Tentamen för Rymdfysik I
2010-10-18

Uppsala universitet
Institutionen för fysik och astronomi
Avdelningen för astronomi och rymdfysik
Anders Eriksson

Please write your **identification code** on **all** papers. Answers may of course be given in Swedish or English, according to your own preference. Be sure to motivate your answers and explain your reasoning (not in Problem 1, where explanations should be attached ONLY if you are uncertain of how to interpret the alternatives).

Time: 14:00 - 19:00

Allowed tools: Mathematics Handbook, Physics Handbook, enclosed formula sheet, calculator. A bilingual dictionary, for example English-Swedish or English-Spanish, 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. Any number of alternatives can be correct (0 – 3). (1 p/question, 10 p in total)

   1:1. Sunspots:
   - A. The number of sunspots varies with an 11 year period.
   - B. Sunspots are cooler than the surrounding plasma.
   - C. The sunspot number correlates well with other magnetic activity on the sun, like solar flares and coronal mass ejections.

   1:2. Magnetic fields:
   - A. In vacuum, the magnetic field from a localized source decreases with distance at least as fast as $1/r^3$.
   - B. When a magnetic field is frozen into the plasma, one can think of magnetic field lines as physical entities moving with the plasma.
   - C. The interplanetary magnetic field is not frozen in to the solar wind, because the solar wind is too hot (around 10 eV, i.e. 100,000 K).

   1:3. Earth's magnetosphere:
   - A. The radiation belts (van Allen bets) contain trapped energetic neutrons and electrons.
   - B. The innermost part of the magnetosphere corotates with the Earth, at least at low latitudes.
   - C. The magnetospheric tail disappears during nighttime, as there is no longer much ionization by solar ultraviolet radiation.

   1:4. Space weather:
   - A. High energy protons from solar flares and other major eruptions on the sun can cause radiation problems on satellites around the Earth.
   - B. A solar flare can cause disruption of electric power systems (transformers, power lines) around 8 minutes later.
   - C. During a geomagnetic storm, the intensity of solar emission at visible wavelengths can increase by more than 50 %.

1:5. Earth's ionosphere:

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

B. The ionospheric E layer is more weakly ionized at night than in daytime, as the solar ultraviolet radiation disappears at night.

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.

1:6. 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 and inside an electron gyroradius.

B. Only the magnetic field can do work on a charged particle, so we can always neglect the gravitational field when considering the motion of protons and electrons around the Earth.

C. In a dipole-like magnetic field, there are three basic periodicities for motion of charged particles: the gyroperiod, the bounce period (between magnetic mirrors), and the period for drifiting a complete orbit around the dipole.

1:7. In a homogeneous collisionless plasma in a constant and homogeneous magnetic field $\mathbf{B}$, a current can be generated by:

A. A constant and homogeneous electric field perpendicular to $\mathbf{B}$.

B. A constant and homogeneous gravitational field perpendicular to $\mathbf{B}$.

C. A constant and homogeneous gravitational field parallel to $\mathbf{B}$.

1:8. Aurora:

A. The most common colour of the aurora is red.

B. The main cause of aurora are protons emitted from the sun, which hit the Earth's upper ionosphere.

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

1:9. Solar wind:

A. Charge-parity (CP) violation results in the Sun getting negatively charged, causing it to repel the electrons that form the solar wind.

B. If it were not for the ionizing radiation from the sun, the ions and electrons in the solar wind would rapidly recombine.

C. The solar wind velocity is (as seen in an inertial frame) is on average directed radially outward from the sun.

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. (f) is the plasmapause

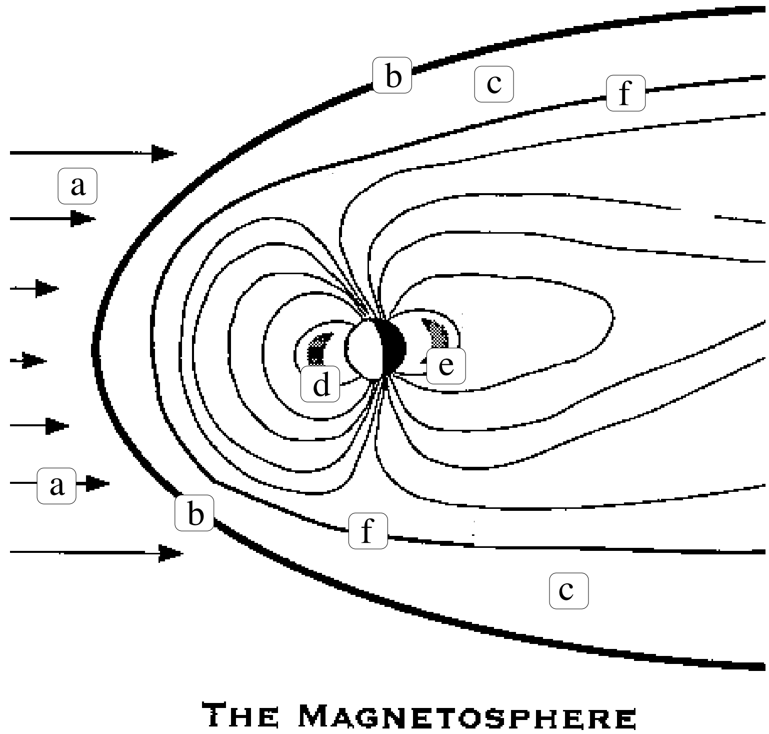

Figure 1:

2. Consider a cylindrical spacecraft of radius 1 m and height 1 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 27°C when the cylinder axis points to the sun.

   (a) Calculate the absorption coefficient if the emission coefficient is 0.2. (2 p)

   (b) If the spacecraft is turned so that the cylinder axis is perpendicular to the solar direction, how much extra power would be needed to keep the spacecraft temperature at 27°C? (2 p)

3. At 21:00 CEST in 2010-10-14, the web site http://www.spaceweather.com listed the following space weather ”current conditions”:

   - Solar wind speed: 290.4 km/s
   - Solar wind density: 6.4 protons/cm^{-3}
   - Interplanetary magnetic field:
     - B_{total}: 1.6 nT
     - B_z: 0.6 nT north

   (a) Given these solar wind conditions, estimate the distance from the centre of the Earth to the magnetopause on the dayside. (2 p)

   (b) For the interplanetary magnetic field, spaceweather.com provides not only the total intensity but also the out-of-ecliptic (northward or southward) component. Why is this component more interesting for space weather than any of the two other vector components (dawn-dusk and sunward-antisunward)? (2 p)

   The Earth’s magnetic field may be approximated by a dipole field with the strength 30 μT on the ground at the equator.

4. Consider a dipole magnetic field line crossing the equatorial plane at a geocentric distance of 4 R$_E$. The geomagnetic field may be taken to be a dipole field with strength 30 μT on the ground at the equator.

(a) At which latitude does this field line reach the Earth's surface? (1 p)

(b) Consider an oxygen ion (O^+) with a kinetic energy of 100 keV and no velocity along the magnetic field, moving in the equatorial plane at 4 R_E from the center of the Earth. Calculate the gyrofrequency and gyroradius for this particle. (2 p)

(c) For the oxygen ion in (c), also calculate the drift velocity, including direction. Start from equations available in the attached formula sheet. (3 p)

5. RHESSI and TRACE are two solar observatory satellites orbiting the Earth.

   (a) Figure 3 (which you find on the very last page, behind the formula sheet) 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)

   (b) Figure 2 shows the ground track of the RHESSI satellite during some orbits around Earth. Use this figure to estimate the inclination of the RHESSI orbit. Motivate your answer. (1 p)

   (c) Assuming a cirular orbit, also calculate the altitude of RHESSI, based on information from Figure 2. (3 p)

Lycka till!

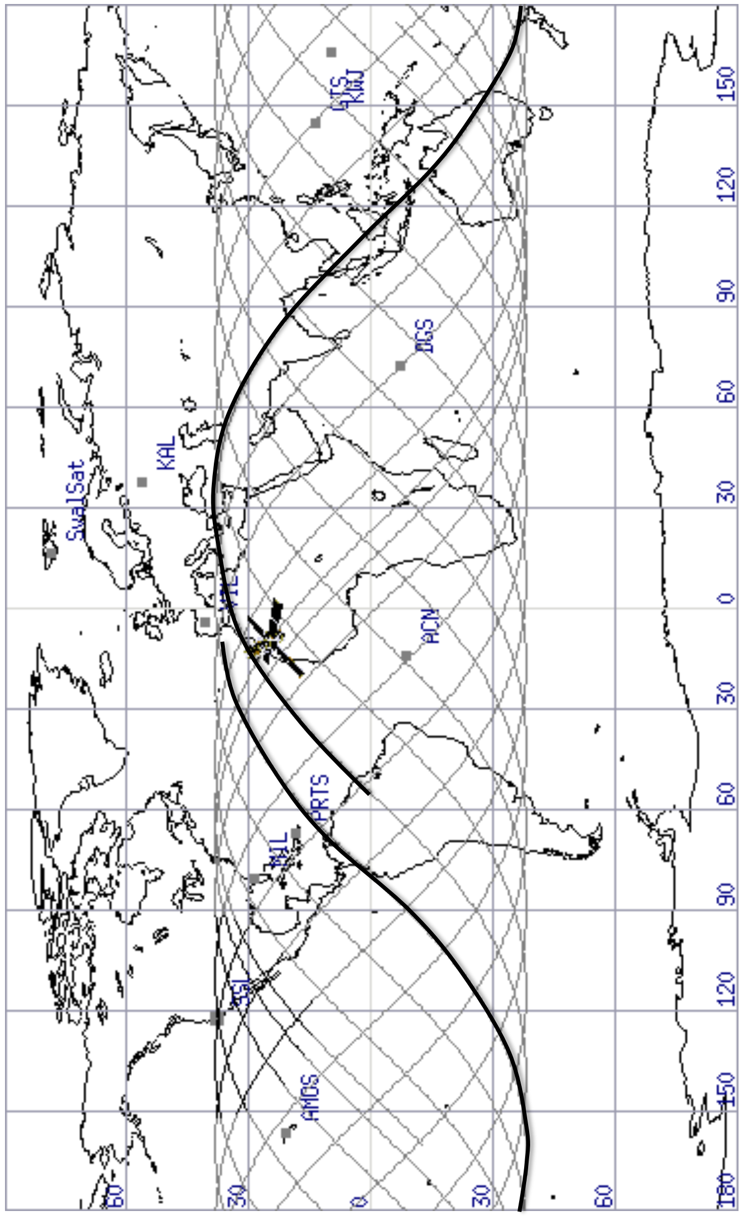

Figure 2: RHESSI ground track. The thick curve represents the ground track during slightly more than one orbit, starting over South America and ending just west of Spain. Image credit: Space Sciences Laboratory, University of California, Berkeley.

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 a charged particle gyrating in a 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 $\mathbf{F}$:

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

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:

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

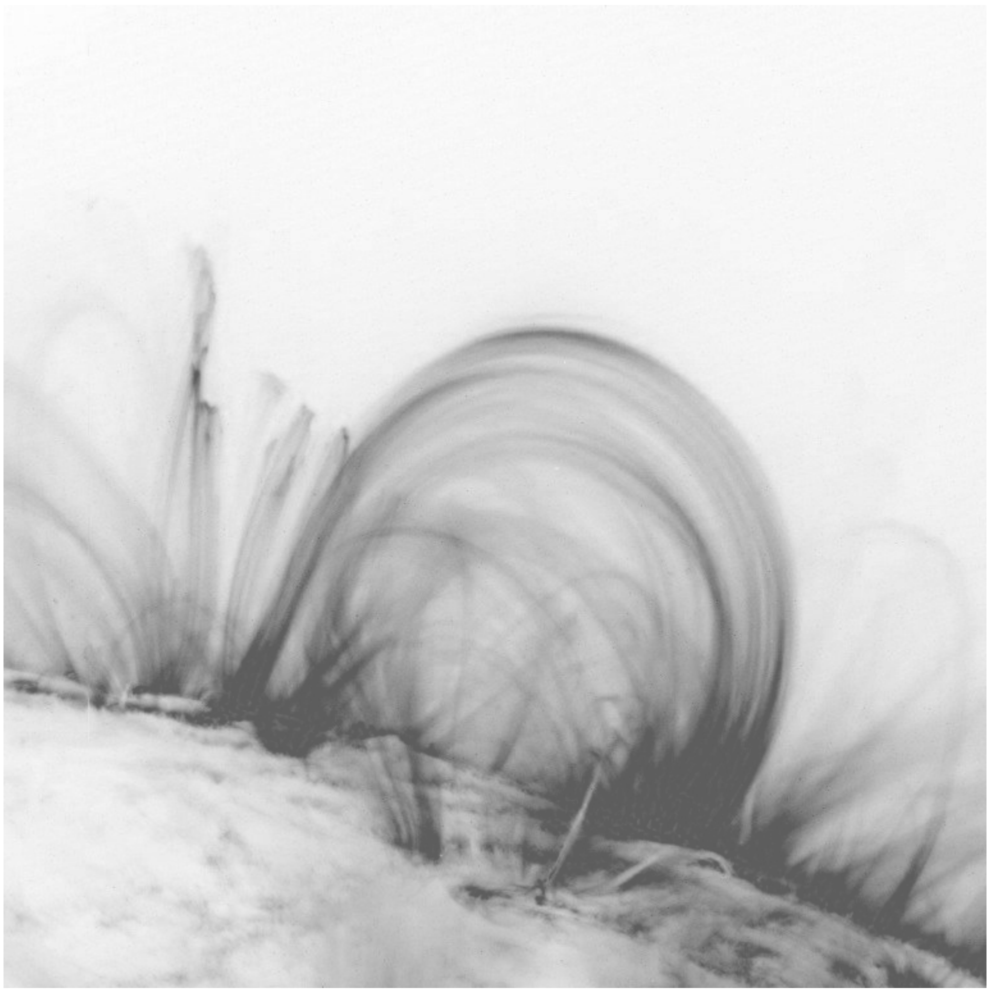

Figure 3: UV image from TRACE. Dark shading is high UV intensity, light is low intensity. Image source: NASA