IB · DP · Physics

2 hours 14 questions

Structured Questions

# 10.2 Fields at Work

10.2.1 Potential & Potential Energy / 10.2.2 Potential Energy Calculations / 10.2.3 Potential Gradient & Difference / 10.2.4 Potential in a Charged Sphere / 10.2.5 Escape Speed / 10.2.6 Orbital Motion, Speed & Energy / 10.2.7 Forces & Inverse-Square Law Behaviour / 10.2.8 Forces on Charges & Masses

| | |
|---|---|
| Easy (5 questions) | /52 |
| Medium (5 questions) | /51 |
| Hard (4 questions) | /40 |
| **Total Marks** | **/143** |

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# Easy Questions

**1 (a)** A planet is in orbit around a star.

State two reasons why a centripetal force is needed for a planet to maintain a circular orbit.

**(2 marks)**

**(b)** The mass of the planet is $9 \times 10^{24}$ kg, the mass of the star is $2 \times 10^{30}$ kg and the radius of the planet's orbit *R* is $5 \times 10^{10}$ m.

Calculate the value of the centripetal force.

**(2 marks)**

**(c)** A spacecraft is launched from the surface of the planet to escape from the planet-star system. The radius of the planet is $8 \times 10^{6}$ m.

Calculate the gravitational potentials which are:

(i) Due to the planet.

[2]

(ii) Due to the star.

[2]

(iii) Due to both the planet and the star.

[1]

**(5 marks)**

**(d)** Calculate the escape speed of the spacecraft from the planet-star system.

**(2 marks)**

**2 (a)** The moon Ganymede moves around the planet Jupiter in a circular orbit.

State the force responsible for this motion and outline why it does no work on Ganymede.

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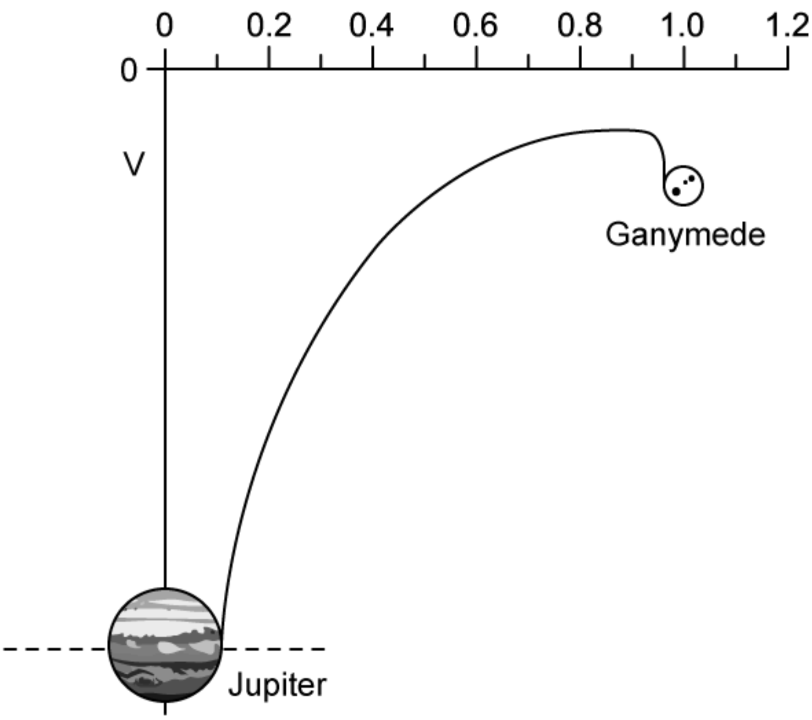
**(2 marks)**

**(b)** The graph shows the variation of the gravitational potential between Jupiter and Ganymede with distance from the centre of Jupiter. The distance from Jupiter is expressed as a fraction of the total distance between the centre of Jupiter and the centre of Ganymede.




Identify a word equation for the distance at which the gravitational force between Jupiter and Ganymede is zero.

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**(1 mark)**

**(c)** By equating the expressions for the gravitational force due to Jupiter and Ganymede, where gravitational potential is at a maximum, show that:

$$\frac{M_J}{(0.9)^2} = \frac{M_G}{(0.1)^2}$$

Where $M_G$ is the mass of Ganymede and $M_J$ is the mass of Jupiter.

**(4 marks)**

**(d)** Taking the mass of Jupiter as $1.898 \times 10^{27}$ kg, determine the mass of Ganymede.

**(2 marks)**

**3 (a)** Titan is a moon of Saturn and is much smaller than Earth. The radius of Earth is 2.48 times the radius of Titan and it is 40 times more massive.

The escape velocity from Earth is 11.2 km $s^{-1}$.

Determine the ratio of the escape velocities of Earth and Titan

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**(2 marks)**

**(b)** Hence calculate the escape velocity from Titan.

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**(1 mark)**

**(c)** Titan orbits Saturn at a distance between the centres of mass, *R* with an orbital period of revolution *T*.

State which forces must be in equilibrium for this orbit to be maintained.

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**(1 mark)**

**(d)** Hence, by using equations for centripetal acceleration and gravitational force, derive an expression in terms of the mass of Saturn for the time period, *T*.

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**(3 marks)**

**4 (a)** The forces between two masses are described as having an inverse-square relationship.

State the meaning of 'inverse-square relationship', both mathematically and qualitatively (in words).

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**(2 marks)**

**(b)** A planet with mass *M* and radius *R* has escape velocity $v_{esc}$.

A prototype rocket is launched with a speed which is only half of the escape speed.

Write an expression, in terms of *M* and *R*, which can be used to calculate the total energy of the rocket at its maximum height.

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**(2 marks)**

**(c)** Write an expression in terms of *M* and *R* to calculate the total energy at the launch of the prototype rocket in part (b).

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**(4 marks)**

**(d)** The prototype rocket, fired with half the escape velocity on Earth, launches with the energy determined in part (c). Assume that air resistance is negligible.

Determine, in terms of *R*, the maximum height *h* which the rocket achieves upon launch.

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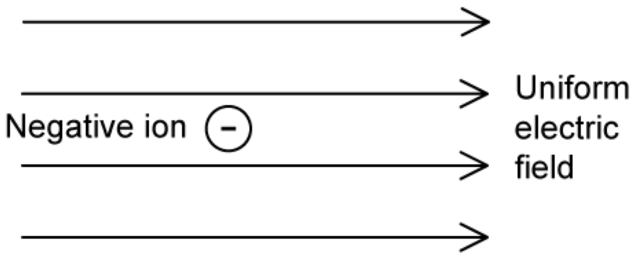
**(3 marks)**

**5 (a)** The diagram shows a negative ion which is free to move in a uniform electric field.




For the negative ion:

(i) State the direction of the electrostatic force acting on it.

[1]

(ii) Explain your answer with reference to the electric field lines in the diagram.

[2]

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**(3 marks)**

**(b)** $4.0 \times 10^{-16}$ J of work is done on the ion to accelerate it through the field a distance of 63 mm in a line parallel to the field lines.

Calculate the magnitude of the electrostatic force acting on the negative ion.

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(5 marks)

**(c)** Complete the sentences to describe similarities between electrostatic and gravitational fields.

I. The magnitude of the gravitational and electrostatic force between two point masses or charges follows the _____ relationship with the separation distance between the point masses or charges.

II. Field lines around a point mass and negative point charge are both _____ and point _____ the mass or charge.

III. The field lines in uniform gravitational and electrostatic fields are both _____ and ______.

(3 marks)

**(d)** Complete the sentences, using words or phrases, to describe the differences between electrostatic and gravitational fields.

I. The gravitational force acts on particles with _____ whilst the electrostatic force acts on particles with _____.

II. The gravitational force is always _____ whilst the electrostatic force can be _____.

III. The gravitational potential is always _____ whilst the electric potential can be either _____.

**(3 marks)**

# Medium Questions

**1 (a)** Outline why the gravitational potential is negative everywhere in space.

**(2 marks)**

**(b)** The gravitational potential of the Sun at its surface is $V$ is $-1.9 \times 10^{11}$ J $kg^{-1}$ at a radial distance $r$ from its core.

The following data are available:

- Mass of Earth = $6.0 \times 10^{24}$ kg
- Distance from Earth to Sun = $1.5 \times 10^{11}$ m
- Radius of Sun = $7.0 \times 10^{8}$ m

Calculate the Earth's gravitational potential energy in its orbit around the Sun.

**(2 marks)**

**(c)** While the Earth orbits the Sun, terrestrial shuttles often enter orbit around Earth. One such shuttle is launched with a kinetic energy $E_K$ given by the expression below:

$$E_K = \frac{5GM_E m}{8R_E}$$

where $G$ is the gravitational constant, $M_E$ is the mass of Earth, and $m$ is the mass of the shuttle. Deduce that the shuttle cannot escape the gravitational field of the Earth.

**(2 marks)**

**(d)** Show that, if the shuttle enters an orbit of radius *R* about the Earth, then its total energy is given by $-\frac{GM_E m}{2R}$ stating an appropriate assumption required.

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**(3 marks)**

**2 (a)** Evaluate this statement of Newton's law of gravitation: "The gravitational force between two masses is proportional to the masses and inversely proportional to the square of the distance between them."

**(2 marks)**

**(b)** A satellite of mass *m* orbits a planet of mass *M*. If the orbital radius is *R* and the orbital period is *T*, show that the ratio $\frac{R^3}{T^2}$ is constant.

**(3 marks)**

**(c)** Calculate the change in gravitational potential energy of the satellite, of mass 39 kg, as it moves from an orbit of height 1100 km above the Earth's surface to one of height 2100 km.

Use the following data:

- Mass of Earth = $6.0 \times 10^{24}$ kg
- Average radius of Earth = $6.4 \times 10^{6}$ m

**(3 marks)**

**(d)** Explain whether the gravitational potential energy has increased, decreased or stayed the same when the orbit changes as in part (c).

**(2 marks)**

**3 (a)** Define *electric potential* at a point in an electric field.

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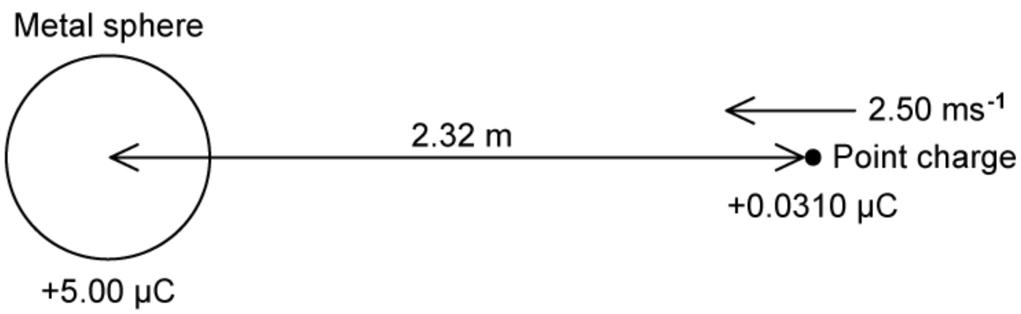
**(2 marks)**

**(b)** A point charge of mass $1.30 \times 10^{-4}$ kg is moving radially towards a small, charged metal sphere as shown.




The electric potential at the surface of the sphere is $9.00 \times 10^{4}$ V. Determine if the point charge will collide with the metal sphere.

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**(5 marks)**

**(c)** Determine the speed at which the point charge is certain to collide with the metal sphere.

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**(2 marks)**

**(d)** Protons are positively charged and are often described as "colliding" in particle accelerator experiments, as well as in the core of stars.

Discuss the implications of two protons colliding in terms of the forces between them. Describe the conditions necessary for such a collision to take place.

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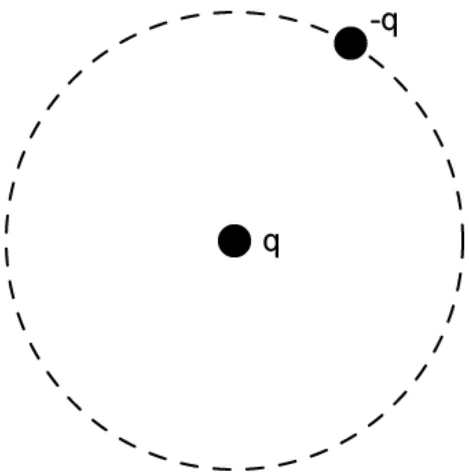
**(4 marks)**

**4 (a)** A charge $-q$ with mass $m$ orbits a stationary charge $q$ with a constant orbital radius $r$.




Draw the electrostatic force on $-q$ due to the electric field created by $q$.

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**(2 marks)**

**(b)** Show that the orbital speed of $v$ is given by:

$$v = \sqrt{\frac{1}{4\pi\varepsilon_0 mr}}\, q$$

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**(2 marks)**

**(c)** Show that the total energy $E$ of the orbiting charge is given by:

$$E = -\frac{1}{8\pi\varepsilon_0}\frac{q^2}{r}$$

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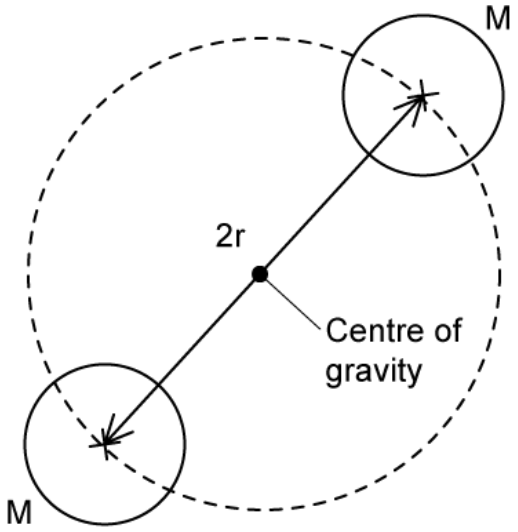
**(3 marks)**

**(d)** Hence, determine an equation for how much energy must be supplied to $-q$ if it is to orbit the stationary charge $q$ at twice the radius in part (c), $2r$.

**(2 marks)**

**5 (a)** Binary star systems involve two stars that orbit a common centre of gravity. One such system is shown.




Each star has a mass *M* and orbital radius *r*, such that their separation is 2*r*.

Deduce that the time period *T* of each star's orbit is related to the orbital radius *r* by the following equation:

$$T^2 = \frac{16\pi^2 r^3}{GM}$$

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**(3 marks)**

**(b)** Show that the kinetic energy of each star in the binary system is given by:

$$E_K = \frac{GM^2}{8r}$$

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**(2 marks)**

**(c)** Hence, show that the total energy of the binary star system is given by the equation:

$$E = -\frac{GM^2}{4r}$$

**(2 marks)**

**(d)** The binary system radiates energy in the form of gravitational waves.

Deduce that the stars move closer to each other as the binary system emits gravitational waves.

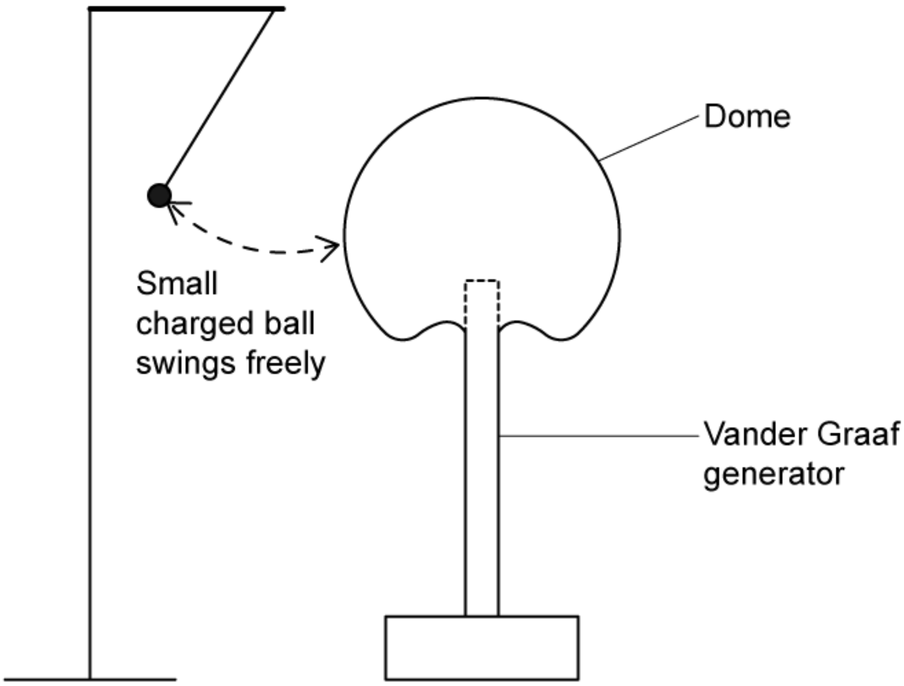
**(3 marks)**

# Hard Questions

**1 (a)** This question is about forces on objects held in fields. The first part is about electrically charged objects and the second part concerns bodies moving in gravitational fields.

The dome of a Van der Graaf generator can be treated as a conducting metal sphere with radius 20 cm. The dome is charged so that it has uniform surface charge + 13.1 μC. A stand is set up nearby, so that a pith ball with radius 1 cm, mass 11 g and charge + 1.8 μC can swing freely near to the dome.

The line of motion of the ball can be treated as normal to the surface of the dome.




The pith ball is held at a point 40 cm from the surface of the dome and pushed, so that it moves towards the dome with initial speed of 2.2 m $s^{-1}$. It stops moving and hangs suspended at a certain distance from the surface of the dome.

Calculate the distance between the surfaces of the dome and the pith ball when the ball stops moving.

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**(4 marks)**

**(b)** In an experiment a coin of 0.5 cm in diameter held at a distance of 55.3 cm from the eye appeared to be exactly the same size as the Moon. The coin was measured using a micrometer screw gauge and the distance to the eye using a metre rule.

The distance to the Moon is 384 400 km and the gravitational field strength on the surface of the Moon is 1.63 N $kg^{-1}$.

By referring to the data

(i) Calculate the mass of the Moon.

[3]

(ii) Determine the percentage error in the answer.

[3]

**(6 marks)**

**(c)** The gravitational field strength on the surface of a particular planet is 1.6 N $kg^{-1}$. The planet orbits a star of similar density, but the diameter of the star is 100 times greater than the planet.

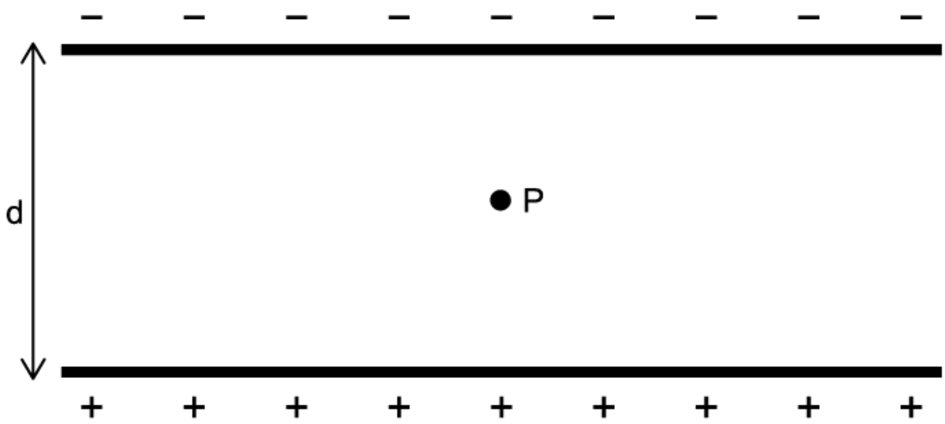
Calculate the gravitational field strength at the surface of the star.

**(5 marks)**

**2 (a)** This question is about forces and work done on objects held in fields. The first part is about charged oil drops in electric fields and the second part about space craft moving in gravitational fields.

Two charged, horizontal, parallel metal plates are a distance *d* apart.

A small oil drop P is positioned between the plates such that when the potential difference between the plates is $V_1$, the drop is stationary. The potential difference is changed to $V_2$ and the drop moves upwards with a constant velocity *v*.




Complete the diagrams with the names, directions and relative magnitudes of the forces acting on the oil drop for the situations when pd = $V_1$ and pd = $V_2$.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**(4 marks)**

**(b)** When a small, smooth sphere moves through a fluid such as air with low velocity *v* it experiences a resistive force. The force can be expressed in terms of a constant *k* so that:

$$\text{resistive force} = kv$$

The magnitude of the charge on the oil drop is *q*, and the distance between the plates is *d*.

Determine an expression which relates the velocity the oil drop moves upwards when the potential difference between the plates changes to the constant *k.*

**(2 marks)**

**(c)** Work is done on the Soyuz spacecraft which is used to transport astronauts to the International Space Station (ISS). The ISS orbits the Earth at a height of 400 km above the Earth's surface. The Soyuz spacecraft has a mass of 7150 kg.

- Mass of the Earth = $5.97 \times 10^{24}$ kg
- Mean radius of the Earth = $6.37 \times 10^{6}$ m

For one trip from Earth to the ISS:

(i) Calculate the work done in taking the Soyuz spacecraft from the Earth's surface to the ISS.

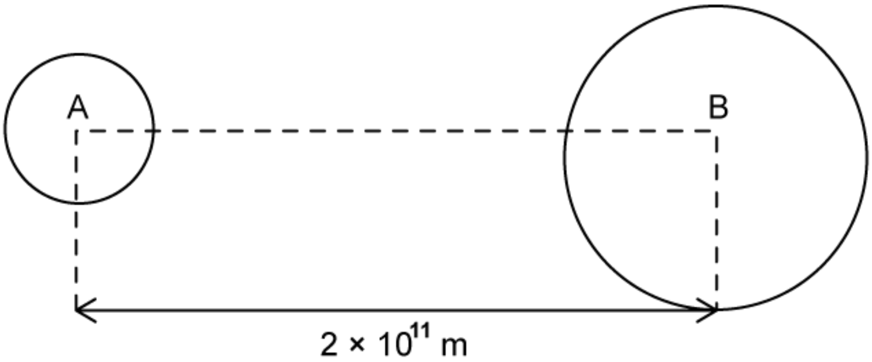
[3]

(ii) State an assumption that was made in the calculation.

[1]

**(4 marks)**

**3 (a)** A binary planet system consists of two stars, A and B.




A has a mass of mass $4.0 \times 10^{30}$ kg and B has a mass of $8.0 \times 10^{30}$ kg. The centres of the stars are separated by a distance of $2 \times 10^{8}$ km.

Calculate the gravitational potential at the midpoint between the stars.

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**(2 marks)**

**(b)** The amount of energy required to send a space probe of mass 1800 kg from the surface of star A to the midpoint between stars A and B is $4.2 \times 10^{11}$ J.

Calculate the gravitational field strength on the surface of star A.

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**(4 marks)**

**(c)** The two stars are drifting apart.

Calculate how far star A will have drifted at the point where its gravitational potential energy has decreased by 10 %.

**(3 marks)**

**4 (a)** The orbits of the Earth and Jupiter are very nearly circular, with radii of $150 \times 10^9$ m and $778 \times 10^9$ m respectively. It takes Jupiter 11.8 years to complete a full orbit of the Sun.

Show that the values in this question are consistent with Kepler's third law.

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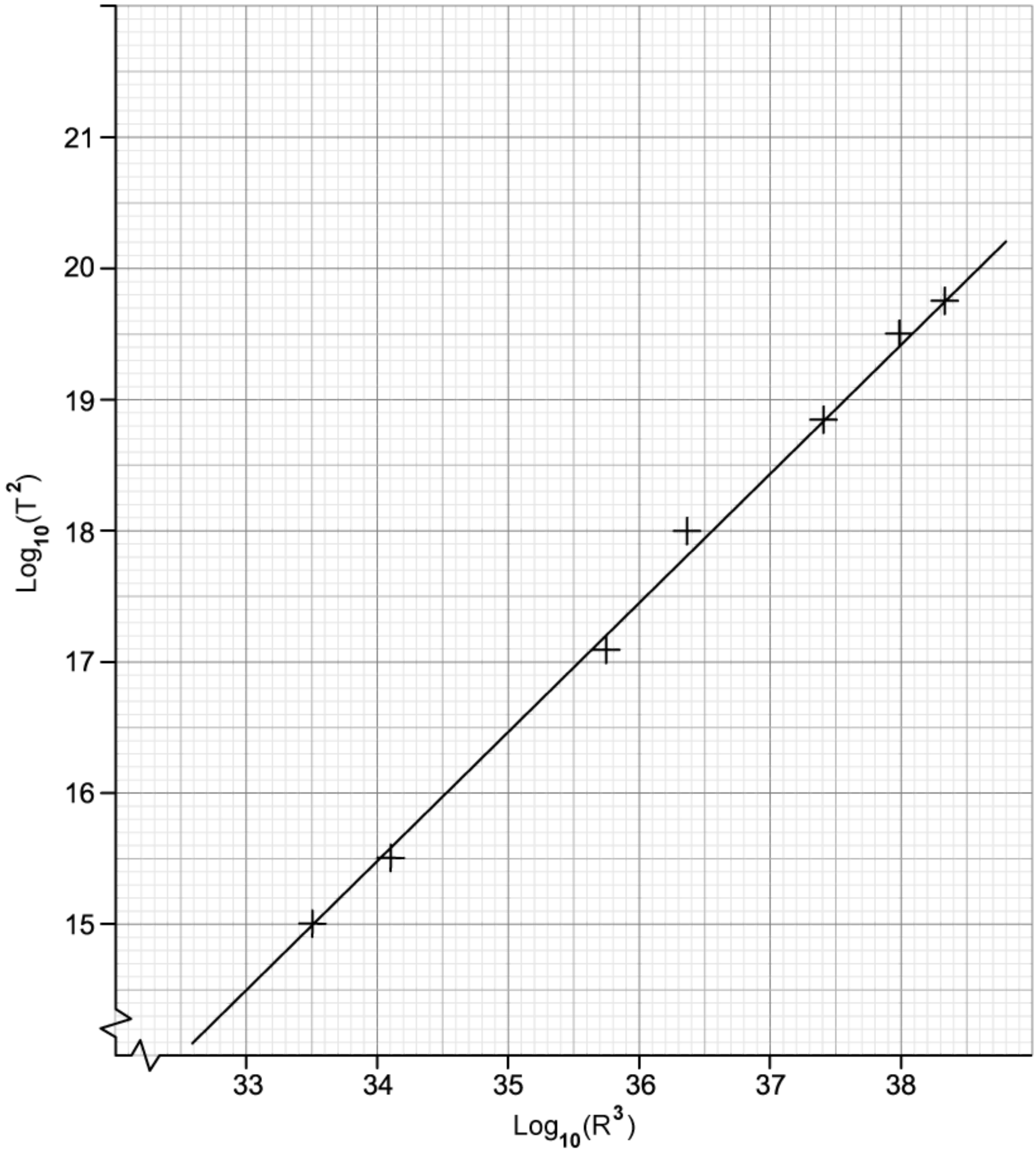
**(2 marks)**

**(b)** Data from the orbits of different planets around our Sun is plotted in a graph of log($T^2$) against log($R^3$) as shown in the graph below, where *T* is the orbital period and *R* is the radius of the planet's orbit.

The values of *T* and *R* have been squared and cubed respectively due to Kepler's Third Law stating that:

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




Calculate the percentage error for the mass of the Sun obtained from the graph.

**(4 marks)**