Tentamen för kursen Rymdfysik (1FA255)
2012-10-22

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Answers should be provided in Swedish or English.
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.

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). Feel free to comment in words if you are uncertain on the interpretation of some alternative or question. (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.

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

C. The general level of solar activity follows the same 11 year period as the sunspots.

1:2. Space plasmas:

A. A planet with a magnetic field, orbiting a star emitting a plasma flow, will have a magnetosphere.

B. A comet often develops two tails streaming in different directions, where one tail consists of plasma and the other of dust.

C. Any sufficiently large volume of a plasma usually contains about equal numbers of positive and negative charges, and thus shows little net charge.

1:3. Magnetic fields in space:

A. Plasma parameters like density and temperature typically have weaker gradient in the direction perpendicular to the magnetic field direction than along the same field.

B. Earth's magnetic field is mainly generated by the Birkeland currents flowing between the magnetosphere and the ionosphere.

C. If the magnetic field is frozen into the plasma, two plasma elements which at one time are on different magnetic field lines will always be so.

1:4. Solar wind:

A. The solar wind is the dominant mass loss for the Sun.

B. Fast solar wind mainly originates in regions of open magnetic field lines on the Sun known as coronal holes.

C. Because of the rotation of the Sun, the solar wind at Earth orbit blows at an angle of about 45 degrees from the direction to the Sun, as seen in a geocentric reference frame.

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 there are much lower because of the lower neutral density at F-layer altitudes.

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

C. The electron density in the Earth's ionosphere is determined by the solar wind intensity and the geomagnetic field strength.

1:6. Spacecraft:

A. Rockets need something to push on, and therefore do not work in vacuum, only inside an atmosphere.

B. As the gravitation from the Earth decreases as $\exp(-z/H)$, where z is the altitude above ground and H is the scale height (see formula sheet), spacecraft at altitudes above about 100 km move in straight lines.

C. Satellites in geostationary orbit need to have a lot of fuel to correct their orbits from the perturbations caused by air friction.

1:7. Aurora:

A. Aurora is sunlight reflected from the Birkeland currents connecting the magnetosphere and ionosphere.

B. The radiation pressure due to auroral light accelerates electrons to keV energies.

C. The auroral light is mainly emitted at altitudes between 100 and 200 km.

1:8. Motion of charged particles:

A. The orbital magnetic moment of an electron moving in a magnetic field is conserved if the field varies only a little during an electron gyroperiod and inside an electron gyroradius.

B. The radiation belts (van Allen belts) contain trapped electrons and ions.

C. In a colissionless magnetic field, an electric field applied perpendicular to the magnetic field does not result in a current: instead, the whole plasma starts to drift.

1:9. Space weather:

A. Increased UV intensity during geomagnetic storms can heat the upper atmosphere so much that spacecraft air friction increases significantly.

B. A geomagnetic storm is due to the impact of solar and solar wind disturbances, often caused by solar flares, CMEs, or fast solar wind streams from coronal holes, on the Earth's magnetosphere.

C. During periods of northward interplanetary magnetic field, reconnection on the dayside magnetopause causes magnetic flux transport to the tail and the storage of magnetic energy in the tail.

1:10. The letters in Figure 1 identify the following regions and boundaries:

A. (b) is the bow shock

B. (d) and (e) are the radiation belts

C. (c) is the magnetosheath

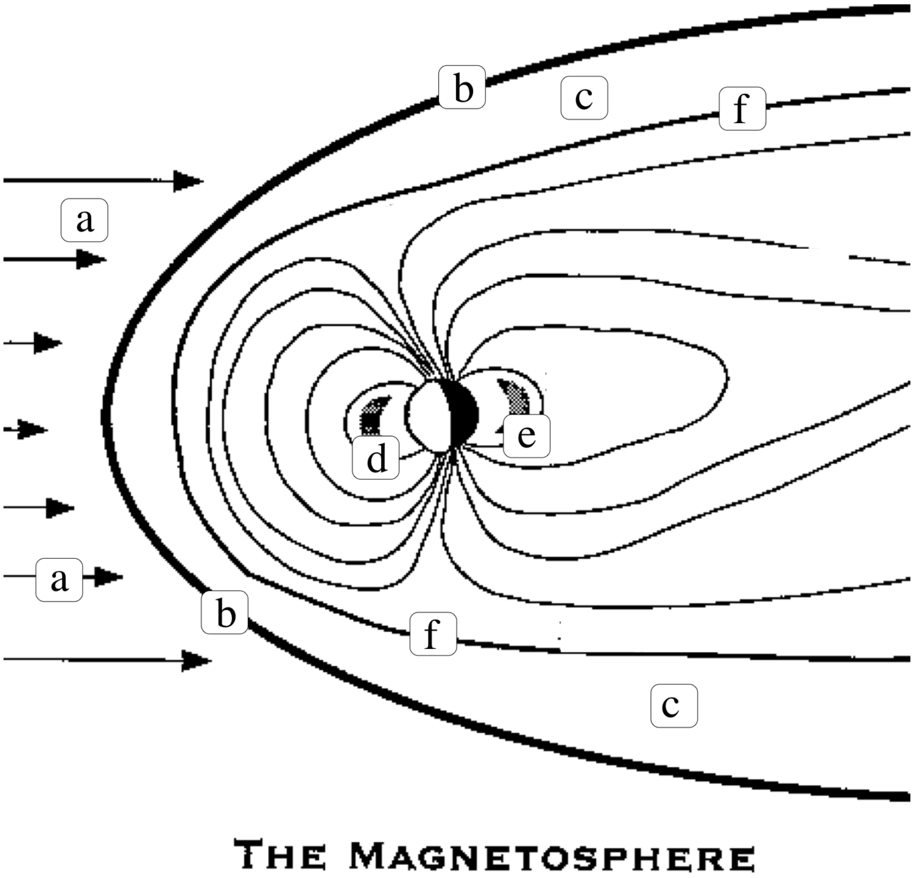

Figure 1: Sketch of the terrestrial magnetosphere.

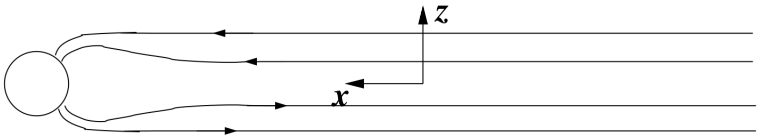

Figure 2: Idealized geometry of the relevant part of the geomagnetic tail (around the origin).

2. Consider the following model of the magnetic field in the central part of the geomagnetic tail:

$$\mathbf{B}(\mathbf{r}) = \begin{cases} -B_0\hat{\mathbf{x}} & , \quad z < -a \\ B_0\,\hat{\mathbf{x}}\,\frac{3\,a^2\,z - z^3}{2\,a^3} & , \quad -a \le z \le a \\ B_0\hat{\mathbf{x}} & , \quad z > a \end{cases}$$

   where $B_0 = 1$ nT, $a = 2000$ km and the coordinates are defined as in Figure 2.

   (a) Calculate the current density $\mathbf{j}(\mathbf{r})$ and the magnetic force density $\mathbf{j}(\mathbf{r}) \times \mathbf{B}(\mathbf{r})$ (magnitudes and directions as functions of position). Also calculate their numerical values at $z = 0$. (3 p)

   (b) Now consider what happens if an instability appears in the region $-a < x < a$, $-10\,a < y < 10\,a$, $-a < z < a$ so that the resistivity in this region includes drastically. When the currents cannot flow through this region as before, where will they close now? How much magnetic energy is stored in this volume? What happens if this is released during a few minutes? (2 p)

3. In the following, assume the geomagnetic field is a dipole field with strength 30 μT on the ground at the equator.

   (a) Show that the kinetic energy of a charged particle moving in a magnetic field, which is constant in time but may vary in space, is constant. (1 p)

   (b) Consider an oxygen ion (O^+) with a kinetic energy of 10 keV and no velocity along the magnetic field, moving in the equatorial plane at a distance of 3 R_E from the center of the Earth. Calculate the two characteristic periods in (b) above which are defined for this particle (the third one is undefined because of the particle's zero velocity along the magnetic field). (3 p)

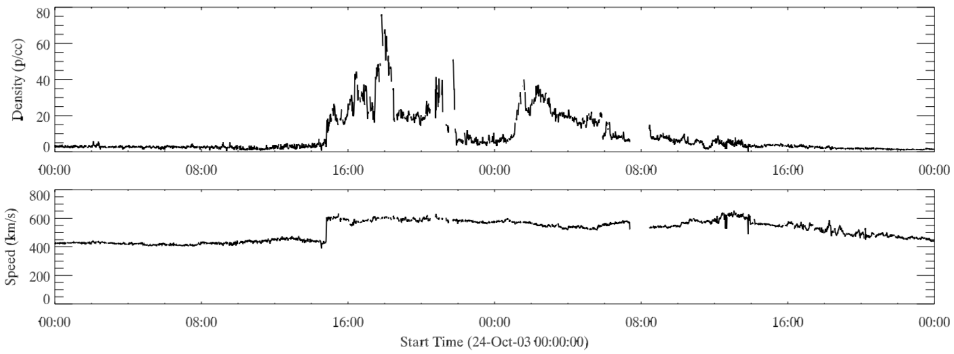

Figure 3: Solar wind measurements from ACE during the so-called Halloween storm of 2003.

4. Figure 3 shows data from the ACE spacecraft, situated at the Sun-Earth Lagrange point L1, during the first days of the so-called Halloween storm of 2003.
   (a) Estimate the minimum and maximum of the geocentric distance to the subsolar point on the magnetopause (where the line between the centres of the Sun and Earth cross the magnetopause) for the period shown. Be careful to state the assumptions you must do. (3 p)
   (b) The flux of energy and momentum in the solar wind increases during the storm. On the other hand, the magnetosphere is compressed by the increase in dynamic pressure, so the cross-sectional area it shows to the solar wind decreases. Do you think the net effect is positive or negative, i.e. that the total energy input from the solar wind to the magnetosphere increases or decreases? Discuss freely, including some quantitative arguments (that is, some equations and numbers), using no more than 150 words. (2 p)

5. In May 2, 2012, ESA announced that the next large scale European space mission will be the Jupiter Icy Moons Explorer, JUICE, for launch in 2022 and arrival at Jupiter in 2030. A suggested scenario for how to get from Earth to Jupiter is shown in Figure 4. In this scenario, there are three flybys of Earth (E1, E3 and E4) and one flyby of Venus (V2). There are also two ”deep space maneuvres” (DSM1 and DSM2) where the thrusters onboard the spacecraft are used to adjust the trajectory.
   (a) The total energy, kinetic plus potential, of a mass m in an elliptic orbit around a body of mass M is given by $E = -GMm/(2a)$, where G is the gravitational constant and a the semi-major axis of the ellipse (that is, half the length of the longest axis of the ellipse). As you can see in Figure 4, the first orbit around the Sun (from launch to E1) is very similar to the Earth orbit. The flybys of Earth and Venus are used for gaining energy from their motion, so that the final Hohmann trajectory (after E4) leads to Jupiter. How much energy has the spacecraft gained from the four flybys, if its mass is 4800 kg? (3 p)
   (b) Assume the spacecraft body to be a cube, 2 m on each side (Figure 5), with perfect internal heat conductivity, and neglect the solar panels and the high gain antenna. If the spacecraft temperature is 30°C at Earth orbit when the $Z_{s/c}$ is directed to the Sun and there is no internal heating (all electrical systems turned off), how much internal heating by onboard systems would be needed to keep it at the same temperature when at Jupiter (for the same pointing of the s/c axes)? (3 p)

Lycka till!

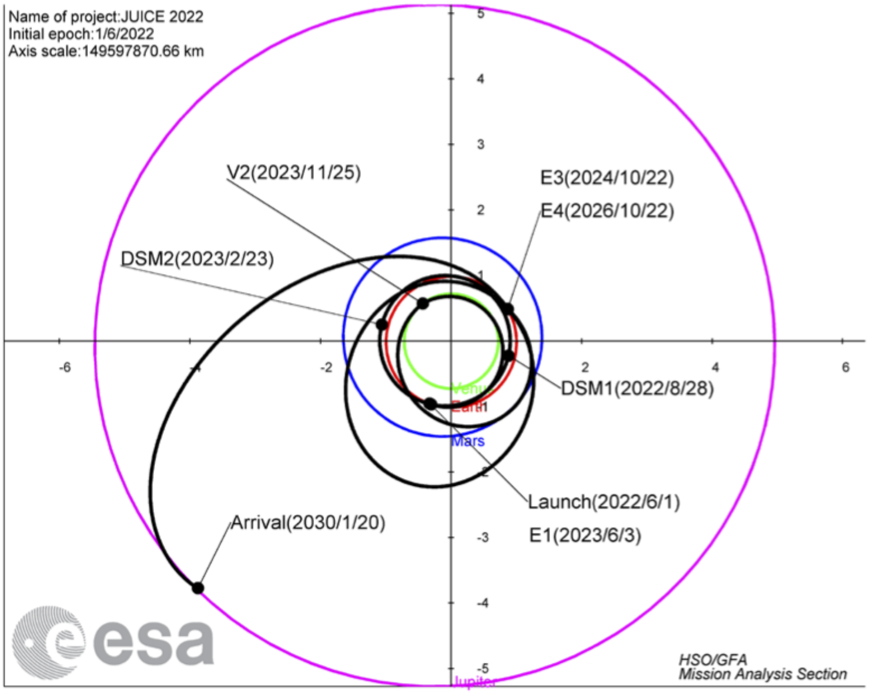

Figure 4: Possible JUICE trajectory to Jupiter. The green, red and blue circles are the orbits of Venus, Earth and Mars, respectively. Image credit: ESA.

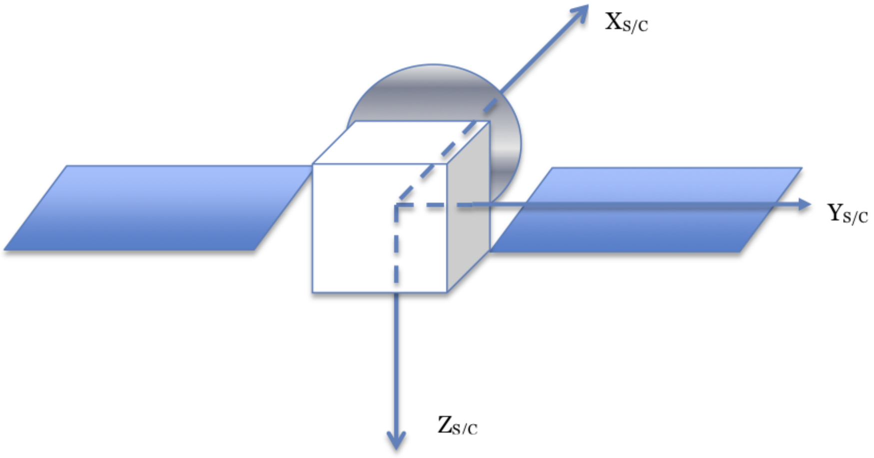

Figure 5: Possible JUICE spacecraft configuration. The blue planes are the solar panels, the grey disk the high gain antenna for communication with the Earth. Image credit: ESA.

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:

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

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:

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

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:

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

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 **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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