(a) Define *gravitational field strength* at a point in a gravitational field.

(b) Tides vary in height with the relative positions of the Earth, the Sun and the Moon which change as the Earth and the Moon move in their orbits. Two possible configurations are shown in Figure 1.

**Figure 1**

Consider a 1 kg mass of sea water at position $P$. This mass experiences forces $F_E$, $F_M$ and $F_S$ due to its position in the gravitational fields of the Earth, the Moon and the Sun respectively.

(i) Draw labelled arrows on both diagrams in Figure 1 to indicate the three forces experienced by the mass of sea water at $P$. 

(3)
(ii) State and explain which configuration, A or B, of the Sun, the Moon and the Earth will produce the higher tide at position P.

________________________________________________________________________

________________________________________________________________________

________________________________________________________________________

(2)

c) Calculate the magnitude of the gravitational force experienced by 1 kg of sea water on the Earth's surface at P, due to the Sun's gravitational field.

radius of the Earth's orbit = 1.5 × 10\(^{11}\) m

mass of the Sun = 2.0 × 10\(^{30}\) kg

universal gravitational constant, \(G\) = 6.7 × 10\(^{-11}\) Nm\(^2\) kg\(^{-2}\)

(Total 9 marks)

For an object, such as a space rocket, to escape from the gravitational attraction of the Earth it must be given an amount of energy equal to the gravitational potential energy that it has on the Earth's surface. The minimum initial vertical velocity at the surface of the Earth that it requires to achieve this is known as the escape velocity.

(a) (i) Write down the equation for the gravitational potential energy of a rocket when it is on the Earth's surface. Take the mass of the Earth to be \(M\), that of the rocket to be \(m\) and the radius of the Earth to be \(R\).

(1)

(ii) Show that the escape velocity, \(v\), of the rocket is given by the equation

\[ v = \sqrt{\frac{2GM}{R}} \]

(2)
(b) The nominal escape velocity from the Earth is 11.2 km s\(^{-1}\). Calculate a value for the escape velocity from a planet of mass four times that of the Earth and radius twice that of the Earth.

(c) Explain why the actual escape velocity from the Earth would be greater than the nominal value calculated from the equation given in part (a)(ii).

(2)

(a) State the law that governs the magnitude of the force between two point masses.

(2)

(Total 7 marks)
(b) The table shows how the gravitational potential varies for three points above the centre of
the Sun.

<table>
<thead>
<tr>
<th>distance from centre of Sun/10^8 m</th>
<th>gravitational potential/10^{10} J kg^{-1}</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.0 (surface of Sun)</td>
<td>-19</td>
</tr>
<tr>
<td>16</td>
<td>-8.3</td>
</tr>
<tr>
<td>35</td>
<td>-3.8</td>
</tr>
</tbody>
</table>

(i) Show that the data suggest that the potential is inversely proportional to the distance
from the centre of the Sun.

(ii) Use the data to determine the gravitational field strength near the surface of the Sun.
(iii) Calculate the change in gravitational potential energy needed for the Earth to escape from the gravitational attraction of the Sun.

- mass of the Earth = $6.0 \times 10^{24}$ kg
- distance of Earth from centre of Sun = $1.5 \times 10^{11}$ m

(iv) Calculate the kinetic energy of the Earth due to its orbital speed around the Sun and hence find the minimum energy that would be needed for the Earth to escape from its orbit. Assume that the Earth moves in a circular orbit.
(a) State, in words, Newton's law of gravitation.

___________________________________________________________________
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___________________________________________________________________
___________________________________________________________________
___________________________________________________________________
___________________________________________________________________
___________________________________________________________________

(2)

(b) Some of the earliest attempts to determine the gravitational constant, $G$, were regarded as experiments to “weigh” the Earth. By considering the gravitational force acting on a mass at the surface of the Earth, regarded as a sphere of radius $R$, show that the mass of the Earth is given by

$$M = \frac{gR^2}{G},$$

where $g$ is the value of the gravitational field strength at the Earth’s surface.

___________________________________________________________________
___________________________________________________________________
___________________________________________________________________
___________________________________________________________________

(2)

(c) In the following calculation use these data.

radius of the Moon = $1.74 \times 10^6$ m
gravitational field strength at Moon’s surface = $1.62$ N kg$^{-1}$
mass of the Earth $M$ = $6.00 \times 10^{24}$ kg
gravitational constant $G$ = $6.67 \times 10^{-11}$ N m$^2$ kg$^{-2}$
Both gravitational and electric field strengths can be described by similar equations written in the form

\[ a = \frac{bc}{d^2}. \]

(a) Complete the following table by writing down the names of the corresponding quantities, together with their SI units, for the two types of field.

<table>
<thead>
<tr>
<th>symbol</th>
<th>gravitational field quantity</th>
<th>SI unit</th>
<th>electrical field quantity</th>
<th>SI unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>gravitational field strength</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>b</td>
<td></td>
<td></td>
<td>( \frac{1}{4\pi\varepsilon_0} )</td>
<td>m F⁻¹</td>
</tr>
<tr>
<td>c</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>d</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(b) Two isolated charged objects, A and B, are arranged so that the gravitational force between them is equal and opposite to the electric force between them.

(i) The separation of A and B is doubled without changing their charges or masses. State and explain the effect, if any, that this will have on the resultant force between them.

______________________________________________________________________________________________________________________________________________________________
(ii) At the original separation, the mass of A is doubled, whilst the charge on A and the mass of B remain as they were initially. What would have to happen to the charge on B to keep the resultant force zero?

______________________________________________________________

______________________________________________________________

(3) (Total 7 marks)

Communications satellites are usually placed in a geo-synchronous orbit.

(a) State two features of a geo-synchronous orbit.

___________________________________________________________________

___________________________________________________________________

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___________________________________________________________________

(2)

(b) Given that the mass of the Earth is $6.00 \times 10^{24}$ kg and its mean radius is $6.40 \times 10^{6}$ m,

(i) show that the radius of a geo-synchronous orbit must be $4.23 \times 10^{7}$ m,

___________________________________________________________________

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(ii) calculate the increase in potential energy of a satellite of mass 750 kg when it is raised from the Earth’s surface into a geo-synchronous orbit.

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(6) (Total 8 marks)
(a) (i) Explain what is meant by \textit{gravitational field strength}.

(ii) Describe how you would measure the gravitational field strength close to the surface of the Earth. Draw a diagram of the apparatus that you would use.

(b) (i) The Earth’s gravitational field strength \((g)\) at a distance \((r)\) of \(2.0 \times 10^7\) m from its centre is \(1.0\) N kg\(^{-1}\). Complete the table with the 3 further values of \(g\).

<table>
<thead>
<tr>
<th>(g/\text{N kg}^{-1})</th>
<th>1.0</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>(r/10^7) m</td>
<td>2.0</td>
<td>4.0</td>
<td>6.0</td>
<td>8.0</td>
</tr>
</tbody>
</table>

(ii) Below is a grid marked with \(g\) and \(r\) values on its axes. Draw a graph showing the variation of \(g\) with \(r\) for values of \(r\) between \(2.0 \times 10^7\) m and \(10.0 \times 10^7\) m.

(iii) Estimate the energy required to raise a satellite of mass 800 kg from an orbit of radius \(4.0 \times 10^7\) m to one of radius \(10.0 \times 10^7\) m.
(a) (i) State the relationship between the gravitational potential energy, \( E_p \), and the gravitational potential, \( V \), for a body of mass \( m \) placed in a gravitational field.

______________________________________________________________

______________________________________________________________

(1)

(ii) What is the effect, if any, on the values of \( E_p \) and \( V \) if the mass \( m \) is doubled?

value of \( E_p \) _________________________________________________

value of \( V \) _________________________________________________

(2)

(b) The diagram above shows two of the orbits, A and B, that could be occupied by a satellite in circular orbit around the Earth, E. The gravitational potential due to the Earth of each of these orbits is:

\[
\begin{align*}
\text{orbit A} & \quad - 12.0 \text{ MJ kg}^{-1} \\
\text{orbit B} & \quad - 36.0 \text{ MJ kg}^{-1}.
\end{align*}
\]

(i) Calculate the radius, from the centre of the Earth, of orbit A.

answer = ____________________ m

(2)

(ii) Show that the radius of orbit B is approximately \( 1.1 \times 10^4 \) km.
(iii) Calculate the centripetal acceleration of a satellite in orbit B.

answer = ____________________ m s\(^{-2}\)  

(iv) Show that the gravitational potential energy of a 330 kg satellite decreases by about 8 GJ when it moves from orbit A to orbit B.

(c) Explain why it is not possible to use the equation \( \Delta E_p = mg\Delta h \) when determining the change in the gravitational potential energy of a satellite as it moves between these orbits.

___________________________________________________________________
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___________________________________________________________________
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(Total 10 marks)

A spacecraft of mass \( m \) is at the mid-point between the centres of a planet of mass \( M_1 \) and its moon of mass \( M_2 \). If the distance between the spacecraft and the centre of the planet is \( d \), what is the magnitude of the resultant gravitational force on the spacecraft?

A \( \frac{Gm(M_1 - M_2)}{d} \)

B \( \frac{Gm(M_1 + M_2)}{d^2} \)

C \( \frac{Gm(M_1 - M_2)}{d^2} \)

D \( \frac{Gm(M_1 + M_2)}{d} \)

(Total 1 mark)
10. Two satellites P and Q, of equal mass, orbit the Earth at radii \( R \) and \( 2R \) respectively. Which one of the following statements is correct?

A. P has less kinetic energy and more potential energy than Q.
B. P has less kinetic energy and less potential energy than Q.
C. P has more kinetic energy and less potential energy than Q.
D. P has more kinetic energy and more potential energy than Q.

(Total 1 mark)

11. A small mass is situated at a point on a line joining two large masses \( m_1 \) and \( m_2 \) such that it experiences no resultant gravitational force. Its distance from the centre of mass of \( m_1 \) is \( r_1 \) and its distance from the centre of mass of \( m_2 \) is \( r_2 \).

What is the value of the ratio \( \frac{r_1}{r_2} \)?

A. \( \frac{m_1^2}{m_2^2} \)
B. \( \frac{m_2^2}{m_1^2} \)
C. \( \sqrt{\frac{m_1}{m_2}} \)
D. \( \sqrt{\frac{m_2}{m_1}} \)

(Total 1 mark)

12. Which one of the following gives a correct unit for \( \frac{G^2}{\ell} \)?

A. N m\(^{-2}\)
B. N kg\(^{-1}\)
C. N m
D. N

(Total 1 mark)
The gravitational field strength at the surface of the Earth is 6 times its value at the surface of the Moon. The mean density of the Moon is 0.6 times the mean density of the Earth.

What is the value of the ratio \( \frac{\text{radius of Earth}}{\text{radius of Moon}} \)?

A 1.8  
B 3.6  
C 6.0  
D 10

(Total 1 mark)

The diagram shows two points, P and Q, at distances \( r \) and \( 2r \) from the centre of a planet.

The gravitational potential at P is \( -16 \text{ kJ kg}^{-1} \). What is the work done on a 10 kg mass when it is taken from P to Q?

A \( -120 \text{ kJ} \)  
B \( -80 \text{ kJ} \)  
C \( +80 \text{ kJ} \)  
D \( +120 \text{ kJ} \)

(Total 1 mark)

The Earth moves around the Sun in a circular orbit with a radius of \( 1.5 \times 10^8 \text{ km} \). What is the Earth’s approximate speed?

A \( 1.5 \times 10^3 \text{ ms}^{-1} \)  
B \( 5.0 \times 10^3 \text{ ms}^{-1} \)  
C \( 1.0 \times 10^4 \text{ ms}^{-1} \)  
D \( 3.0 \times 10^4 \text{ ms}^{-1} \)

(Total 1 mark)
The gravitational field strength on the surface of a planet orbiting a star is 8.0 \text{ N kg}^{-1}. If the planet and star have a similar density but the diameter of the star is 100 times greater than the planet, what would be the gravitational field strength at the surface of the star?

A \quad 0.0008 \text{ N kg}^{-1}

B \quad 0.08 \text{ N kg}^{-1}

C \quad 800 \text{ N kg}^{-1}

D \quad 8000 \text{ N kg}^{-1}

(Total 1 mark)

Which one of the following statements about Newton’s law of gravitation is correct?

Newton’s law of gravitation explains

A \quad the origin of gravitational forces.

B \quad why a falling satellite burns up when it enters the Earth’s atmosphere.

C \quad why projectiles maintain a uniform horizontal speed.

D \quad how various factors affect the gravitational force between two particles.

(Total 1 mark)

Two satellites, P and Q, of the same mass, are in circular orbits around the Earth. The radius of the orbit of Q is three times that of P. Which one of the following statements is correct?

A \quad The kinetic energy of P is greater than that of Q.

B \quad The weight of P is three times that of Q.

C \quad The time period of P is greater than that of Q.

D \quad The speed of P is three times that of Q.

(Total 1 mark)

If an electron and proton are separated by a distance of $5 \times 10^{-11}$ m, what is the approximate gravitational force of attraction between them?

A \quad 2 \times 10^{-57} \text{ N}

B \quad 3 \times 10^{-47} \text{ N}

C \quad 4 \times 10^{-47} \text{ N}

D \quad 5 \times 10^{-37} \text{ N}

(Total 1 mark)
Mark schemes

1 (a) force acting per unit mass or \( g = \frac{F}{m} \) or \( g = \frac{GM}{R^2} \) with terms defined

\( g = \)

(b) (i) direction of \( F_E \) correct in each diagram

direction of \( F_M \) correct in each diagram

direction of \( F_S \) correct in each diagram

\( F_S \) must be distinguished from \( F_M \)

penalty of 1 mark for any missing labelling

(ii) sun and moon pulling in same direction / resultant of \( F_M \) and \( F_S \) is greatest /
clear response including summation of \( F_M \) and \( F_S \)

configuration A

(c) \( F = \frac{GMm}{R^2} \)

correct substitution \( \frac{6.7 \times 10^{-11} \times 2.0 \times 10^{30}}{(1.5 \times 10^{11})^2} \)

\( (5.95 \text{ or } 5.96 \text{ or } 5.9 \text{ or } 6.0) \times 10^{-3} \text{ N kg}^{-1} \)

2 (a) (i) g.p.e. = \( G \frac{Mm}{R} \) must be equation (condone “\( V = \)”)  

\( g.p.e. = \)

(ii) equate with k.e. must be seen

cancelling correct \( m \) must be seen
(b) correct ratios taken \( \frac{v^2}{v_E^2} = 2 \)

\[ v = 15.8(4) \text{ km s}^{-1} \]

A1

(c) mention of air resistance

M1

k.e. of rocket → internal energy of rocket and atmosphere/
work is done against air resistance

A1

(a) force is proportional to the product of the two masses

B1

force is inversely proportional to the square of their separation
(condone radius between masses)

or

equation M0 : masses defined A1 separation defined A1

B1

(b) (i) appreciation that potential x distance from centre of sun =
constant

or calculation of \( Vr \) for two sets of values \( 1.33 \times 10^{20} \)

or uses distance ratio to calculate new \( V \) or \( r \)

C1

calculation of all three + conclusion

or uses distance ratios twice+ conclusion

conclusion must be more than 'numbers are same'

(condone 'signs' and no use of powers of 10)

A1

2
(ii) \( V = GM/r \) and \( g = GM/r^2 \)

or

\( g = V/r \) (no mark for \( E \) or \( g = V/d \) or \( E = V/r \ ))

substitution of one set of data to obtain \( GM \) \((1.33 \times 10^{20})\)

or \( 19 \times 10^{10}/7 \times 10^8 \) seen

\[ 271 \text{ N kg}^{-1} \text{ (m s}^{-2} \text{) (J kg}^{-1} \text{ m}^{-1}) \]

(iii) potential energy of the Earth = \((-)GMm/r \)

or potential difference formula + \( r^2 = \infty \)

or potential at position of Earth = \(-8.87 \times 10^8 \text{ J kg}^{-1} \)

(from \( Vr = 1.33 \times 10^{20} \))

correct substitution (allow ecf for \( GM \) from (ii))

or

potential energy = potential x mass of Earth

\[ \text{change in PE} = 5.32 \times 10^{33} \text{ J (cnao)} \]

\( Fd \) approach is PE so 0 marks
(iv) speed of Earth round Sun = \(2\pi r/T\) or \(3.0 \times 10^4\) m s\(^{-1}\)

or \(KE = \frac{GMm}{2r}\)

KE of Earth = \(\frac{1}{2} \times 6 \times 10^{24} \times \text{their } v^2 \ (2.68 \times 10^{33}\text{J})\)

energy needed = difference between (iii) and orbital KE \(2.64 \times 10^{33}\text{J}\)

or KE in orbit = half total energy needed to escape \((-1\text{ for AE})\)

(a) attractive force between two particles (or point masses) \(1\)
proportional to product of masses and inversely proportional to square of separation [or distance] \(1\)

(b) (for mass, \(m\), at Earth’s surface) \(mg = \frac{GMm}{R^2}\) \(1\)
rearrangement gives result \(1\)

(c) \(M_{moon} = \frac{gR^2}{G} = \frac{1.62 \times (1.74 \times 10^6)^2}{6.62 \times 10^{24}}\) \(1\)

= \(7.35 \times 10^{22}\) kg \(1\)

\[
\frac{M_{moon}}{M_{earth}} = \frac{7.35 \times 10^{22}}{6.00 \times 10^{24}} (= 0.0123) : 1.23\%
\]
(a)

<table>
<thead>
<tr>
<th>_______</th>
<th>N kg(^{-1})</th>
<th>electric field strength</th>
<th>N C(^{-1}) or V m(^{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td>gravitational constant</td>
<td>N m(^2) kg(^{-2})</td>
<td>_______</td>
<td>_______</td>
</tr>
<tr>
<td>mass</td>
<td>kg</td>
<td>charge</td>
<td>C</td>
</tr>
<tr>
<td>distance (from mass to point)</td>
<td>m</td>
<td>distance (from charge to point)</td>
<td>m</td>
</tr>
</tbody>
</table>

(b) (i) none (1)

both \(F_E\) and \(F_G\) \(\propto \frac{1}{r^2}\) (hence both reduced to \(\frac{1}{4}\) [affected equally] (1)

(ii) charge on B must be doubled (1)

(a) period = 24 hours or equals period of Earth’s rotation (1)
remains in fixed position relative to surface of Earth (1)
equatorial orbit (1)
same angular speed as Earth or equatorial surface (1)

(b) (i) \(\frac{GMm}{r^2} = m\omega^2 r\) (1)

\[ T = \frac{2\pi}{\omega} \] (1)

\[ r\left(\frac{GMT^2}{4\pi^2}\right)^{1/3} = \left(\frac{6.67 \times 10^{-11} \times 6 \times 10^{24} \times (24 \times 3600)^2}{4\pi^2}\right)^{1/3} \] (1)

(gives \(r = 42.3 \times 10^3\) km)
(ii) \[ \Delta V = GM \left( \frac{1}{R} - \frac{1}{r} \right) \] (1)

\[ = 6.67 \times 10^{-11} \times 6 \times 10^{24} \times \left( \frac{1}{6.4 \times 10^{6}} - \frac{1}{4.23 \times 10^{7}} \right) \]

\[ = 5.31 \times 10^{7} \text{ (J kg}^{-1} \text{) } \] (1)

\[ \Delta E_p = m\Delta V = 750 \times 5.31 \times 10^{7} = 3.98 \times 10^{10} \text{ J } \] (1)

(allow C.E. for value of \( \Delta V \))

[alternatives:

calculation of \( \frac{GM}{R} \) (6.25 \times 10^{7}) \) or \( \frac{GM}{r} \) (9.46 \times 10^{6}) \) (1)

or calculation of \( \frac{GMm}{R} \) (4.69 \times 10^{10}) \) or \( \frac{GMm}{r} \) (7.10 \times 10^{9}) \) (1)

calculation of both potential energy values (1)

subtraction of values or use of \( m\Delta V \) with correct answer (1)]

7

(a)  
(i) force per unit mass (allow equation with defined terms)  

B1  

(ii) diagram of method that will work  

(pendulum / light gates / solenoid and mechanical gate / strobe photography / video)  

B1

pair of measurements (eg length of pendulum and (periodic) time / distance and time of fall – could be shown on diagram)  

M1

instruments to measure named quantities (may be on diagram)  

A1

correct procedure (eg calculate period for range of lengths, measure the time of fall for range of heights)  

B1

good practice – series of values and averages / use of gradient of graph  

B1

appropriate formula and how \( g \) calculated  

B1

(b)  
(i) evidence of \( gr^2 \) being used  

C1

values of 0.25, 0.11, 0.06(25)  

no s.f. penalty here unless values given as fractions  

A1  

(2)
(ii) points correctly plotted on grid (e.c.f.)

smooth curve of high quality at least to $10 \times 10^7$ m, no intercept on $r$ axis

(iii) attempt to use area under curve

evidence of $\times 800$ kg

$(4.3 - 5.3) \times 10^9$ J

or

use of equation for potential $\Delta E_G = m(g_1r_1 - g_2r_2)$

evidence of $\times 800$ kg

$(4.7 - 4.9) \times 10^9$ J

max 2 if assumed values of $G$ and $M$ used

allow calculation of $GM$ from graph followed by substitution into $\Delta E_G = M_G(m/r_1 - m/r_2)$ for 3 marks

\[ \text{(3)} \]

(a) (i) relationship between them is $E_p = mV$ (allow $\Delta E_p = m\Delta V$) [or $V$ is energy per unit mass (or per kg)] (1)

(ii) value of $E_p$ is doubled (1)

value of $V$ is unchanged (1)

(b) (i) use of $V = -\frac{GM}{r}$ gives $r_A = \frac{6.67 \times 10^{-11} \times 5.98 \times 10^{24}}{12.0 \times 10^6}$ (1)

$= 3.3(2) \times 10^7$ (m) (1)

(ii) since $V \propto \left(-\right)\frac{1}{r}$

\[ \frac{r_A}{r_B} = \frac{\gamma_A}{\gamma_B} = \frac{36.0}{12.0} = 3 \]

\[ r_3 = \frac{3.32 \times 10^7 \text{ m}}{3} \] (1)

(which is $\approx 1.1 \times 10^4$ km) (1)
(iii) centripetal acceleration \( g_B = \frac{GM}{r_B^2} = \frac{6.87 \times 10^{-11} \times 5.98 \times 10^{24}}{(1.11 \times 10^7)^2} \) (1)

[allow use of \( 1.1 \times 10^7 \) m from (b)(ii)]

\[ = 3.2 \text{ (m s}^{-2}\text{)} \) (1)

[alternatively, since \( g_B = \left( -\frac{v_B}{v_z} \right)_B \), \( g_B = \frac{36.0 \times 10^6}{1.11 \times 10^7} \) (1)]

\[ = 3.2 \text{ (m s}^{-2}\text{)} \) (1)]

(iv) use of \( \Delta E_p = m\Delta V \) gives \( \Delta E_p = 330 \times (-12.0 - (-36.0)) \times 10^6 \) (1)

(which is \( 7.9 \times 10^9 \) J or \( \approx 8 \text{ GJ} \))

(c) \( g \) is not constant over the distance involved

(or \( g \) decreases as height increases
or work done per metre decreases as height increases
or field is radial and/or not uniform) (1)
Examiner reports

1  (a) Most candidates managed to give an acceptable definition of gravitational field strength. Those who did not usually failed because they omitted to mention unit mass or because they confused field strength with potential or potential energy.

(b) (i) This part was also well done. Some candidates gave confused labelling, showed their forces in the wrong direction, or omitted to show the forces on both of the diagrams.

(ii) Explanations were often not clear: some candidates created a difficulty by referring to the resultant force when they probably were thinking of the resultant force of only $F_M$ and $F_S$. A few candidates sought to give explanations relating to the distances between the Earth and the Sun or Moon, highlighting the need to advise candidates not to rely on judgements of distance from diagrams which are not to scale.

(c) This calculation was done well by most of the candidates. A few tried to use an equation for potential rather than force and some made processing errors, often forgetting to square the orbital radius even though they had shown it as being squared in their equation.

2  (a) (i) Several candidates failed to write *an equation* for this part, simply giving one term.

(ii) Few candidates were able to relate the kinetic energy to the gravitational potential energy to produce a convincing development of the escape velocity equation.

(b) This part was usually done well.

(c) Answers to this part were frequently too loosely phrased to gain credit. References to *wind resistance* and *friction* were commonplace.

3  (a) This was done well by the majority of candidates. A common error was to state that the force is inversely proportional to the square of the radius.

(b) (i) Most candidates knew a method of showing the inverse proportionality. However, many used only two of the sets of data or provided only a series of numbers without any explanation of what they were doing or providing any conclusion. In the worst cases, answers were set out poorly and any reasoning was hard to follow.

(ii) Although many arrived at the correct answer, there were many dubious equations to justify the final result. To gain full credit, candidates were expected to write down an appropriate gravitational field equation from which to proceed. Some recalled the value for $G$ although the questions asked them to ‘use the data’.

(iii) There were relatively few correct answers to this part. Many candidates could not identify an appropriate equation to use or did not realise that they had the value for $GM$ from earlier parts. Some determined the energy needed for the Earth to move from the surface of the Sun to the position of the Earth’s orbit. Those who recalled $G$, having no value for the mass of the Sun, determined the energy required for the Earth to escape from the Earth.

(iv) Most were able to gain some credit for this part, gaining marks for calculating the speed of the Earth in its orbit and/or for use of the KE formula. Many either ignored the last part or added the KE in orbit to their answer to part (iii).
Missing from most attempted statements in part (a) were the expected references to point
masses and to an attractive force. Many candidates simply tried to put the well-known formula
into words, whilst others referred to the sum of the masses rather than the product of them.

The equation $g = -\frac{GM}{r^2}$ is given in the Data booklet and mechanical rearrangement of it
leads directly to the expression in part (b). However, this was not what was required by the
wording of the question, and the many candidates who tried this approach were not given any
marks. The acceptable starting point was to equate the gravitational force with $mg$.

Answers to part (c) were frequently completely successful, making an interesting contrast with
the earlier parts of this question. The main problems here were omission of kg after the mass of
the moon, significant figure penalties, and arithmetical slips – typically forgetting to square the
denominator.

Although part (a) was relatively novel, most candidates could handle the comparison of
gravitational and electric fields. The gaps in the second line of the table could be filled directly by
use of the Data Booklet, but most of the other entries required a little more thought. Derived units
were sometimes quoted (but not accepted) for the electric field strength: candidates were
expected to know that this is N C$^{-1}$ or V m$^{-1}$. In the fourth line, distance (or radius) squared was a
surprisingly common wrong answer.

In pan (b)(i) quite a large number of candidates did not state that the resultant force would be
unchanged, even though they had correctly considered the separate effects of a $1/r^2$
relationship on both the gravitational and electric forces. The most frequent wrong response was
that the force (presumably the resultant force) would decrease by a factor of four. In part (b)(ii)
many candidates stated that the charge should be increased, without indicating that it should be
doubled – this was expected for the mark to be awarded.

Two appropriate features of a geo-synchronous orbit were usually given by the candidates in part
(a), but the marks for them were often the last that could be awarded in this question. The
required radius in part (b)(i) came readily to the candidates who correctly equated the
gravitational force on the satellite with $m\omega^2r$, applied $T = 2\pi/\omega$, and completed the calculation by
substituting $T = 24$ hours and the values given in the question. Other candidates commonly
presented a tangled mass of unrelated algebra in part (b)(i), from which the examiners could
rescue nothing worthy of credit.

In part (b)(ii) an incredible proportion of the candidates assumed that it was possible to calculate
the increase in the potential energy by the use of $mg \Delta h$, in spite of the fact that the satellite had
be raised vertically through almost 36,000 km. These attempts gained no marks. Other efforts
started promisingly by the use of $V = -\frac{GM}{r}$, but made the crucial error of using $(4.23 \times 10^7 - 
6.4 \times 10^6)$ as $r$ in the denominator. Some credit was available to candidates who made progress
with a partial solution that proceeded along the correct lines, such as evaluating the gravitational
potential at a point in the orbit of the satellite. Confusion between the mass of the Earth and the
mass of the satellite was common when doing this.
Many very good answers were seen in part (a) (i), expressed either fully in words or simply by quoting $E_p = mV$. The corresponding equation for an incremental change, $\Delta E_p = m\Delta V$, was also acceptable but mixed variations on this such as $E_p = m\Delta V$ (which showed a lack of understanding) were not. The consequences of doubling $m$ were generally well understood in part (a) (ii), where most candidates scored highly, but some inevitably thought that $E_p$ would be unchanged whilst $V$ would double.

Candidates who were not fully conversant with the metric prefixes used with units had great difficulty in part (b), where it was necessary to know that 1 MJ = $10^6$ J, 1 GJ = $10^9$ J, and (even) 1 km = $10^3$ m. Direct substitution into $V = (-) \frac{GM}{r}$ (having correctly converted the value of $V$ to J kg$^{-1}$) usually gave a successful answer for the radius of orbit A in part (b) (i). A similar approach was often adopted in part (b) (ii) to find the radius of orbit B, although the realisation that $V \propto \frac{1}{r}$ facilitated a quicker solution. Some candidates noticed that $V_B = 3 \frac{V_A}{2}$ and guessed that $r_B = \frac{r_A}{3}$, but this was not allowed when there was no physical reasoning to support the calculation.

Part (b) (iii) caused much difficulty, because candidates did not always appreciate that the centripetal acceleration of a satellite in stable orbit is equal to the local value of $g$, which is equal to $\frac{GM}{r^2}$. This value turns out to equal $\frac{V}{r}$, which provided an alternative route to the answer. Many incredible values were seen, some of them greatly exceeding 9.81 m s$^{-2}$.

Part (c) was generally well understood, with some very good and detailed answers from the candidates. Alternative answers were accepted: either that $g$ is not constant over such large distances, or that the field of the Earth is radial rather than uniform.

Direct application of Newton’s law of gravitation easily gave the answer in this question, which had a facility of 78%. A very small number of incorrect responses came from assuming that the law gives $F \propto \frac{1}{r}$ – represented by distractors A and D. Rather more (14%) chose distractor B; these students probably added the two component forces acting on the spacecraft instead of subtracting them.

This question provided poorer discrimination between candidates’ abilities than any other question in this test. Candidates ought to know that satellites speed up as they move into lower orbits, and therefore gain kinetic energy if their mass is unchanged. It should also be clear that satellites lose gravitational potential energy as they move closer to Earth. Therefore it is surprising that only 55% of the candidates gave the correct answer. The fairly even spread of responses amongst the other distractors suggests that many candidates were guessing.

This question was on gravitational effects. Rearrangement of possible units to obtain the ratio of the quantities $g^2 / G$ was required; almost 70% of the candidates could do this correctly but 20% chose distractor B (N kg$^{-1}$ instead of N m$^{-2}$).

This question was more demanding algebraically and involved use of a density value to determine the ratio of Earth’s radius to the Moon’s radius. Slightly under half of the candidates chose the correct value; incorrect responses were fairly evenly spread between the other distractors and the question discriminated poorly. This suggests that many were guessing.
Candidates found this question, on gravitational potential, a little easier, because its facility was almost 60%. Whether the work done was positive or negative must have troubled many, because distractor B (-80 kJ rather than +80 kJ) was the choice of 28%.

This question where the purpose was to calculate the Earth’s orbital speed, combined circular motion with gravitation. 62% of the students were successful, whilst incorrect answers were spread fairly evenly between the three incorrect responses.

This question which tested how g is connected to the diameter for two stars of similar density, was the most demanding question on the test – its facility was only 39%. Equating \(mg\) with \(\frac{GMm}{R^2}\) and then substituting \((\frac{4}{3})\pi R^3 \rho\) for \(M\) ought to have shown that \(g\) is proportional to the product \(Rp\). Consequently, if \(\rho\) is taken to be the same, \(g \propto R\). Yet 33% of the students suggested that \(g\) would be 100 times smaller (distractor A), and not 100 times bigger, when the diameter was 100 times larger.

This question involving statements about Newton’s law of gravitation, had a facility of 85%. When pre-tested, this question had been found appreciably harder but was more discriminating than on this occasion.

This question with a facility of 41%, was also demanding. Here several factors - kinetic energy, weight, time period and speed - had to be considered for two satellites in different circular orbits. The three incorrect answers had a fairly even distribution of responses.

Data for the gravitational constant and the masses of the electron and proton had to be extracted from the Data Sheet (see Reference Material) for use in this question where the topic was the gravitational force between two particles. Over four-fifths of the students succeeded with this.