SEMESTER 2 EXAMINATION 2014-2015

SPACE PLASMA PHYSICS

Duration: 120 MINS (2 hours)

This paper contains 8 questions.

Answer **all** questions in **Section A** and **only two** questions in **Section B**.

Section A carries 1/3 of the total marks for the exam paper and you should aim to spend about 40 mins on it.

Section B carries 2/3 of the total marks for the exam paper and you should aim to spend about 80 mins on it.

An outline marking scheme is shown in brackets to the right of each question.

A Sheet of Physical Constants is provided with this examination paper.

Only university approved calculators may be used.

A foreign language word to word® translation dictionary (paper version) is permitted provided it contains no notes, additions or annotations.

Section A

A1. Auroral electron precipitation ionises the gas in the Earth's upper atmosphere through collisions. Briefly describe two other processes that ionise a gas to form a plasma. A hypothetical planet has an upper atmosphere which is dominated by atomic neon, which has an ionisation potential of 21.6 eV. Calculate the temperature needed to ionise the upper atmosphere of the planet, and the wavelength of radiation required to do likewise. [4]

A2. During a geomagnetic storm the magnetic field measured at the Earth's equator was observed to decrease by 1%. With the aid of diagrams and words, explain:

(a) magnetic gradient drift, [2]

(b) magnetic curvature drift, [2]

(c) how these effects cause the observed decrease in the magnetic field. [3]

A3. What is the plasma beta, and what is its relevance to the behaviour of a plasma? [2]

A4. Explain what is meant by the pitch angle of a charged particle in a magnetic field. Hence, derive a formula for the magnetic field strength at the point where a particle reverses direction in the Earth's dipole field, in terms of the magnetic field strength and pitch angle of the particle at the equator. [5]

A5. Explain the meaning of the terms "open" and "closed" when describing Earth's magnetic field lines. [2]

Section B

B1. (a) Derive an expression for the 'garden hose' angle of the Parker spiral of the solar wind, explaining why the spiral forms. In order to explain all terms, use two well-labelled diagrams, one in the Geocentric Solar Ecliptic (GSE) frame, and one in the frame rotating with the Sun. What happens to the spiral when the solar wind speed increases? [5]

(b) JSO is a coordinate system equivalent to GSE, but applied to Jupiter (i.e. the X-axis is directed from the centre of the planet to the Sun). If the solar wind speed at Jupiter is 500 km s^{-1}, what angle does the IMF make with the JSO X-axis near Jupiter? Is the angle greater or smaller than that near Earth, for the same solar wind speed? (The radius of Jupiter's orbit $r_j = 5.2$ AU and the solar rotation period is 25 days.) [2]

(c) At a time when the solar wind velocity at Earth is radial at 650 km s^{-1} and the interplanetary magnetic field in the GSE frame has components (0, 0, -2) nT, the Stern gap, or region of open field lines in interplanetary space, has width $\Delta Y = 7.5R_E$ (at all values of X). The magnetosphere has a radius of cross section of $30R_E$ in the Y plane, and magnetospheric convection has achieved steady state. If each newly opened field line takes 100 minutes to traverse the polar cap, calculate the area of the ionospheric polar cap, where the magnetic field $B_i = 5 \times 10^{-5}$ T. [4]

(d) What is the voltage across the Stern gap under the conditions given in (b)? Calculate the reconnection efficiency. [4]

(e) Explain what a plasmoid is and how they form in the Earth's magnetotail during a substorm, by using a time series of four labelled diagrams of the magnetotail to show the key stages of the formation and evolution. What happens to the plasmoid after formation? [5]

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B2. (a) Outline and discuss the factors that influence the size of Earth's magnetosphere in the direction towards the Sun, and its maximum radius of cross section when viewed from the Sun. Include the relevant key equations in your answer. [4]

(b) Outline and discuss qualitatively (no equations are necessary) the factors that influence the length of Earth's magnetotail. Consider both the connected and disconnected parts of the magnetotail. [3]

(c) Assuming a solar wind proton number density of $n_{sw} = 10^6$ m^{-3}, estimate the solar wind speed required for satellites in geostationary orbit (radius $r_{geo} = 6.6R_E$) to encounter the dayside magnetosheath. Start from the equations for the relevant pressures at the nose of the magnetosphere, and explain all assumptions made. The magnetic moment of Earth, $M_E = 7.8 \times 10^{15}$ Tm^3, and you may assume the Earth's dipole field is given by

$$B_m(r, \lambda) = \frac{M_E}{r^3}(3\sin^2\lambda + 1)^{1/2}$$

where λ is magnetic latitude and r is the distance from the centre of the Earth. [7]

(d) Make two sketches showing the currents that flow in the magnetopause and cross-tail neutral sheet: one for the GSE (Geocentric Solar Ecliptic) ZX plane ($Y = 0$) and the other for a plane parallel to the GSE YZ plane at a point downtail. Label currents with their names. [6]

B3. Consider a plasma with a Boltzmann density distribution, where T is the temperature of both ions and electrons, n_0 is the number density of both ions and electrons, and the ions have a single positive charge, q.

(a) Describe what happens to the plasma when a positive test charge of charge q is introduced. Write expresions for the number density of both the electrons and ions at equilibrium, in terms of T, n_0, q, and the electric potential, ϕ. Explain any assumptions you make. [3]

(b) Hence show that

$$\nabla^2\phi = \left(\frac{n_0 q^2}{\epsilon_0 k_B T}\right)\phi.$$

(Hint: Use the Taylor expansion $e^x = 1 + x + ...$) [5]

(c) Given that the solutions in spherical coordinates centred on the test charge for ϕ are

$$\phi = \phi_0(r)e^{r/\lambda_D} \quad \text{and} \quad \phi = \phi_0(r)e^{-r/\lambda_D} \quad \text{where} \quad \lambda_D = \sqrt{\frac{\epsilon_0 k_B T}{n_0 q^2}},$$

use the boundary conditions for a plasma at $r = \infty$ and r close to zero to show which solution applies to the plasma, and to explain the significance of $\phi_0(r)$ and λ_D. Draw a rough graph showing the variation of potential with r to aid your explanation. [6]

(d) The solar wind near Earth has a number density $n_0 = 10^4$ m^{-3} and a temperature $T = 5 \times 10^6$ K. Calculate λ_D for the solar wind plasma, and hence state whether the first plasma criterion is satisfied. [2]

(e) The second plasma criterion is

$$n_o\lambda_D^3 \gg 1.$$

Explain how this criterion quantifies the definition of a free particle in a plasma. [4]

END OF PAPER