The Earth’s magnetosphere

text-book chapters 13 – 15,
except reconnection (14.2–3) and convection (15.2–3)
What is a magnetosphere?

- Term introduced by Thomas Gold in 1959
  - Earth’s magnetic field determines the motion of the charged particles

- Not a “sphere”
  - solar wind deforms the shape of the magnetosphere

- Proper magnetospheres (objects with internal $\mathbf{B}$)
  - Mercury, Earth, Jupiter, Saturn, Uranus, Neptune
  - neutron stars, pulsars, …
  - magnetized moons (Ganymede) and asteroids (Gaspra?)
  - actually also the environments of stars and galaxies belong to this group

- Solar wind-induced magnetospheres
  - Venus, Mars, comets
Bow shock

Balogh et al.
Magnetopause

- Chapman and Ferraro early 1930s: there exists a boundary to the Earth’s magnetic field
- early 1960s: Explorer 10 and 12 provided first measurements of this boundary

Outside: shocked solar wind, magnetosheath

Inside: magnetospheric boundary layers
Pressure balance btw. SW and m’sphere

Solar wind dynamical pressure \((\rho_m V^2)\) at 1 AU: \(\sim 10^{-9} \text{ Nm}^{-2}\) (1 nPa)

Magnetic pressure is 1 nPa at about 10 \(R_E\) \((1 R_E \approx 6370 \text{ km})\) (where the magnetospheric plasma pressure \(p = nk_B T\) is much smaller)

Pressure balance equation:

\[
K \rho_{m,SW} V_{SW}^2 \cos^2 \psi = \frac{B_{MS}^2}{2\mu_0}
\]

\(K = \begin{cases} 
2 & \text{for elastic collision} \\
1 & \text{for inelastic collision} \\
0.9 & \text{according to observations and modelling}
\end{cases}
\)

\(\psi\) is the angle between the m’pause normal and SW flow
Normalized to the subsolar point on the magnetopause

Dynamic pressure

Magnetic pressure

streamlines

magnetopause

magnetosheath

13 \( R_E \) 10 \( R_E \) Typical values
The larger the solar wind dynamic pressure is the closer to Earth magnetopause it is pushed.

Magnetopause: \( \sim 10 \, R_E \)

Bow shock: \( \sim 13 \, R_E \)

solar wind dynamic pressure at 1 AU typically \( \sim \text{few nPa} \)
Extreme compression of the magnetosphere

Huge dynamic pressure!

Magnetopause pushed well inside geosynchronous orbit into 5.3 $R_E$

Russell et al., 2000
Day the solar wind disappeared

- May 10-12, 1999: solar wind virtually disappeared
  - density dropped to a fraction of its normal density
  - Affected the shape of the magnetosphere

See the story: unusual display of auroras at the northpole

http://science.nasa.gov/newhome/headlines/ast13dec99_1.htm
Dynamic pressure less than 0.1 nPa

Bow shock $\sim 53 R_E$

(normally $\sim 13 R_E$)
The Chapman-Ferraro current

- Sydney Chapman and Vincenzo Ferraro first deduced the basic nature of the interaction between the solar wind and the Earth’s magnetic field in 1930s:

  Earth confined by a 3D sheet current that cancels the field outside the sheet and enhances it inside

- solar wind particles deflected by the Earth’s magnetic field

- In the equatorial plane in front of the Earth: dawn to dusk

- In the first approximation magentopause forms at a distance where the solar wind dynamic pressure equals the magnetic pressure of the Earth’s field (8-11 Re)
The Chapman-Ferraro current

diamagnetic current shielding the Earth’s magnetic field from the solar wind

\[ \nabla \times J = \frac{B \times \nabla \nabla}{B^2} \]

polar cusp

two singular points

image dipole

dipole

neutral point

field line

magnetopause

magnetosphere

solar wind

north

evening

Chapman-Ferraro current

Q

S = ¥
Deformation of the dipole field

Here:
half of $\mathbf{B}$ is from the dipole
half from $\mathbf{J}_{CF}$

magnetopause

---

dipole field
compressed by $\mathbf{J}_{CF}$
Note: the pressure balance predicts a raindrop-shaped magnetosphere.

The real magnetosphere has a long tail → solar wind energy powers a current system to sustain the tail.

Tangential stress

- about 10% of all solar wind energy entering the magnetosphere
Structure of the magnetosphere
Flow around the magnetosphere

- properties of the flow in the magnetosheath surrounding the magnetosphere
- gas-dynamic solar wind model (ignores all magnetic forces on the flow)
- model depends on: shape of the obstacle, Mach number, and the polytropic index
- solve jump conditions across the bow shock
- calculate the flow in magnetosheath by assuming ideal hydrodynamic conditions
 Shock theory:
maximum density compression at the shock: \( \frac{(\gamma + 1)}{(\gamma - 1)} \) (4 for \( \gamma = 5/3 \))

temperature jump
\[
\frac{T}{T_\infty} = 1 + \frac{(\gamma - 1)M_\infty^2}{2} \left( 1 - \frac{V^2}{V_\infty^2} \right)
\]

¥ refers to upstream values, \( M_\wp \) is the upstream Mach number
solar wind flow lines

Bow shock

Distance from the Sun-Earth-line

Distance along the Sun-Earth-line

streamlines

shock

magnetosheath

field line closer together

magnetopause

supersonic flow

subsonic flow
density isocontours

most compressed plasma

Temperature increase also highest here (~factor of 20)
Plasma depletion layer

Southwood and Kivelson, 1995
Magnetopause current (simple model)

- magnetopause represents a surface of current layer
- separating solar wind (high density, low $B$) from the magnetosphere (low density, high $B$)

Proton and electron sense a Lorentz force $\mathbf{v} \times \mathbf{B}$ when they begin to penetrate the magnetopause

→ after half orbit they exit the boundary in y-direction:

proton: $2 \ r_{Lp}$
electron: $2 \ r_{Le}$

Larmor radius: $r_L = \frac{m v}{eB}$
Let’s calculate strength of this current:

flux of protons that cross \( y = y_0 \) per unit time

\[ 2r_{L_p}n\nu \]

current crossing \( y = y_0 \) per unit length in \( z \) is:

\[ I = 2r_{L_p}n\nu e = \frac{2nm_p}{B_z}v^2 \]

Apply Ampere’s law across the boundary and note that

\[ I = \int jdx \]

\[ \rightarrow B_z = \mu_0 I \quad \rightarrow \quad \frac{B_z^2}{2\mu_0} = nm_p\nu^2 = \rho_{SW}V_{SW}^2 \]

back to pressure balance criterion

In fluid (MHD) picture:

MP current must provide \( J \times B \) force integrated across the boundary needed to balance the rate of change of solar wind momentum.

Momentum flux into the boundary:

\[ 2\rho_{SW}V_{SW}^2 \]

\[ \rightarrow \quad 2\rho_{SW}V_{SW}^2 = |J \times B| = B^2 / \mu_0 \]

Particle and fluid picture give equivalent answers!

Warning: The real magnetopause is thicker!
Geomagnetic tail

- nightside magnetosphere stretched into a long tail
- reservoir of plasma and energy (released into the inner magnetosphere during substorms)
- ISEE-3 and Geotail: well-defined even > 200 Re

- most volume occupied by two large tail lobes
  - field lines nearly parallel
    - north lobe: point Earthwards
    - south lobe: away from the Earth
  - low density plasma $0.01 \text{ cm}^{-3}$
  - high magnetic fields
- tail lobes separated by high density, low $B$ plasma sheet
Follow the lobe field lines to the Earth → polar cap
(polar cap bounded by the auroral oval)

Field lines from the plasma sheet map to nighttime auroral oval
Tail lobe size

Assume the tail lobe to be a semicircle (radius $R_T$)

Tail magnetic flux is \[ \Phi_T = \frac{1}{2} \pi R_T^2 B_T \]

Polar cap magnetic flux
\[ \Phi_{PC} = \pi (R_E \sin \theta_{PC})^2 B_{PC} \]

Insert $q_{PC} = 15^\circ$, $B_{PC} = 60 \mu T$

\[ \Rightarrow \quad \Phi_{PC} \approx 5 \times 10^8 \text{ Wb} \]

Equate the fluxes \[ \Phi \]
\[ \frac{R_T}{R_E} = \left( \frac{2 B_{PC}}{B_T} \right)^{1/2} \sin \theta_{PC} \]

Mid-tail: $B_T \approx 20 \text{ nT} \quad \rightarrow \quad R_T \approx 20 \ R_E$
Far-tail: $B_T \approx 10 \text{ nT} \quad \rightarrow \quad R_T \approx 28 \ R_E$
Tail Current Sheet

- tail must contain a current in the equatorial plane
- closes as magnetopause currents
Tail current sheet

Harris model: Pressure balance btw the lobe field and the plasma sheet:

\[
\frac{B_T^2}{2\mu_0} = n k_B (T_e + T_i) \quad 20 \text{ nT} \leftrightarrow 0.16 \text{ nPa}
\]

Ampère’s law across the current sheet: \( 2B_T = \mu_0 I \)

Turning 20 nT field to the opposite direction requires a current of 30 mA/m (i.e., 30 A/km, or \(2 \times 10^5\) A/\(R_E\))

Tail is long \(\rightarrow\) the total tail current is of the order of 10 MA
Plasma domains inside the m’sphere
1. Tail lobes:

\[ N \sim 0.01 \, \text{cm}^{-3} \]
\[ \beta \approx 10^{-3} \]
cool particles
open magnetic field lines

2. Plasma Sheet-Boundary Layer (PSBL)

\[ N \sim 0.1 \, \text{cm}^{-3} \]
closed field lines
boundary between the plasma sheet and the lobes

3. (Central) Plasma Sheet

\[ N \sim 0.1-1 \, \text{cm}^{-3} \]
\[ \beta \approx 1 - 10 \]
energies: electrons \( \leq 1 \) keV
protons \( \approx 5 - 8 \) keV
closed field lines
Polar cusps, reconnection and diffusion at the magnetospheric boundary
Feed the solar wind plasma to the magnetospheric boundary layers
Solar wind plasma enters through the cusp and across LLBL & HLBL

Low Latitude Boundary Layer (LLBL)
- Mix of magnetosheath and magnetosphere plasma
- open and closed field lines

High Latitude Boundary Layer (HLBL; or plasma mantle)
- tailward flows
- gradual transition from magnetosheath to lobe properties

Cusp
- Magnetic null points in a closed magnetopause model (Chapmann-Ferraro: ‘horns’)
- solar wind plasma has direct access
Particles mirror at strong $\mathbf{B}$ near the Earth

Field lines convect tailward and become a lobe field lines

Decreasing energy and density with deeper penetration into the mantle towards the magnetosphere

high-energy ions

low energy ions
## Typical plasma and field parameters

<table>
<thead>
<tr>
<th></th>
<th>Magnetosheath</th>
<th>Tail lobe</th>
<th>Plasma-sheet boundary layer</th>
<th>Central plasma sheet</th>
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</thead>
<tbody>
<tr>
<td>$N$ (cm⁻³)</td>
<td>8</td>
<td>0.01</td>
<td>0.1</td>
<td>0.3</td>
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<tr>
<td>$T_i$ (eV)</td>
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<td>300</td>
<td>1000</td>
<td>4200</td>
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<tr>
<td>$T_e$ (eV)</td>
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<td>50</td>
<td>150</td>
<td>600</td>
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<tr>
<td>$B$ (nT)</td>
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<td>20</td>
<td>10</td>
</tr>
<tr>
<td>$\beta$</td>
<td>2.5</td>
<td>$3 \times 10^{-3}$</td>
<td>$10^{-1}$</td>
<td>6</td>
</tr>
</tbody>
</table>
The inner magnetosphere

- Inner radiation belt
- Plasma sheet
- Solar wind
- Geostationary orbit at L=6.6
- Outer radiation belt
- Ring current
Radiation belts

First observations
James Van Allen, Explorer 1, 1958

Explorer 1: first satellite launched by U.S. in January 31, 1958. carried only one instrument (geiger counter) that confirmed the existence of the radiation belts.

Geiger counter saturated when crossing the inner and outer belts.
Recall from the previous course:

**L-parameter:** \( L = \frac{r_0}{R_E} \)

\( R_E \) is the radius of Earth

For given \( L \) the field line crosses the surface at latitude

\[ \lambda_e = \arccos \frac{1}{\sqrt{L}} \]
Inner belt:

- mostly protons  $0.1 - 40$ MeV
- extends about $L=1$
- relatively stable
- by-product of collisions by cosmic ray ions with atoms of the atmosphere
Outer belt:

- electrons keV’s – MeV’s
- extends to L~ 3-10 (strongest L ~ 4-5)
- inward radial diffusion and local acceleration
- variable
The electron belts

Relativistic electrons
- appear during magnetic storms (to be discussed later)
- form the most serious hazard to spacecraft “killer electrons”

CRRES observations of fluxes of > 5 MeV electrons
August 1990 – October 1991
Ring current

Drift motion causes a westward current

\[ \mathbf{J}_{RC} = \mathbf{J}_M + \mathbf{J}_G + \mathbf{J}_C \]

Total current 1 – 10 MA
During strong storms even larger

The number densities of radiation belt particles (high energies) is low → they carry very small current!

Strongest \( L \sim 4 \)
Distributed \( L=2-7 \)

Mainly consists of protons. Also He+ and O+
During magnetic storms new particles are injected to the ring current region from the tail → ring current intensifies → decreases Earth’s magnetic field at low latitudes.

Dst index: global storm time index
\[ p_{fast}^+ + H_{slow} \rightarrow H_{ENA} + p^+ \]
\[ p_{fast}^+ + O_{slow} \rightarrow H_{ENA} + O^+ \]

ENA=energetic neutral atom
(unaffected by EM fields)

ring current decays by charge-exchange: fast protons give their charge to slow H atoms of the exosphere (non-collisional atmosphere above 500 km) → ring current can be imaged using ENA.

ENA from IMAGE satellite
during a magnetic storm on May 23, 2000

Brandt et al., 2005

Brandt et al., 2002
Plasmasphere

Expansion of cool ($\leq 1$ eV) ionospheric plasma
- within quasi-dipolar field lines (small $L$)
- co-rotates with the Earth
- $L$-shell extent vs. magnetic activity ($Kp$) and asymmetries discussed later
- plasmasphere rotates 10% slower than the Earth, 27-hours
- “shoulder”
- how plasma is lost from plasmasphere?
Geostationary orbit

- 6.6 $R_E$
- Centrifugal force balances gravity for a spacecraft that is in a circular orbit with a period of one orbit per day
- ~Inner boundary of the plasma sheet
- Conditions vary with geomagnetic activity
  
  Quiet times: Earthward of the plasma sheet
  Disturbed times: bathed in the hot plasma sheet
C. Russell, The solar wind interaction with the Earth’s magnetosphere: Tutorial