TA *[87 marks]*

This question is about relativistic kinematics.

1a. An observer at rest relative to Earth observes two spaceships. Each spaceship is moving with a speed of 0.85*c* but in opposite directions. The observer measures the rate of increase of distance between the spaceships to be 1.7*c*. *[5 marks]*

(i) Outline whether this observation contravenes the theory of special relativity.

(ii) Determine, according to an observer in one of the spaceships, the speed of the other spaceship.

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1b. The observer on Earth in (a) watches one spaceship as it travels to a distant star at a speed of 0.85*c*. According to observers on the spaceship, this journey takes 8.0 years. *[9 marks]*

(i) Calculate, according to the observer on Earth, the time taken for the journey to the star.

(ii) Outline whether the time interval measured by the observer on Earth is a proper time interval.

(iii) Calculate, according to the observer on Earth, the distance from Earth to the star.

(iv) The observers in the spaceship send a message to Earth halfway through their journey. Determine how long it takes the message to arrive at Earth according to the observers on the spaceship.

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This question is about relativistic energies.

2a. Calculate the speed of an electron when its total energy is equal to five times its rest mass energy. *[3 marks]*

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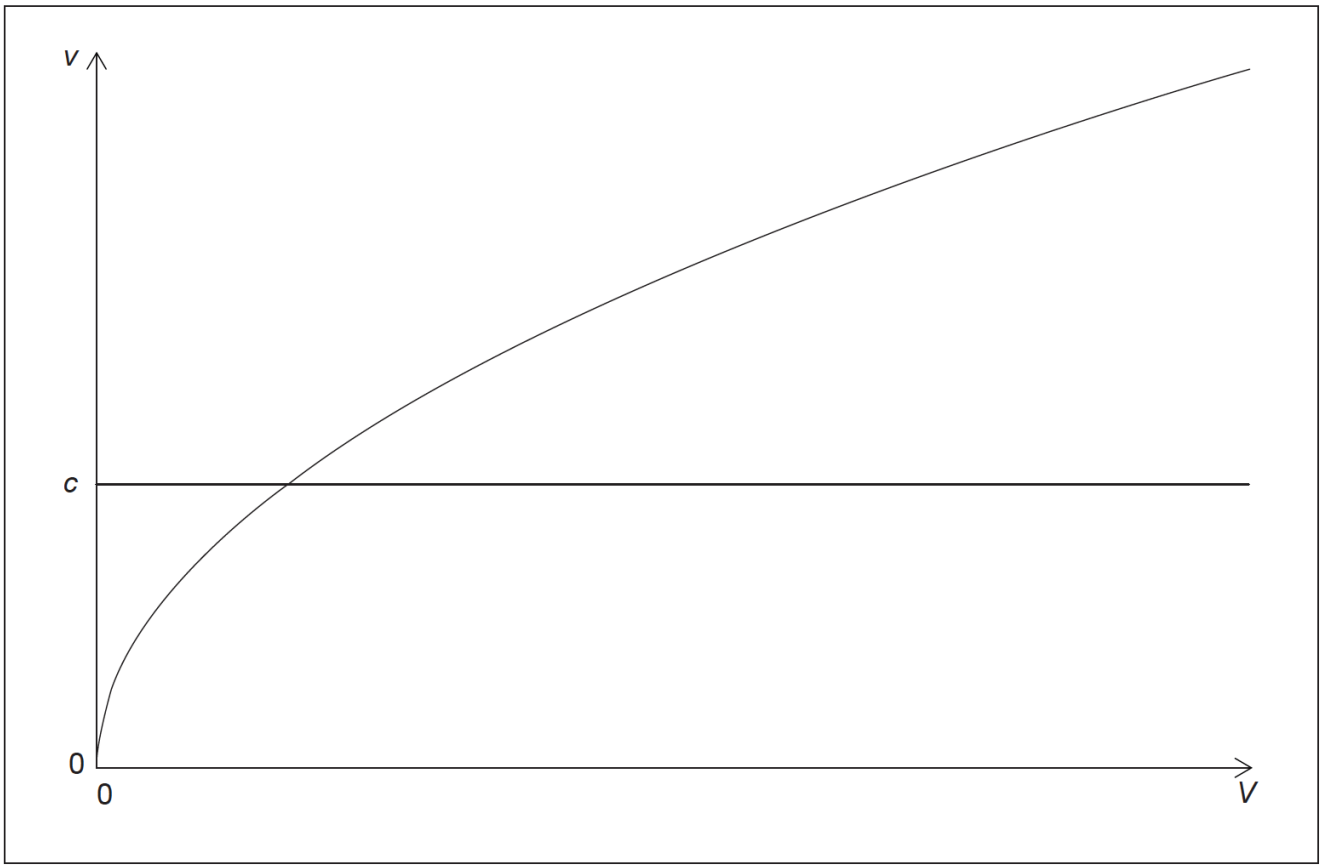
2b. The electron is accelerated from rest through a potential difference V. The graph shows how the speed v of the electron after acceleration varies with V assuming that Newtonian mechanics applies. *[2 marks]*



On the graph, sketch a line to show the variation with V of v according to relativistic mechanics.

This question is about general relativity.

3a. Calculate the Schwarzschild radius for an astronomical object of mass 5.0×10^{30} kg. *[2 marks]*

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3b. A spaceship is travelling towards the object in (a). The spaceship moves in a straight line such that its distance of closest approach would be about 10^7m. Discuss why the presence of the object in (a) will **not** significantly affect the motion of the spaceship. *[2 marks]*

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3c. An observer, when viewing a distant galaxy, sees two images of the galaxy separated by a small angle. A massive star is positioned between the observer and the galaxy. Outline how these observations give support to the theory of general relativity. *[3 marks]*

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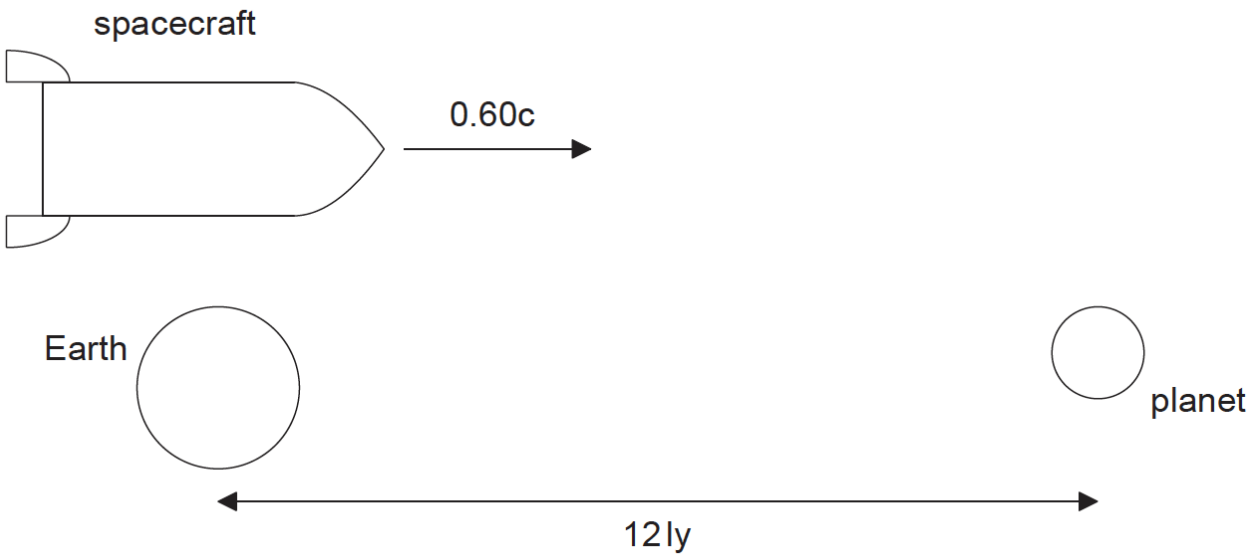
This question is about relativistic kinematics.

A spacecraft leaves Earth and moves towards a planet. The spacecraft moves at a speed 0.60c relative to the Earth. The planet is a distance of 12ly away according to the observer on Earth.



4a. Determine the time, in years, that it takes the spacecraft to reach the planet according to the *[3 marks]*

(i) observer on Earth.

(ii) observer in the spacecraft.

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4b. The spacecraft passes a space station that is at rest relative to the Earth. The proper length of the space station is 310 m. *[3 marks]*

(i) State what is meant by proper length.

(ii) Calculate the length of the space station according to the observer in the spacecraft.

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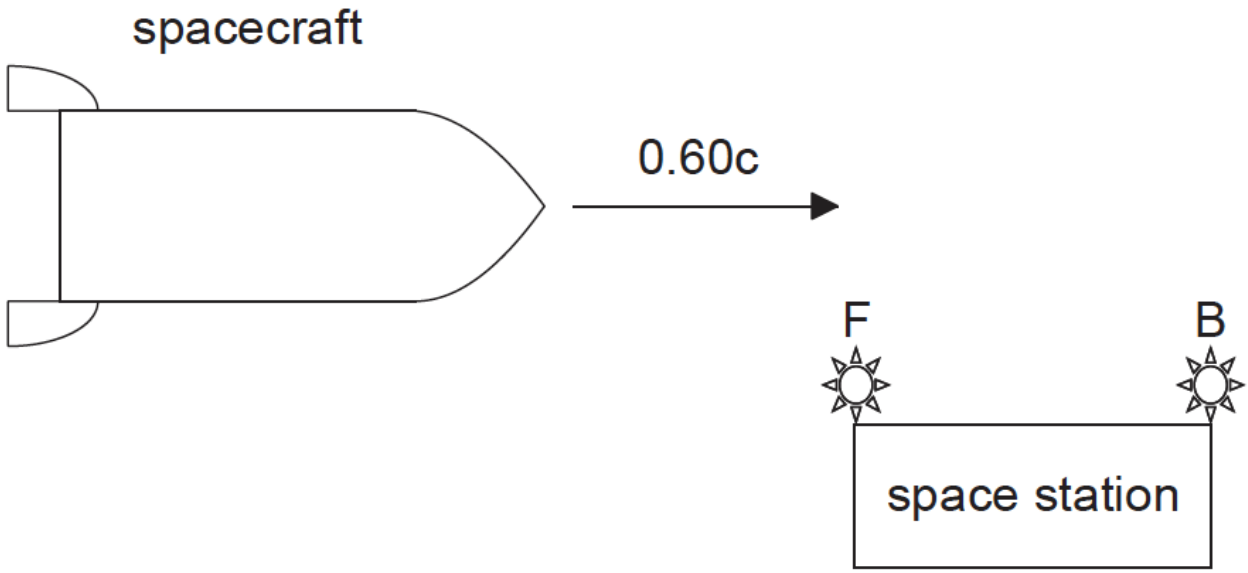
4c. F and B are two flashing lights located at the ends of the space station, as shown. As the spacecraft approaches the space station in (b), F and B turn on. The lights turn on simultaneously according to the observer on the space station who is midway between the lights. *[4 marks]*



State and explain which light, F **or** B, turns on first according to the observer in the **spacecraft**.

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This question is about relativistic mechanics.
A proton is accelerated from rest through a potential difference of 1.5 GV.
Calculate, for the accelerated proton, the

5a. total energy. *[2 marks]*

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5b. momentum. *[2 marks]*

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5c. speed. *[2 marks]*

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This question is about gravitation.

Planets move in orbits around the Sun. Explain this observation according to

6a. Newton’s universal law of gravitation. *[2 marks]*

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6b. Einstein’s theory of general relativity. *[2 marks]*

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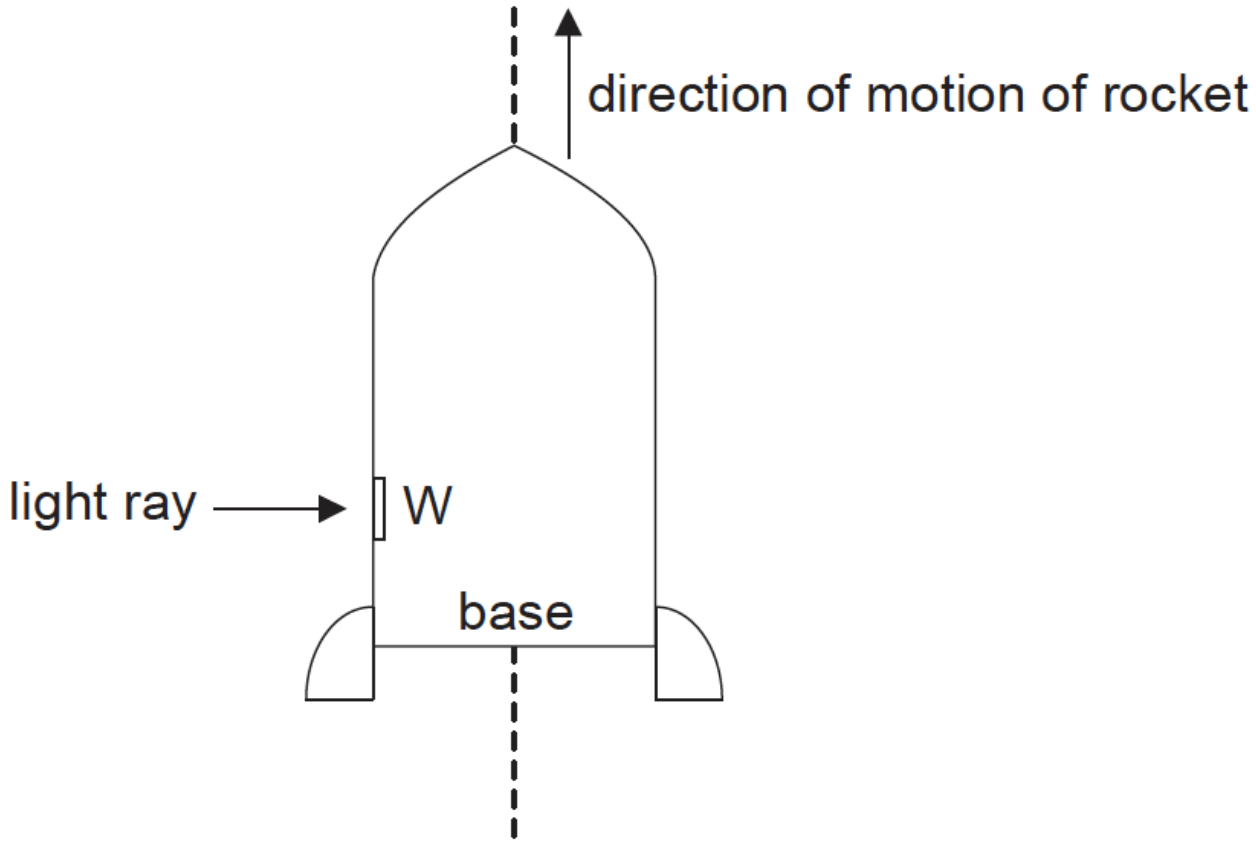
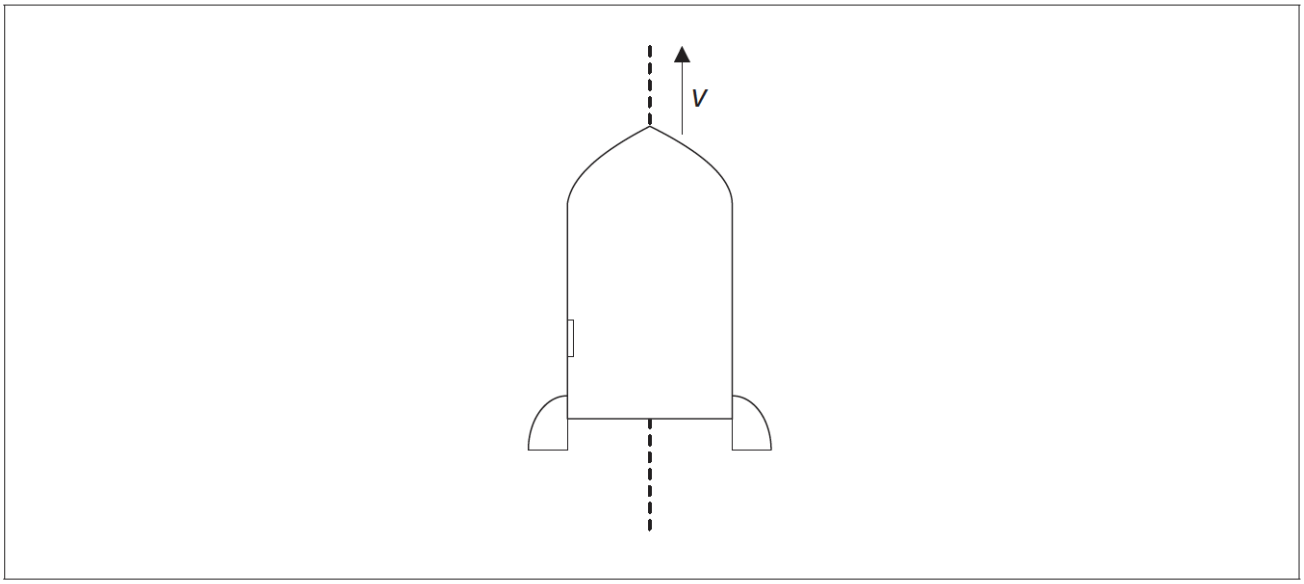
This question is about general relativity.

A rocket is in outer space far from all masses. It moves along the dotted line according to an inertial observer located outside the rocket.

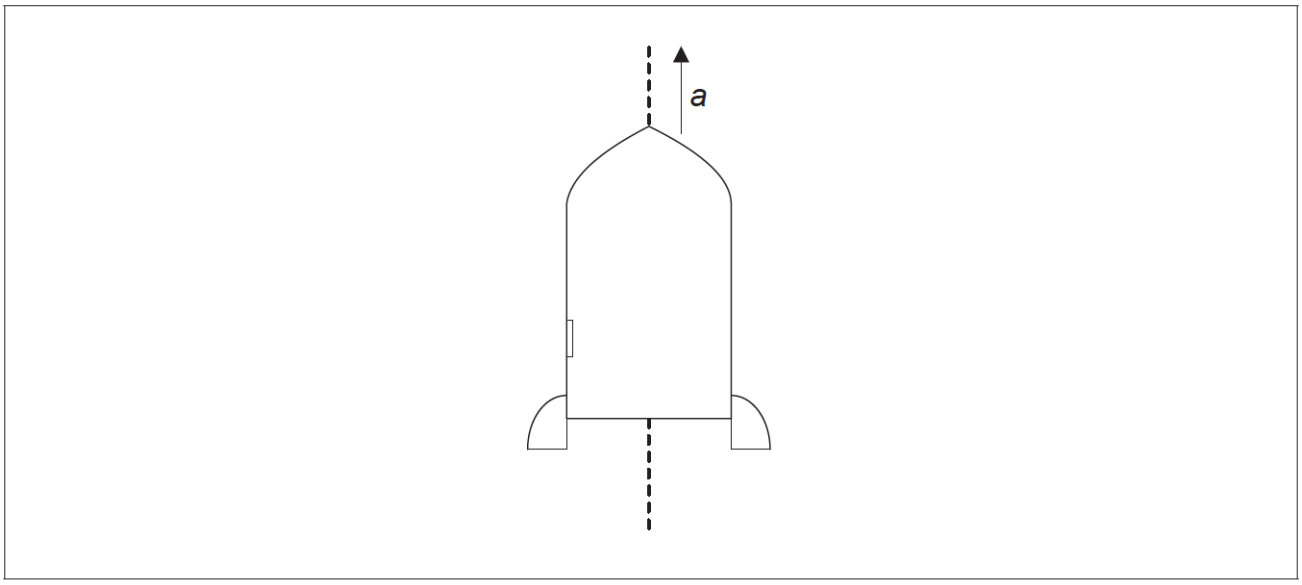


7. A ray of light is moving at right angles to the direction of the rocket according to the same inertial observer. The ray of light enters the rocket through a window W. Draw the path of the light ray according to an observer at rest inside the rocket, *[2 marks]*

(i) when the rocket is moving at constant speed *v*.



(ii) when the rocket is moving at constant positive acceleration *a*.



This question is about relativistic kinematics.

8a. State what is meant by an inertial frame of reference. *[1 mark]*

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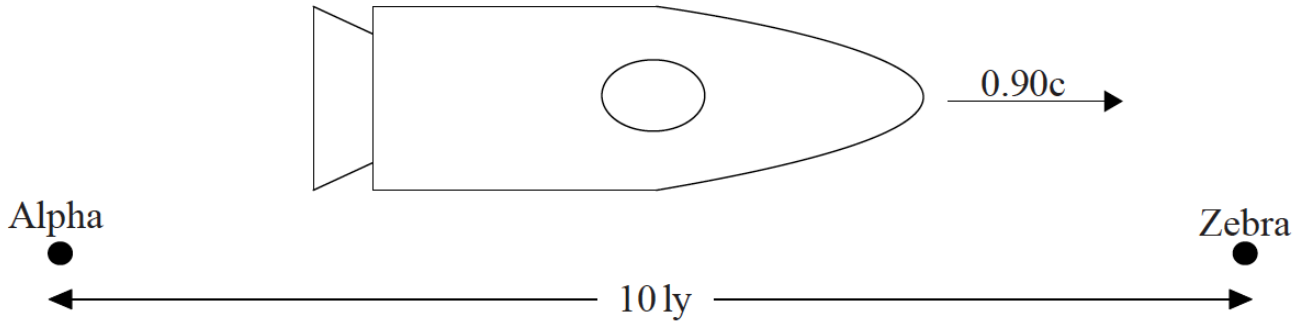
8b. A spaceship travels from space station Alpha to space station Zebra at a constant speed of 0.90c relative to the space stations. The distance from Alpha to Zebra is 10ly according to space station observers. At this speed γ=2.3. *[3 marks]*



Calculate the time taken to travel between Alpha and Zebra in the frame of reference of an observer

(i) on the Alpha space station.

(ii) on the spaceship.

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8c. Explain which of the time measurements in (b)(i) and (b)(ii) is a proper time interval. *[2 marks]*

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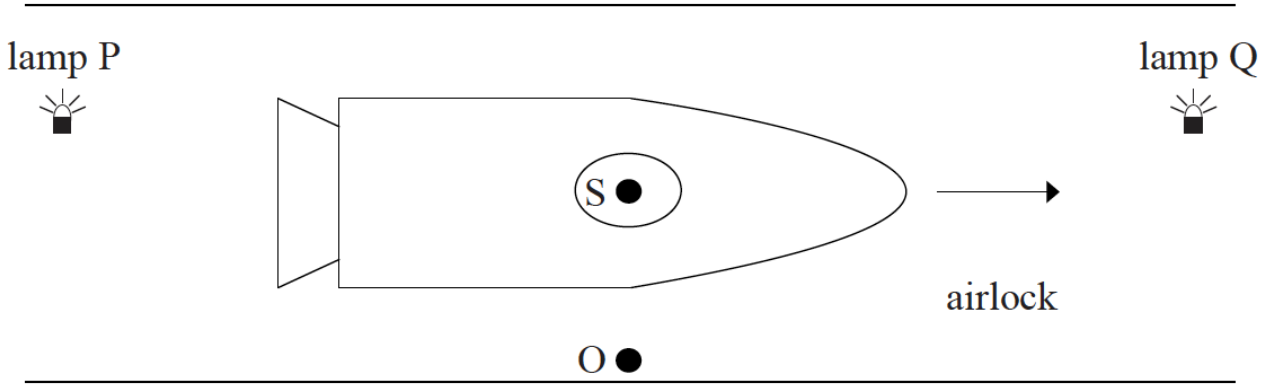
8d. The spaceship arrives at Zebra and enters an airlock at constant speed. O is an observer at rest relative to the airlock. Two lamps P and Q emit a flash simultaneously according to the observer S in the spaceship. At that instant, O and S are opposite each other and midway between the lamps. *[3 marks]*



Discuss whether the lamps flash simultaneously according to observer O.

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9. This question is about relativistic dynamics. *[4 marks]*

A proton is accelerated from rest through a potential difference of 2.5 GV. Determine the momentum of the proton after acceleration.

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This question is about general relativity.

10a. State the principle of equivalence. *[1 mark]*

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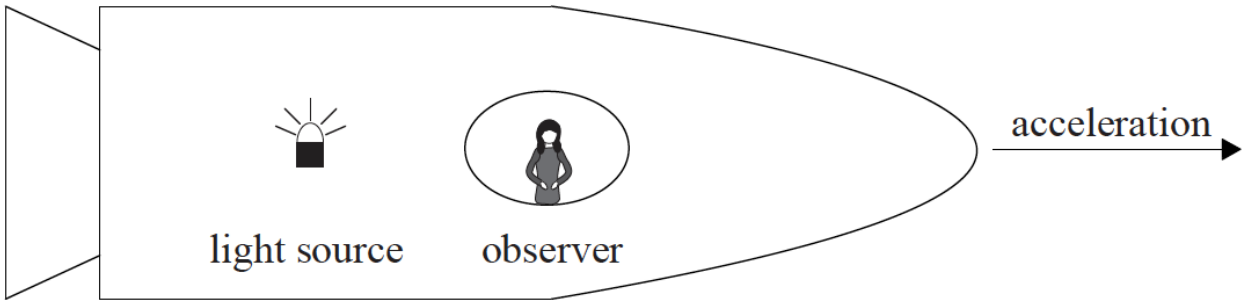
10b. An observer in a spaceship moving at constant speed measures the frequency f_0 of light emitted by a source. *[5 marks]*
The spaceship now accelerates to the right.



The observed frequency changes to f.

(i) Outline why, during the acceleration, f is less than f_0.
(ii) Explain how the result outlined in (b)(i) leads to the deduction that time dilates near a planet.

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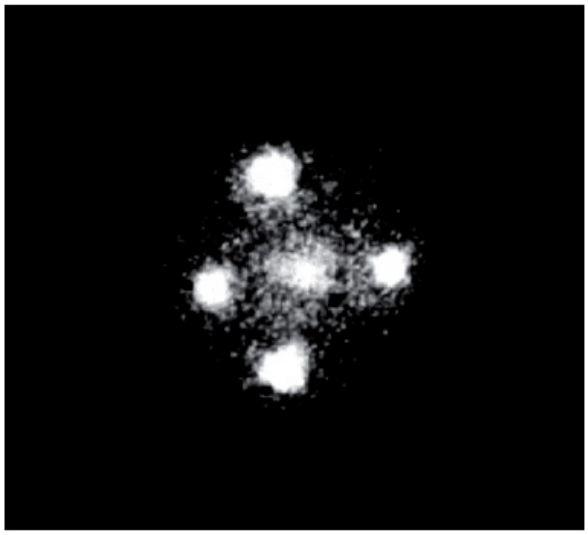
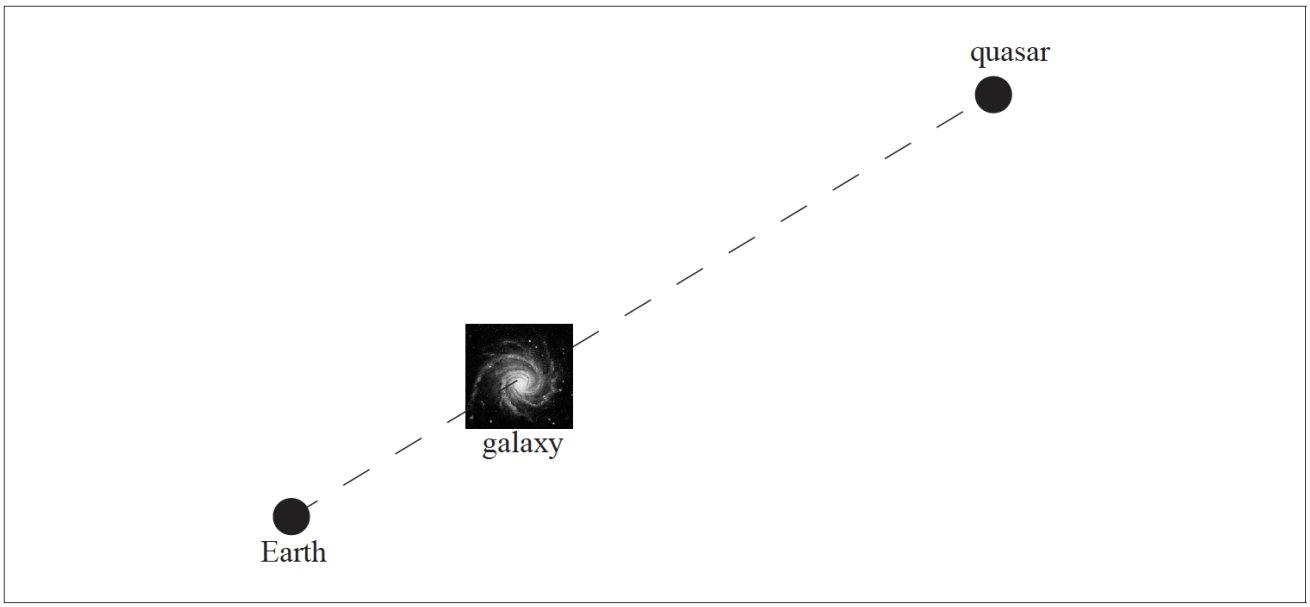
11. This question is about evidence that supports general relativity. *[3 marks]*

The astronomical photograph taken from Earth shows four separate images of a single distant quasar that appear to surround a galaxy. The galaxy is closer to Earth than the quasar.



[Source: www.hubblesite.org/newscenter/archive/releases/1990/20/image/a/]

Outline how one image of the quasar is formed. You may draw on the diagram below that shows the arrangement of the Earth, the galaxy and the quasar to support your answer.



[Source: adapted from www.sciencephoto.com/media/332699/enlarge]

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This question is about rest mass and relativistic energy.

12a. (i) Define the *rest mass* of a particle. *[2 marks]*

(ii) The rest mass of a particle is said to be an invariant quantity. State, with reference to special relativity, what is meant by the term invariant.

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12b. In a thought experiment, two particles X and Y, each of rest mass 380 $MeVc^{-2}$, are approaching each other head on. *[5 marks]*

The speed of X and of Y is 0.60 c relative to a laboratory.

(i) Calculate the momentum of X in the frame of reference in which Y is at rest.

(ii) As a result of the collision a single particle Z is formed. Determine the rest mass of Z. The gamma factor for a speed of 0.60 c is 1.25.

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This question about general relativity.

13a. State the principle of equivalence. *[1 mark]*

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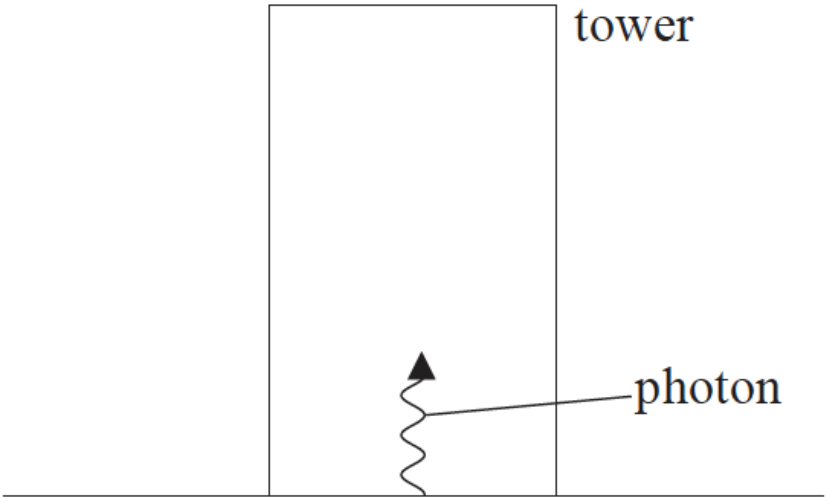
13b. A gamma-ray photon is emitted from the base of a tower towards the top of the tower. *[5 marks]*



(i) Explain, using the principle of equivalence, why the frequency of the photon as measured at the top of the tower is less than that measured at the base of the tower.

(ii) The frequency of the photon at the base is 3.5×10^{18} Hz and the tower is 23 m high. Determine the shift Δf in the frequency of the photon at the top of the tower.

(iii) Suggest, using your answer to (b)(ii), why the photon frequency must be measured very precisely for this experiment to be successful.

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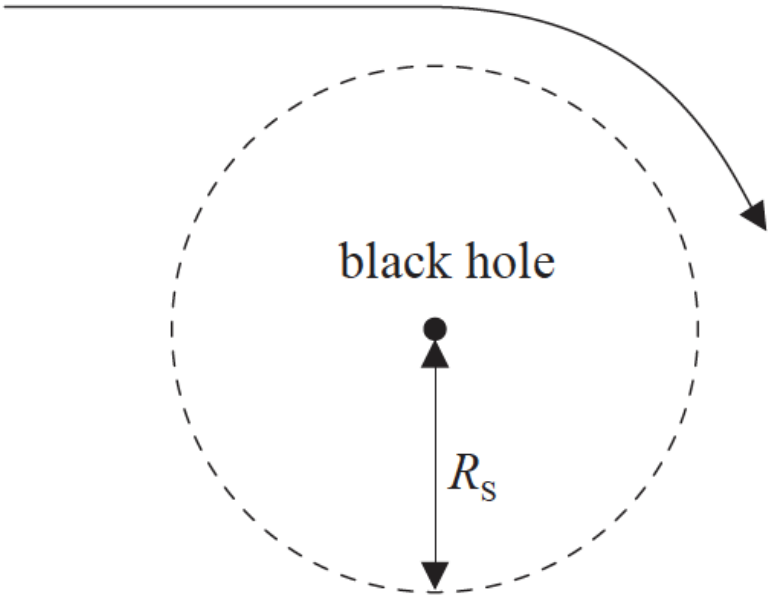
This question is about black holes.

The diagram shows the path of a light ray in the space around a black hole.



(not to scale)

The radius of the dotted circle is the Schwarzschild radius of the black hole.

14a. Define the *Schwarzschild radius* of a black hole. *[1 mark]*

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14b. Explain, using the concept of spacetime, why the path of the light ray is straight at distances far from the black hole and curved when near the black hole. *[3 marks]*

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