Tentamen för Rymdfysik I
2010-03-15

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Please write your **name** on **all** papers, and on the first page your **address, e-mail** and **phone number** as well. Answers may of course be given in Swedish or English, according to your own preference.

Time: 14:00 - 19:00

Allowed tools: Mathematics Handbook (or equivalent), Physics Handbook, enclosed tables and formula sheets, calculator. A bilingual dictionary, for example English-Swedish or English-German, may also be used. Solutions should be written in Swedish or English.

1. Here follows a set of multiple choice questions, where you must find out which statements are correct. For each question (1-1, 1-2 etc), there is only one correct combination of answers, say ”A and C” or ”none”. To score on a question, you need to have exactly the right combination. Any number of alternatives can be correct (0 – 3). (1 p/question, 10 p in total)

   1:1. Solar activity:

   A. Solar flares are huge eruptions from the Sun, emitting large amounts of energetic particles and intense radiation during their brief lifetime (a few hours).

   B. The number of sunspots varies with an 11 year period (or has at least done so for the last 250 years).

   C. The intensity of sunlight in the visible range of wavelengths can increase by an order of magnitude during a solar flare eruption.

   1:2. Solar system plasmas:

   A. Venus and the Earth have ionospheres, but because of the decrease in temperature with distance to the Sun, there is no ionized upper layer in the atmospheres of Jupiter and Saturn.

   B. Due to the solar wind interaction with a comet, it often develops two tails streaming in different directions, where one tail consists of plasma and the other of dust.

   C. The Earth's magnetotail points away from the Sun at midnight and toward the Sun at noon.

   1:3. Magnetic fields in space:

   A. In vacuum, the magnetic field from a source localized within some sphere decreases with distance at least as fast as $1/r^3$ outside the sphere.

   B. The concept of ”frozen-in” magnetic field lines applies if the magnetic field in the frame of reference of the plasma is zero.

C. The interplanetary magnetic field decays much slower with distance from the sun than a vacuum field, because the magnetic field is frozen in to the expanding solar wind.

1:4. Solar wind:

A. The solar wind is supersonic (i.e. it blows faster than the sound speed in itself).

B. The solar wind accounts for about 20% of the total mass loss rate (measured in kg/s) of the sun.

C. The typical solar wind temperature is around 5-10 eV (50,000 - 100,000 K), so interplanetary spacecraft must be provided with heat shields.

1:5. Earth's ionosphere:

A. The E-layer has much higher electron density at day than at night, because of ionizing radiation from the sun. For the F-layer, the daily variation is not so strong, as the recombination rates are much slower at F-layer altitudes.

B. Due to collissions between particles, the conductivity in the direction perpendicular to the magnetic field is much higher in the ionosphere than in the magnetosphere.

C. The density of neutral gas shows a maximum in the E-layer, at least at daytime.

1:6. Satellite orbits:

A. Geostationary satellites always stay above the same spot on the North or South Pole.

B. At perigee, a satellite has its highest speed.

C. The geostationary orbit is possible due to a balance between the gravitational pull of the earth and the sun.

1:7. Rockets:

A. Rockets work only in an atmosphere, because they need something to push against.

B. Rockets work only in an atmosphere, because they need oxygen for burning their fuel.

C. When launching a rocket, burning all the fuel at once saves fuel as compared to burning the same amount of fuel during a longer time.

1:8. Particle motion:

A. If there is an electric field $\mathbf{E}$ perpendicular to the magnetic field $\mathbf{B}$ in a collisionless plasma, all the plasma (ions and electrons) drift in the same direction, which is perpendicular to $\mathbf{E}$ as well as to $\mathbf{B}$.

B. The magnetic field does no work on a charged particle.

C. The ∇B drift acts in opposite directions on electrons and positive ions, and hence can drive a current.

1:9. Magnetosphere:

A. The plasmasphere is filled with a relatively cold and dense plasma, corotating with the Earth.

B. The cross-tail current flows in the duskward (eng. dusk = sw. skymning) direction.

C. The magnetopause separates the cold plasmasphere plasma from the hotter and more tenuous radiation belts.

1:10. Space weather:

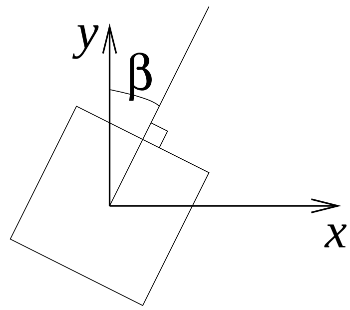

Figure 1:

A. X-rays released in a solar flare reach the Earth after about 24 hours.
B. During northward interplanetary magnetic field, reconnection on the dayside magnetopause transports magnetic flux to the tail, where the magnetic energy density increases.
C. Heating of the Earth's upper atmosphere and ionosphere during a solar storm cause the atmosphere to expand, thereby increasing the air friction felt by a spacecraft.

2. Consider a cubic spacecraft in interplanetary space at 2 AU distance from the Sun. One of the normal directions to the cube sides (the z-direction in Figure 1, where the x-axis points to the Sun) is perpendicular to the direction to the solar direction. All surfaces are covered by a material with absorbtion and emission coefficients of 0.5 and 0.2, respectively. Internal sources of heating can be neglected. What are the maximum and and minimumum temperatures of the spacecraft, and at what values of the angle β do these occur? (3 p)

3. An electron on a magnetic field line reaching the Earth at a (magnetic) latitude of 60 degrees has its mirror point at an altitude of 10,000 km (that is, $10 \cdot 10^3$ km).

   (a) At what geocentric distance does it cross the (magnetic) equatorial plane, and what is its pitch angle there? (3 p)

   (b) Close to its mirror point, the electron happens to collide with a proton. In the collission, the electron's pitch angle jumps to 60 degrees. What will be the altitude of the electron's new mirror point? *Note added after the exam: this leads to an equation without analytical solution, but which can either be solved numerically or by some approximation.* (2 p)

4. ESA is preparing a mission called Swarm, to study the details of the geomagnetic field, consisting of three satellites in circular polar orbits around the Earth. Two of the satellites are to travel at 450 km altitude and the third at 550 km. The Swedish Institute of Space Physics in Uppsala delivers part of the Electric Field Instrument onboard Swarm.

   Where needed, you may in the following assume that the satellite orbits have inclination 90°, that the geomagnetic field is a perfect dipole with symmetry axis identical to the Earth's rotation axis, that the plasma perfectly corotates with the Earth, and that the electric field in the plasma rest frame is zero.

   (a) What will be the difference in orbital period (in minutes) between the two lower and the upper spacecraft? (2 p)

   (b) What is the maximum magnetic field strength encountered by the lower satellite? At what latitude is this magnetic field measured? (2 p)

(c) What is the maximum horizontal[1]electric field component measured by the lower satellite? At what latitude is this maximum horizontal electric field detected? (3 p)

5. The attached printout of the Spaceweather.com web pages of yesterday night gives the solar and solar wind conditions at the time. For the data refering to a specific coordinate system, this is the GSE (geocentric solar ecliptic) system, which is a right-handed Cartesian system centred in the Earth with its X-axis pointing to the Sun and Z to ecliptic north (i.e. out of the Earth's plane of motion around the sun).

   (a) From the data given in the left column, estimate the distance from the centre of the Earth to the magnetopause along the Sun-Earth line, with some reasonable assumptions on e.g. the geomagnetic field. (2 p)

   (b) The likelihoods for significant geomagnetic disturbances within the next 0-24 and 24-48 hour periods are given as 10% and 30-35%, respectively (depending on latitude), and the probability of an M class solar flare is estimated as 10% in both time periods. Discuss, in as much relevant detail as you like but not on much more than one page, what observations reported on the page may support these forecasts. (3 p)

Lycka till!

[1] Note added after exam: This word was missing in the original exam.

Space Physics Formulas:
Complement to Physics Handbook

Charge density in plasma with charge particle species s:

$$\rho = \sum_s q_s n_s$$

Current density:

$$\mathbf{j} = \sum_s q_s n_s \mathbf{v_s}$$

Galilean transformations:

$$\mathbf{E}' = \mathbf{E} + \mathbf{v} \times \mathbf{B}, \qquad \mathbf{B}' = \mathbf{B}$$

Dipole magnetic field:

$$\mathbf{B}(r,\theta) = -B_0 \left(\frac{R_0}{r}\right)^3 \left(2\hat{\mathbf{r}}\cos\theta + \hat{\theta}\sin\theta\right)$$

Dipole field lines:

$$r/\sin^2\theta = \text{const.}$$

Magnetic field energy density and pressure:

$$w_B = p_B = \frac{B^2}{2\mu_0}$$

Equation of motion of neutral gas:

$$\rho_{\text{m}} \frac{d\mathbf{v}}{dt} = -\nabla p + \text{other forces}$$

Equation of motion of gas of charged particles:

$$mn\frac{d\mathbf{v}}{dt} = nq(\mathbf{E} + \mathbf{v} \times \mathbf{B}) - \nabla p + \text{other forces}$$

MHD equation of motion:

$$\rho_{\text{m}} \frac{d\mathbf{v}}{dt} = \mathbf{j} \times \mathbf{B} - \nabla p + \text{other forces}$$

Equation of continuity:

$$\frac{\partial n}{\partial t} + \nabla \cdot (n\mathbf{v}) = Q - L$$

Equation of state for ideal gas:

$$p = nKT$$

Condition for ”frozen-in” magnetic field:

$$\mathbf{E} + \mathbf{v} \times \mathbf{B} = 0$$

Ohm’s law:

$$\mathbf{j} = \begin{pmatrix} \sigma_{\text{P}} & \sigma_{\text{H}} & 0 \\ -\sigma_{\text{H}} & \sigma_{\text{P}} & 0 \\ 0 & 0 & \sigma_{\|} \end{pmatrix} \begin{pmatrix} E_x \\ E_y \\ E_{\|} \end{pmatrix}$$

Conductivities:

$$\begin{aligned}\sigma_{\mathrm{P}} &= \frac{ne}{B}\left(\frac{\omega_{\mathrm{ci}}\nu_{\mathrm{i}}}{\omega_{\mathrm{ci}}^2+\nu_{\mathrm{i}}^2}+\frac{\omega_{\mathrm{ce}}\nu_{\mathrm{e}}}{\omega_{\mathrm{ce}}^2+\nu_{\mathrm{e}}^2}\right)\\ \sigma_{\mathrm{H}} &= \frac{ne}{B}\left(\frac{\omega_{\mathrm{ci}}^2}{\omega_{\mathrm{ci}}^2+\nu_{\mathrm{i}}^2}-\frac{\omega_{\mathrm{ce}}^2}{\omega_{\mathrm{ce}}^2+\nu_{\mathrm{e}}^2}\right)\\ \sigma_{\parallel} &= ne^2\left(\frac{1}{m_{\mathrm{i}}\nu_{\mathrm{i}}}+\frac{1}{m_{\mathrm{e}}\nu_{\mathrm{e}}}\right)\end{aligned}$$

Cyclotron frequency (gyrofrequency):

$$f_{\mathrm{c}} = \omega_{\mathrm{c}}/(2\pi) = \frac{1}{2\pi}\frac{qB}{m}$$

Magnetic moment of charged particle gyrating in magnetic field:

$$\mu = \frac{1}{2}mv_{\perp}^2/B$$

Magnetic force on magnetic dipole:

$$\mathbf{F}_B = -\mu\nabla B$$

Drift motion due to general force $\mathbf{F}$:

$$\mathbf{v}_{\mathbf{F}} = \frac{\mathbf{F}\times\mathbf{B}}{qB^2}$$

Pitch angle:

$$\tan\alpha = v_{\perp}/v_{\parallel}$$

Electrostatic potential from charge Q in a plasma:

$$\Phi(r) = \frac{Q}{4\pi\epsilon_0}\frac{e^{-r/\lambda_{\mathrm{D}}}}{r}$$

Debye length:

$$\lambda_{\mathrm{D}} = \sqrt{\frac{\epsilon_0 KT}{ne^2}}$$

Plasma frequency:

$$f_{\mathrm{p}} = \omega_{\mathrm{p}}/(2\pi) = \frac{1}{2\pi}\sqrt{\frac{ne^2}{\epsilon_0 m_{\mathrm{e}}}}$$

Rocket thrust:

$$T = v_{\mathrm{e}}\frac{\mathrm{d}m}{\mathrm{d}t}$$

Specific impulse:

$$I_{\mathrm{sp}} = \frac{\int T\,\mathrm{d}t}{m_{\mathrm{fuel}}g} = v_{\mathrm{e}}/g$$

The rocket equation:

$$\Delta v = -gt_{\mathrm{burn}} + v_{\mathrm{e}}\ln\left(1+\frac{m_{\mathrm{fuel}}}{m_{\mathrm{payload+structure}}}\right)$$

Emitted thermal radiation power:

$$P_{\mathrm{e}} = \varepsilon\sigma A_{\mathrm{e}}T^4$$

Absorbed solar radiation power:

$$P_{\mathrm{a}} = \alpha A_{\mathrm{a}}I_{\mathrm{rad}}$$

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