ESS 7
Lectures 10, 11 and 12
April 23, 26 and 28
The Magnetosphere
Setting the **Magnetosphere Scene**

What we have learned so far:
- Solar wind is a supersonic flow
- Has structure and varies with solar cycle
- Must make a transition to subsonic flow at bow shock

<table>
<thead>
<tr>
<th>Solar min</th>
<th>Solar max</th>
</tr>
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</table>

Inside the bow shock is shocked, compressed solar wind. This is known as the magnetosheath, and flows around Earth.

Pressure around Earth must be high to divert the flow. However, Earth’s magnetic field is strong near the planet and it controls the plasma there. The solar wind cannot easily enter.
An Obstacle in the Solar Wind

– Back in 1930 Chapman and Ferraro foresaw that a planetary magnetic field could provide an effective obstacle to the solar-wind plasma.

– The solar-wind dynamic pressure presses on the outer reaches of the magnetic field confining it to a magnetospheric cavity that has a long tail consisting of two antiparallel bundles of magnetic flux that stretch in the antisolar direction.

– The pressure of the magnetic field and plasma it contains establishes an equilibrium with the solar wind.
The Earth’s Magnetic Field (Spherical Coordinates)

- To a first approximation the magnetic field of the Earth can be expressed as that of a dipole. The dipole moment of the Earth is tilted ~11° to the rotation axis with a present day value of 8X10^{15}Tm^3 or 30.4x10^{-6}TR_E^3 where R_E=6371 km (one Earth radius).

- In a coordinate system fixed to this dipole moment

\[ B_r = 2Mr^{-3} \cos \theta \]

\[ B_{\theta} = Mr^{-3} \sin \theta \]

\[ B_{\phi} = 0 \]

\[ B = Mr^{-3} (1 + 3 \cos^2 \theta)^{\frac{1}{2}} \]

where \( \theta \) is the magnetic colatitude, and M is the dipole magnetic moment.
The Earth's Magnetic Field (Cartesian Coordinates)

- Alternately in Cartesian coordinates

\[ B_x = 3xzM_z r^{-5} \]
\[ B_y = 3yzM_z r^{-5} \]
\[ B_z = (3z^2 - r^2)M_z r^{-5} \]

where the z-axis is along the dipole magnetic moment.
Dipole Magnetic Field Lines and the L Parameter

• The magnetic field line for a dipole. Magnetic field lines are everywhere tangent to the magnetic field vector.

\[ \frac{dr}{B_r} = r \frac{d\theta}{B_\theta} \quad d\phi = 0 \]

• Integrating \( r = r_0 \sin^2 \theta \) where \( r_0 \) is the distance to equatorial crossing of the field line. It is most common to use the magnetic latitude \( \lambda \) instead of the colatitude where L is measured in \( R_E \).

\[ r = L \cos^2 \lambda \]
Properties of the Earth’s Magnetic Field

- The dipole moment of the Earth presently is \( \sim 8 \times 10^{15} \text{T m}^3 \) (\( 3 \times 10^{-5} \text{TRE}^3 \)).
- The dipole moment is tilted \( \sim 11^0 \) with respect to the rotation axis.
- The dipole moment is decreasing.
  - It was \( 9.5 \times 10^{15} \text{T m}^3 \) in 1550 and had decreased to \( 7.84 \times 10^{15} \text{T m}^3 \) in 1990.
  - The tilt also is changing. It was \( 3^0 \) in 1550, rose to \( 11.5^0 \) in 1850 and has subsequently decreased to \( 10.8^0 \) in 1990.
- In addition to the tilt angle the rotation axis of the Earth is inclined by \( 23.5^0 \) with respect to the ecliptic pole.
  - Thus the Earth’s dipole axis can be inclined by \( \sim 35^0 \) to the ecliptic pole.
  - The angle between the direction of the dipole and the solar wind varies between \( 56^0 \) and \( 90^0 \).
Three Kinds of Pressure

- Dynamic pressure is like pressure of a flowing fluid

\[ P_D = \rho V^2 \]

where \( \rho \) is the mass density \((\text{kg/m}^3)\) and \( V \) is the velocity.

- Thermal pressure of a fluid even if it is stationary.

\[ P_T = nkT \]

where \( n \) is the number density, \( k \) is the Boltzmann constant \((1.38 \times 10^{-23} \text{JK}^{-1})\) and \( T \) is the temperature.

- The magnetic field can also exert pressure

\[ P_B = \frac{B^2}{2\mu_0} \]

where \( B \) is the magnetic field intensity \((\text{Teslas})\) and \( \mu_0 \) is the permeability of free space \(= 4\pi \times 10^{-7} \text{Hm}^{-1} \)
Solar Wind Pressure at the Earth

- Assume that the solar wind has a velocity of 400km/s, density of 5cm\(^{-3}\), temperature of 2\times10^5K, and magnetic field strength of 5nT

\[
P_D = \rho V^2 = 1.4 \times 10^{-9} \text{ Pa}
\]

\[
P_T = nkT = 1.4 \times 10^{-11} \text{ Pa}
\]

\[
P_B = \frac{B^2}{2\mu_0} = 1.0 \times 10^{-11} \text{ Pa}
\]
Forming the Magnetopause

- The dynamic pressure is much larger than the thermal pressure or magnetic pressure in the solar wind.
- Within the magnetosphere the magnetic pressure of the Earth’s internal field dominates.
- To a good approximation the boundary (the magnetopause) between the region dominated by the solar wind and the region dominated by the Earth (the magnetosphere) can be found by balancing the solar wind dynamic pressure with the magnetic pressure of the Earth.
The Dynamic Pressure and the Magnetopause

- The red line is the bow shock
- The blue line is the magnetopause
- The magnetosheath pushes on the magnetopause but because of magnetic field pressure the magnetopause pushes back and deflects the flow
- As the solar wind speeds up and pushes harder, both boundaries are pushed back
- The light blue dashes are the important geosynchronous orbit (to be discussed)

Model by Petrinec & Russell (UCLA)
An Obstacle in the Solar Wind

The solar-wind *dynamic pressure* presses on the outer reaches of the magnetic field confining it to a magnetospheric cavity that has a long tail consisting of two antiparallel bundles of magnetic field that stretch in the antisolar direction.

The pressure of the magnetic field and plasma establishes an equilibrium with the solar wind.

Shielding the Earth from the Solar Wind

- Ideally when the pressures are in balance the Earth’s field will be shielded from the solar wind in a cavity called the magnetosphere.
- The interaction sets up Chapman-Ferraro currents on the boundary which cancel the Earth’s magnetic field outside.
- Near the pole there is a singular point in the field where $|B| = 0$. This is called the neutral point.
- The C-F current circulates in a sheet around the neutral point.
- This current is symmetric about the equator with a corresponding circulation around the southern neutral point.
The Location of the Magnetopause

- The magnetic field inside the boundary is the total field from dipole and boundary current. For an infinite planar sheet current the field would be exactly doubled. Inside a spherical boundary the multiplication factor is 3. The factor f must lie in this range.

- Equate and substitute for the dipole strength variation with distance.

- Solve for the dimensionless standoff distance $L_s$.

\[
\begin{align*}
  p_{\text{dyn}} &= p_B \\
  p_{\text{dyn}} &= kmnu^2 \\
  p_B &= \frac{(fB_D)^2}{2\mu_0} \\
  B_D &= B_0 \left( \frac{R_E}{R_s} \right)^3
\end{align*}
\]

Where $k \approx 0.9$ is the elasticity of particle collisions and $f$ is the factor by which the magnetospheric magnetic field is enhanced by the boundary current. $R_s$ is the subsolar standoff distance. $B_0$ is the field at the surface of the Earth.

\[
L_s = \left( \frac{R_s}{R_E} \right) = \left[ \left( \frac{f^2}{k} \right) \frac{B_0^2}{2\mu_0 mnu^2} \right]^{\frac{1}{6}}
\]
The Effect of Magnetopause Currents

- Close to the Earth the dipole field dominates and there is little distortion.

- Further away there is a significant change in the shape of the field lines with all field lines passing through the equator closer to the Earth than dipole field lines from the same latitude.

- All dipole field lines that originally passed through the equator more than 10 Re sunward of the Earth are bent back and close on the night side.
Observing the Magnetopause

• Data from two spacecraft show two crossings of the boundary.
• Initially both spacecraft are inside the magnetosphere (strong field).
• The boundary moves inward and crosses first the ISEE-1 spacecraft (thick line) and later the ISEE-1 spacecraft (thin line).
• Some time later the boundary reverses and moves outward appearing first at ISEE-2 and later at ISEE-1.
• The spacecraft separation along the average normal divided by the time delay gives the boundary velocity.
• The time profile scaled by the velocity gives the spatial profile of the boundary.
• The thickness of the magnetopause varies from 200 to 18000 km with a most probably thickness of 700 km.
The Magnetotail

- Behind the Earth, the solar wind extends the magnetosphere a long distance (>3000R_E) away from the Earth on the night side, forming the magnetotail.
Magnetic Field Strength

12/17/2007 Time = 12:00:00 UT y = 0.00R_E

Model at CCMC: OpenGGCM
Particle Density

12/17/2007 Time = 12:00:00 UT y = 0.00R_E

Model at CCMC: OpenGGCM
The Magnetotail

- It acts as a reservoir for plasma and energy. Energy and plasma from the tail are released into the inner magnetosphere aperiodically during magnetospheric substorms.

- A current sheet lies in the middle of the tail and separates it into two regions called the lobes.
  - The magnetic field in the north (south) lobe is directed away from (toward) the Earth.
  - The magnetic field strength is typically ~20 nT.
  - Plasma densities are low (<0.1 cm⁻³). Very few particles in the 5-50keV (1eV = 1.6X10⁻¹⁹J it is the energy an electron gains by being accelerated through one volt) range. Cool ions observed flowing away from the Earth with ionospheric composition. The tail lobes normally lie on “open” magnetic field lines.
The Equatorial Current Sheet

- The tail lobes are separated by an equatorial current sheet extending across the tail from dawn to dusk.
- Magnetic currents must close – these close on the tail magnetopause.
- A current creates a magnetic field.
- To determine the direction of the magnetic field that results place your thumb in the direction of the current. Your bent fingers will point in the direction of the magnetic field – toward the Earth in the north and away in the south.
Opposed Fields Lead to Current Sheet in Tail

12/17/2007 Time = 12:00:00 UT \( y = 0.00R_E \)

Model at CCMC: OpenGGCM
The Cross Section of the Tail

- The plasma sheet is found between the lobes in the tail.

- It contains hot (3keV ions and 1keV electrons).

- Observers have identified small regions within the plasma sheet (red, yellow and blue).

- The plasma (polar) mantle is found near the magnetopause (green).
The Magnetotail – Noon Midnight View
Magnetotail Structure – Plasma Mantle, Plasma Sheet Boundary Layer and Central Plasma Sheet

• The plasma mantle has a gradual transition from magnetosheath to lobe plasma values.
  – Flow is always tailward
  – Flow speed, density and temperature all decrease away from the magnetopause.

• Ions in the plasma sheet boundary layer (PSBL) typically flow at 100s of km/s parallel or antiparallel to the magnetic field.
  – Frequently counterstreaming beams are observed: one flowing earthward and one flowing tailward.
  – The PSBL is thought to be on “closed” magnetic field lines.

• The central plasma sheet (CPS) consists of hot (kilovolt) particles.
  – The CPS is usually on “closed” field lines.
Magnetotail Structure - the Low Latitude Boundary Layer

- The low latitude boundary layer (LLBL) contains a mix of magnetosheath and magnetospheric plasma.
  - Plasma flows can be found in almost any direction but are generally intermediate between the magnetosheath flow and magnetospheric flows.
  - The LLBL extends from the dayside just within the magnetopause along the flanks of the magnetosphere forming a boundary between the plasma sheet and the magnetosheath.
# Typical Magnetotail Plasma and Field Parameters

<table>
<thead>
<tr>
<th></th>
<th>Magneto-sheath</th>
<th>Tail Lobe</th>
<th>Plasma-Sheet Boundary Layer</th>
<th>Central Plasma Sheet</th>
</tr>
</thead>
<tbody>
<tr>
<td>n (cm(^{-3}))</td>
<td>8</td>
<td>0.01</td>
<td>0.1</td>
<td>0.3</td>
</tr>
<tr>
<td>T(_i) (eV)</td>
<td>150</td>
<td>300</td>
<td>1000</td>
<td>4200</td>
</tr>
<tr>
<td>T(_e) (eV)</td>
<td>25</td>
<td>50</td>
<td>150</td>
<td>600</td>
</tr>
<tr>
<td>B (nT)</td>
<td>15</td>
<td>20</td>
<td>20</td>
<td>10</td>
</tr>
<tr>
<td>(\beta)</td>
<td>2.5</td>
<td>3x10(^{-3})</td>
<td>10(^{-1})</td>
<td>6</td>
</tr>
</tbody>
</table>

*Beta is the ratio of the plasma thermal pressure to the magnetic pressure*

\[
\beta = \frac{nkT}{B^2/2\mu_0}
\]
Reconnection

- The magnetotail is formed by the process of reconnection,

- Reconnection is thought to drive magnetospheric dynamics and the dynamics of the solar corona.
The Energy of Particles in Space

- Energy that a particle with the charge of an electron gets in falling through a potential drop of 1 Volt- 1 eV = 1.6X10^{-19} Joules (J).
  - Energies in space plasmas go from electron Volts to kiloelectron Volts (1 keV = 10^3 eV) to millions of electron Volts (1 meV = 10^6 eV)
  - Cosmic ray energies go to gigaelectron Volts ( 1 geV = 10^9 eV).
The Reconnection Process

• As long as frozen in flux holds plasmas can mix along flux tubes but not across them.
  – When two plasma regimes interact a thin boundary will separate the plasma
  – The magnetic field on either side of the boundary will be tangential to the boundary (e.g. a current sheet forms).

• When a magnetized plasma parcel (a flux tube) with one polarity is brought up to a magnetized plasma parcel with the opposite magnetic reconnection occurs.
  – Field lines connect and change their topologies or connectedness.
  – The straight field lines moving from the top and bottom toward the middle of the picture reconnect and form the bent field lines on the sides.
  – The flux tubes then move apart toward the left and right.
Frozen in Flux and Reconnection

- The plasma flowing into the reconnection region from the top and bottom is frozen into the flow.

- It does not hold in a small region in the center of the figure. This “diffusion” region is where the flux tubes are cut and find new partners.

- Reconnection allows previously unconnected regions to exchange plasma and hence mass, energy and momentum.

- Although frozen in flux breaks down in the diffusion region it still holds in the regions outside of the diffusion region.

- The reconnection process can accelerate the plasma.
By the 1950’s it was realized that plasma flows observed in the polar and auroral ionospheres must be driven by magnetospheric flows.
- Flow in the polar regions was from noon toward midnight.
- Return flow toward the Sun was at somewhat lower latitudes.
- This flow pattern is called magnetospheric convection.

Dungey in 1961 showed that if magnetic field lines reconnected in front of the magnetosphere the required pattern would result.

This allows solar wind energy to be directly coupled into the magnetosphere.
Magnetic Reconnection
(Dungey, PRL, 6(2), 47, 1961)

- Recall that the solar wind can have northward or southward parts to its magnetic field (IMF)
- Earth’s field where the solar wind hits is always northward (dipole field)
- If IMF is southward, then we can get reconnection at the frontside

- Through reconnection at the front side, SW plasma can enter
- It brings energy and magnetic field into the magnetosphere
- At the tail reconnection site, flow is jetted out toward Earth

1961 was a good year – there were two main theories and now, 50 years later, these ‘competing’ theories are both right (see next slide)
'Viscous' Interaction


- Various physical processes cause drag at the magnetopause
- A boundary layer of tailward flowing plasma is created inside the magnetopause
- The pressure gradient eventually drives a return flow to the dayside
- Without such return all the flux on the dayside would end up in the tail
- This is similar to what happens in a fluid with viscosity but the origin of drag is not fluid viscosity
- This gives a "closed" magnetosphere

- Maybe 10% as efficient as reconnection and important when IMF is northward

Similar to circulation behind an obstacle in fluid (viscous) flow, but recall, in space collisionless
The Formation of the Magnetotail and Flows in the Magnetosphere

- When IMF driven by the solar -wind has a southward $B_Z$ reconnection occurs between field lines 1 (closed with both ends at the Earth) and the IMF field line 1’
  - This forms two new field lines with one end at the Earth and one end in the solar wind (called open).
  - The solar wind will pull its end tailward
    \[ \vec{V}_{SW} = \frac{\vec{E}_{sw} \times \vec{B}_{sw}}{|\vec{B}|^2} \]
- The lower panel shows the motion of the flux tubes in the ionosphere.
- In the ionosphere tailward flow in the solar wind will drive flow tailward as well.
Magnetospheric Convection – Steps 2, 3, 4 and 5

• The newly reconnected flux tube will move be dragged tailward by the solar wind (steps 2, 3, 4 and 5).
• The part of the flux tube above the ionosphere but inside the magnetopause forms the tail lobes.
• If the process of removing flux from the dayside continued indefinitely without returning some flux the Earth’s field would be lost.
**Returning Flux to the Dayside - Steps 6, 7, 8 and 9**

- At a tail reconnection site (called an x-line) the lobe field lines (5 and 5’) reconnect at position (66’) to form new closed field lines 7 and new IMF field lines (7’).

- The new IMF field line 7’ is distorted and stressed and moves tailward.

- The new closed field line 7 is stressed and moves earthward.

- The flow circuit is finally closed when the newly closed field lines flow around either the dawn or dusk flanks of the magnetosphere to the dayside (8 and 9).

- The insert shows the flow pattern in the ionosphere that results. The return flow in the ionosphere is a lower latitudes than the tailward flow.
The Electric Field Across the Magnetosphere

- The process of reconnection causes plasma to flow in the magnetosphere and therefore creates an electric field

\[
\vec{E} = -\vec{v} \times \vec{B}
\]

\[
E = -\nabla \phi = \frac{\Delta \phi}{2R_{PC}} = v_{PC}B_{PC}
\]

where \( R_{PC} \) is the radius of the polar cap, \( v_{PC} \) is the plasma flow speed and \( B_{PC} \) is magnetic field strength in the polar cap. For typical ionospheric parameters

\[
\Delta \phi \approx 53kV
\]

and the electric field is directed from dawn to dusk.

- The solar wind electric field across a distance equal to one diameter of the tail (50\( R_E \)) is about 640 kV. Thus about 10% of the flux that impacts the magnetosphere interacts with it. The rest goes around the sides of the magnetosphere.
The Convection in the Inner Magnetosphere

- The cross magnetosphere electric field drives flows toward the Sun in the equator. There is another electric field. It causes plasma close to the Earth to go around the planet once every 24 hours – corotation.
- When we include corotation the electric potential becomes

\[ \phi = -E_0 r \sin \phi - \frac{\omega_E B_0 R_E^3}{r} \]

where \( E_0 \) is the cross tail electric field, \( \phi \) is the azimuthal angle, \( r \) is the radial distance, \( \omega_E \) is the angular frequency of the Earth, and \( B_0 \) is the magnetic field magnitude at the equator at \( 1R_E \).
- Contours of constant potential give the motion of the flux tube.
The Plasmasphere

- Near the Earth the corotation term dominates the effective potential while far out in the tail the convection potential dominates.

- On the dusk side the two terms fight each other and at one point the velocity is zero.

- The solid line shows a separatrix inside of which plasma from the tail can’t enter.

- Cold particles that lie inside the separatrix go continuously around the Earth. They form the plasmasphere. It is filled with dense cold plasma from the ionosphere.
• Images in the EUV from the IMAGE spacecraft on May 24, 2000.
• The 30.4nm emission from helium ions appears as a pale blue cloud.
• The “bite out” in the lower right is caused by the Earth’s shadow. The helium is excited by sunlight.
• The emission at high latitudes is from aurora and is thought to be caused by 53.9nm emission from atomic oxygen.
The Equation of Motion of Charged Particles

• Equation of motion

\[ \vec{F} = m\vec{a} = m \frac{d\vec{v}}{dt} = q\vec{E} + q\vec{v} \times \vec{B} + \vec{F}_g \]

• SI Units
  – mass (m) - kg
  – length (l) - m
  – time (t) - s
  – electric field (E) - V/m
  – magnetic field (B) - T
  – velocity (v) - m/s
  – \( F_g \) stands for non-electromagnetic forces (e.g. gravity) - usually ignorable.
Gyromotion (aka Circular Motion)

- B acts to change the motion of a charged particle only in directions perpendicular to the motion.
  - Set $E = 0$, assume $B$ along $z$-direction.

$$m\ddot{v}_x = qv_y B$$
$$m\ddot{v}_y = -qv_x B$$

$$\ddot{v}_x = \frac{q\dot{v}_y B}{m} = -\frac{q^2 v_x B^2}{m^2}$$
$$\ddot{v}_y = -\frac{q^2 v_y B^2}{m^2}$$

- Equations of circular motion with angular frequency (cyclotron frequency or gyro frequency)

$$\Omega_c = \frac{qB}{m}$$

- If $q$ is positive particle gyrates in left handed sense
- If $q$ is negative particle gyrates in a right handed sense
Only the Electric Field can Energize Particles

- Radius of circle (\( \rho_c \)) - cyclotron radius or Larmor radius or gyro radius.
  \[ v_\perp = \rho_c \Omega_c \]
  \[ \rho_c = \frac{mv_\perp}{qB} \]
  - The gyro radius is a function of energy.
  - Energy of charged particles is usually given in electron volts (eV)
- The circular motion does no work on a particle
  \[ \vec{F} \cdot \vec{v} = m \frac{d\vec{v}}{dt} \cdot \vec{v} = \frac{d\left(\frac{1}{2}mv^2\right)}{dt} = q\vec{v} \cdot (\vec{v} \times \vec{B}) = 0 \]
- A particle can stay in orbit forever.
An Electric Field can Modify the Particles Motion

• Assume $\vec{E} \neq 0$ but $\vec{B}$ still uniform and $F_g=0$.
• As a particle gyrates it moves along $\vec{E}$ and gains energy.
• Later in the circle it losses energy.
• This causes different parts of the “circle” to have different radii - it doesn’t close on itself.
• The particle moves with a velocity

$$\vec{u}_E = \frac{\vec{E} \times \vec{B}}{B^2}$$
The EXB Motion of Charged Particles

Accelerated by the E field and thus the gyroradius is larger on this part of the orbit.
Gradient Drift Motion

• Any force capable of accelerating and decelerating charged particles can cause them to drift.
  \[ \vec{u}_F = \frac{\vec{F} \times \vec{B}}{qB^2} \]
  
  – If the force is charge independent the drift motion will depend on the sign of the charge and can form perpendicular currents.

• Changing magnetic fields cause a drift velocity.
  
  – If \( \vec{B} \) changes over a gyro-orbit the radius of curvature will change.
  
  – \( \rho_c = \frac{mv_\perp}{qB} \) gets smaller when the particle goes into a region of stronger \( B \). Thus the drift is opposite to that of \( \vec{E} \times \vec{B} \) motion.

  \[ \vec{u}_g = -\frac{1}{2} mv_\perp^2 \frac{\nabla \times \vec{B}}{qB^3} = \frac{1}{2} mv_\perp^2 \frac{\vec{B} \times \nabla B}{qB^3} \]
Particles can Drift Completely Around the Earth

\[ \vec{u}_g = \frac{-1}{2} m v^2 \frac{\nabla B \times \vec{B}}{q B^3} = \frac{1}{2} m v^2 \frac{\vec{B} \times \nabla B}{q B^3} \]

- The gradient is

\[ \nabla B = \frac{\partial B_x}{\partial x} \hat{i} + \frac{\partial B_y}{\partial y} \hat{j} + \frac{\partial B_z}{\partial z} \hat{k} \]

- The gradient points in the direction of increasing B.
- Because the gradient drift velocity depends on the charge electrons drift in one direction and ions drift in the opposite direction.
- This is drawing of an ion drifting in the magnetosphere in a clockwise direction.
General Motion of a Charged Particle

• In general particles can move along the magnetic field as well as perpendicular to it.
• The magnetic field magnitude gets larger as the particles move to higher latitude.
• When the particles get near the Earth they can turn around (called mirroring) and return in the direction from which they came.
• This is called bounce motion.
Particles Mirroring and Drifting in a Dipole Magnetic Field
Particles Mirroring and Drifting in a Dipole Magnetic Field
The Three Types of Motion of Charged Particles

- Gyro Motion
- Bounce Motion
- Drift Motion
The Van Allen Radiation Belts

- Energetic particles on trapped orbits for the radiation belts. There are both electron and proton radiation belts.
The Electron Radiation Belts
The Electron Radiation Belts in 3D
The Ring Current

- Electrons and protons drift around the Earth in opposite directions.

- This motion leads to an electrical current flowing around the Earth.

- The current is carried by particles with energies (50keV to 200keV).

Image of ring current particles taken with an energetic neutral atom imager.