Lecture #7: Overview of the Earth's Magnetosphere

I. Basics of the Earth's Environment

A. General Comments:
   1. The sun and its effect on the Earth has traditionally been studied as the field of Solar-Terrestrial Physics, but today is encompassed in the more broad field of Space Physics.
   2. This lecture aims to provide a qualitative view of the Earth's magnetosphere as a general introduction to the field.

B. The Sun and the Earth
   1. Equatorial plane of Earth's orbit:
      a. \( J_E = 2.8 \times 10^{-6} \text{ rad/s} \)
      \( \omega_E = 7.3 \times 10^{-5} \text{ rad/s} \)
      \( \omega_E = \) sidereal period \( \approx 23.9 \text{ h} \)
      \( \frac{2\pi}{J_E} \)
      (Rotation rate in inertial space)
      \( R = 1 \text{AU} = 1.5 \times 10^{11} \text{ m} \)

b. Geocentric Solar Ecliptic (GSE) Coordinates

   NOTE: Numerous other useful coordinate systems are defined in Appendix A of KR95.
2. Typical Views and terminology
   a. Noon-Midnight Meridional Plane
   - Noon
   - Midnignt
   - Dayside
   - Nightside

   - 23.5° tilt of rotation axis

   b. Equatorial Plane:
   - Noon
   - Dusk
   - Dawn
   - Planetary Motion (toward dawn)

3. Solar Wind Flow and the Interplanetary Magnetic Field (IMF)
   a. The solar wind flows radially outward from the Sun
   b. The low resistivity of the interplanetary medium means that, at large scales, ideal MHD is a reasonable representation of the magnetized solar wind plasma.
   c. Therefore, the magnetic field lines are drawn into the radial flow
   d. But, the Sun rotates with a period of about 26-27 days, and this twists the magnetic field into a spiral

"Parker Spiral"

Average IMF has angle of $\alpha = 45^\circ$ (w.r.t. radial) at the orbit of the Earth.
I. B. (Continued)

4. Solar Wind Properties (see KR Table 4.1)

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
<th>General Properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proton density, ( n_p )</td>
<td>6.6 cm(^{-3} )</td>
<td>i) Super-Alfvenic Flow</td>
</tr>
<tr>
<td>Electron density, ( n_e )</td>
<td>7.1 cm(^{-3} )</td>
<td>ii) Plasma ( \beta \sim 1 )</td>
</tr>
<tr>
<td>Alpha (( \text{He}^{2+} )) density, ( n_\alpha )</td>
<td>0.25 cm(^{-3} )</td>
<td>iii) ( T_p \sim T_e )</td>
</tr>
<tr>
<td>Solar wind speed, ( v_{sw} )</td>
<td>450 km/s</td>
<td>iv) Weakly collisional</td>
</tr>
<tr>
<td>Proton temperature, ( T_p )</td>
<td>1.2 \times 10^5 K</td>
<td></td>
</tr>
<tr>
<td>Electron temperature, ( T_e )</td>
<td>1.4 \times 10^5 K</td>
<td></td>
</tr>
<tr>
<td>Magnetic Field, ( B )</td>
<td>7 nT</td>
<td></td>
</tr>
<tr>
<td>Ion Plasma beta, ( \beta_i = \frac{2n_e n_p T_p}{B^2} )</td>
<td>0.56</td>
<td></td>
</tr>
<tr>
<td>Sound Speed</td>
<td>60 km/s</td>
<td></td>
</tr>
<tr>
<td>Alphra Speed</td>
<td>40 km/s</td>
<td></td>
</tr>
<tr>
<td>Average collision time</td>
<td>4 \times 10^6 s</td>
<td></td>
</tr>
<tr>
<td>Travel time to 1 AU</td>
<td>4.7 \times 10^5 s ( \approx 4 ) days</td>
<td></td>
</tr>
</tbody>
</table>

b. Relative to the Earth, the solar wind hits the Earth's magnetosphere with an aberration \( \alpha \approx 5^\circ \).

\[ v_{sw} = 450 \text{ km/s} \]
\[ v_e = 30 \text{ km/s} \]

This is usually neglected in simple models.

II. Interaction of the Solar Wind with the Earth's Magnetosphere

A. General Comments:

1. Because the solar wind flow is supersonic and super-Alfvenic, \( \frac{v_{sw}}{v_A} \approx 10 \), a bow shock is generated ahead of the magnetosphere.
2. At the bow shock, the solar wind flow abruptly drops to subsonic/sub-Alfvenic velocities in the magneto sheath, allowing to drop to zero at the magnetopause.
II. B. The Bowshock, Magnetosheath, and Magnetopause

1. The Bowshock transitions from supersonic to subsonic flow
   a. Plasma is compressed and heated at the bowshock
   b. The plasma slows down in the magnetosheath and changes direction to flow around the magnetopause
   c. The magnetopause is the outer boundary of the Earth's magnetosphere

2. Ion and Electron Foreshocks, Quasi-parallel & Quasi-perpendicular Shocks

   a. Interplanetary Magnetic Field (IMF) arrives at Parker angle $\alpha \approx 45^\circ$
   b. Regions where $\mathbf{B} \parallel \mathbf{\hat{n}}$ (shock normal) are quasi-parallel shocks
   c. Regions where $\mathbf{B} \perp \mathbf{\hat{n}}$ are quasi-perpendicular shocks
   d. Accelerated electrons and ions can stream along $\mathbf{B}$, leading to electron and ion foreshocks.
II. & 3. Spacecraft Simplify of Bowsheek and Star Wind

a. Orbit of spacecraft remains constant in inertial space as Earth orbits the Sun.

III. Earth's Magnetosphere!

A. Intrinsic Dipole Field
1. The dipole field is tilted from the rotational axis by $10.8^\circ$.
2. The solar wind strongly distorts the internal dipole field in the outer magnetosphere beyond a few $R_E = 6.378$ km.

B. Stretched Magnetosphere

GSM - Geocentric Solar Magnetic System (see KR, App. A)
1. Solar UV radiation leads to ionization of the neutral atmosphere, leading to the generation of the ionosphere above 80 km.

2. The ionosphere at low & mid-latitudes gradually merges into the plasmasphere, a torus-shaped cool, dense plasma in which the magnetosphere co-rotates with the Earth.

3. Outer boundary is the plasmapause, where $n_e$ drops from 500 cm$^{-3}$ to 1 cm$^{-3}$. 

4. Inner Magnetosphere

- Solar Wind
  - Vsw

- Magnetic Field
  - Magnetopause
  - North Lobe
  - South Lobe
  - Magnetotail
  - Cusp
  - Magnetosheath

5. (Meridional plane)
4. Beyond the plasmaopause, or $2 \text{Re} \leq R \leq 6 \text{Re}$, are the radiation belts, consisting of trapped, high energy (keV) populations of ions and electrons (discovered by Van Allen).

5. In the magnetotail, most of the plasma is contained in the midplane in the plasma sheet, connected magnetically to the high-latitude auroral ionosphere.

E. Currents in the Magnetosphere:
1. Five principal current systems
   a. Magnetopause (Chapman-Ferraro) current
   b. Tail (Neutral Sheet) current
   c. Ring current
   d. Field-aligned (Birkeland) currents
   e. Ionospheric currents

2. These currents play a strong role in modifying the outer magnetospheric magnetic field configuration.
Lecture 7 (Continued)

II. F. Dynamics of the Magnetosphere

1. The dayside magnetospheric field is oriented northward.
2. When the IMF has a northward component, the solar wind plasma primarily flows around the magnetopause boundary.
3. When the IMF has a southward component, however, magnetic reconnection can occur at the dayside, allowing some of the dayside magnetic flux to be swept towards the tail, dragged by the solar wind flow.
4. At the tail, reconnection of the sunward, north lobe with the antisunward south lobe can occur, leading to an antisunward flow in the equatorial plane (plasma sheet).

5. Dungey Model

![Diagram of magnetic field lines and reconnection regions](image)