Tentamen för Rymdfysik I
2006-06-12

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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: 15:00 - 20:00

Allowed tools: Mathematics Handbook, Physics Handbook, enclosed formula sheet, calculator. A bilingual dictionary, for example English-Swedish or English-French, 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 B” or ”none”. To score on a question, you need to have exactly the right combination. You are welcome to add comments to your answers. Any number of alternatives can be correct (0 – 3). (1 p/question, 10 p in total)

   1:1. Reconnection and substorms:

   - A. Reconnection is the common mechanism driving explosive magnetic events like solar flares and geomagnetic substorms.
   - B. During reconnection, magnetic energy is converted to particle energy in the plasma.
   - C. The energy released in a geomagnetic substorm has been stored in the geomagnetic tail.

   1:2. Solar activity:

   - A. The activity of the sun varies in a 22-year cycle. If the last solar maximum was around year 2000, the next solar maximum will be around 2022.
   - B. The intensity of visible light from the sun drops by around 50% from solar maximum to solar minimum.
   - C. The sunspot number anticorrelates with the solar activity: more sunspots means the sun is colder and less active.

   1:3. Rockets and propulsion:

   - A. Big rockets are most effective, because the fuel needed to attain a certain velocity depends logarithmically on the spacecraft mass.
   - B. Rockets are often launched westwards to take advantage of the rotation of the Earth.
   - C. The fraction of mass that is fuel can be as high as 90% for a rocket ready for launch.

   1:4. Magnetosphere:

   - A. The magnetosphere disappears at nighttime, because the ionization by solar radiation then stops.
   - B. Electrical currents flow on the magnetopause, which is the outer boundary of the magnetosphere.
   - C. Magnetic field lines leaving the Earth at low latitudes (close to the equator) are closed (return back to the Earth without leaving the magnetosphere).

   1:5. Shock waves:

A. Outside the ionosphere, the space plasma is too tenuous for any shocks to form.
B. Only planets with a magnetic field can have a bow shock.
C. The termination shock close to the heliopause is where the solar wind abruptly slows down when meeting the interstellar medium.

1:6. 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 or inside an electron gyroradius.
B. In a hydrogen plasma in thermodynamic equilibrium, protons move much faster than electrons.
C. A gravitational field perpendicular to a magnetic field can give rise to electric currents in a plasma.

1:7. Plasmas:

A. A plasma is a gas of charged particles.
B. Plasmas are usually dominated by electrons. The ions are almost always only a small fraction of the total number of particles.
C. The electric field on large scales in space and time is usually related to the flow velocity and the magnetic field by the relation $\mathbf{E} + \mathbf{v} \times \mathbf{B} = 0$.

1:8. Ionosphere:

A. The electron density in the ionosphere is determined by the solar wind intensity and the Earth's magnetic field strength.
B. Due to collissions between particles, the conductivity in the direction parallel to the magnetic field is lower in the ionosphere than in the magnetosphere.
C. Field-aligned currents can flow along the magnetic field from the magnetic tail into the ionosphere, flow perpendicular to $\mathbf{B}$ in the ionosphere, and then flow up along the magnetic field lines from a different part of the ionosphere.

1:9. Aurora:

A. The aurora is mainly caused by electrons from the sun, hitting the Earth's atmosphere at the poles.
B. The aurora is mainly caused by electrons accelerated inside the Earth's magnetosphere in regions where field-aligned currents flow.
C. The main reason why auroras are easier to see in Kiruna than in Berlin in winter is that the sky in Kiruna is darker, so that the aurora can easily be detected.

1:10. Satellites:

A. The perigee is the point on a satellite orbit where the satellite distance from the centre of the Earth is largest.
B. A satellite in geostationary orbit stays over the same geographical point on the Earth's equator all the time.
C. Electrical systems onboard satellites are most often powered by electricity from solar cells.

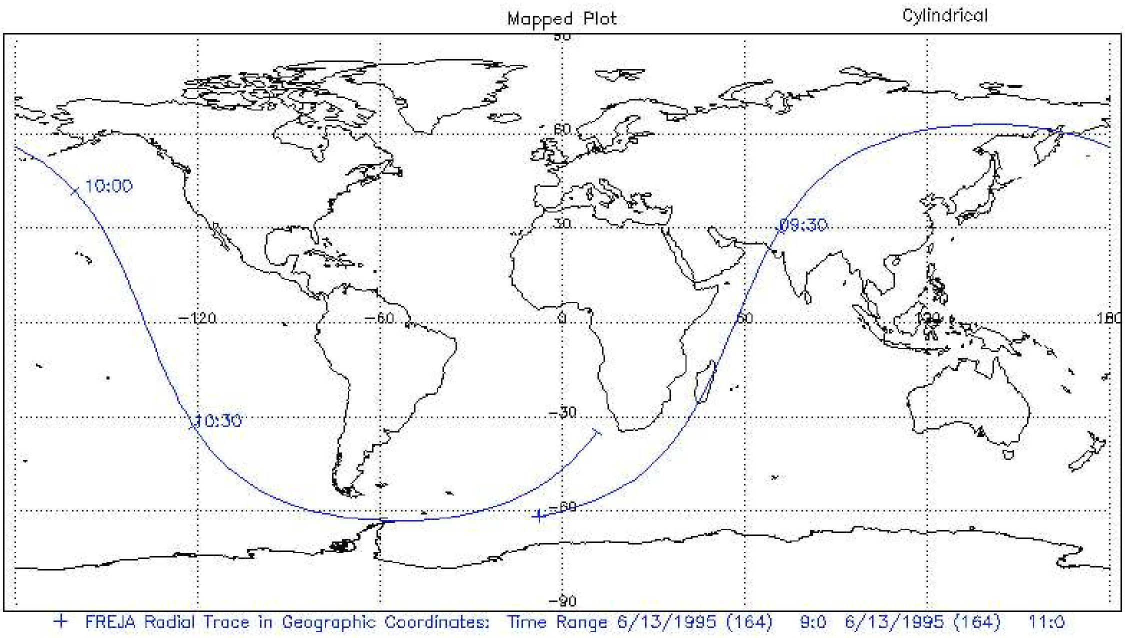

Figure 1: The ground track of Freja between 9:00 and 11:00 UT on June 13, 1995

2. Consider a spacecraft formed as a rectangular box of, 2 x 2 x 4 m, with uniform surface properties and good thermal conductivity. At a distance of 1 AU from the sun, the equilibrium temperature of the spacecraft is 30°C when one of the 2 x 2 m surfaces points to the sun.
   - (a) If internal sources (for example, onboard computers) produce 50 W of heat, how much does the temperature increase? (3 p)
   - (b) At what distance from the sun will the spacecraft have a temperature of 30°C, if it is turned so that one of the 2 x 4 m points to the sun and all internal heating sources are turned off? (3 p)

3. The Swedish-German Freja satellite was launched in October 1992 into a near-circular, eastward orbit around the Earth, with orbital period 1 h 50 min. Figure 1 shows the ground track of Freja during one full orbit, i.e. the motion of the point on the Earth's surface directly below the satellite.
   - (a) Why isn't the ground track a closed curve? The orbit is a closed curve, isn't it? (1 p)
   - (b) Estimate Freja's inclination. (1 p)
   - (c) Calculate Freja's speed and altitude (height above the Earth). (2 p)

4. (a) A charged particle moving in a dipole field generally has three characteristic periods of the motion (or three characteristic frequencies, if you so prefer). Which are they? Here you only have to explain their physical meaning, give their usual names and tell why they exist, all in words, not to give any mathematical derivations. (2 p)
   - (b) Consider an oxygen ion (O^+) with a kinetic energy of 1 MeV 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 frequencies in (a) above which are defined for this particle (one is undefined because of the particle's zero velocity along the magnetic field). The geomagnetic field may be taken to be a dipole field with strength 30 μT on the ground at the equator. (3 p)

Cluster (SC1) Electric and Magnetic Field Data

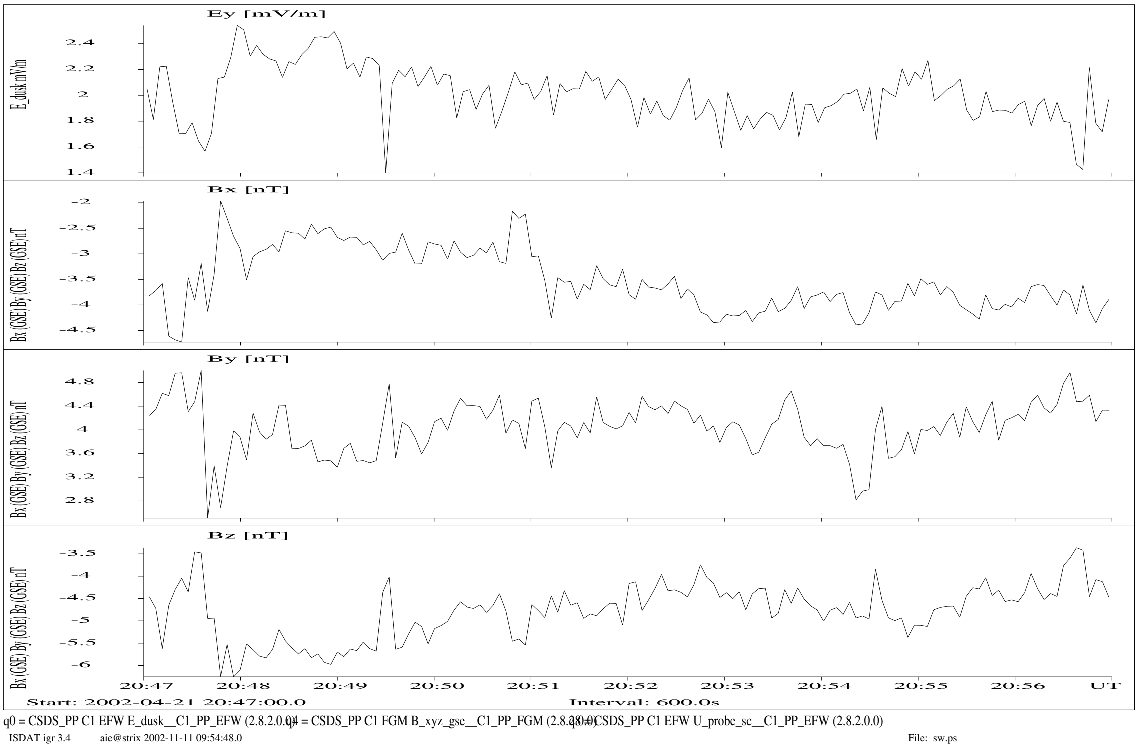

Figure 2: Cluster electric and magnetic field data. From top to bottom: E_Y, B_X, B_Y, B_Z (GSE coordinate system).

5. (a) The four Cluster satellites are orbiting the Earth at between 4 and 18 R_E geocentric distance. Figure 2 shows data from one of the spacecraft during a short portion of the orbit. Data are shown in the GSE coordinate system, where the X axis points to the sun and the Z axis to the ecliptic north pole. The top plot (labelled "E_dusk") shows the Y component of the electric field. The next three plots, shows the X, Y and Z components of the magnetic field. Assume that the spacecraft is in a plasma flowing along the -X axis. How fast is the plasma flow? And given this result and the data presented, in what plasma region do you think Cluster was at the time of the observation? (3 p)

   (b) Figure 3 shows an image of the sun in the ultraviolet frequency range, acquired by the TRACE satellite. High UV intensity, marked by darker shading in the figure, indicates high plasma temperatures (and possibly high densities), so the picture is actually an image of plasma structures. Draw a few magnetic field lines in this figure, and give a physical motivation why you drew them as you did. (Please hand in Figure 3 itself, with your B-field lines drawn on top of it; if you want to keep the rest of the exam problem set, you can detach just the page with the figure.) (2 p)

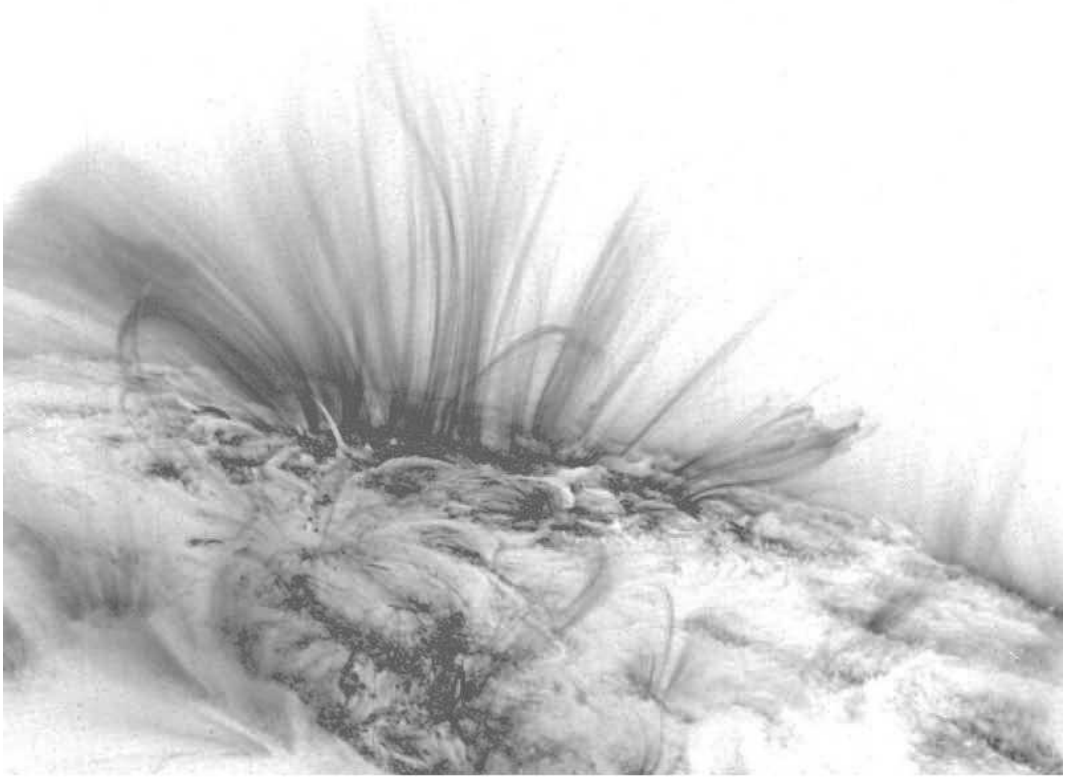

Figure 3: UV image from TRACE. Dark shading is high UV intensity, light is low intensity.

Lycka till!

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:

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

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:

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

Conductivities:

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

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:

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

Magnetic force on magnetic dipole:

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

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

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

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:

$$\lambda_\mathrm{D} = \sqrt{\frac{\epsilon_0 K T}{n e^2}}$$

Plasma frequency:

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

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:

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

Emitted thermal radiation power:

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

Absorbed solar radiation power:

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