Tentamen för kursen Rymdfysik (1FA255)
2017-10-24

Uppsala universitet
Institutionen för fysik och astronomi
Avdelningen för astronomi och rymdfysik
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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.

The exam has two parts:

- **Part A** must be satisfactorily solved in order to pass the course. This part is only graded by pass/fail.
- **Part B** must be solved if you wish to get a higher grade than pass (3 in the Swedish 3-4-5 system, E in ECTS). Grades will depend on the number of points you score on this part.

Part A

1. (a) Are the following statements true or false? You do not need to give any motivation or explanation, but can add comments if you feel the need to do so.

   i. Rockets are most often launched westward, to counteract Earth's rotation.

   ii. The main advantage of a multistage rocket is that the air friction can be minimized at any altitude.

   iii. Lagrange points are particular points in the geostationary orbit where as seen from a point on the Earth, a satellite stays at the same position with respect to the Sun.

   iv. The mass of a rocket (including fuel) scales approximately exponentially with the velocity increase it provides.

   v. In an elliptic orbit around Earth, atmospheric friction is highest at perigee. Atmospheric friction therefore tends to make such an orbit more circular (less eccentric).

   (b) Consider a spacecraft in the shape of a cube with sides 1.27 m, with α/ϵ = 0.4, no internal heat sources and perfect heat conductivity. The spacecraft is located at 1 AU from the Sun but sufficiently far from the Earth to neglect heat exchange with it. How should the spacecraft point with respect to the sun in order to keep as cool as possible, and what will the equilibrium temperature be in this case? The solar constant is 1370 W/m^2 and the Stefan-Boltzmann constant is 5.67×10^{-8} W m^{-2}K^{-4}.

2. (a) Are the following statements true or false? You do not need to give any motivation or explanation, but can add comments if you feel the need to do so.

   i. Plasmas are expected to be electrically neutral on length scales greater than the Debye length.

   ii. If the electric field in a plasma, as measured in its rest frame, is everywhere zero, two particles initially connected by a magnetic field line always will be so.

iii. At 1 AU, the solar wind energy density is dominated the thermal contribution $\sim nKT$ (rather than the magnetic energy density $B^2/(2\mu_0)$ or bulk kinetic energy density $mnv^2/2$).

iv. In a dipole field, B_r decays with distance r from the centre of the source as $1/r^2$, while the other two components of the magnetic field decay as $1/r$.

v. The solar wind reaches the Earth at an angle typically about 45 degrees from the Sun, due to the plasma flow following the field lines of the interplanetary magnetic field, whose shape on average show a Parker spiral pattern.

(b) The attached figure shows 24 hours of solar wind data from the DSCOVR spacecraft acquired on April 30, 2017 near the first Sun-Earth Lagrange point. Magnetic field data are given in the GSE coordinate system, in which $\hat{\mathbf{x}}$ points to the sun. From top to bottom, the plots show B_x, B_y, B_z (all in nT) and the solar wind speed in km/s.

With suitable assumptions, calculate all three GSE components of the electric field which would be measured by an electric field instrument on DSCOVR at time 12:00.

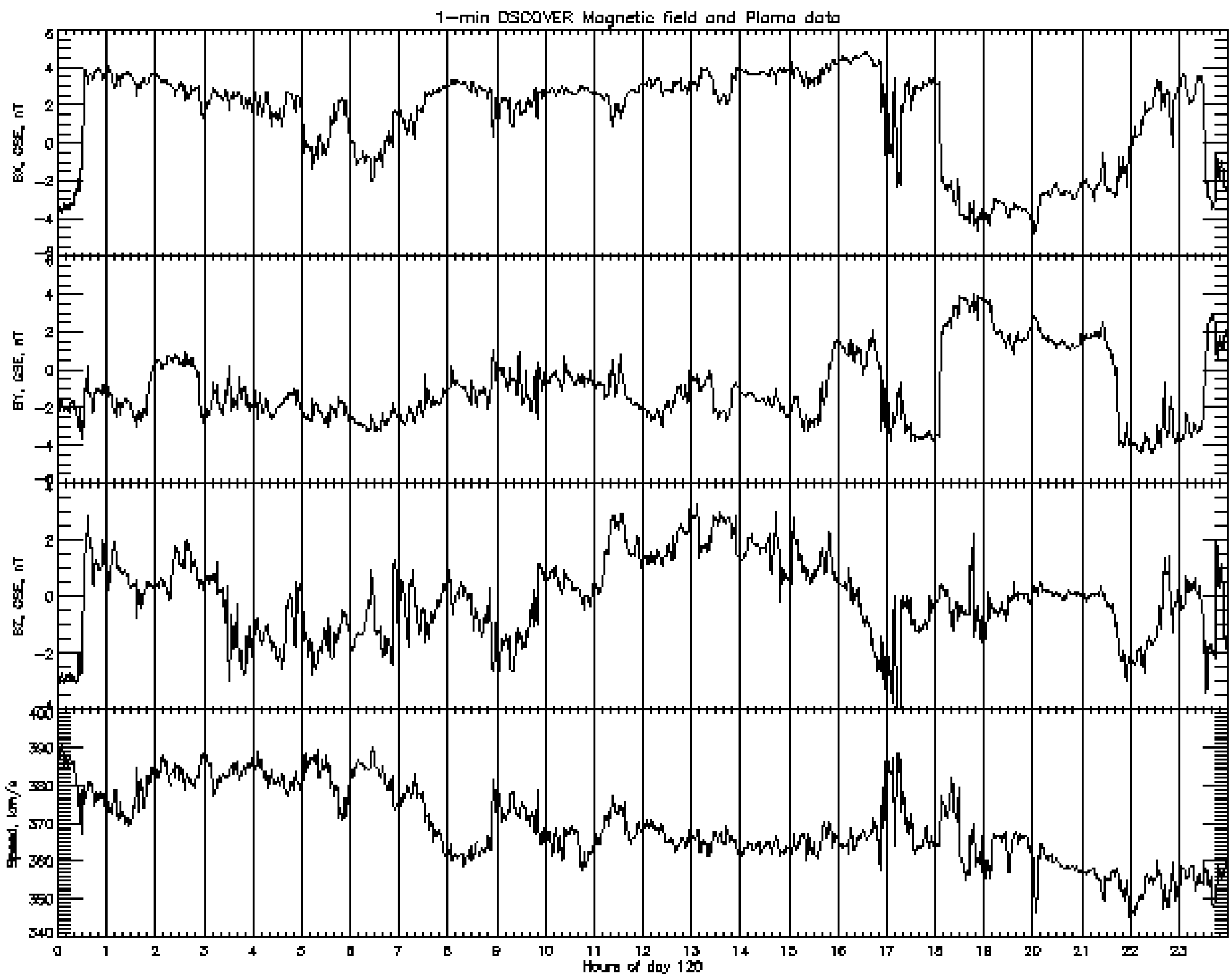


Figure 1: Magnetic field and solar wind data from DSCOVR.

3. (a) Are the following statements true or false? You do not need to give any motivation or explanation, but can add comments if you feel the need to do so.

i. The magnetic moment due to the gyration of a charged particle in a magnetic field is an adiabatic invariant if the interplanetary magnetic field is southward.

ii. The ExB drift causes a current to flow in the plasma, because electrons and ions respond to an electric field by moving in opposite directions.

iii. If a particle has pitch angle 90 degrees at the point on a magnetic field line where the magnetic field strength is smallest, the particle will not reach any other points on this field line.

iv. In general, the bounce period is longer than the drift period, for particles moving in dipolar fields.

v. In a homogeneous magnetic field, all particles of the same species, for example electrons, have the same gyroradius.

(b) An electron has pitch angle 30 degrees in the equatorial plane at geocentric distance 3 RE. Can it reach the a point at geocentric distance 1.5 RE on the same field line?

4. (a) Are the following statements true or false? You do not need to give any motivation or explanation, but can add comments if you feel the need to do so.

i. An ionosphere will form around any planet with an atmosphere orbiting a star emitting ionizing radiation.

ii. The aurora is mainly due to keV electrons hitting the upper atmosphere.

iii. Reconnection on the dayside magnetopause occurs mainly when the interplanetary magnetic field (IMF) is southward (Bz ¿ 0).

iv. Dissociative recombination is an important plasma loss mechanism in the Earth's ionosphere.

v. The E layer in the Earth's ionosphere disappears quickly at night since the ionization source is no longer present and the recombination is fast at this altitude.

vi. Due to collisions, an electric field perpendicular to the magnetic field can drive a current in the ionosphere but not in the magnetosphere.

(b) Figure 2 shows the space weather status and forecast from spaceweather.com as of 15:45 CEST in Oct 18, 2017. Figure 3 shows solar wind data acquired upstream of the Earth at the first Lagrange point for the last week. Which aspects of the forecast can you actually compare to the data for Oct 19-23 in Figure 3? How well do you think the forecast did, as far as can be seen in Figure 3? When do you think the chances to see any aurora in this period were best? Your answer should probably be between ten lines and one page in length.

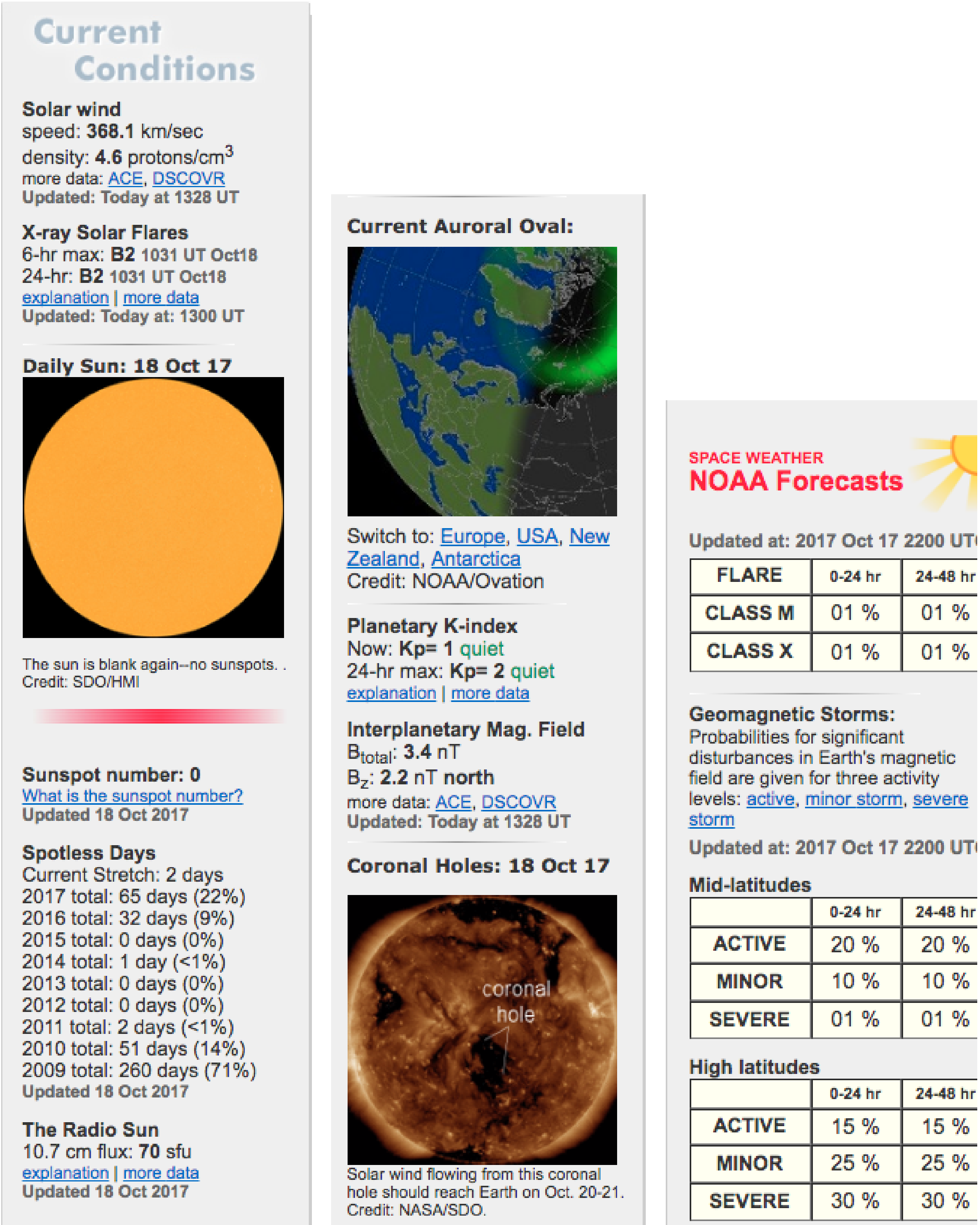
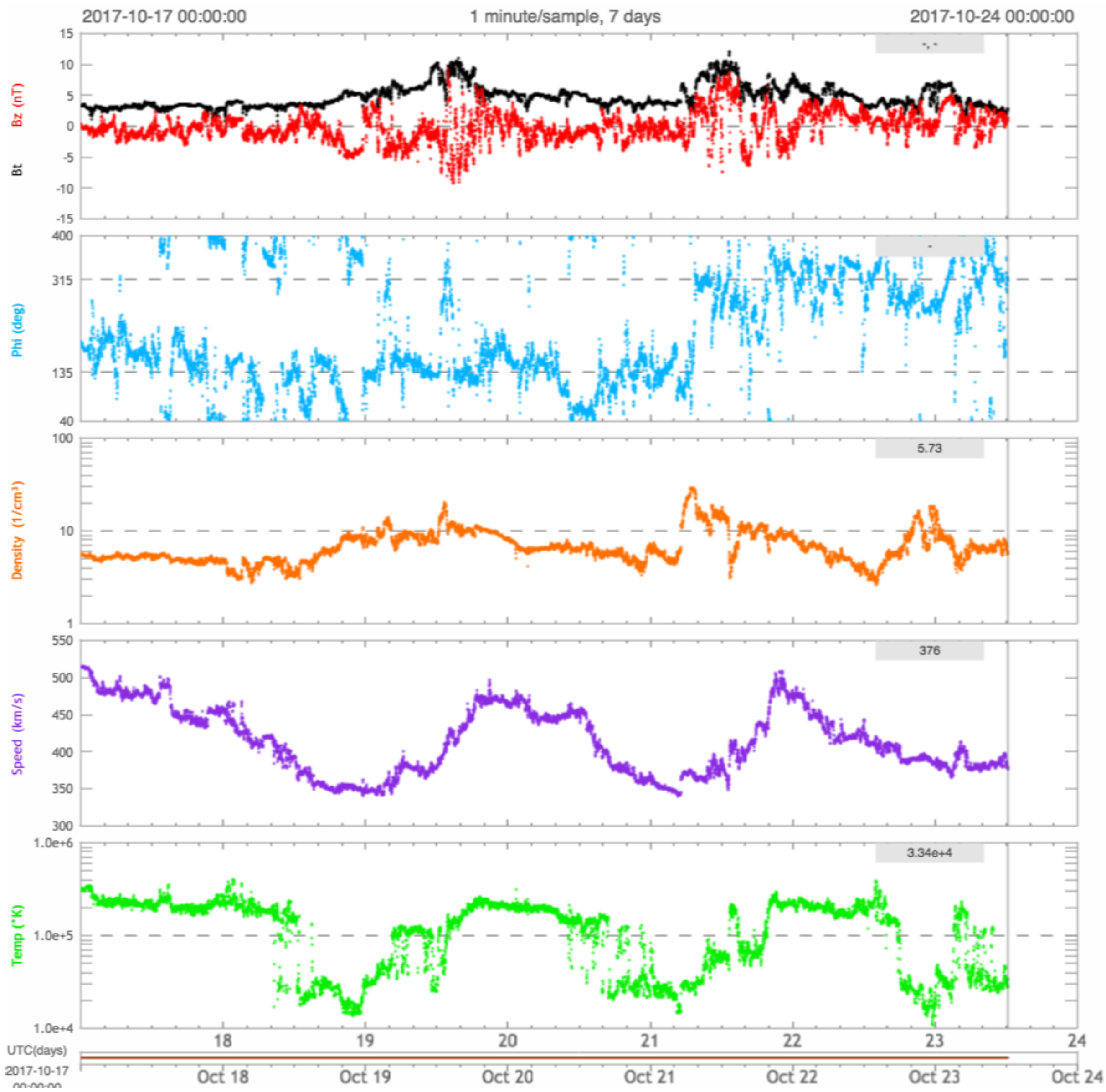

Current Conditions
Solar wind
speed: 368.1 km/sec
density: 4.6 protons/cm3
more data: ACE, DSCOVR
Updated: Today at 1328 UT
X-ray Solar Flares
6-hr max: B2 1031 UT Oct18
24-hr: B2 1031 UT Oct18
explanation | more data
Updated: Today at: 1300 UT
Daily Sun: 18 Oct 17
The sun is blank again--no sunspots. . Credit: SDO/HMI
Sunspot number: 0
What is the sunspot number?
Updated 18 Oct 2017
Spotless Days
Current Stretch: 2 days
2017 total: 65 days (22%)
2016 total: 32 days (9%)
2015 total: 0 days (0%)
2014 total: 1 day (<1%)
2013 total: 0 days (0%)
2012 total: 0 days (0%)
2011 total: 2 days (<1%)
2010 total: 51 days (14%)
2009 total: 260 days (71%)
Updated 18 Oct 2017
The Radio Sun
10.7 cm flux: 70 sfu
explanation | more data
Updated 18 Oct 2017
Current Auroral Oval:
Switch to: Europe, USA, New Zealand, Antarctica
Credit: NOAA/Ovation
Planetary K-index
Now: Kp= 1 quiet
24-hr max: Kp= 2 quiet
explanation | more data
Interplanetary Mag. Field
Btotal: 3.4 nT
Bz: 2.2 nT north
more data: ACE, DSCOVR
Updated: Today at 1328 UT
Coronal Holes: 18 Oct 17
coronal hole
Solar wind flowing from this coronal hole should reach Earth on Oct. 20-21. Credit: NASA/SDO.
SPACE WEATHER
NOAA Forecasts
Updated at: 2017 Oct 17 2200 UT
FLARE | 0-24 hr | 24-48 hr
CLASS M | 01 % | 01 %
CLASS X | 01 % | 01 %
Geomagnetic Storms:
Probabilities for significant disturbances in Earth's magnetic field are given for three activity levels: active, minor storm, severe storm
Updated at: 2017 Oct 17 2200 UT
Mid-latitudes
| 0-24 hr | 24-48 hr
ACTIVE | 20 % | 20 %
MINOR | 10 % | 10 %
SEVERE | 01 % | 01 %
High latitudes
| 0-24 hr | 24-48 hr
ACTIVE | 15 % | 15 %
MINOR | 25 % | 25 %
SEVERE | 30 % | 30 %

Figure 2:



2017-10-17 00:00:00
1 minute/sample, 7 days
2017-10-24 00:00:00
Bz (nT)
Bt
Phi (deg)
5.73
Density (1/cm³)
376
Speed (km/s)
3.34e+4
Temp (°K)
UTC(days)
2017-10-17
Oct 18
Oct 19
Oct 20
Oct 21
Oct 22
Oct 23
Oct 24

Figure 3:

Part B

5. (a) Assuming a dipolar geomagnetic field, at what geocentric distance does a field line starting in Uppsala (latitude 60°) reach the equatorial plane? (1 p)
   (b) What is the orbital speed and period of a satellite in circular orbit at that distance? (1 p)
   (c) The total energy (kinetic plus potential) of a satellite in an elliptic orbit of semimajor axis a is $E = -GmM/(2a)$, where M is the Earth mass, G is the gravitational constant and m is the spacecraft mass. Let E_0 be the energy in an initial circular orbit with geocentric distance as above, and E_1 the energy in a final orbit with the same apogee but perigee at 1.5 R_E. Calculate the relative change in energy, $(E_1 - E_0)/E_0$. Describe how you would do to change the orbit from the initial to the final one, assuming you have a good thruster rocket aboard your satelite (no values for needed thrust, fuel mass etc need be derived). (3 p)

6. Ganymede, Jupiter's largest moon, has an approximately dipolar magnetic field of its own.
   (a) At the orbit of Ganymede, the magnetic field of Jupiter itself may be assumed to be homogeneous and perpendicular to the Ganymede orbital plane. Provide an expression for the combined magnetic field near Ganymede (in spherical coordinates centred in the moon) for the two cases that Ganymede's magnetic axis is parallel or antiparallel to the field from the planet. Assume the magnetic field strength of Ganymede's internal dipole field on its surface at the equator is about 8 times as strong as the value of Jupiter's field at Ganymede orbit. You do not need to calculate any numerical values. (2 p)
   (b) Sketch qualitatively the magnetic field lines around the moon for the two cases. Identify regions of (i) field lines only connecting to Jupiter, (ii) field lines only reaching the moon and (iii) field lines connecting Jupiter and the moon. (2 p)
   (c) At this distance, the plasma in Jupiter's magnetosphere corotates with the planet. The corotation speed may be assumed to be greater than the speed of the moon in its orbit. Discuss what this may imply for Ganymede's plasma environment in terms of magnetic reconnection, for the two cases. If such occur, where do you expect it to happen? What could it lead to? (2 p)
   (d) Ganymede also has a conductive ionosphere, as does Jupiter. This has been related to the appearance of auroral emissions on Jupiter in the spots in the northern and southerh hemispheres where the magnetic field lines reach Ganymede. How could these auroral spots relate to Ganymede, its motion through Jupiter's magnetosphere, and its ionosphere? (2 p)

7. A spacecraft capable of detecting ions and electrons is located at $r = 5\ R_E$ in the equatorial plane, at dawn (06:00 hours local time). Reconnection in the magnetotail causes high energy protons and electrons to be injected into the magnetosphere at midnight (00:00 hours local time), after which they begin to drift according to the ∇B force acting on them. The protons are injected with a range of energies from 1 to 10 keV, while the electrons have energies from 10 to 100 keV. Assume that all particles have a 90° pitch angle, and that the Earth's magnetic field is that of a dipole with equatorial field strength $B_E = 31\ \mu$T, and Earth's radius $R_E = 6370$ km.
   (a) Derive an expression for the time taken for these ions and electrons to drift once around the Earth. (3 p)
   (b) Which type of particles will the spacecraft detect first, and why? Will they be ions or electrons, and what energy will they have; 1, 10 or 100 keV? (1 p)

8. GI 581g is an exoplanet reported in 2010 to orbit the star Gliese 581 and speculated to have conditions favorable for life. However, even its existence could not be confirmed by other observations. We thus have a lot of freedom to speculate freely, so let us assume it has an atmosphere which at high altitudes mainly consists of molecular oxygen O_2. The main components of the ionosphere could then be oxygen ions O_2^+ and electrons, and we assume a peak density 10^6 cm^{-3}. Assume that the loss process is dissociative recombination O_2^+ + e $\rightarrow$ O + O with reaction constant $\alpha = 6 \cdot 10^{-14}$ m^3/s. Estimate the typical lifetime of an oxygen ion O_2^+ ion. The rotation of the planet gives a day of about 26 hours. Will the ionosphere of GI 581g disappear at night or will it persist? (3 p)

Lycka till!

Space Physics Formulas:
Complement to Physics Handbook

Charge density and current density from particle species s:

$$\rho = \sum_s q_s n_s, \qquad \mathbf{j} = \sum_s q_s n_s \mathbf{v_s}$$

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 particle species s:

$$m_s n_s \frac{d\mathbf{v_s}}{dt} = n_s q_s(\mathbf{E} + \mathbf{v_s} \times \mathbf{B}) - \nabla p_s + \text{o.f.}$$

MHD equation of motion:

$$\rho_\text{m}\frac{d\mathbf{v}}{dt} = \mathbf{j} \times \mathbf{B} - \nabla p + \text{o.f.} = -\nabla\left(p + \frac{B^2}{2\mu_0}\right) + \frac{1}{\mu_0}(\mathbf{B}\cdot\nabla)\mathbf{B} + \text{o.f.}$$

Equation of continuity:

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

Equation of state for ideal gas:

$$p = nKT$$

Dynamic pressure:

$$p_\text{dyn} = \frac{1}{2}nmv^2$$

Condition for "frozen-in" magnetic field:

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

Ohm's law:

$$\mathbf{j} = \begin{pmatrix} \sigma_\text{P} & -\sigma_\text{H} & 0 \\ \sigma_\text{H} & \sigma_\text{P} & 0 \\ 0 & 0 & \sigma_\parallel \end{pmatrix} \begin{pmatrix} E_x \\ E_y \\ E_\parallel \end{pmatrix} = \sigma_\text{P}\mathbf{E}_\perp + \sigma_\text{H}\frac{\mathbf{B} \times \mathbf{E}_\perp}{B} + \sigma_\parallel \mathbf{E}_\parallel$$

Conductivities:

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

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:

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

Total energy of elliptic orbit of semimajor axis a:

$$E = -\frac{GMm}{2a}$$

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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