# Solar wind - Earth’s magnetosphere coupling

*Ericsson Lopez*

*Quito Astronomical Observatory, Ecuador*

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# Outline

- Solar wind
- Magnetosphere
- Effects on the Earth
- Microphysics
- Macrospopic aproximation
- Magnetic field reconnection
- Ring Currents
- Geomagnetic Storms

# Solar wind

The concept of continuous solar wind developed in 1950's:

- Biermann (1951, 1957) observed comet tails
- Parker (1959) showed that the solar corona must expand

***Corona, is indeed very hot, so hot that the hydrogen and helium can escape gravitational attraction*** → ***form a steadily streaming outflow of material called the solar wind***

- ***fully ionized plasma***
- ***supersonic above a few solar radii***
- ***drags also the solar magnetic field outward (IMF)***
- ***the magnetic field in a spiral form (garden hose effect)***

# Characteristics

| Parameter | Minimum | Average | Maximum |
|---|---|---|---|
| Flux (cm^-2$^{s}$-1^) | 1 | 3 | 100 |
| Velocity (km/s) | 200 | 400 | 900 |
| Density (cm^-3^) | 0.4 | 6.5 | 100 |
| Helium % | 0 | 5 | 25 |
| B (nT) | 0.2 | 6 | 80 |

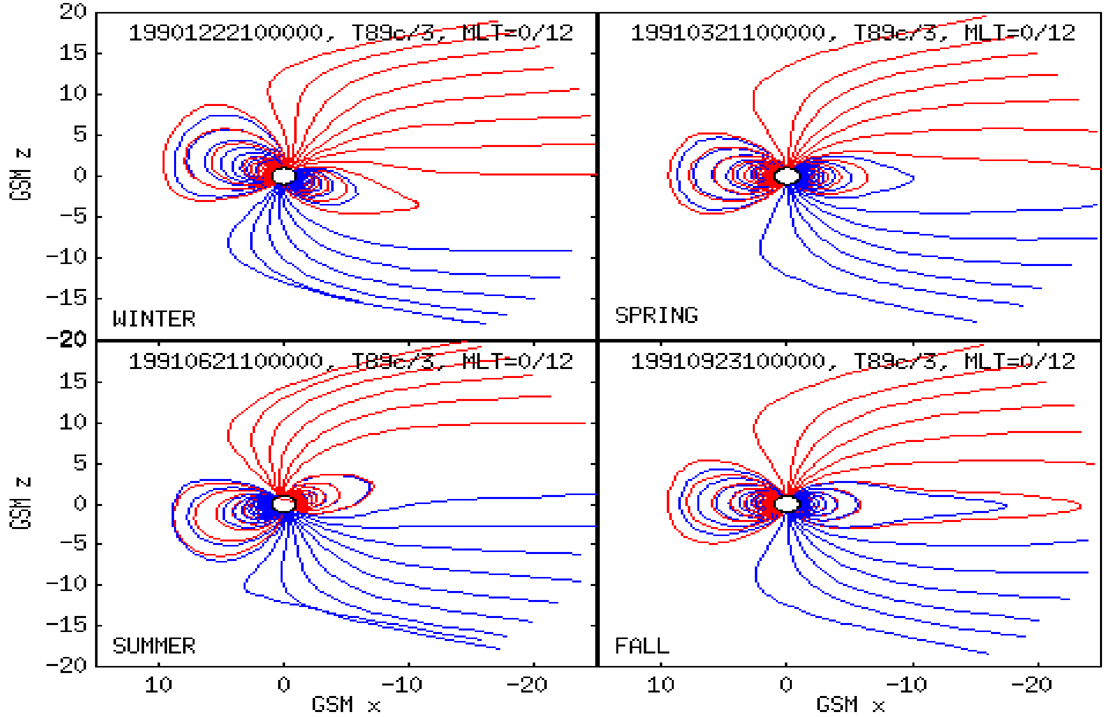
- The solar wind plasma consist of primarily of hot electrons and protons with a minor fraction of He2+ ions and some other heavier ions.
- The scale sizes of solar wind/IMF structures is typically smaller than the extent of the Earth's magnetosphere (about 40 Re; see, e.g., Russell et al., 1980; Crooker et al., 1982)

# Effects on Earth

- conducting electrical current and carrying a large amount of kinetic and electrical energy.
- drives the magnetospheric convection system via the electric field it creates, and energizes much of the plasma on the Earth's magnetic field lines.
- drives field line resonances and other geomagnetic pulsations.
- creates geomagnetic activity.
- heats the polar upper atmosphere.
- drives large neutral atmospheric winds.

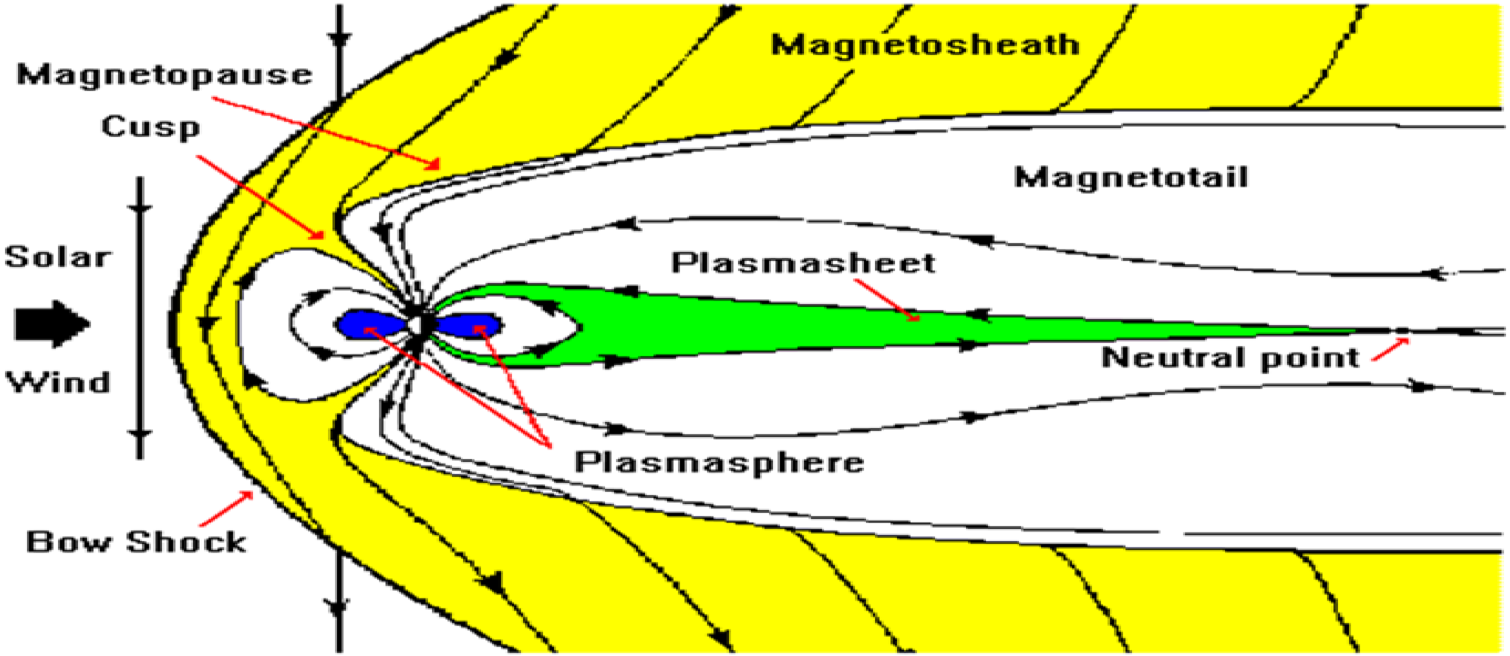
***The upper atmosphere is the final recipient of all the energy and momentum that enters the magnetosphere.***

# Magnetosphere




***Magnetic moment 8x10^15 Tm^3: at the equator on the Earth's surface of about 30,000 nT at 10 Earth radii (RE) of about 30 nT.***

# Magnetosphere



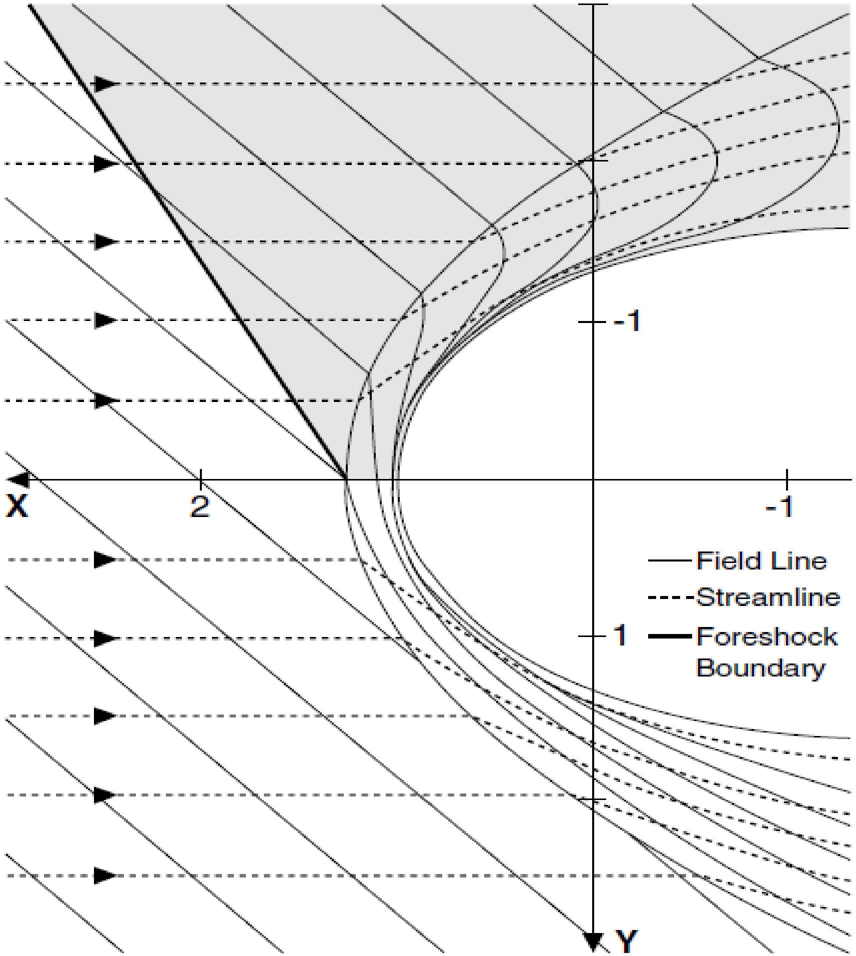
- Shock waves are formed in front of the planets
- The properties of the plasma that makes direct contact with the magnetosphere are different than those of the solar wind.
- Having been altered by a standing bow shock wave.

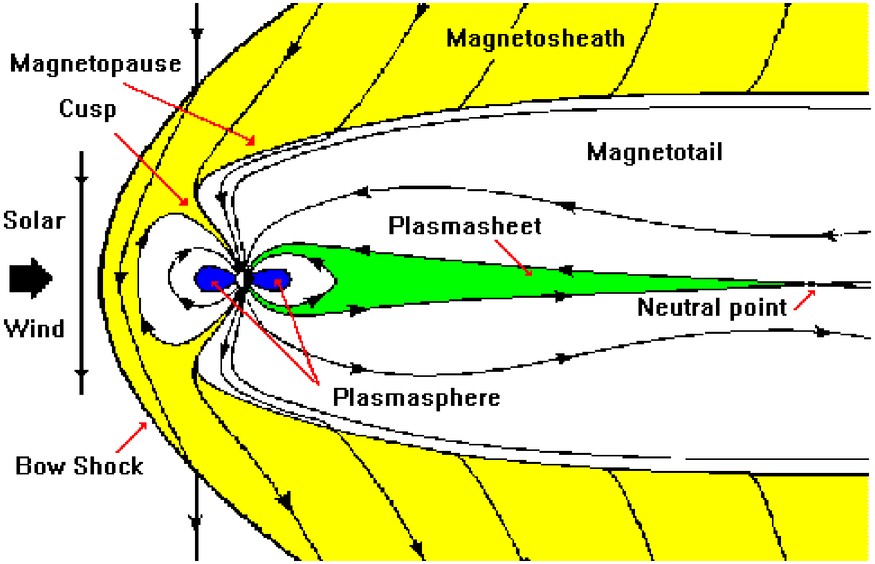
***The pressure in the magnetic field is about 2 nPa***

$$\approx$$

***flowing plasma is also about 2 nPa***

# Magnetosheath and the magnetosphere



# MICROPHYSICS

- In order to understand how the solar wind interacts with the magnetosphere and in turn the magnetosphere reacts to this interaction, we need to examine the motion of charged particles in magnetic fields and the creation of the electric and magnetic fields by these same particles.

- Four basic laws govern the behavior of the charges, currents, magnetic fields and electron fields in a plasma:
  - Maxwell's laws.
  - Conservation of mass,
  - Conservation of momentum
  - Conservation of energy.

***Govern the types and speeds of waves in the plasma:***

Disturbances of three types propagate in this magnetized solar wind plasma: The fast mode wave compresses the magnetic field and plasma; the intermediate mode wave bends the flow and magnetic field, but does not compress it; and the slow mode wave rarefies the field while it compresses the plasma and viceversa.

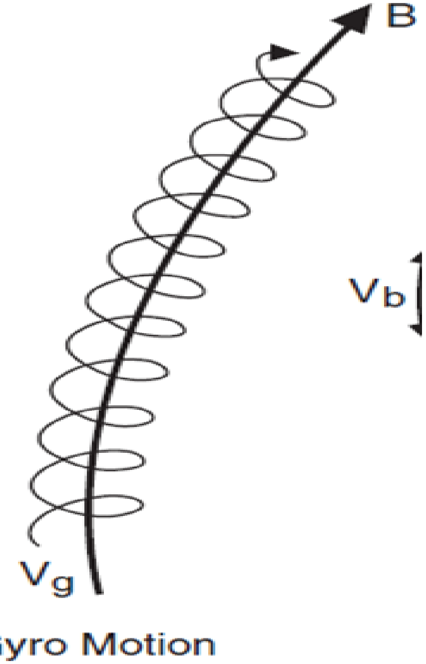
# *Adiabatic invariants*

- Charged particle experiences a Lorentz force:

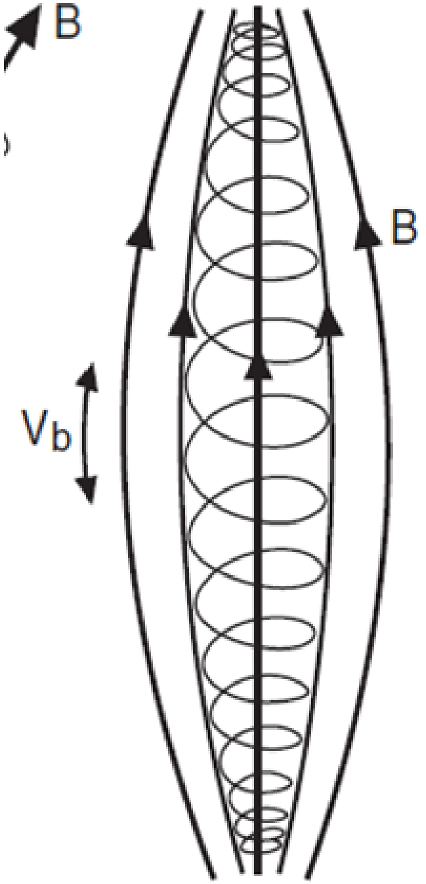
$$\mathbf{w = qB/m}$$

**The first adiabatic invariant:**

$$mV_{\perp}^{2}/(2B)$$



**_Magnetic field lines converge_**



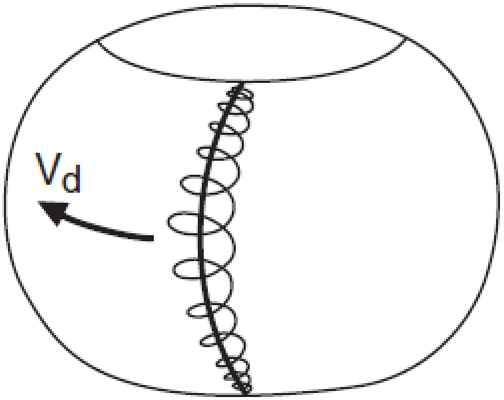

Bounce Motion

**_the particle to reflect and bounce back and forth along the magnetic field line_**

**Second adiabatic invariant:** The parallel momentum, i.e. the mass times the velocity, integrated along the motion of the particle is also conserved.

If the bounce path shortens, then the parallel energy of particle increases. Fermi acceleration

***If a field line is curved and the particle moves parallel to the field line, it will drift perpendicular to the magnetic field***




Drift Motion

- If the magnetic field strength varies with distance: the gyrating particle will drift perpendicular to the gradient

Both the curvature and gradient drifts are proportional to energy

In the Earth's magnetosphere the gyrating and drifting particles lead to a current encircling the magnetosphere $\rightarrow$ Ring current

depression in the magnetic field on the surface of the Earth. $\alpha$ Energy of the particles

$$100 \text{ nT} \approx 2.8 \times 10^{15} \text{J}$$

- Another important drift occurs in the presence of an electric field perpendicular to the magnetic field

If an electric field is applied across a plasma, an electron or an ion will be accelerated

***there is no current associated with this drift***

# Macroscopic approach

***This "fluid" approach to the treatment of a plasma is called the magnetohydrodynamic approach, or MHD***

$$P = R\rho T \text{ (Perfect Gas)} \quad \frac{\partial \rho}{\partial t} = -\nabla \cdot (\rho \mathbf{u}) \text{(Continuity)}$$

$$\nabla \cdot \mathbf{B} = 0, \quad \frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{u} \times \mathbf{B} - \eta \nabla \times \mathbf{B}) \text{ (Induction)}$$

$$\frac{\partial}{\partial t}(\rho \mathbf{u}) = -\nabla \cdot (\rho \mathbf{u}\mathbf{u}) - \nabla P + \rho \mathbf{g} + \nabla \cdot \tau + \mathcal{F}_{other} \text{ (Momentum)}$$

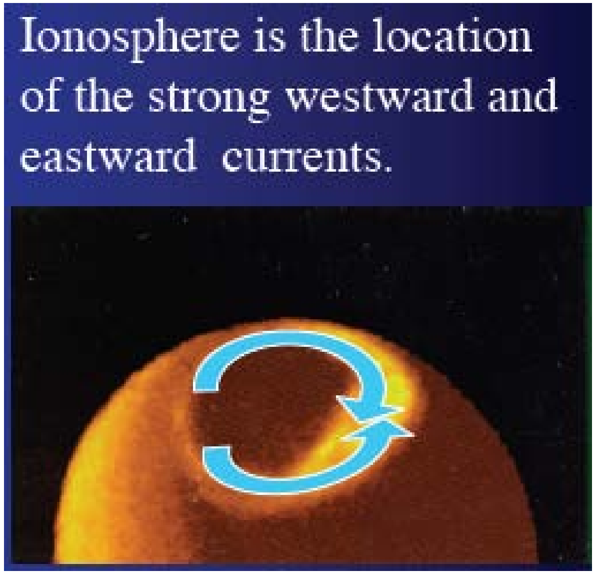
$$(\frac{\partial}{\partial t} + \mathbf{u} \cdot \nabla)\left(\frac{P}{\rho^{\gamma}}\right) = \text{Source and Loss terms (Energy)}$$

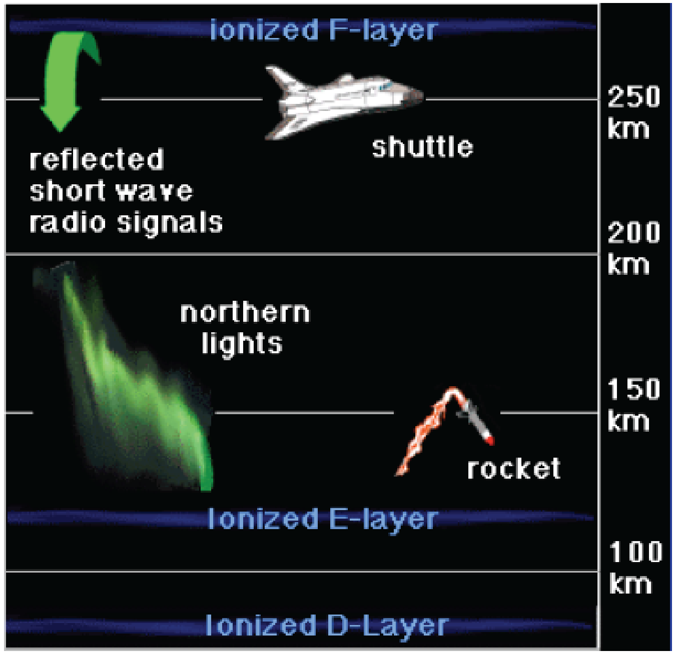
# The Coupling

One of the main tasks in space physics is to explain the various ways the Sun/solar wind, magnetosphere, ionosphere and even upper atmosphere (thermosphere) are coupled to each other.

- ***Solar wind – magnetosphere:*** *probably realized via a magnetic reconnection process between the (solar wind carried) IMF Bz component and the geomagnetic field.*
- ***Magnetosphere – ionosphere:*** *Ionosphere and magne-tosphere are closely linked together via magnetic field lines. Magnetospheric electric fields map down to the ionosphere:* ***plasma convection, frictional heating and plasma instabilities.***

- **Ionosphere – thermosphere:** *Collisions between the convecting ionospheric plasma and the neutral atmosphere leads to generation of neutral winds and Joule heating of the neutral gas.*




- Solar wind properties ultimately control the interactions

# Main effects

- The main product of the solar wind - magnetosphere coupling is the large scale magnethospheric electric field that drives plasma convection.
- In addition, the magnetospheric cavity is affected by the solar wind pressure pulses.
- The energy that is transported from the the solar wind into the magnetosphere creates geomagnetic activity and drives different kind of geomagnetic pulsations.

# Magnetospheric electric field

The are two main sources of magnetospheric electric fields:

- **Dawn-to-dusk directed ("convection") field related to the solar wind.**
- **Co-rotation electric field related to the rotation of the Earth along its spin axis.**

***The electric fields have a strong effect on the drift paths of the magnetospheric plasma.***

***The low energy particles move primarily under the E×B drift***

***The energetic particles, following the magnetic drifts more readily, are also affected by the convection field***

# Convection field

- Initially suggested by Dungey (1961).
- Reconnection of the interplanetary and geomagnetic field lines partially opens Earth´s magnetic field to the solar wind:

The magnetospheric potential and electric field:

$$\phi_{conv} = A\left(\frac{r}{R_E}\right)^2 \sin\varphi, \quad \text{where} \quad A = \frac{0.045}{\left(1 - 0.159K_p + 0.0093K_p^2\right)^3} kV$$

and $\varphi = 0°$ points to the midnight, $\varphi = 90°$ towards dawn, etc…

$$\vec{E}_{conv} = -\nabla\phi_{conv} = -\frac{\partial\phi_{conv}}{\partial r}\hat{e}_r - \frac{1}{r}\frac{\partial\phi_{conv}}{\partial\varphi}\hat{e}_\varphi$$

$$= -\frac{2A}{R_E}\left(\frac{r}{R_E}\right)\sin\varphi\,\hat{e}_r - \frac{A}{R_E}\left(\frac{r}{R_E}\right)\cos\varphi\,\hat{e}_\varphi$$

***Volland's potential distribution (Volland, 1973)***

***Maynard and Chen (1975)***

# Co-rotation field

***Using the simple dipole model for B:***

***B =B0 / r^3 and  Erot x B drift***

***Produce an azimuthally symmetric field:***

$$\frac{\vec{E}_{cor} \times \vec{B}}{B^2} = \frac{E_{cor}}{B_0 R_E^3 / r^3} \hat{e}_r \times \hat{e}_z = \omega_E r \, \hat{e}_\varphi \quad \Rightarrow \quad E_{cor} = \frac{-\omega_E R_E B_0}{r^2 / R_E^2} = \frac{C/R_E}{\left(r/R_E\right)^2}$$

$$\vec{E}_{cor} = -\nabla \phi_{cor} = -\frac{\partial \phi_{cor}}{\partial r} \hat{e}_r \quad \Rightarrow \quad \frac{\partial \phi_{cor}}{\partial r} = -\frac{C/R_E}{\left(r/R_E\right)^2} \quad \Rightarrow \quad \phi_{cor} = \frac{C}{r/R_E}$$

$$C = -\omega_E R_E^2 B_0 = -\frac{2\pi}{24\,h} \times \left(6371.2\,km\right)^2 \times 3.1 \cdot 10^{-5}\,T = -92\,kV$$

# Solar wind pressure pulses

- The solar wind pressure variations are associated either with tangential discontinuities or interplanetary shocks

The pressure pulses have an important role in the solar wind:

1) compress the magnetopause
2) enhance magnetospheric magnetic field strength,
3) excite resonant azimuthal magnetic field oscillations.

# Magnetic field reconnection

- The concept of merging or reconnection of magnetic field lines is widely used in magnetospheric and solar physics.

- The basic idea behind reconnection is that (partly) antiparallel magnetic field lines can, when meeting, merge together and produce two topologically totally different field lines.

- It is the main process that transports mass, momentum, and energy from the solar wind into the magnetosphere.

***The physics underlying reconnection occurs on the sub-gyroscale where the ions and eventually the electrons encounter magnetic structure that demagnetizes the charged particles so that they no longer are tied to the magnetic field and drift across it.***

This process allows field lines from different plasma regimes to connect.

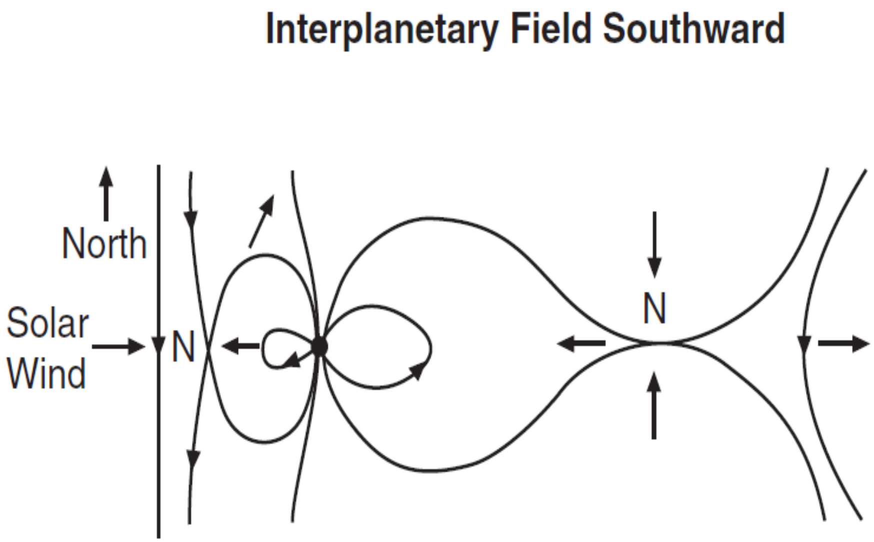
***The reconnection is the mechanism in which the magnetic field of the solar wind links with the magnetic field of the magnetosphere***

There are several reasons to believe the existence of such a process:

- there is a clear correlation between the IMF Bz direction and geomagnetic activity.
- some measurements indicate the presence of unexplained processes at the magnetopause
- some theories may be able to explain reconnection (e.g., the tearing mode instability)

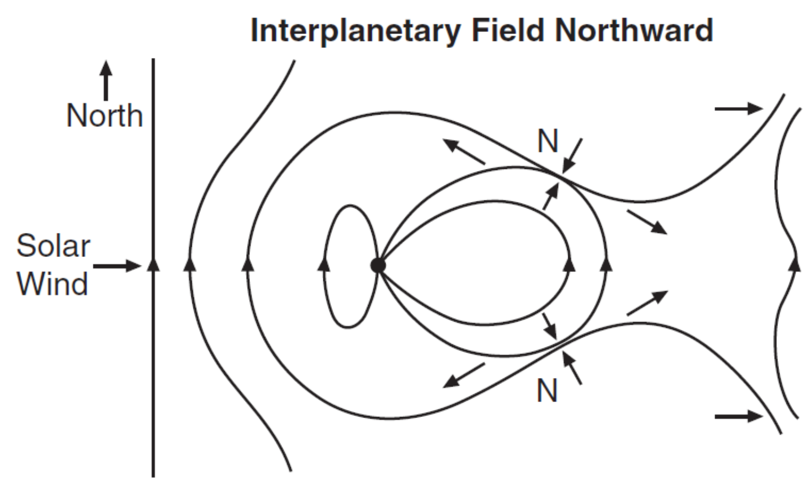
There are two basic types of reconnection models:

- quasi-static reconnection (QSR)
- flux transfer event (FTE)




The main mechanism by which the magnetized solar wind powers the magnetosphere was first proposed by J. W. Dungey

The resulting V-shaped magnetic fields attempt to straighten and accelerate plasma



# Disturbances

1. **The fast mode compresses the plasma and the magnetic field together**
2. **The intermediate mode twists the field and the flow but does not change the density or the magnetic field strength.**
3. **The slow mode weakens the magnetic field when it compresses the density.**

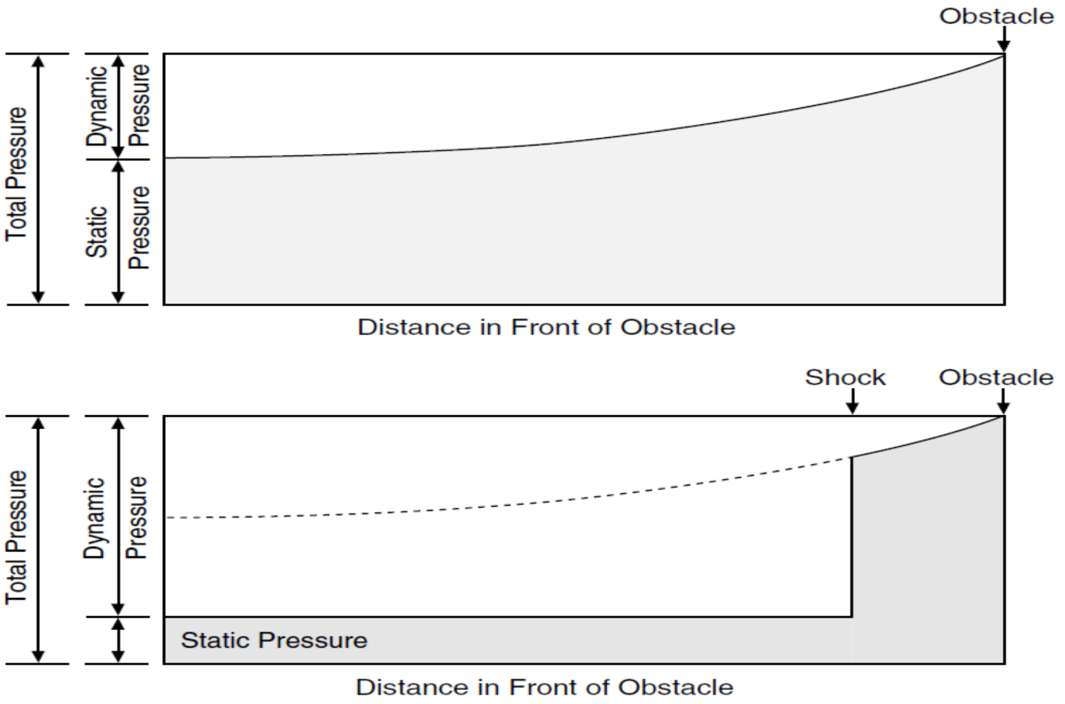
***The fast and slow waves can steepen into shocks***

# The Earth's Bow Shock

- The function of this non-linear bow wave is to deflect the plasma around the magnetospheric obstacle.

Understanding why a bow shock forms in front of the Earth

The curve along which the flow and the magnetic field suddenly changes from being straight to being curved is the shock front



# Politropic index

- The formation of the shock heats and compresses the flow by converting dynamic pressure to thermal pressure.
- The factors that control the compression in an ideal fluid are the polytropic index.

***If the polytropic index is 5/3 then the solar wind plasma can be compressed by a factor of 4.***

If the polytropic index is 2 $\rightarrow$ solar wind can be compressed only a factor of 3 $\rightarrow$ further out from the obstacle.

Most research points to a value of 5/3

- If the Mach number of the shock drops below unity as would happen if the density of the solar wind dropped to $0.1\ cm^{-3}$ or if the magnetic field strength increased to 40 nT.

Then the bow shock would weaken and move away from the obstacle and disappear.

- The physics of the bow shock is rich with processes that heat the plasma, scatter and reflect the particles

# The Size of the Magnetosphere

We need to understand the pressure applied to the magnetosphere by the solar wind.

- In a straightforward manner:

$$(\rho u^2 + nkT + B^2/2\mu_o)\, S = \text{constant}$$

Conservation of the momentum in a stream tube

This formula allows us to use the incoming solar wind dynamic pressure, $\rho u^2$, which dominates over the thermal and magnetic pressures.

- solar wind pressure: $\rho u^2$
- pressure in the magnetic field: $(aB_o/L^3_{mp})^2$

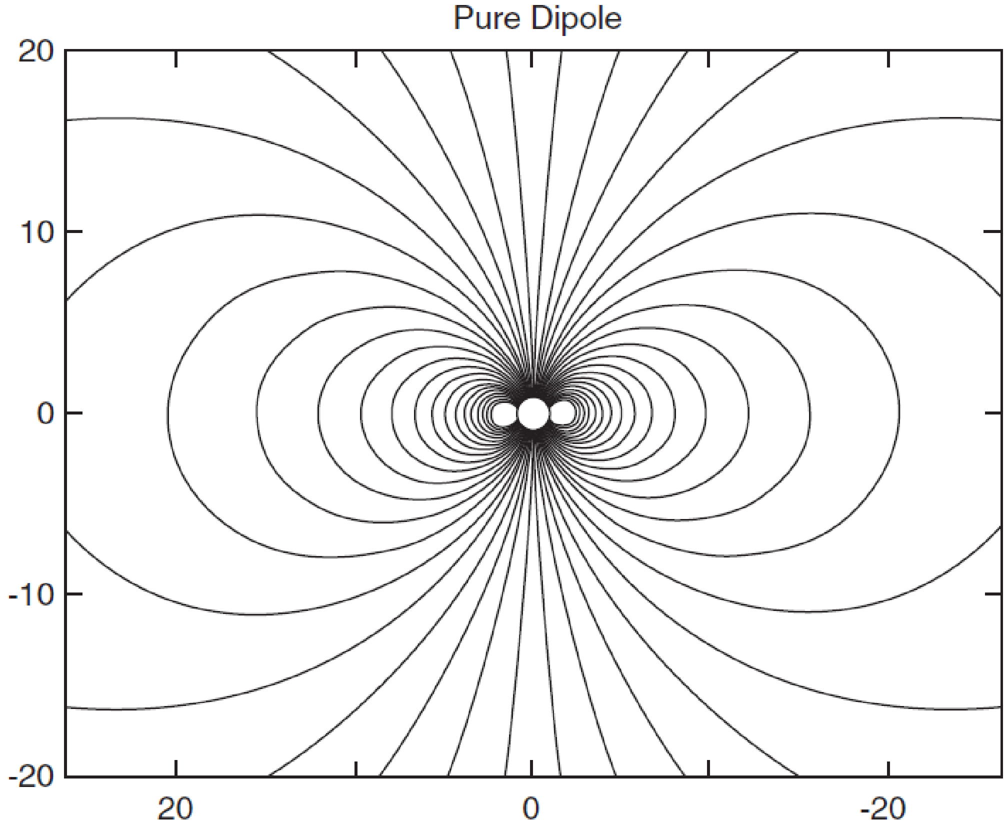
$$L_{mp} = 107.4\,(n_{sw}\,u_{sw}^{2})^{-1/6}$$

Where: $n_{sw}$ is the solar wind proton number density in cm-3, $u_{sw}$ is the proton bulk velocity in km/s, and $L_{mp}$ is the distance in $R_E$

- ***The size of the terrestrial magnetosphere is determined by the balance between the solar wind dynamic pressure and the pressure exerted by the magnetosphere (magnetic field).***

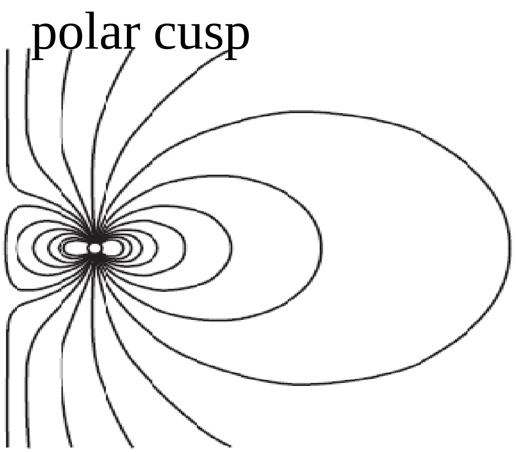
- ***The shape of the magnetosphere is additionally influenced by the drag of the solar wind or tangential stress, on the magnetosphere.***

***An equilibrium between these two forces is found in the dipole magnetic field.***

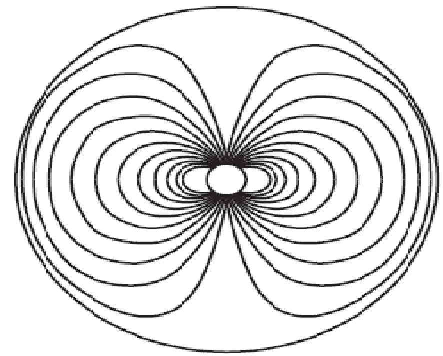



***The interaction of the solar wind with a dipole magnetic field is going to be somewhat more complicated.***

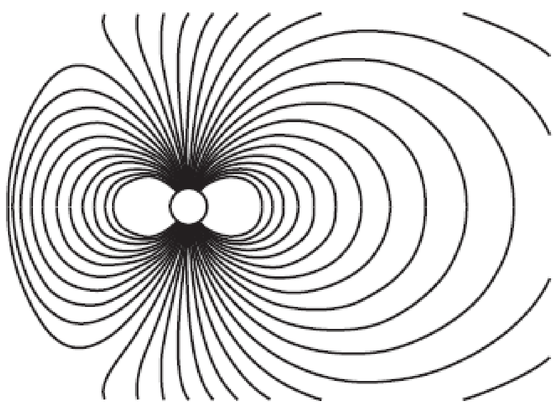
# ***Chapman and Ferraro magnetopause***



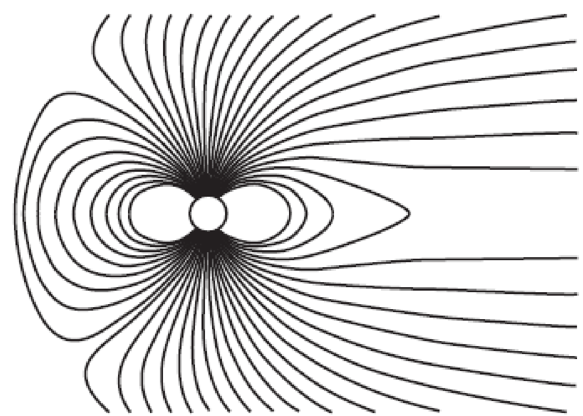

Planar Magnetopause



Spherical Magnetopause



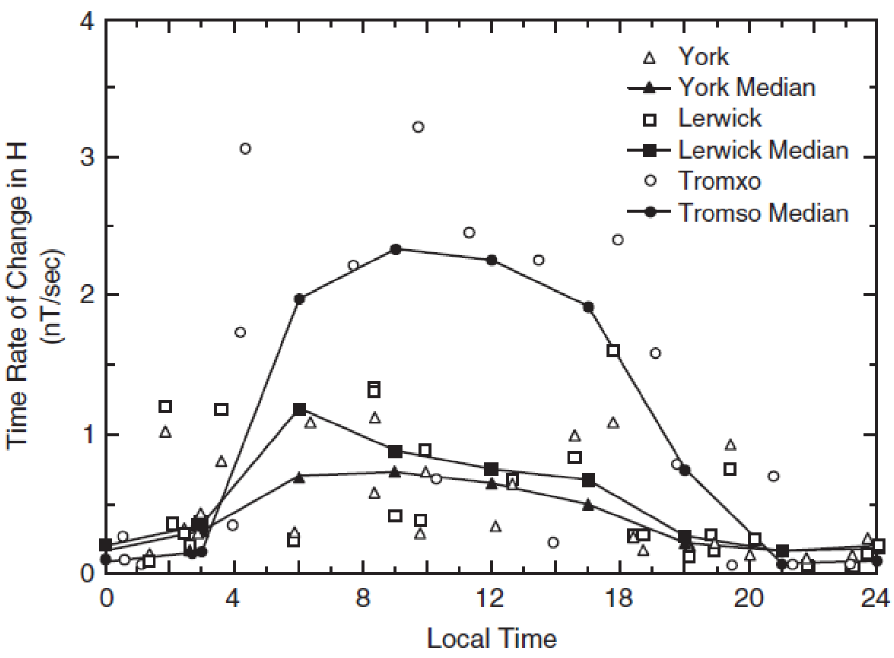
Elliptical Magnetopause



Empirical Magnetosphere

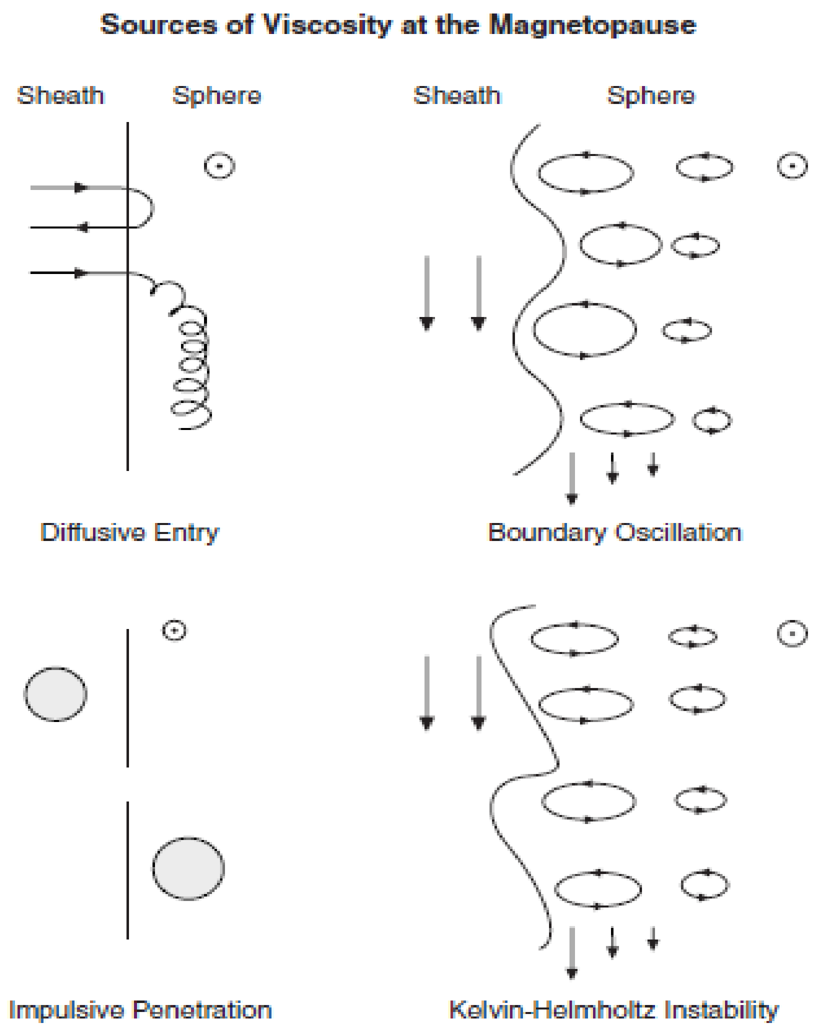
- The magnetopause currents that bound the magnetosphere are sensitive to the square root of the solar wind dynamic pressure.

- When the dynamic pressure of the solar wind changes, the currents increase as the magnetosphere reduces and the magnetic field seen on the surface of the Earth rises.




Values greater than about 7 nT/s can be harmful to electrical transmission systems.

# Tangential Stress




Tangential stresses also affect the shape and cause momentum transfer across the boundary.

***Several different mechanisms:***

- diffusive entry
- Impusive penetration
- Boundary Oscillation
- Kelvin-Helmholtz instability

# The Ring Current

The trapping regions of high-energy charged (cf. ring current) particles surrounding the Earth are called radiation (or van Allen) belts:

- The energy content of the radiation belt is generally fairly constant except during periods known as geomagnetic storms.
- The ring current causes a net decrease in the magnetic field on the surface of the Earth as opposed to the magnetopause current that causes an increase.
- The energy of these circulating particles can be calculated from their effect on the ground-level magnetic field.
- Protons with energies exceeding 10 MeV

# Storm-time index: *Dst*

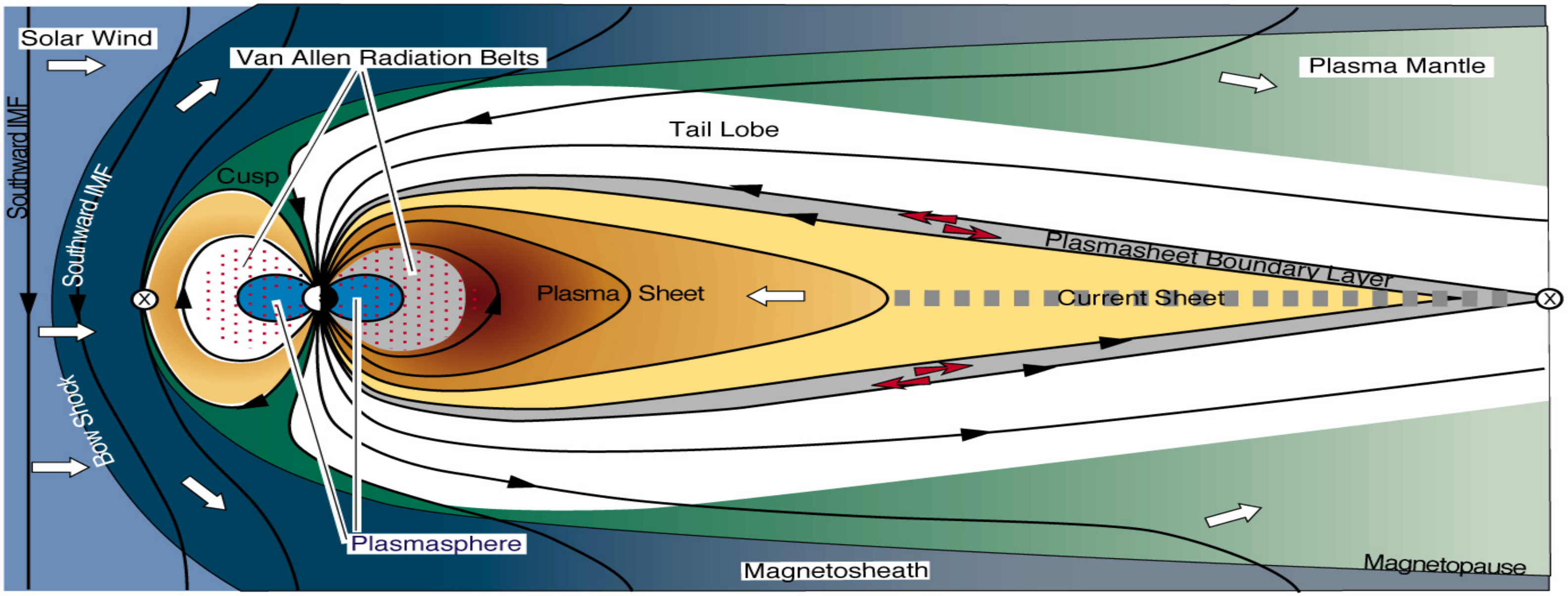
(from ground based magnetic field measurements)

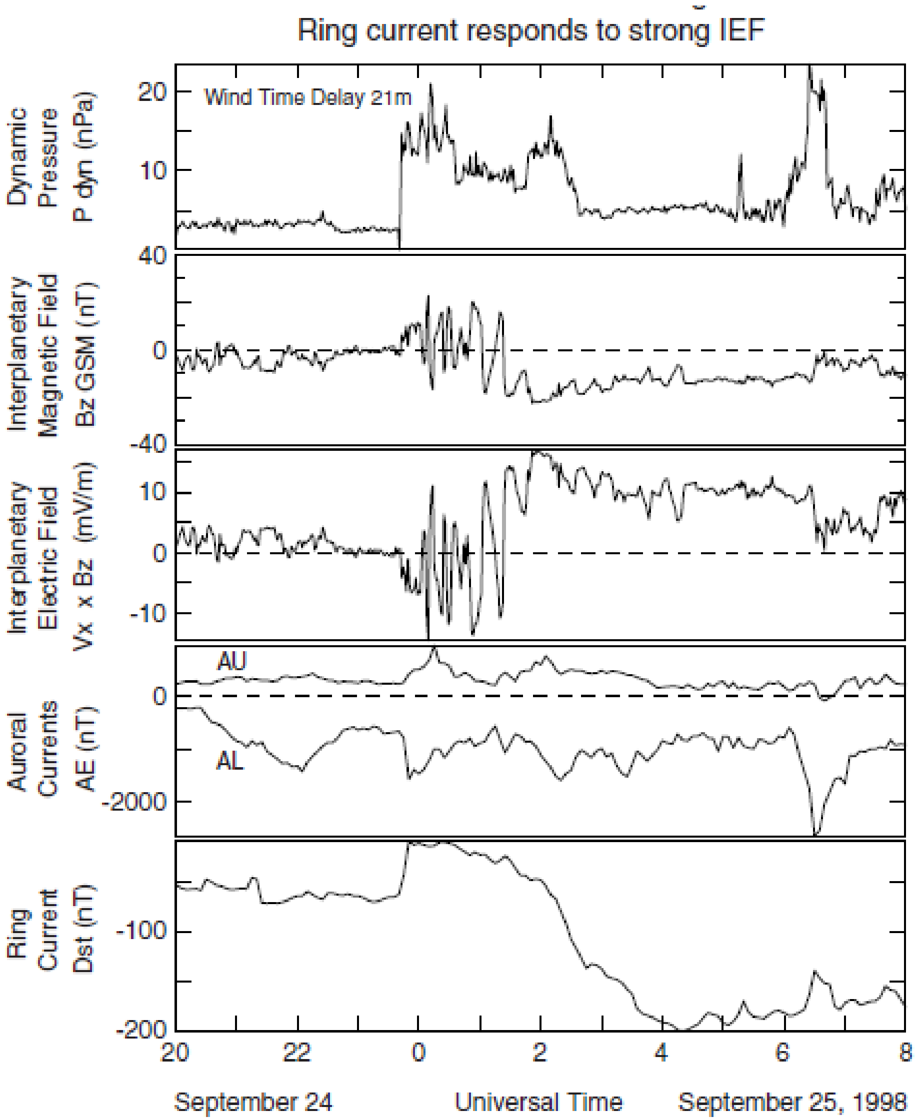
- The effect of the currents on the dayside magnetopause is to enhance the magnetic field on the surface of the Earth.
- The effect of the tail current system is to oppose the Earth's field and has a stronger effect on the nightside.
- day-night gradient in the field due to external sources.

*Dst* index provides a good measure of the ring current

# Geomagnetic Storms

- A geomagnetic storm occurs when the energy content of the radiation belts, i.e. the ring current, increases to unusually large values.






The solar wind condition and magnetospheric response during a geomagnetic storm.

Injection of energetic plasma into the ring current.

# Substorms

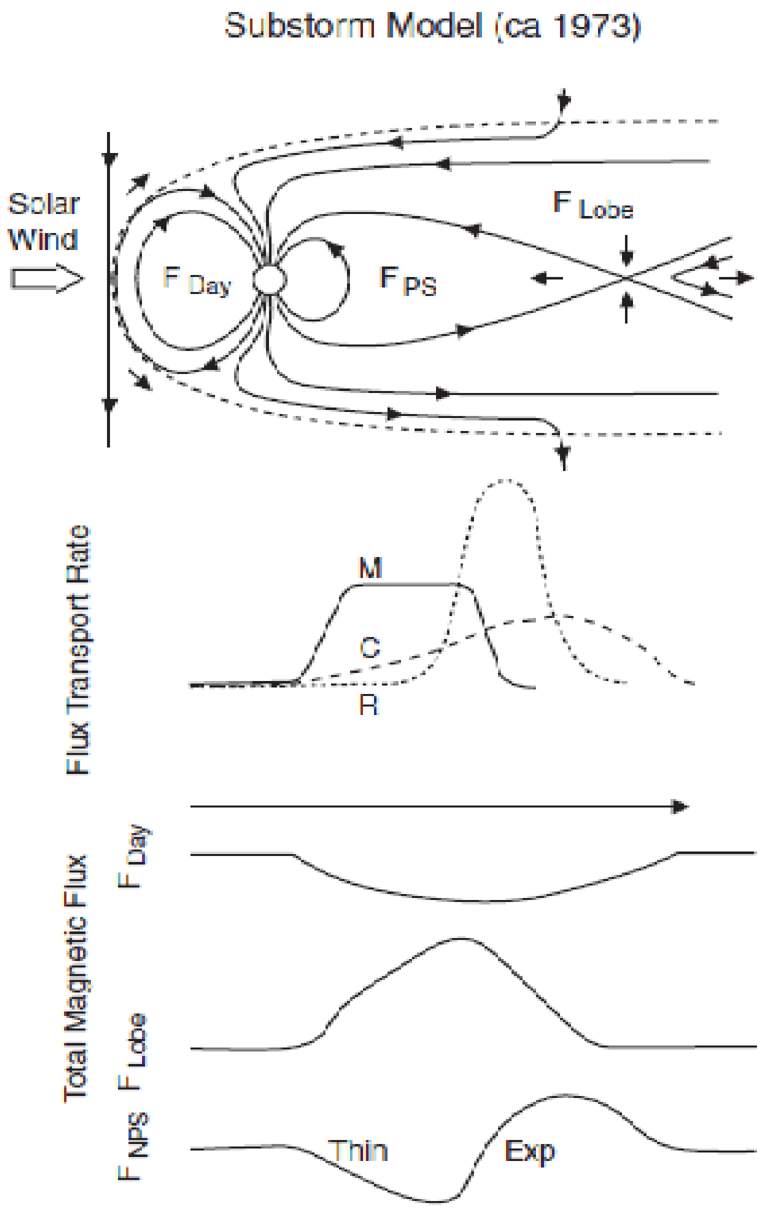
*Associated with southward interplanetary magnetic field*

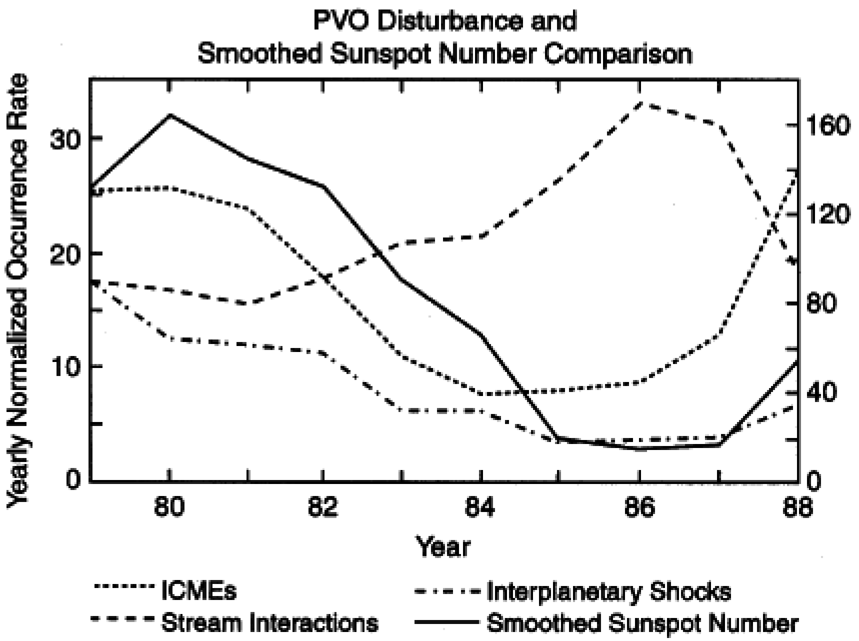
Two basic classes of geomagnetic activity:

- Storms show a strong ring current and have durations that are any long or longer.
- Substorms are characterized by high latitude current intensifications and occur over intervals of hours, often repeating every few hours.
- Substorms do occur during storms, but perhaps unexpectedly this energy release is often accompanied, not by an injection of energy into the ring current, but by a loss of energy from the ring current

According to the many phenomenological features, substorms have been divided into three phases (Rostoker et al., 1980):

- growth phase
- expansion phase
- recovery phase
- Auroral substorm is a spectacle people living at auroral latitudes.
- Auroral substorms can be seen in the ground based magnetometer recondings due to created ionospheric currents During the growth phase, energy is stored within the magnetosphere as excess magnetic flux in the tail lobes. This energy is dissipated explosively during the substorm expansion phase into magnetosphere and ionosphere (e.g., Baker et al., 1997a). The energy put into the plasmoids returns eventually to the solar wind.




The substorm appears to intimately involve the tail for storage and release of energy.

The storm appears to be associated with the penetration of the solar-wind induced plasma circulation deep into the magnetosphere and the resulting enhancement of the ring current.

- solar wind speed correlates well with geomagnetic activity.
- IMF affects the geomagnetic activity. This is because the southward IMF component enhances the coupling between the solar wind and the magnetosphere/ionosphere system.
- The level of the geomagnetic activity is measured using different activity indices, most of which are based on ground-based magnetometer recordings. Storms, the main contributors to space weather

| Storm strength | Dst [nT] | Bz [nT] | dT [h] |
| --- | --- | --- | --- |
| Intense | -100 | -10 | 3 |
| Moderate | -50 | -5 | 2 |
| Small (typical substorm!) | -30 | -3 | 1 |

The largest storms are often related to coronal mass ejections

# SUMMARY

- The magnetospheric size is controlled by the solar wind dynamic pressure (5 $R_E$ in radius and as large as 20 $R_E$).
- While the normal stresses are applied by the dynamic pressure, the tangential stress is applied principally by the reconnection process.
- The amount of reconnection at the magnetopause and its consequences depend strongly on the interplanetary magnetic field orientation.
- Reconnection during intervals of strongly southward field transfers magnetic flux to the tail.

- Reconnection above the cusp during intervals of strongly northward field can add more magnetic flux to the dayside while removing it from the tail.
- Coronal mass ejections can lead to intervals of prolonged southward interplanetary magnetic fields.
- These CMEs follow the sunspot cycle and cause the terrestrial geomagnetic cycle to follow suit.
- Accurate long term prediction of space weather depends on our ability to predict the properties of an CME.
- While we do not have a complete understanding of all the processes in the magnetosphere, it is clear that the majority of the processes ultimately derive their energy from the solar wind through the reconnection process.

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