Rewarding Learning

Advanced Extension Award
2007

Physics

Advanced Extension Award

H7651

H7651

THURSDAY 28 JUNE, AFTERNOON

TIME

3 hours.

INSTRUCTIONS TO CANDIDATES

In the boxes on the answer booklet, write your centre number, candidate number and subject title.
Answer **all seven** questions.

INFORMATION FOR CANDIDATES

The total mark for this paper is 100.
The mark for each part of a question is shown in brackets and the total mark is given at the end of the question.
The values of physical constants and relationships you may require are given on a separate information leaflet which is an insert to the paper. Any additional data are given in the appropriate question.
The approximate time which you should spend on any one question is given at the start of the question.
You are reminded of the need to organise and present your answers clearly and logically and to use specialist vocabulary where appropriate.
Materials required for examination – Answer booklet, Calculator.
Items included with question paper – Information Leaflet (insert).

ADVICE TO CANDIDATES

In calculations you are advised to show all the steps in your working, giving your answers at each stage. Give final answers to a justifiable number of significant figures.

1 *You are advised to spend about 40 minutes on this question.*

Read the passage and then answer the questions which follow.

Plasma – the fourth state of matter

The state of matter consisting of ionised atoms and electrons is called a plasma. In a sense, plasma is the normal state of matter, as it predominates in most parts of the universe. Most matter in the universe is sufficiently hot, as in stars, or sufficiently diffuse, as in interstellar space, to be highly ionised. Closer to home, the outer layer of the Earth's atmosphere, called the ionosphere, is a plasma of great importance in the propagation of radio waves. On the surface of the Earth plasmas are readily produced, notably in nuclear fusion devices, but do not occur naturally.

One of the most important properties of a plasma relates to the number density of ions and electrons, that is, to the number of these particles per unit volume. All plasmas obey the macroscopic neutrality condition

$$n_i = n_e \qquad \textbf{Equation 1.1}$$

where n_i is the number density of ionised atoms and n_e the number density of electrons. However, the condition can be violated on a microscopic scale, and by asking for what time the condition can be broken we arrive at a fundamental frequency. This quantity sets the natural scale for time in a plasma.

If the electrons in a plasma are momentarily displaced with respect to the ions and are then released, they will oscillate about the equilibrium situation with a characteristic angular frequency ω_p given by

$$\omega_p = 2\pi f_p = \sqrt{\frac{n_e e^2}{\varepsilon_0 m_e}} \qquad \textbf{Equation 1.2}$$

where e is the elementary charge, m_e is the electron mass and ε_0 is the permittivity of free space.

This is called the angular *plasma frequency*. The time from maximum displacement to equilibrium is a quarter of a period. Thus the plasma corrects the violation of charge neutrality in a time of the order of $1/\omega_p$. This must be considered the natural unit of time in a plasma.

The theory of plasma oscillations for an ionised gas was first proposed by Langmuir in 1929. However, the same idea had been used by Rayleigh in 1906. Rayleigh believed in J J Thomson's model of the atom as a 'plum pudding' in which the electrons (the plums) were distributed uniformly in a sphere of positive charge (the pudding). Rayleigh tried to relate the frequency of oscillation of the plums in the pudding to atomic spectra. The angular frequency of oscillations of electrons in the sphere of positive charge is given by **Equation 1.2**. Each oscillating electron causes the generation of electromagnetic waves of the same angular frequency.

Note that a plasma oscillation is not a wave. However, waves can propagate in a plasma under certain conditions. An electromagnetic wave can propagate through a plasma only if its angular frequency is higher than the angular plasma frequency; a wave impinging on a plasma is totally reflected if its angular frequency is less than ω_p. This is the principle of amplitude-modulated (AM) radio propagation beyond the direct line of sight. The radio wave is simply reflected from the lower surface of the ionosphere, and hence travels round the curve of the Earth. Frequency-modulated (FM) and television signals of angular frequency higher than ω_p go right through the ionosphere. Thus, for good reception of FM or television signals, it is important to be within direct line of sight of the transmitter.

(a) Explain briefly what is meant by the following words or phrases, as used in the context of the passage:

(i) diffuse (*line 3*),

(ii) angular frequency (*line 18*),

(iii) violation of charge neutrality (*lines 13, 23–24*). [3]

(b) Explain why the atmosphere just above the Earth's surface is not a plasma. [1]

(c) Summarise the experimental evidence that caused the rejection of the plum-pudding model of the atom (*lines 27–29*). Use information from your knowledge of scattering as a means of probing matter. [4]

(d) **(i)** Explain the statement linking a quarter of a period of plasma oscillation to a time of the order of $1/\omega_p$ (*lines 22–25*). [3]

(ii) This statement goes on to suggest that $1/\omega_p$ is a natural unit of time (*lines 24, 25*).

Discuss the disadvantages of replacing the second with this unit. [2]

(e) Under certain atmospheric conditions, the value of the number density of ionised atoms and electrons in the ionosphere may be abnormally high. This is likely to cause unsatisfactory reception of television signals.

(i) Suggest a cause for the number density of ionised atoms and electrons being abnormally high. [1]

(ii) Explain why television reception may be unsatisfactory when the number density is abnormally high. [4]

(f) The spectrum of atomic hydrogen contains lines with a minimum wavelength of 9×10^{-8} m. Assume that the plum-pudding model (*lines 26–32*) applies to the hydrogen atom, with its one electron in a sphere of positive charge equal to that of the proton.

(i) Make a calculation to estimate the radius of the sphere of positive charge in a hydrogen atom corresponding to the generation of electromagnetic radiation of wavelength 9×10^{-8} m. [4]

(ii) Comment on this application of the plum-pudding model to the hydrogen spectrum. [2]

[Total: 24 marks]

2 (*You are advised to spend about 20 minutes on this question*)

An equation representing the conversion of hydrogen nuclei to helium nuclei in the Sun is

$$4\,{}^{1}_{1}\mathrm{H} \rightarrow {}^{4}_{2}\mathrm{He} + 2\,{}^{0}_{1}\mathrm{e} + Q_1.$$

The symbol ${}^{0}_{1}\mathrm{e}$ represents a particle called a positron. Each positron produced in the reaction combines with a free electron ${}^{0}_{-1}\mathrm{e}$:

$${}^{0}_{1}\mathrm{e} + {}^{0}_{-1}\mathrm{e} \rightarrow Q_2.$$

In these equations, Q_1 and Q_2 represent the energies released. The rest masses of the particles involved are listed below.

${}^{1}_{1}\mathrm{H}$,	1.00728 u
${}^{4}_{2}\mathrm{He}$,	4.00150 u
${}^{0}_{1}\mathrm{e}$,	0.00055 u
${}^{0}_{-1}\mathrm{e}$,	0.00055 u

(a) Find the energies Q_1 and $Q_{2.}$ Give your answers in joules. [6]

(b) The rate at which solar energy is incident normally on an area of one square metre at the top of the Earth's atmosphere is 1.4×10^3 W. The distance of the Earth from the Sun is 1.5×10^{11} m. Assume that the Sun radiates as a point source, and that its power is generated solely by the reactions described above.

Estimate the rate of conversion of hydrogen to helium in the Sun. Give your answer in $\mathrm{kg\,s^{-1}}$. [7]

[Total 13 marks]

3 (*You are advised to spend about 30 minutes on this question*)

Exoplanets

The discovery of planets that are not in our solar system, but which orbit other stars, has recently created a great deal of excitement in astronomy. The existence of such 'exoplanets' is sometimes discovered by monitoring the intensity of light from a star as measured on Earth, and observing a distinct lowering of this intensity as an exoplanet passes in front of the star, temporarily blocking out some of the star's light.

This phenomenon is illustrated by the intensity data for a star shown in the sketch graph of **Fig. 3.1**.

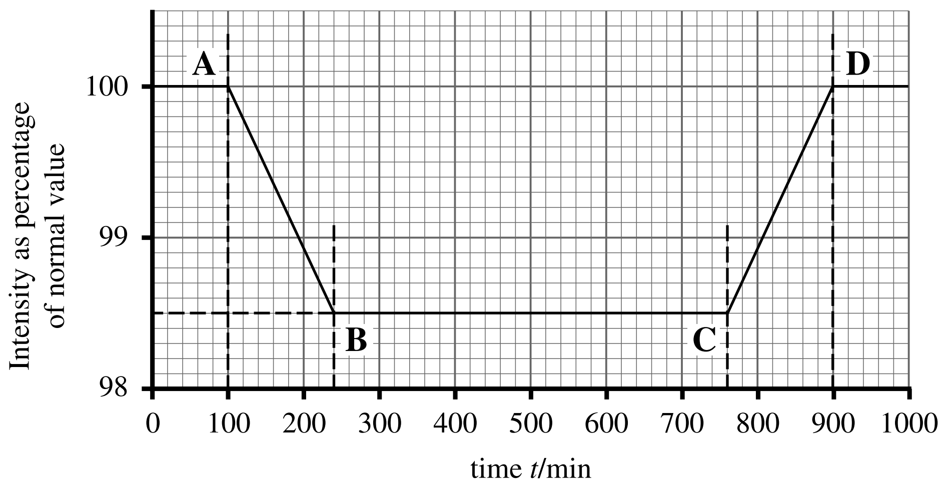

Fig. 3.1

Observed intensity of star as a percentage of that normally observed

(a) Consider the force acting on the exoplanet and hence explain why the orbit must be in an equatorial plane, that is any plane through the centre of the star. [3]

(b) **(i)** Suggest how the reduction in the intensity of the star might be measured. [1]

(ii) Explain the physical origin of the three regions **AB**, **BC** and **CD** in **Fig. 3.1**. You may illustrate your answer with labelled sketches. [4]

(c) The comparative reduction in intensity in region **BC** of **Fig. 3.1** can be used to estimate the diameter of the exoplanet relative to the size of its star.

(i) Derive a relation between the fractional reduction in intensity $\Delta I/I_0$ in region **BC** of **Fig. 3.1** in terms of the radius r of the exoplanet and the radius R of its star. [2]

(ii) Use information from **Fig. 3.1** and your relation in **(i)** to show that the radius of the exoplanet is approximately 0.12 times the radius of its star. Give your answer to three significant figures before rounding to the 0.12 factor. [2]

(d) **(i)** Estimate the average observed speed of the exoplanet across the star's disc in regions **AB** and **CD** by taking values from **Fig. 3.1** and using the approximate result $r = 0.12R$. Give your answer in terms of R, i.e. in units of R min^{-1}. [3]

(ii) The exoplanet is moving with uniform angular velocity in its circular orbit about the star. However, measurements from region **BC** of **Fig. 3.1** give a different average speed of the exoplanet across the star's disc from that calculated in **(d)(i)**. (You are **not** asked to take the measurements or make further calculation.) State whether the average speed in region **BC**, obtained from measurements in this region of the graph, is greater or less than that in regions **AB** and **CD**, and suggest an explanation. [3]

[Total 18 marks]

4 (*You are advised to spend about 20 minutes on this question.*)

(a) State one common feature of, and one fundamental difference between, electric and gravitational fields. [2]

(b) **Fig. 4.1** shows two parallel metal plates separated by a distance d. There is a potential difference V between the plates.

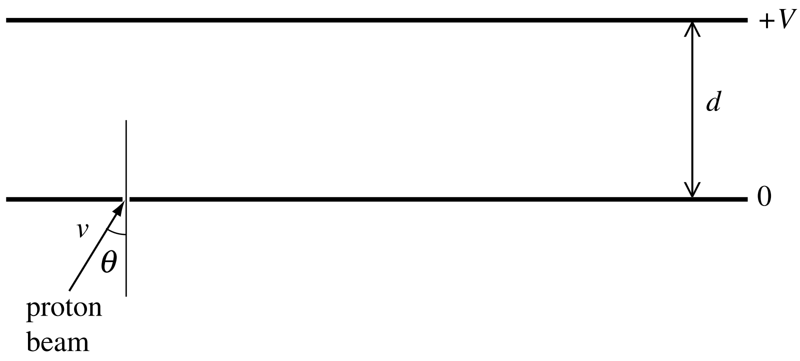

Fig. 4.1

A proton beam is injected into the uniform electric field between the plates through a small hole in the lower plate. The initial velocity v of the protons in the beam is at an angle θ to the normal to the plate.

For the given values of V and v, there is a maximum possible value of θ, equal to θ_{max}, for which the beam can reach the upper plate. For values of θ greater than θ_{max}, the beam does not reach the upper plate, but returns in a curve to the lower plate.

(i) Find θ_{max} for the case in which $V = 1200\,\text{V}$ and $v = 8.0 \times 10^5\,\text{m}\,\text{s}^{-1}$. [5]

(ii) The situation for the case in which θ has a value θ_0 just greater than θ_{max} is illustrated in **Fig. 4.2**. The returning proton beam strikes the lower plate at a point distant x from the entrance hole.

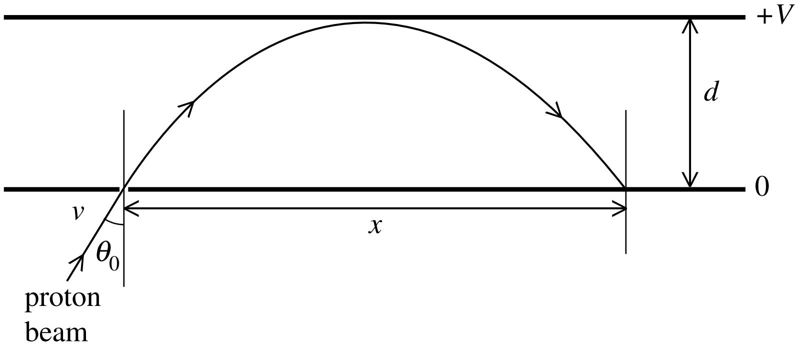

Fig. 4.2

Find an expression for x in terms of d and θ_0 only. [5]

[Total 12 marks]

5 (*You are advised to spend about 20 minutes on this question*)

Satellites move in space using ion propulsion systems. These work by injecting gas atoms into a reaction chamber, in which the atoms lose one or more electrons, causing them to become positive ions. These positive ions are then accelerated by an electric field, passing through a porous accelerating electrode. After passing through the electrode the ions are neutralised by a low energy electron beam. The neutral atom beam then exits the propulsion system, driving the satellite forwards.

In one propulsion system the gas to be ionised is xenon, of atomic mass 131 u. In the reaction chamber the xenon atoms lose one electron only. The atoms in the propelling beam move at a speed of $2.5 \times 10^4\,\mathrm{m\,s^{-1}}$ relative to the satellite.

(a) **(i)** Explain the physical principle underlying the forward movement of the satellite as a result of the projection of the beam of atoms from the propulsion system. [2]

(ii) Suggest why it is desirable that the atoms in the propulsion beam should be neutral. [2]

(iii) Calculate the potential difference through which a singly-charged xenon ion must be accelerated from rest to give it a speed of $2.5 \times 10^4\,\mathrm{m\,s^{-1}}$. [3]

(b) The satellite powered by the xenon system has a mass of 1200 kg and increases its speed by $8.0\,\mathrm{m\,s^{-1}}$ in one day. Calculate the force provided by the propulsion unit. [2]

(c) The battery providing the accelerating potential for the ions in the reaction chamber is charged using solar energy. However, when the satellite is moving towards the Sun, the resultant force on it is not simply that provided by the propulsion unit. Suggest **two** additional contributions to the force on the satellite. In each case, state and explain whether the contribution will tend to increase the resultant force or decrease it. [4]

[Total 13 marks]

6 (*You are advised to spend about 15 minutes on this question*)

(a) A long, straight wire of radius r_1 comes to a certain equilibrium temperature when there is a current I_1 in it.

Another long, straight wire, of the same length and made of the same metal, has a different radius r_2. A current I_2 is needed to achieve the same equilibrium temperature, under the same surrounding conditions.

Obtain an expression for the ratio I_1/I_2 in terms of r_1 and r_2 only. [4]

(b) A circular coil of flexible wire is mounted on a spindle which is mounted so that the plane of the coil is normal to a region of uniform magnetic flux density. By pulling on one end of the wire the coil may be unwound. The arrangement is sketched in **Fig. 6.1**.

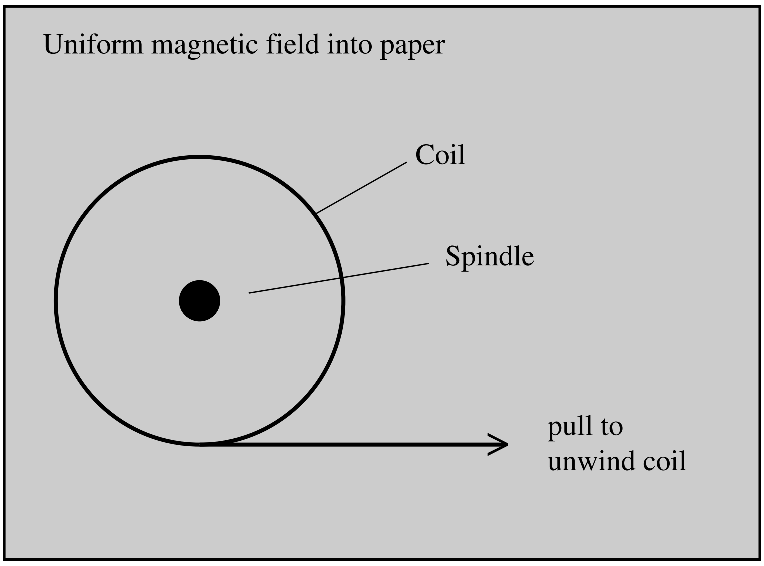

Fig. 6.1

The coil is unwound at a steady rate. A voltmeter is connected across the ends of the coil.

Explain how the laws of Faraday and Lenz apply to this situation.
What change, if any, would occur if the coil were unwound at a greater, steady rate? [4]

[Total 8 marks]

7 (*You are advised to spend about 25 minutes on this question*)

Of all the aspects of the universe that physicists have attempted to understand, the explanation of the various ways in which light can behave has been one of the most challenging. Write an account of the nature of light, making reference to experiments that support the different aspects of your answer.

In addition to the content of your answer, you will be assessed on the quality of your written communication.

[Total 12 marks]

THIS IS THE END OF THE QUESTION PAPER

ADVANCED EXTENSION AWARD

PHYSICS

Information Leaflet

The following may be of use in answering some of the questions.

Values of constants

speed of light in free space	$c = 3.00 \times 10^{8}\ \mathrm{m\ s^{-1}}$
permeability of free space	$\mu_0 = 4\pi \times 10^{-7}\ \mathrm{H\ m^{-1}}$
permittivity of free space	$\varepsilon_0 = 8.85 \times 10^{-12}\ \mathrm{F\ m^{-1}}$
	$\left(\dfrac{1}{4\pi\varepsilon_0} = 9 \times 10^{9}\ \mathrm{F^{-1}\ m}\right)$
elementary charge	$e = 1.60 \times 10^{-19}\ \mathrm{C}$
the Planck constant	$h = 6.63 \times 10^{-34}\ \mathrm{J\ s}$
unified atomic mass unit	$1\ \mathrm{u} = 1.66 \times 10^{-27}\ \mathrm{kg}$
electron mass	$m_e = 9.11 \times 10^{-31}\ \mathrm{kg}$
proton mass	$m_p = 1.673 \times 10^{-27}\ \mathrm{kg}$
neutron mass	$m_n = 1.675 \times 10^{-27}\ \mathrm{kg}$
molar gas constant	$R = 8.31\ \mathrm{J\ K^{-1}\ mol^{-1}}$
the Avogadro constant	$N_A = 6.02 \times 10^{23}\ \mathrm{mol^{-1}}$
the Boltzmann constant	$k = 1.38 \times 10^{-23}\ \mathrm{J\ K^{-1}}$
gravitational constant	$G = 6.67 \times 10^{-11}\ \mathrm{N\ m^{2}\ kg^{-2}}$
acceleration of free fall on the Earth's surface	$g = 9.81\ \mathrm{m\ s^{-2}}$
normal atmospheric pressure	$p_{atm} = 1.01 \times 10^{5}\ \mathrm{Pa}$
electron volt	$1\ \mathrm{eV} = 1.60 \times 10^{-19}\ \mathrm{J}$

Formulae

The following equations may be useful in answering some of the questions in the examination:

Mechanics

equations for uniformly accelerated motion	$v = u + at$
	$s = \frac{1}{2}(u + v)t$
	$s = ut + \frac{1}{2}at^2$
	$v^2 = u^2 + 2as$

Momentum and Energy

force = rate of change of momentum	$F = \dfrac{\Delta(mv)}{\Delta t}$
power	$P = Fv$

Kinetic Theory

kinetic theory of gases	$pV = \frac{1}{3}Nm\overline{c^2}$
average kinetic energy of a molecule	$\frac{1}{2}m\overline{c^2} = \frac{3}{2}kT = \dfrac{3RT}{2N_A}$

Electricity

terminal potential difference	$V_{load} = \mathcal{E} - Ir$
discharge of capacitor	$Q = Q_0 e^{-t/RC}$
time constant	$\tau = RC$

Atomic and Nuclear physics

radioactive decay	$\dfrac{\Delta N}{\Delta t} = -\lambda N$
	$N = N_0 e^{-\lambda t}$
half-life	$T_{\frac{1}{2}} = \dfrac{\ln 2}{\lambda}$

Energy

mass-energy relationship	$E = mc^2$

Quantum Physics

energy-frequency relationship for photons	$E = hf$
de Broglie equation	$\lambda = \frac{h}{p}$

Waves and Oscillations

two-slit interference	$\lambda = ay/d$ **or** $\lambda = xs/D$
simple harmonic motion	$a = -(2\pi f)^2 x$
	$x = A \cos 2\pi ft$ $x = A \sin 2\pi ft$

Fields

gravitational fields	$g = \frac{F}{m}$
	$g = \frac{GM}{r^2}$
electric fields	$E = \frac{F}{q}$
	$E = \frac{1}{4\pi\varepsilon_0}\frac{q}{r^2}$
	$E = \frac{V}{d}$

Magnetic effect of currents

force on a current-carrying conductor	$F = BIl$
force on a moving charge	$F = Bqv$
magnetic flux	$\Phi = BA$
induced e.m.f.	$\mathcal{E} = -\frac{\mathrm{d}(N\Phi)}{\mathrm{d}t}$

Mathematical equations

areas and volumes	area of circle = πr^2
	surface area of cylinder = $2\pi rh + 2\pi r^2$
	volume of cylinder = $\pi r^2 h$
	surface area of sphere = $4\pi r^2$
	volume of sphere = $\frac{4}{3}\pi r^3$
radians	arc = $r\theta$
	$\sin\theta \approx \tan\theta \approx \theta$ and $\cos\theta \approx 1$ for small θ
logarithms	$\ln(x^n) = n \ln x$ $\ln(e^{kx}) = kx$