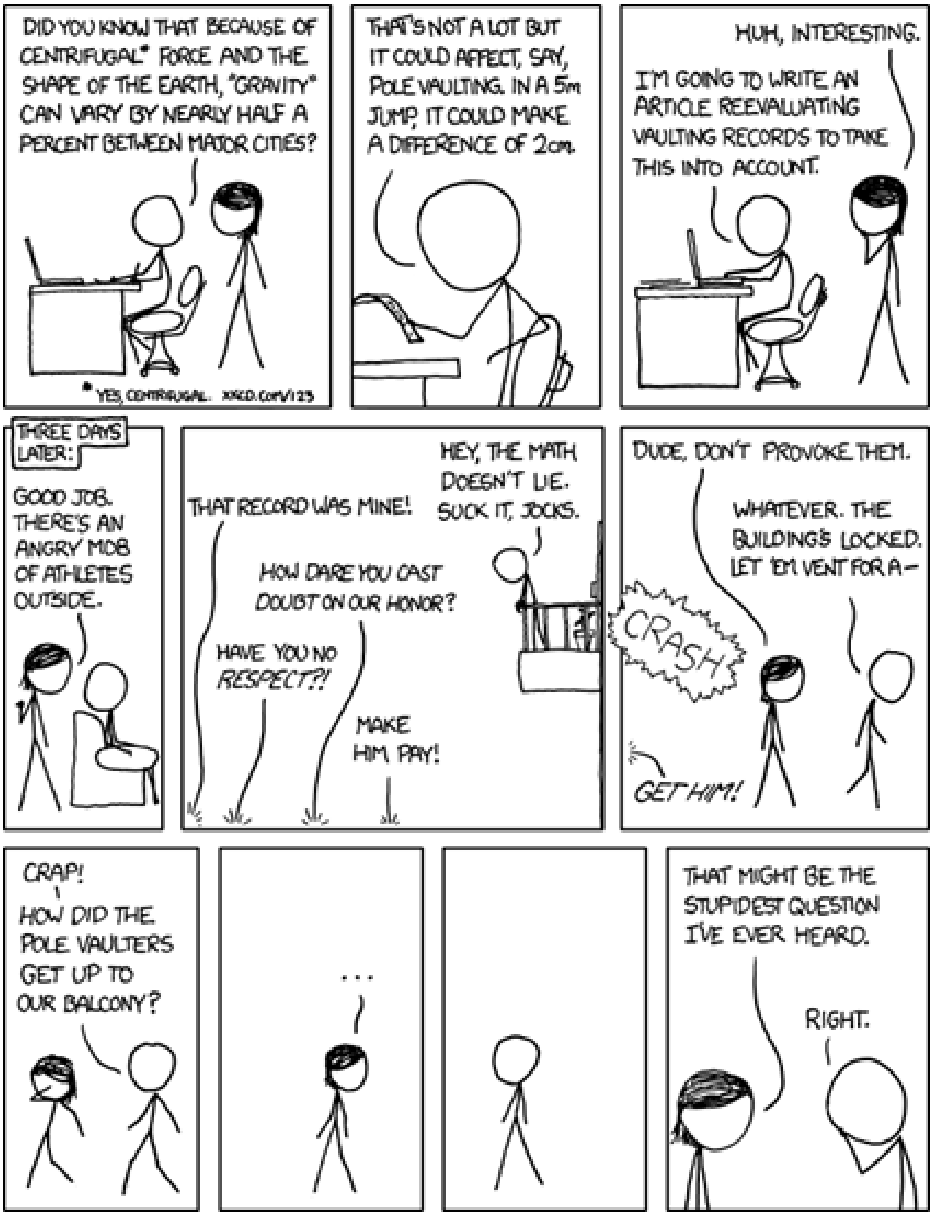
Advanced Higher Physics

Past Paper Questions

1.4 Gravitation



4. The NASA space probe Dawn has travelled to and orbited large asteroids in the solar system. Dawn has a mass of 1240 kg.

The table gives information about two large asteroids orbited by Dawn. Both asteroids can be considered to be spherical and remote from other large objects.

Name	*Mass* ($\times 10^{20}$ kg)	*Radius* (km)
Vesta	2·59	263
Ceres	9·39	473

(a) Dawn began orbiting Vesta, in a circular orbit, at a height of 680 km above the surface of the asteroid. The gravitational force acting on Dawn at this altitude was 24·1 N.

(i) Show that the tangential velocity of Dawn in this orbit is 135 m s^{-1}. **2**

(ii) Calculate the orbital period of Dawn. **3**

(b) Later in its mission, Dawn entered orbit around Ceres. It then moved from a high orbit to a lower orbit around the asteroid.

(i) State what is meant by the *gravitational potential of a point in space*. **1**

(ii) Dawn has a gravitational potential of $-1{\cdot}29 \times 10^4$ J kg^{-1} in the high orbit and a gravitational potential of $-3{\cdot}22 \times 10^4$ J kg^{-1} in the lower orbit.

Determine the change in the potential energy of Dawn as a result of this change in orbit. **4**

5. Two students are discussing objects escaping from the gravitational pull of the Earth. They make the following statements:

Student 1: A rocket has to accelerate until it reaches the escape velocity of the Earth in order to escape its gravitational pull.

Student 2: The moon is travelling slower than the escape velocity of the Earth and yet it has escaped.

Use your knowledge of physics to comment on these statements. **3**

3. A spacecraft is orbiting a comet as shown in Figure 3.

The comet can be considered as a sphere with a radius of $2 \cdot 1 \times 10^3$ m and a mass of $9 \cdot 5 \times 10^{12}$ kg.

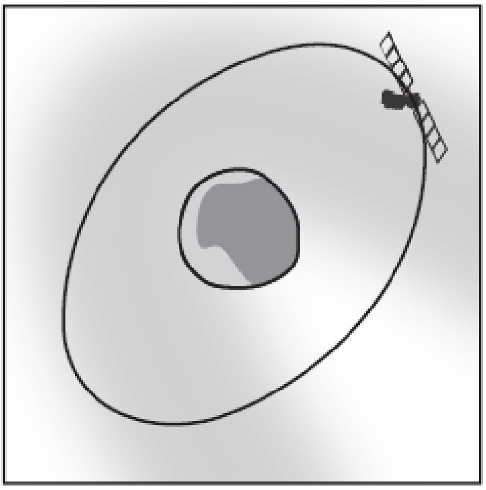


Figure 3 (not to scale)

(a) A lander was released by the spacecraft to land on the surface of the comet. After impact with the comet, the lander bounced back from the surface with an initial upward vertical velocity of $0 \cdot 38\ \text{m s}^{-1}$.

By calculating the escape velocity of the comet, show that the lander returned to the surface for a second time. 4

(b) (i) Show that the gravitational field strength at the surface of the comet is $1 \cdot 4 \times 10^{-4}\ \text{N kg}^{-1}$. 3

(ii) Using the data from the space mission, a student tries to calculate the maximum height reached by the lander after its first bounce.

The student's working is shown below

$$v^2 = u^2 + 2as$$

$$0 = 0 \cdot 38^2 + 2 \times \left(-1 \cdot 4 \times 10^{-4}\right) \times s$$

$$s = 515 \cdot 7\ \text{m}$$

The actual maximum height reached by the lander was not as calculated by the student.

State whether the actual maximum height reached would be greater or smaller than calculated by the student.

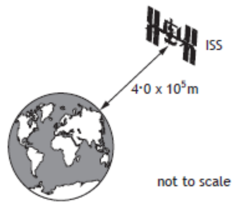
You must justify your answer. 3

3. The International Space Station (ISS) is in orbit around the Earth.

(a) (i) The gravitational pull of the Earth keeps the ISS in orbit.

Show that for an orbit of radius r the period T is given by the expression

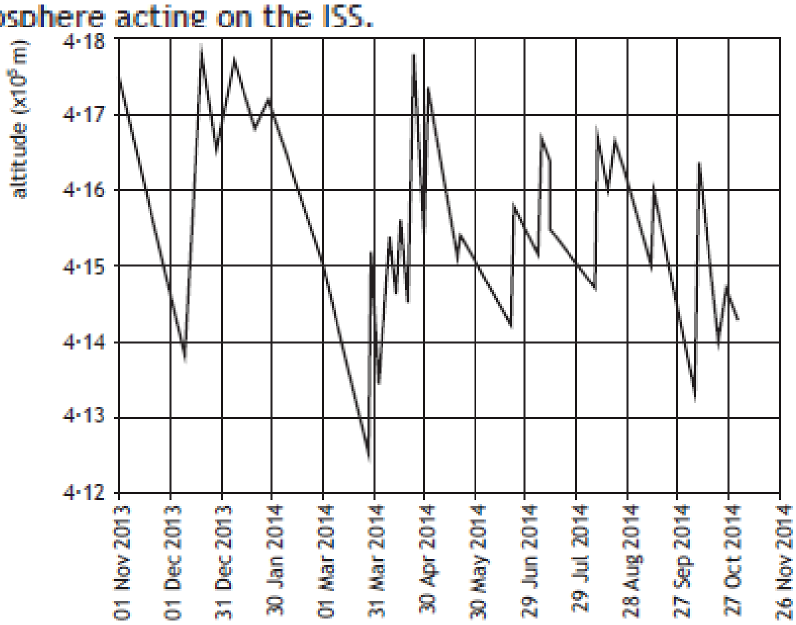
$$T = 2\pi\sqrt{\frac{r^3}{GM_E}}$$



where the symbols have their usual meaning. **2**

(ii) Calculate the period of orbit of the ISS when it is at an altitude of $4{\cdot}0 \times 10^5$ m above the surface of the Earth. **2**

(b) The graph in Figure 3B shows how the altitude of the ISS has varied over time. Reductions in altitude are due to the drag of the Earth's atmosphere acting on the ISS.



(i) Determine the value of Earth's gravitational field strength at the ISS on 1 March 2014. **4**

(ii) In 2011 the average altitude of the ISS was increased from 350 km to 400 km.

Give an advantage of operating the ISS at this higher altitude. **1**

(c) Clocks designed to operate on the ISS are synchronised with clocks on Earth before they go into space. On the ISS a correction factor is necessary for the clocks to remain synchronised with clocks on the Earth.

Explain why this correction factor is necessary. **2**

5. A team of astrophysicists from a Scottish University has discovered, orbiting a nearby star, an exoplanet with the same mass as Earth.

By considering the escape velocity of the exoplanet, the composition of its atmosphere can be predicted.

(a) Explain the term *escape velocity*. 1

(b) Derive the expression for escape velocity in terms of the exoplanet's mass and radius. 3

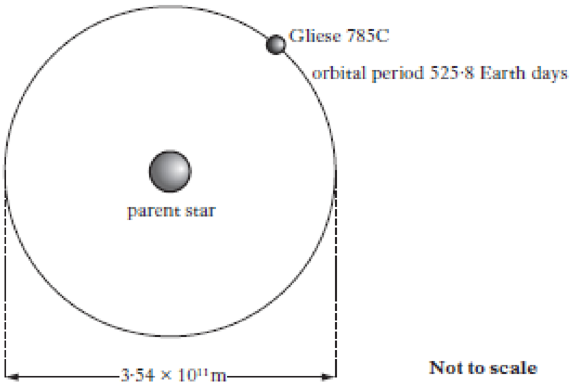
(c) The radius of the exoplanet is $1{\cdot}09 \times 10^{7}$ m.

Calculate the escape velocity of the exoplanet. 3

Revised 2015

3. (*a*) Many planets outside the Solar System have been discovered in recent years. These planets are known as exoplanets.

One exoplanet is Gliese 785C. Data relating to the circular orbit of Gliese 785C around its parent star is shown in Figure 3A.



(i) Show that the mass *M* of the parent star can be written as

$$M = \frac{4\pi^2 r^3}{GT^2}$$

where the other symbols have their usual meanings. 2

(ii) Determine the mass of the parent star. 2

(*b*) Consider the Earth and Moon as an isolated system.

Point X is $3\cdot00 \times 10^8$ m from the centre of the Earth as shown in Figure 3B.

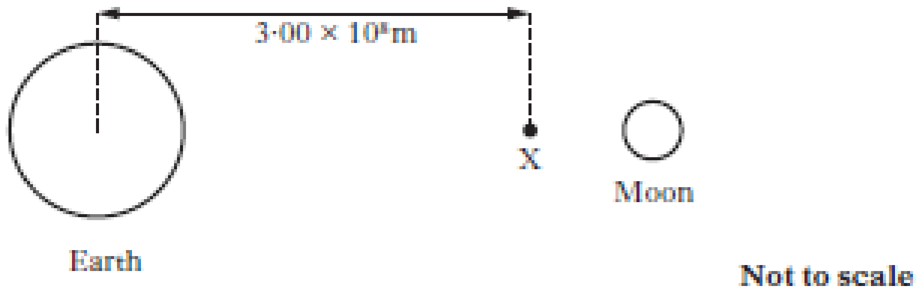


Figure 3B

(i) Calculate the magnitude of the resultant force acting on a 2·0 kg mass at point X. **3**

(ii) Calculate the gravitational potential at point X due to the Earth. **2**

(iii) By considering its definition, explain why the gravitational potential at any point has a negative value. **2**

(11)

2015

3. The International Space Station (ISS) is in orbit around the Earth. **MARKS**

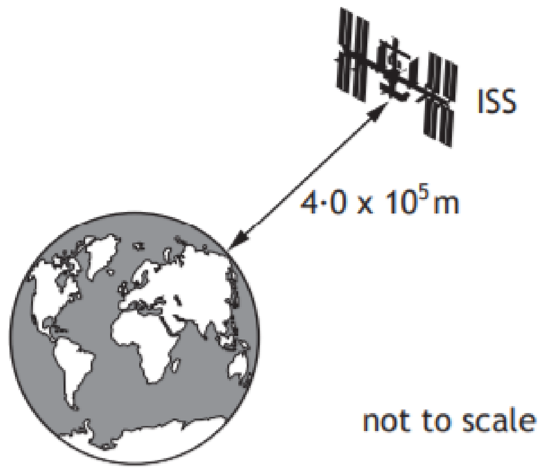


Figure 3A

(a) (i) The gravitational pull of the Earth keeps the ISS in orbit.

Show that for an orbit of radius r the period T is given by the expression

$$T = 2\pi\sqrt{\frac{r^3}{GM_E}}$$

where the symbols have their usual meaning. **2**

(ii) Calculate the period of orbit of the ISS when it is at an altitude of $4 \cdot 0 \times 10^5$ m above the surface of the Earth. **2**

(b) The graph in Figure 3B shows how the altitude of the ISS has varied over time. Reductions in altitude are due to the drag of the Earth's atmosphere acting on the ISS.

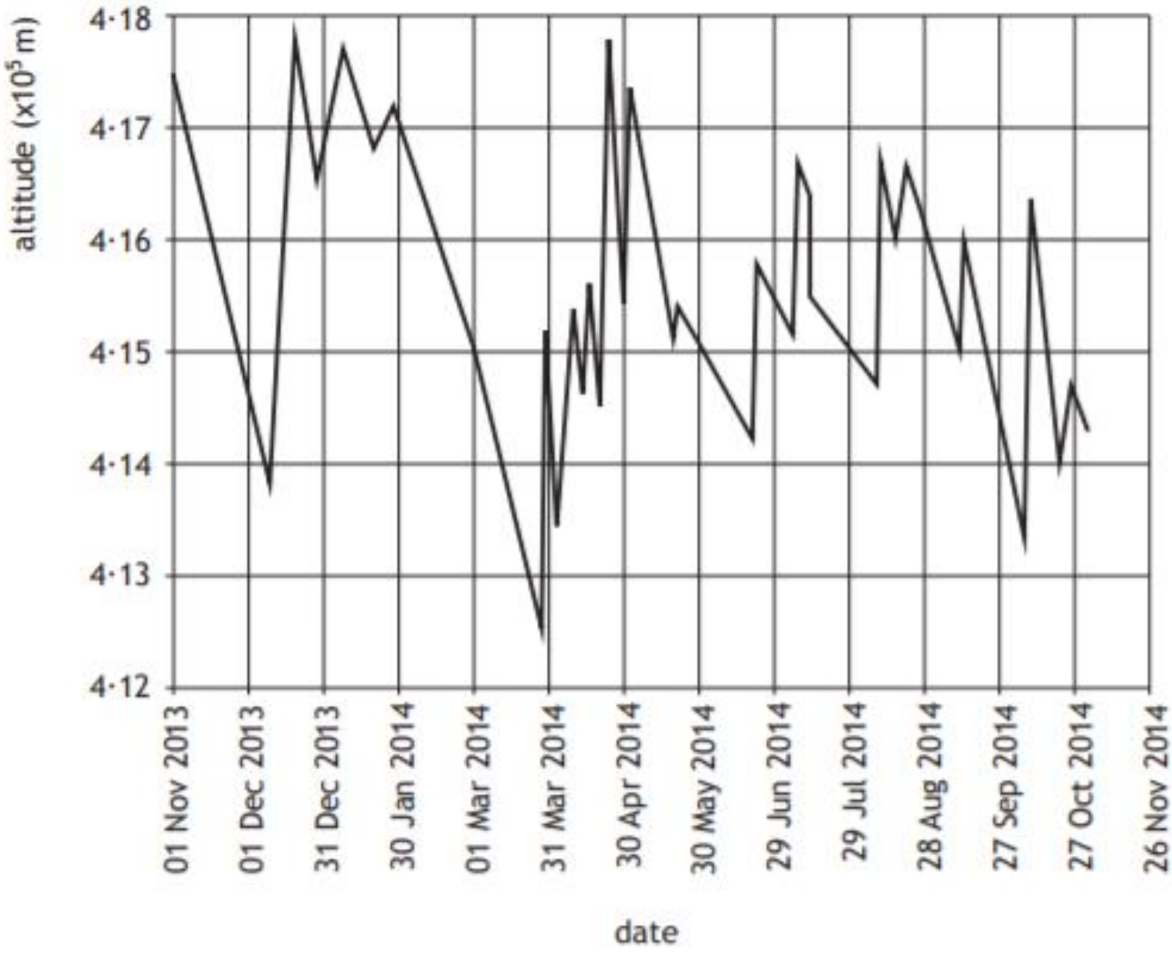


Figure 3B

(i) Determine the value of Earth's gravitational field strength at the ISS on 1 March 2014. **4**

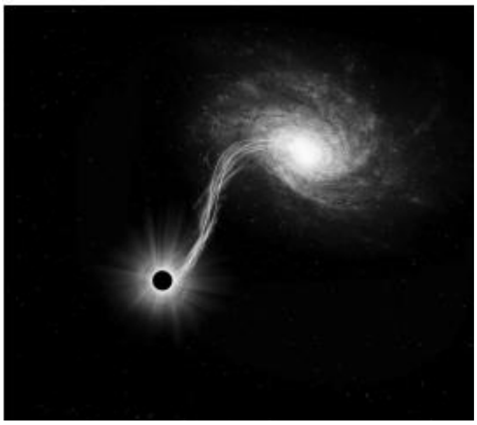
(ii) In 2011 the average altitude of the ISS was increased from 350 km to 400 km.

Give an advantage of operating the ISS at this higher altitude. **1**

(c) Clocks designed to operate on the ISS are synchronised with clocks on Earth before they go into space. On the ISS a correction factor is necessary for the clocks to remain synchronised with clocks on the Earth.

Explain why this correction factor is necessary. **2**

4. Cygnus X-1 is an X-ray source in the constellation Cygnus that astrophysicists believe contains a black hole. An artist's impression is shown in Figure 4A.



The mass of the black hole has been determined to be 14·8 Solar masses.

(*a*) (i) State what is meant by the Schwarzschild radius of a black hole. **1**

(ii) Calculate the Schwarzschild radius of the black hole in Cygnus X-1. **3**

3. A team of astrophysicists from a Scottish University has discovered, orbiting a nearby star, an exoplanet with the same mass as Earth.

By considering the escape velocity of the exoplanet, the composition of its atmosphere can be predicted.

(*a*) (i) Explain the term *escape velocity*. **1**

(ii) Derive the expression for escape velocity in terms of the exoplanet's mass and radius. **2**

(iii) The radius of this exoplanet is 1·7 times that of the Earth.

Calculate the escape velocity of the exoplanet. **3**

(*b*) Astrophysicists consider that a gas will be lost from the atmosphere of a planet if the typical molecular velocity (v_{rms}) is $\frac{1}{6}$ or more of the escape velocity for that planet.

The table below gives v_{rms} for selected gases at 273 K.

Gas	v_{rms} (m s^{-1})
Hydrogen	1838
Helium	1845
Nitrogen	493
Oxygen	461
Methane	644
Carbon dioxide	393

The atmospheric temperature of this exoplanet is 273 K.

Predict which of these gases could be found in its atmosphere. **2**

(8)

Marks

3. Planets outside our solar system are called exoplanets.

One exoplanet moves in a circular orbit around a star as shown in Figure 3.

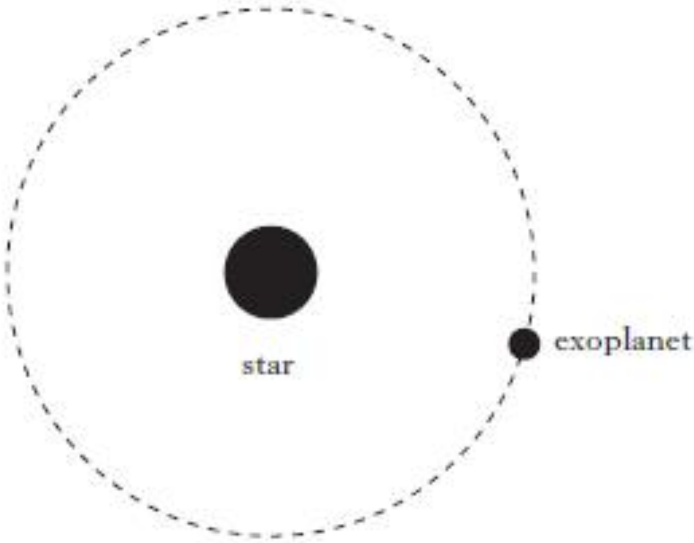


Figure 3

The period of orbit is 14 days. The mass M_s of the star is $1{\cdot}7 \times 10^{30}$ kg.

(*a*) (i) Show that the radius of the orbit can be given by the relationship

$$r^3 = GM_s \frac{T^2}{4\pi^2}$$

where the symbols have their usual meaning. **2**

(ii) Calculate the radius of this orbit. **1**

(*b*) The radius of the exoplanet is $1{\cdot}2 \times 10^8$ m and its mass is $5{\cdot}4 \times 10^{26}$ kg. Calculate the value of the gravitational field strength g on the surface of the exoplanet. **2**

(*c*) Astrophysicists have identified many black holes in the universe.

(i) State what is meant by the term *black hole*. **1**

(ii) A newly discovered object has a mass of $4{\cdot}2 \times 10^{30}$ kg and a radius of $2{\cdot}6 \times 10^4$ m.

Show by calculation whether or not this object is a black hole. **2**

(8)

4. (*a*) Show that the gravitational field strength at the surface of Pluto, mass M_p, is given by

$$g = \frac{GM_p}{r^2}$$

where the symbols have their usual meanings. **1**

(*b*) Figure 4A shows how the gravitational potential varies with distance from the centre of Pluto.

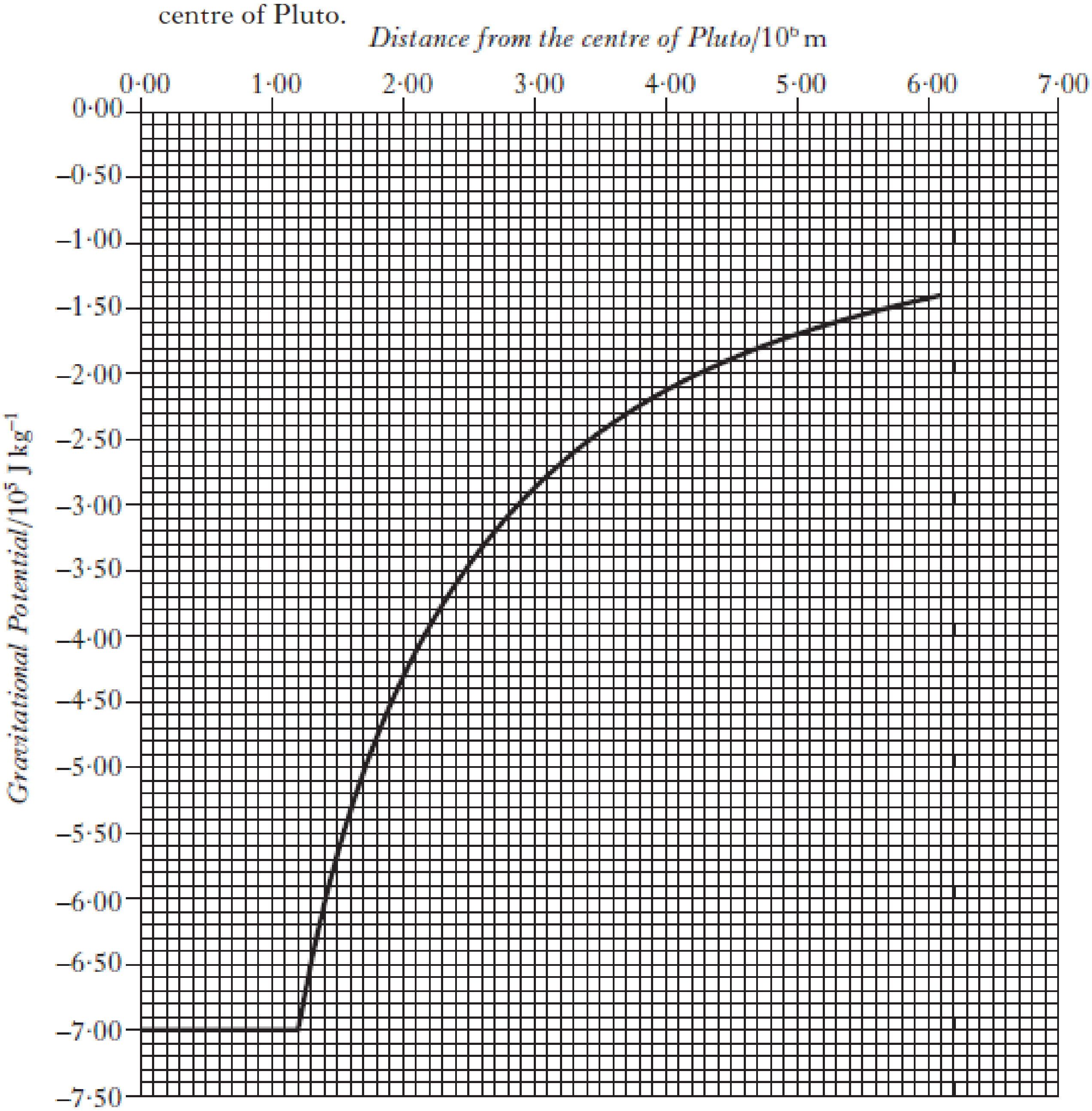


Figure 4A

(i) The mass of Pluto is $1{\cdot}27 \times 10^{22}$ kg. Calculate the gravitational field strength at the surface of Pluto. **2**

(ii) A meteorite hits the surface of Pluto and ejects a lump of ice of mass 112 kg. The ice is captured in an orbit $1{\cdot}80 \times 10^6$ m from the centre of Pluto. Calculate the gravitational potential energy of the ice at this height. **2** (*c*) In 2015 the New Horizons space probe is due to arrive at Pluto. The space probe will move between Pluto and its moon, Charon, as shown in Figure 4B. Pluto has a mass seven times that of Charon and their average separation is $1{\cdot}96 \times 10^7$ m.

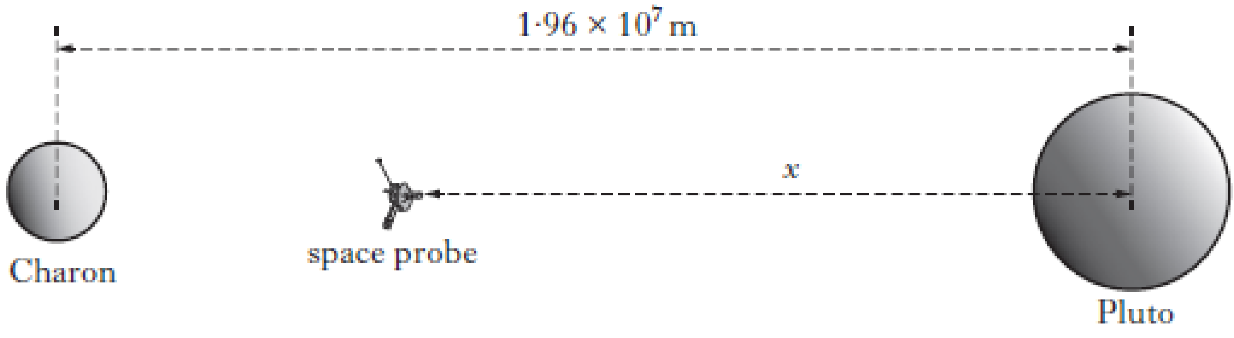


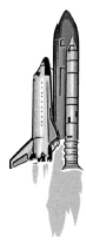
Figure 4B

Calculate the distance x from the centre of Pluto where the resultant gravitational force acting on the probe is zero. Ignore any orbital motion of the two objects. **3**

(8)

Traditional 2011

1. Figure 1A shows a space shuttle shortly after take-off.



(*a*) Immediately after take off, the vertical displacement of the shuttle for part of its journey can be described using the equation

$$s = 3{\cdot}1t^2 + 4{\cdot}1t.$$

(i) Find, by differentiation, the equation for the vertical velocity of the shuttle. **1**

(ii) At what time will the vertical velocity be 72 m s^{-1}? **2**

(iii) Calculate the vertical linear acceleration during this time. **1**

(*b*) A theory suggests that a burned out star can collapse to form a black hole.

(i) Explain why a *black hole* appears black. **1**

(ii) Explain the term *escape velocity*. **1**

(iii) Derive an expression for the escape velocity at the surface of a star of mass M and radius r. **2**

(iv) A star collapses to form a black hole of mass $4{\cdot}58 \times 10^{30}$ kg. Even in these extreme conditions the expression in part (iii) applies. Calculate the maximum radius of the black hole. **2**

(v) Calculate the minimum density ρ of this black hole. **3**

(13)

Marks

3. An X-ray binary system consists of a star in a **circular** orbit around a black hole as shown in Figure 3A.

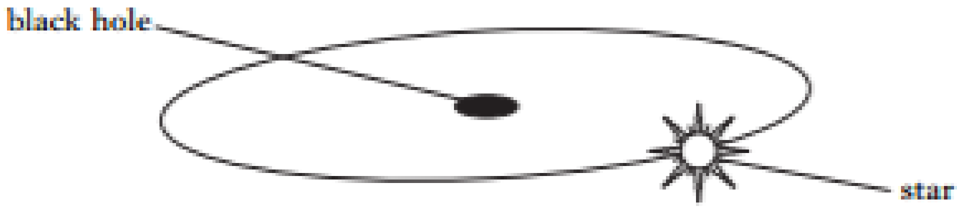


Figure 3A

The star has a mass of $2 \cdot 0 \times 10^{30}$ kg and takes 5·6 days to orbit the black hole. The orbital radius is $3 \cdot 6 \times 10^{10}$ m.

(*a*) Show that the angular velocity of the star is $1 \cdot 3 \times 10^{-5}$ rad s^{-1}. **1**

(*b*) Calculate the mass of the black hole. **3**

(*c*) (i) Show that the potential energy of the star in its orbit is $-4 \cdot 4 \times 10^{41}$ J. **1**

(ii) Calculate the kinetic energy of the star. **2**

(iii) Calculate the total energy of the star due to its motion and position. **1**

(*d*) The binary system orbits in the same plane as an earth-based telescope, as shown in Figure 3B.

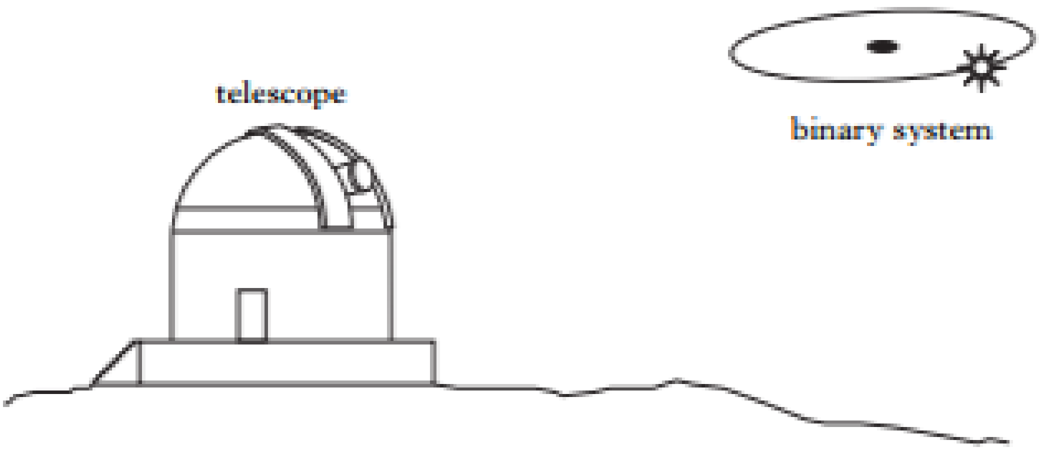


Figure 3B

Light from the star is analysed and found to contain the emission spectrum of hydrogen gas. The frequency of a particular line in the spectrum is monitored and a periodic variation in frequency is recorded.

Explain the periodic variation in the frequency. **2**

(10)

Marks

1. Figure 1A shows a space shuttle shortly after take-off.

Figure 1A

(*a*) Immediately after take off, the vertical displacement of the shuttle for part of its journey can be described using the equation

$$s = 3{\cdot}1t^2 + 4{\cdot}1t.$$

(i) Find, by differentiation, the equation for the vertical velocity of the shuttle. **1**

(ii) At what time will the vertical velocity be $72\,\text{m}\,\text{s}^{-1}$? **2**

(iii) Calculate the vertical linear acceleration during this time. **1**

(*b*) A theory suggests that a burned out star can collapse to form a black hole.

(i) Explain why a *black hole* appears black. **1**

(ii) Explain the term *escape velocity*. **1**

(iii) Derive an expression for the escape velocity at the surface of a star of mass M and radius r. **2**

(iv) A star collapses to form a black hole of mass $4{\cdot}58 \times 10^{30}$ kg. Even in these extreme conditions the expression in part (iii) applies. Calculate the maximum radius of the black hole. **2**

(v) ~~Calculate the minimum density ρ of this black hole.~~ **3**

(13)

Marks

2. (*a*) The gravitational field strength g on the surface of Mars is $3{\cdot}7\ \text{N kg}^{-1}$.
The mass of Mars is $6{\cdot}4 \times 10^{23}$ kg.
Show that the radius of Mars is $3{\cdot}4 \times 10^{6}$ m. **2**

(*b*) (i) A satellite of mass m has an orbit of radius R. Show that the angular velocity ω of the satellite is given by the expression

$$\omega = \sqrt{\frac{GM}{R^3}}$$

where the symbols have their usual meanings. **2**

(ii) A satellite remains above the same point on the equator of Mars as the planet spins on its axis.

Figure 4 shows this satellite orbiting at a height of $1{\cdot}7 \times 10^{7}$ m above the Martian surface.

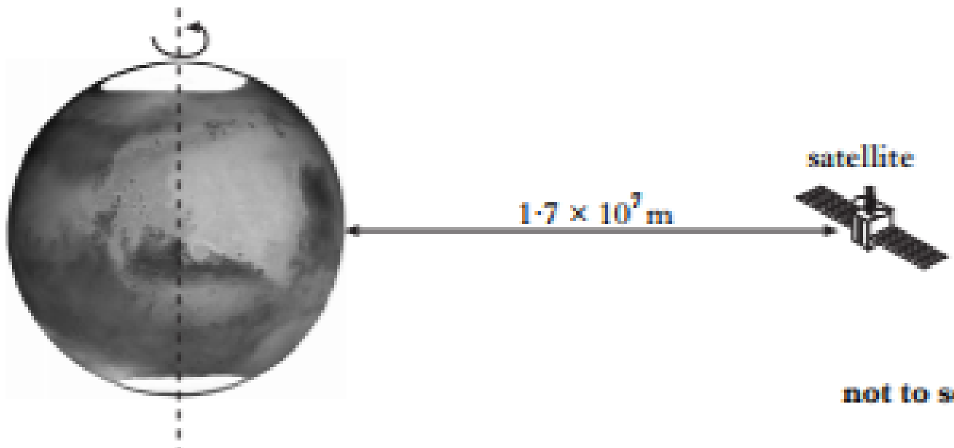


Figure 4

Calculate the angular velocity of the satellite. **2**

(iii) Calculate the length of one Martian day. **2**

(*c*) The following table gives data about three planets orbiting the Sun.

Planet	Radius R of orbit around the Sun/10^9 m	Orbit period T around the Sun/years
Venus	108	0·62
Mars	227	1·88
Jupiter	780	12·0

Use **all** the data to show that T^2 is directly proportional to R^3 for these three planets. **3**

Traditional 2007

Marks

3. (*a*) The Moon orbits the Earth due to the gravitational force between them.

   (i) Calculate the magnitude of the gravitational force between the Earth and the Moon. **2**

   (ii) Hence calculate the tangential speed of the Moon in its orbit around the Earth. **2**

   (iii) Define the term *gravitational potential* at a point in space. **1**

   (iv) Calculate the potential energy of the Moon in its orbit. **2**

   (v) Hence calculate the total energy of the Moon in its orbit. **2**

   (*b*) (i) Derive an expression for the escape velocity from the surface of an astronomical body. **2**

   (ii) Calculate the escape velocity from the surface of the Moon. **2**

(13)

Traditional 2006

Marks

3. (*a*) (i) State what is meant by *gravitational field strength*. **1**

   (ii) The gravitational field strength at the surface of Mars is 3·7 $N\,kg^{-1}$.

   The radius of Mars is $3{\cdot}4 \times 10^3$ km.

   (A) Use Newton's universal law of gravitation to show that the mass of Mars is given by the equation

$$M = \frac{gr^2}{G}$$

   where the symbols have their usual meaning.

   (B) Calculate the mass of Mars. **3**

   (*b*) A spacecraft of mass 100 kg is in circular orbit 300 km above the surface of Mars.

   (i) Show that the force exerted by Mars on the spacecraft is $3{\cdot}1 \times 10^2$ N. **2**

   (ii) Calculate the period of the spacecraft's orbit. **3**

(9)

Marks

3. (*a*) (i) A satellite orbits a planet of mass M. The orbital radius of the satellite is R and the orbital period is T.
Show that

$$T^2 = \frac{4\pi^2 R^3}{GM}.$$ **2**

(ii) Calculate the time taken by the Moon to make one complete orbit of the Earth. **2**

(*b*) A satellite orbits 400 km above the Earth's surface as shown in Figure 4.

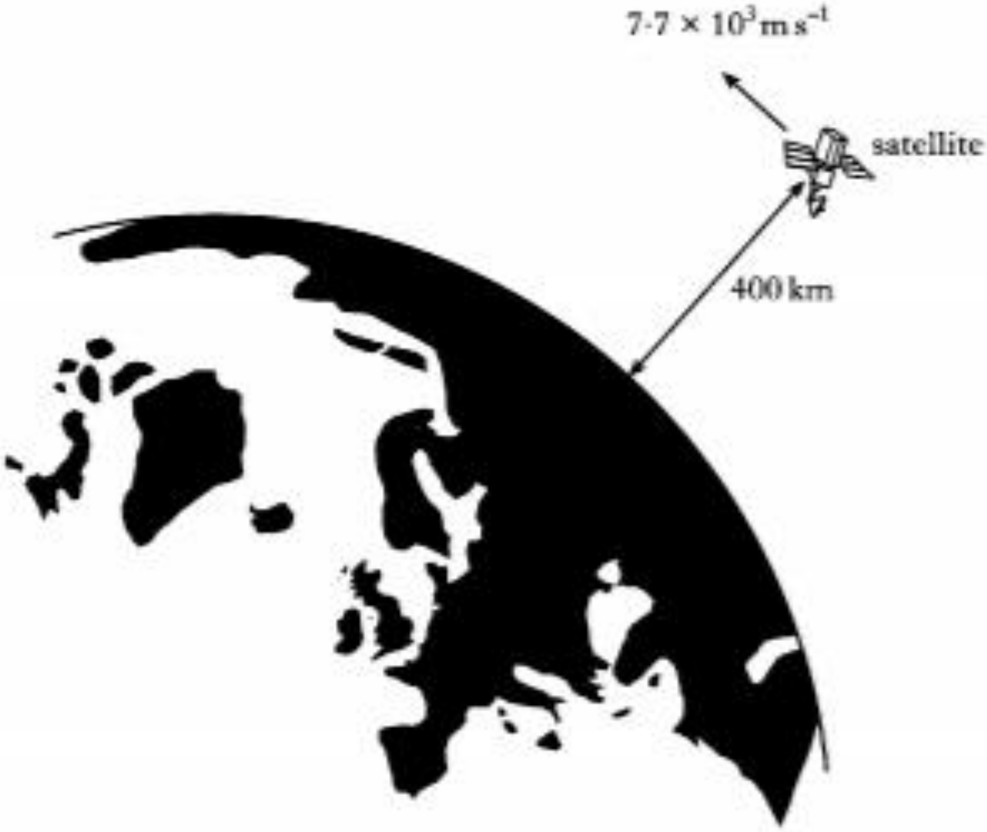


Figure 4

The satellite has a mass of 900 kg and a speed of $7{\cdot}7 \times 10^3\,m\,s^{-1}$.

(i) Show that the potential energy of the satellite is $-5{\cdot}3 \times 10^{10}$ J. **2**

(ii) Calculate the total energy of the satellite. **2**

(8)

Marks

4. The gravitational pull of the Earth keeps a satellite in a circular orbit.

(*a*) Show that for an orbit of radius r the period T is given by

$$T = 2\pi\sqrt{\frac{r^3}{GM_E}}$$

where the symbols have their usual meanings. 2

(*b*) A polar orbiting satellite is used to map the Earth by photographing strips of the surface as it orbits, as shown in Figure 4.

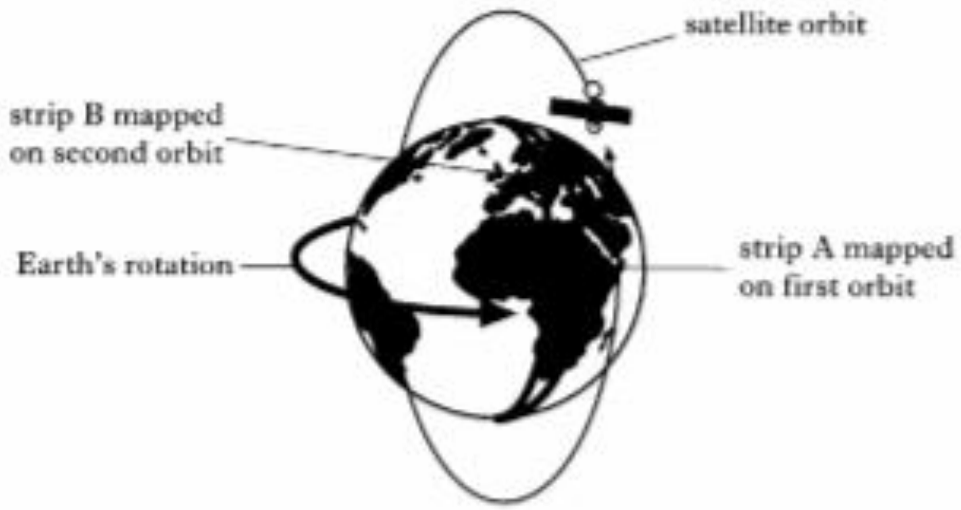


Figure 4

The plane of the satellite orbit is fixed. The Earth rotates and so the satellite maps a different strip on each orbit.

(i) The satellite orbits at a height of 80 km above the surface of the Earth. Assuming the Earth to be spherical, show that the period of the orbit is approximately 86 minutes.

(ii) The Earth's angular velocity is $7 \cdot 3 \times 10^{-5}$ rad s^{-1}.
Calculate the distance along the equator between strips A and B which are mapped on consecutive orbits. 4

(6)

Marks

4. The gravitational pull of the Earth keeps a satellite in a circular orbit.

(a) Show that for an orbit of radius r the period T is given by

$$T = 2\pi\sqrt{\frac{r^3}{GM_E}}$$

where the symbols have their usual meanings. **2**

(b) A polar orbiting satellite is used to map the Earth by photographing strips of the surface as it orbits, as shown in Figure 4.

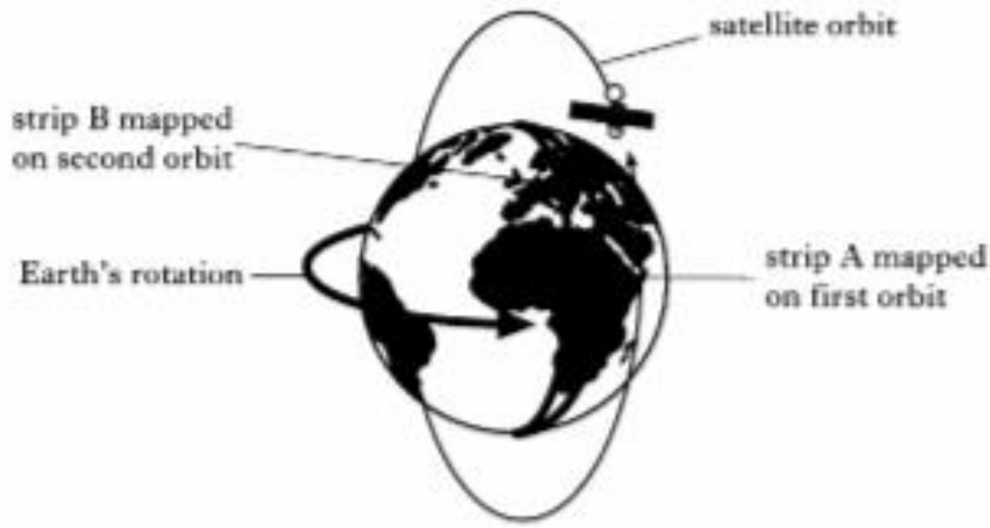


Figure 4

The plane of the satellite orbit is fixed. The Earth rotates and so the satellite maps a different strip on each orbit.

(i) The satellite orbits at a height of 80 km above the surface of the Earth. Assuming the Earth to be spherical, show that the period of the orbit is approximately 86 minutes.

(ii) The Earth's angular velocity is $7 \cdot 3 \times 10^{-5}$ rad s^{-1}.
Calculate the distance along the equator between strips A and B which are mapped on consecutive orbits. **4**

(6)

MARKS

3. (*a*) Figure 6 shows the Earth and the Moon, not drawn to scale.

Copy and complete the diagram to show the shape of the gravitational field lines between the Earth and the Moon. **2**

Figure 6

(*b*) Near the Moon the gravitational field can be considered to be radial.

Following a meteorite impact, a rock of mass 15 kg is ejected vertically from the Moon's surface. The rock just reaches a point P, which is $5{\cdot}0 \times 10^5$ m above the surface of the Moon.

The radius of the Moon is $1{\cdot}7 \times 10^6$ m.

(i) Calculate the potential energy of the rock:

(A) on the surface of the Moon;

(B) at point P.

(ii) Hence calculate the kinetic energy of the rock as it leaves the surface of the Moon.

(iii) Calculate the speed at which the rock is ejected from the surface of the Moon. **6**

(8)

Marks

3. (*a*) The gravitational force exerted by the Earth maintains a satellite in a circular orbit of radius *r*.

By equating the expressions for gravitational force and centripetal force, show that

$$r^3 = \frac{GM_E}{4\pi^2}T^2$$

where the symbols have their usual meanings. **2**

(*b*) The orbital period of a geostationary satellite is equal to the period of rotation of the Earth about its axis.

Calculate:

(i) the height of the satellite above the Earth's surface;

(ii) the speed of the satellite in its orbit. **5**

(*c*) Another satellite is in an orbit of radius $6{\cdot}7 \times 10^6$ m around the Earth. This satellite is to be boosted to escape velocity.

(i) Explain the term "escape velocity".

(ii) Use the expression

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

to calculate the escape velocity. **3**

(10)

3. (*a*) Pallas is an asteroid or minor planet which orbits the Sun between Mars and Jupiter.

Details of Pallas are given below.

Diameter of Pallas = 522 km

Distance from the Sun = $4{\cdot}14 \times 10^{11}$ m

Mass of Pallas = $2{\cdot}18 \times 10^{20}$ kg

Time to orbit the Sun = 4·61 Earth years

(i) Calculate the gravitational field strength "g" at the surface of Pallas.

(ii) A future exploration might include putting a spacecraft in orbit around Pallas. Calculate the period of a spacecraft which orbits 10 km above the surface of Pallas. **5**

(*b*) (i) Relativistic mass is given by the equation

$$m = \frac{m_0}{\sqrt{1 - \frac{v^2}{c^2}}}$$

where the symbols have their usual meanings.

Calculate the speed a spacecraft would have to reach if its relativistic mass were to be ten times greater than its rest mass.

(ii) Science fiction often describes spacecraft reaching speeds greater than the speed of light. Use the equation to show that it is not possible for a spacecraft to exceed the speed of light. **3**

(8)