.4 by calculating the value of escape velocity.

Table 3.4

Planet	Mass, M / kg	Radius, R / m	Escape velocity, v / m s^{-1}
Venus	4.87×10^{24}	6.05×10^{6}	
Mars	6.42×10^{23}	3.40×10^{6}	
Jupiter	1.90×10^{27}	6.99×10^{7}	

Escape velocity of Mars is low, therefore the gases are easier to escape to outer space. This causes the density of the atmosphere on Mars to be low (100 times less dense than Earth's atmosphere). Jupiter on the other hand has such a high escape velocity that hot gases on its surface cannot escape into outer space. Knowledge on escape velocity is important to determine how spacecrafts can land and take off safely from a planet.

Recall

Characteristics of planets in the Solar System

http://bt.sasbadi.com/p4109

Example 1

The Moon and the Sun are two bodies in the Solar System. Table 3.5 shows the values of the mass and radius of the Moon and the Sun. Compare:

(i) gravitational acceleration on the Moon and the Sun

(ii) escape velocity from the Moon and from the Sun

based on data provided in Table 3.5.

Table 3.5

Body	Mass, M / kg	Radius, R / m
Moon	7.35×10^{22}	1.74×10^{6}
Sun	1.99×10^{30}	6.96×10^{8}

Solution:

(i) Gravitational acceleration is calculated using the formula $g = \frac{GM}{R^2}$

The Moon

$$g = \frac{(6.67 \times 10^{-11}) \times (7.35 \times 10^{22})}{(1.74 \times 10^{6})^2}$$
$$= 1.62 \text{ m s}^{-2}$$

The Sun

$$g = \frac{(6.67 \times 10^{-11}) \times (1.99 \times 10^{30})}{(6.96 \times 10^{8})^2}$$
$$= 274.0 \text{ m s}^{-2}$$

(ii) Escape velocity is calculated using the formula $v = \sqrt{\frac{2GM}{R}}$

The Moon

$$v = \sqrt{\frac{2 \times (6.67 \times 10^{-11}) \times (7.35 \times 10^{22})}{1.74 \times 10^{6}}}$$
$$= 2.37 \times 10^{3} \text{ m s}^{-1}$$

The Sun

$$v = \sqrt{\frac{2 \times (6.67 \times 10^{-11}) \times (1.99 \times 10^{30})}{(6.96 \times 10^{8})}}$$
$$= 6.18 \times 10^{5} \text{ m s}^{-1}$$

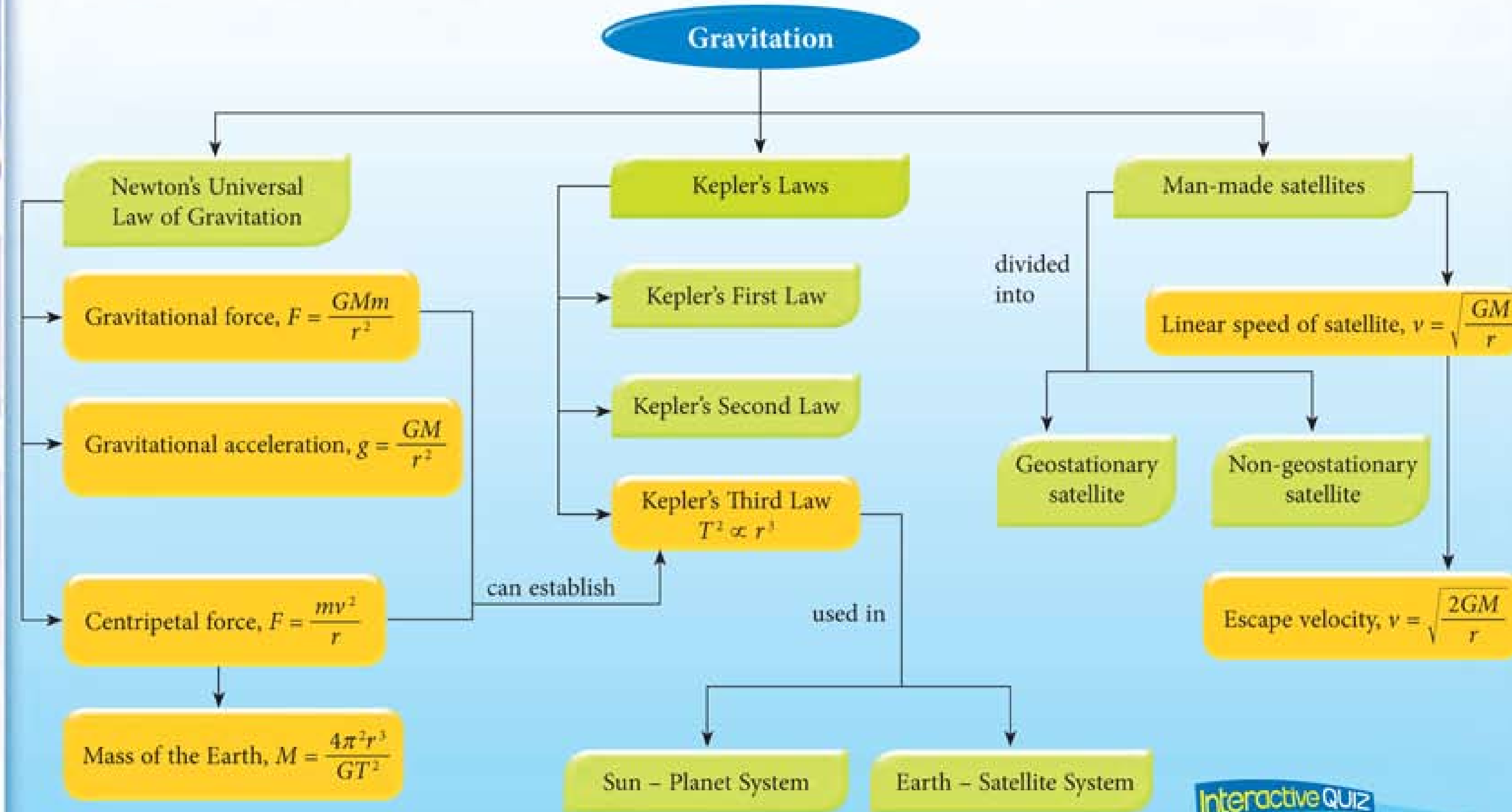
- The Moon has low gravitational acceleration and escape velocity because the mass of the Moon is smaller than that of the Sun.
- The Sun is the largest body in the Solar System. Gravitational acceleration on the Sun and escape velocity from the Sun have the highest values compared with those of the Moon as well as other planets.

Formative Practice 3.3

1. Compare and contrast geostationary and non-geostationary satellites.
2. What factors determine the linear speed of satellites orbiting the Earth?
3. State two factors which influence the value of escape velocity from a planet.
4. Discuss whether escape velocity from the Earth for spacecraft X of mass 1 500 kg is different from spacecraft Y of mass 2 000 kg.
5. Proba-1 satellite orbits the Earth at a height of 700 km. What is the linear speed of this satellite?

   [$G = 6.67 \times 10^{-11}$ N m^2 kg^{-2}, mass of the Earth = 5.97×10^{24} kg, radius of the Earth = 6.37×10^{6} m]

Conceptual Framework



Interactive QUIZ

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SELF-REFLECTION

1. New things I learnt in this chapter on gravitation are ____________.
2. The most interesting thing I learnt in this chapter on gravitation is ____________.
3. Things I still do not fully understand or comprehend are ____________.
4. My performance in this chapter,

   Poor | 1 | 2 | 3 | 4 | 5 | Excellent

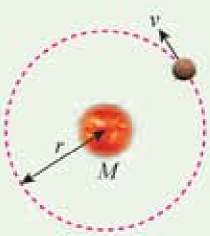
5. I need to ____________ to improve my performance in this chapter.

Download and print Self-reflection Chapter 3

http://bt.sasbadi.com/p4112

Performance Evaluation

1. Figure 1 shows planet Mars orbits the Sun in a circular motion with orbital period, T.



m = mass of Mars
M = mass of the Sun
r = radius of orbit of Mars
v = linear speed of Mars

Figure 1

(a) For planet Mars, write the formula for:
   (i) gravitational force in terms of m, M and r
   (ii) centripetal force in terms of m, v and r
   (iii) linear speed in terms of r and T

(b) Derive an expression for the mass of the Sun in terms of r and T by using the three formulae in (a).

(c) Radius of orbit of Mars is $r = 2.28 \times 10^{11}$ m and its orbital period is $T = 687$ days. Calculate the mass of the Sun.

2. A satellite orbits the Earth with radius, r and orbital period, T.
   (a) Write down the linear speed of the satellite in terms of r and T.
   (b) Use other suitable formulae to establish the formula for linear speed of the satellite in terms of r and M. M is the mass of the Earth.
   (c) Why does the linear speed of a satellite orbiting the Earth not depend on the mass of the satellite?

3. Figure 2 shows the orbit of planet Uranus.

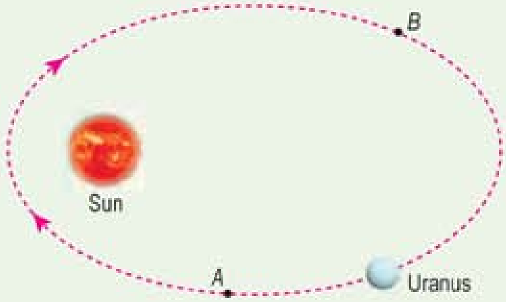


Figure 2

Describe the change in linear speed of planet Uranus when it moves from point A to point B.

4. Figure 3 shows the Earth, the Moon and a satellite.

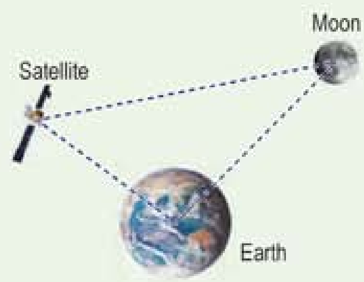


Figure 3

   (a) Which pair of bodies experience the smallest gravitational force?
   Give a reason for your answer.
   (b) Calculate the gravitational force between the Earth and the satellite.
   [Mass of the Earth = 5.97×10^{24} kg, mass of satellite = 1.2×10^{3} kg, distance between centre of the Earth and centre of the satellite = 7.87×10^{6} m]

5. (a) What are the factors that determine the value of the gravitational acceleration?
   (b) A satellite is at a distance of 4.20×10^{7} m from the centre of the Earth.
   What is the value of the gravitational acceleration at this position?
   [Mass of the Earth = 5.97×10^{24} kg]

6. Figure 4 shows the Earth and planet Neptune.

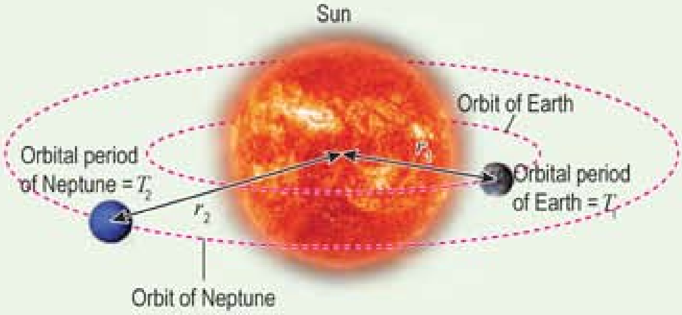


Figure 4

(a) Write down the relationship between orbital period and radius of orbit for the Earth and Neptune.

(b) Orbital period of the Earth is 365 days and radius of orbit of the Earth is 1.50×10^{11} m. Calculate the radius of orbit of Neptune if its orbital period is 5.98×10^4 days.

7. The Earth orbits the Sun with radius of orbit of 1.50×10^{11} m and orbital period of 1 year. Radius of orbit of planet Saturn is 1.43×10^{12} m. What is the orbital period of Saturn?

8. A spacecraft orbits the Earth at a height of 1 600 km. Calculate the escape velocity for the spacecraft.
[$G = 6.67 \times 10^{-11}$ N m^2 kg^{-2}, mass of the Earth = 5.97×10^{24} kg, radius of the Earth = 6.37×10^6 m]

9. Figure 5 shows planet Saturn with rings made up of small particles around it. Planet Saturn has a mass of 5.68×10^{26} kg and radius of 6.03×10^7 m.

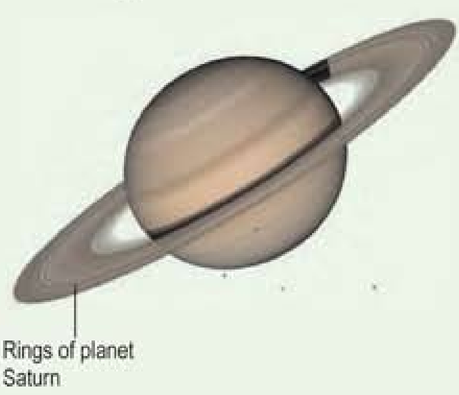


Figure 5

(a) Calculate the escape velocity of planet Saturn.

(b) Discuss the possibility of the small particles in the rings of planet Saturn escaping into the outer space.

10. Figure 6 shows three bodies *A*, *B* and *C*. It is given that the gravitational force between *A* and *B* is *P*.

Figure 6

State in terms of *P*, the gravitational force between
(i) *B* and *C*
(ii) *A* and *C*

11. Table 1 shows information on three types of orbits *X*, *Y* and *Z* for a satellite orbiting the Earth.

Table 1

Orbit	Shape of orbit	Height of orbit / m	Orbital period / hours
X	Ellipse	6.70×10^3	1.41
Y	Circle	3.59×10^7	24.04
Z	Circle	5.43×10^7	41.33

A space agency wishes to launch two satellites, *P* and *Q* to orbit the Earth. Satellite *P* is an Earth imaging satellite that can capture images of various locations on the surface of the Earth while satellite *Q* is a communication satellite.

Using the information in Table 1, determine which orbit is suitable for satellite *P* and satellite *Q*. Explain your choice.

12. Assume you are a scientist. Your group has found a new system of bodies. This system is made up of a star at the centre and five planets in a circular orbit around the star. Table 2 shows information on this system of bodies.

Table 2

Body	Mass / kg	Radius of body / m	Radius of orbit / m
Star	5.90×10^{29}	6.96×10^8	–
Planet *A*	2.80×10^{22}	1.07×10^6	2.86×10^{10}
Planet *B*	6.30×10^{23}	2.30×10^6	9.85×10^{10}
Planet *C*	7.40×10^{22}	3.41×10^6	1.15×10^{11}
Planet *D*	4.60×10^{25}	1.32×10^7	5.32×10^{11}
Planet *E*	1.90×10^{21}	2.42×10^5	2.13×10^{12}

(a) Calculate the gravitational acceleration, escape velocity and orbital period of each planet.

(b) How do the values of gravitational acceleration, escape velocity and orbital period influence the suitability of a new planet to be inhabited by humans?

(c) Choose the most suitable planet to be inhabited by humans. Give a reason for your choice.

Enrichment Corner

13. Assuming humans have successfully inhabited planet Mars. You and a group of scientists are required to invent a system of man-made satellites around Mars. These man-made satellites consist of weather satellites, planet surface mapping satellites and communication satellites. Table 3 shows information on planet Mars.

Table 3

Mass / kg	6.42×10^{23}
Radius of planet / m	3.40×10^{6}
Period of revolution / hours	24.6

Based on the information in Table 3, propose the characteristics of the satellite orbit in terms of orbital height, orbital period, linear speed of satellite, launch base as well as other suitable factors.