Solar Wind/Outer Magnetosphere

GEM Student Tutorial

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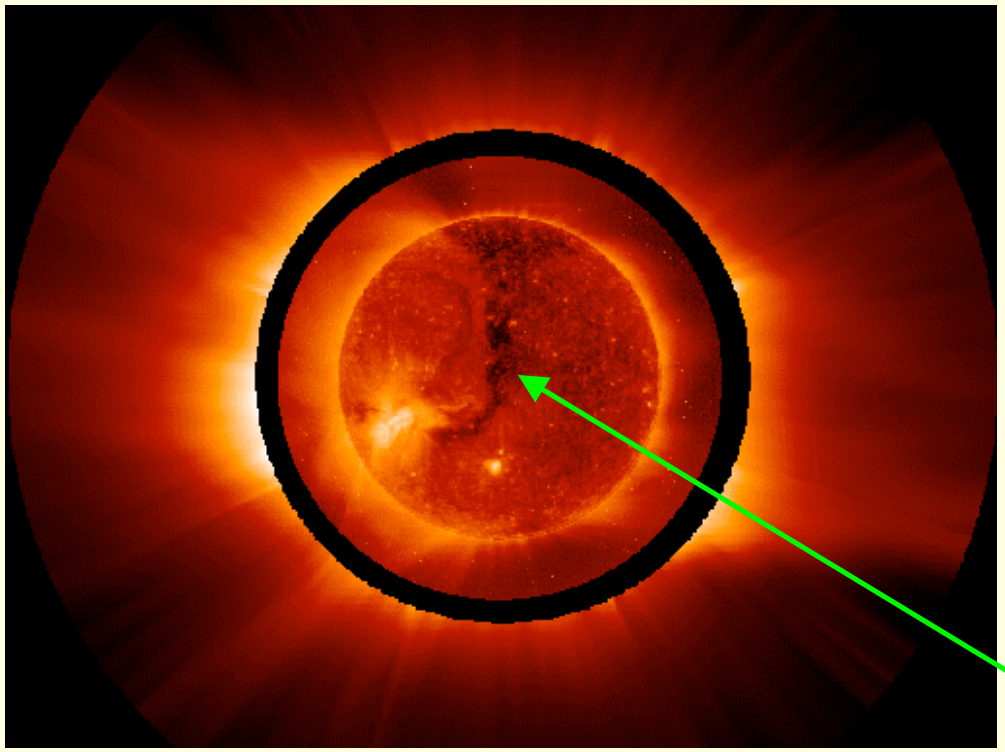
The Solar Wind

- Hot plasma (10^6 K) from the solar corona is the source of the solar wind
- The coronal plasma is accelerated and flows radially outward from the sun, filling interplanetary space
- Particles are accelerated to supersonic outflow velocities within 1.5 solar radii of the solar surface
- Solar wind properties at Earth (1 AU):
  - Speed ~400 km/s
  - Speed range ~200-700 km/s, and transient events such as CMEs can be VERY fast (up to 1500 km/s)
  - Number density ~ 7 cm^{-3}
  - Magnetic field ~ 5 nT
  - Electron temperature ~ 10^5 K
  - Proton temperature ~3 x 10^4 K

Picture of a total solar eclipse - solar corona is visible

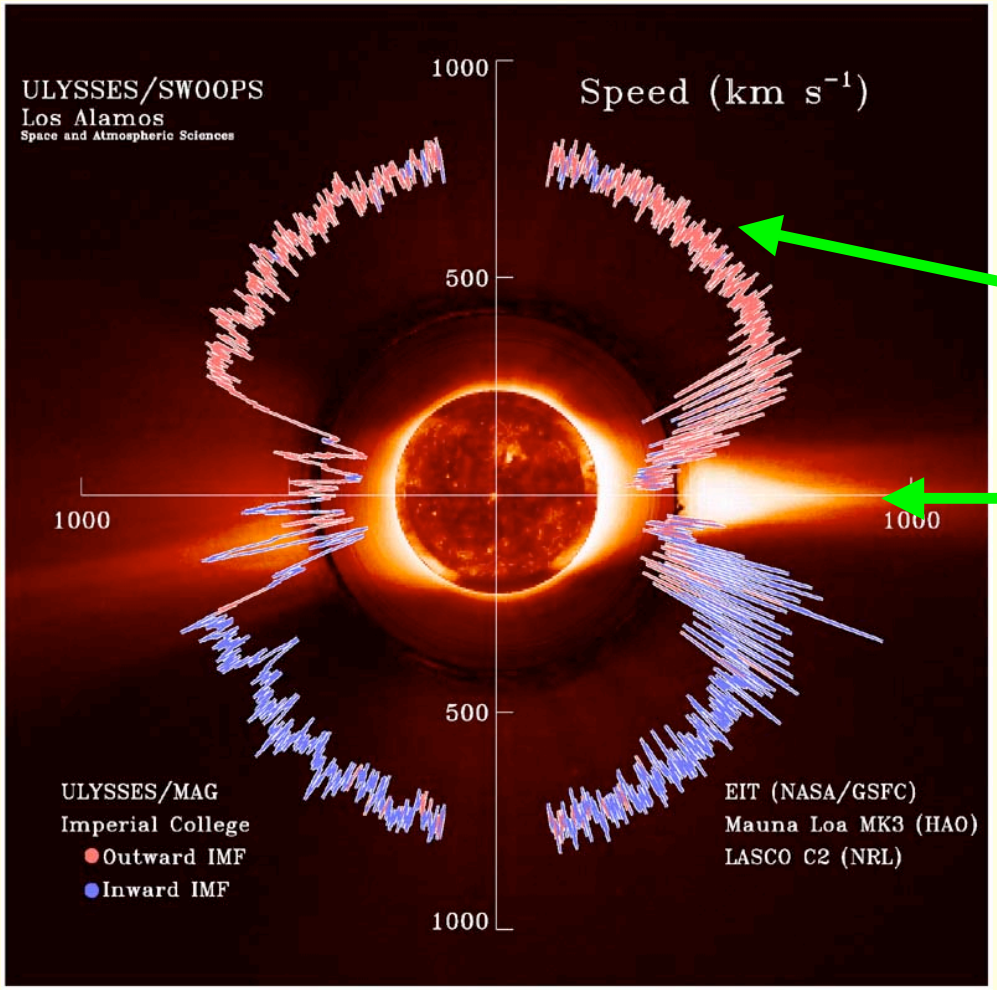
The Solar Corona: The Source of the Solar Wind



http://sohowww.nascom.nasa.gov/gallery/images/uvcswitheit.html

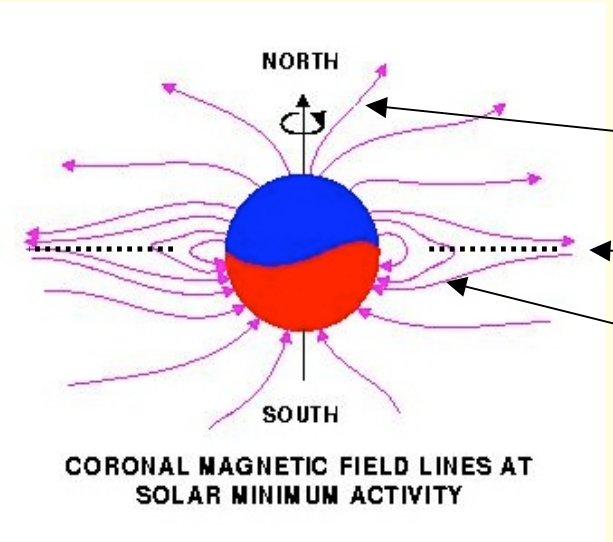
- Left is a composite image taken by two instruments on the Solar and Heliosphere Observatory (SOHO):
  - Ultraviolet Coronagraph Spectrometer (UVCS), outer region
  - Extreme Ultraviolet Image Telescope (EIT), inner region
- SOHO is located at L1
- With the composite image you can relate corona structure to surface features
- Solar magnetic field controls structure of corona
- Dark areas across disk of Sun correspond with coronal holes – higher speed solar wind originates here
- Slower speed solar wind originates near Helmet Streamers

Magnetic Structure and Solar Wind Speed During Solar Minimum

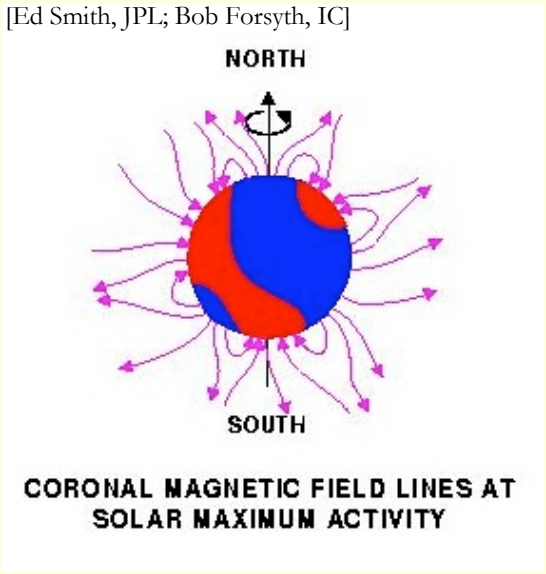


- ULYSSES: Orbit takes spacecraft over Sun's poles
- Higher speed solar wind observed over polar coronal holes
- Slower speed solar wind observed near helmet streamers
- Magnetic field is well ordered during solar minimum

The Sun's Magnetic Topology

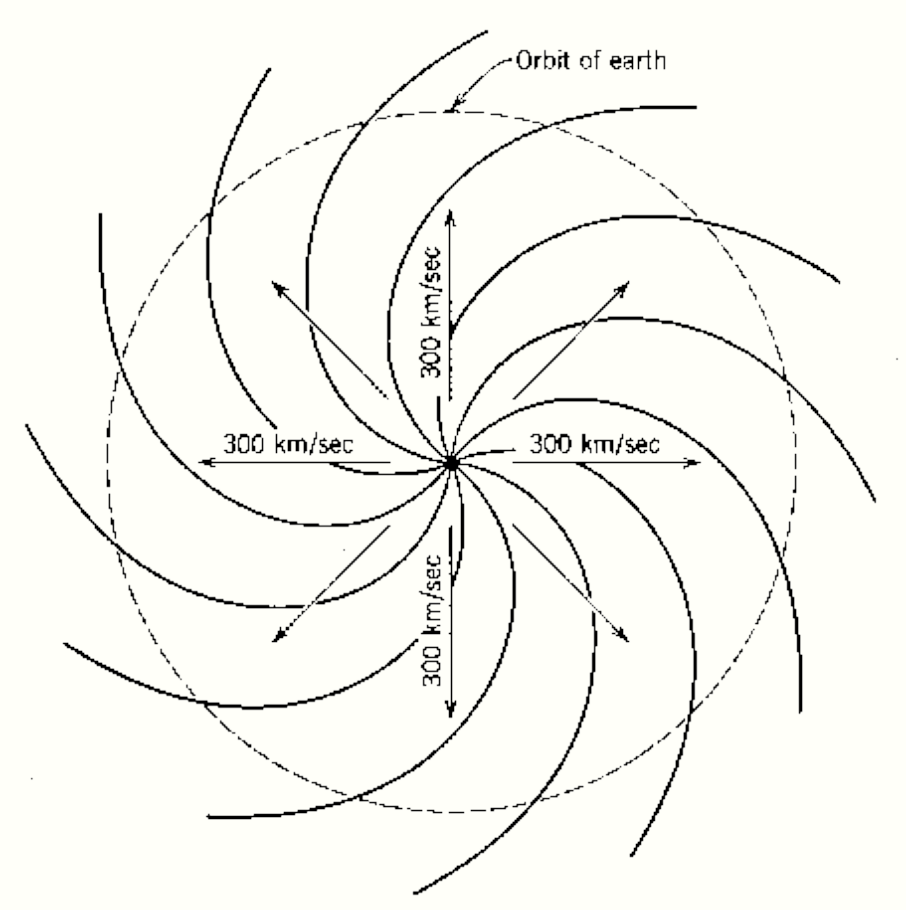


[Ed Smith, JPL; Bob Forsyth, IC]



- Different magnetic polarities on solar surface are indicated with Blue or Red
- Coronal Holes – regions of open magnetic field (fast wind)
- Current Sheet separates regions of different polarity
- Helmet Streamers- boundary between closed and open magnetic field (slow wind)
- Solar minimum – magnetic field topology is well ordered
- Solar maximum – magnetic field topology is complicated
- Frozen in flux - magnetic field is drawn out by expanding Solar wind plasma and fills the Heliosphere, referred to as the Interplanetary Magnetic field (IMF)
- As the solar wind is expanding radially outward, the Sun is rotating…

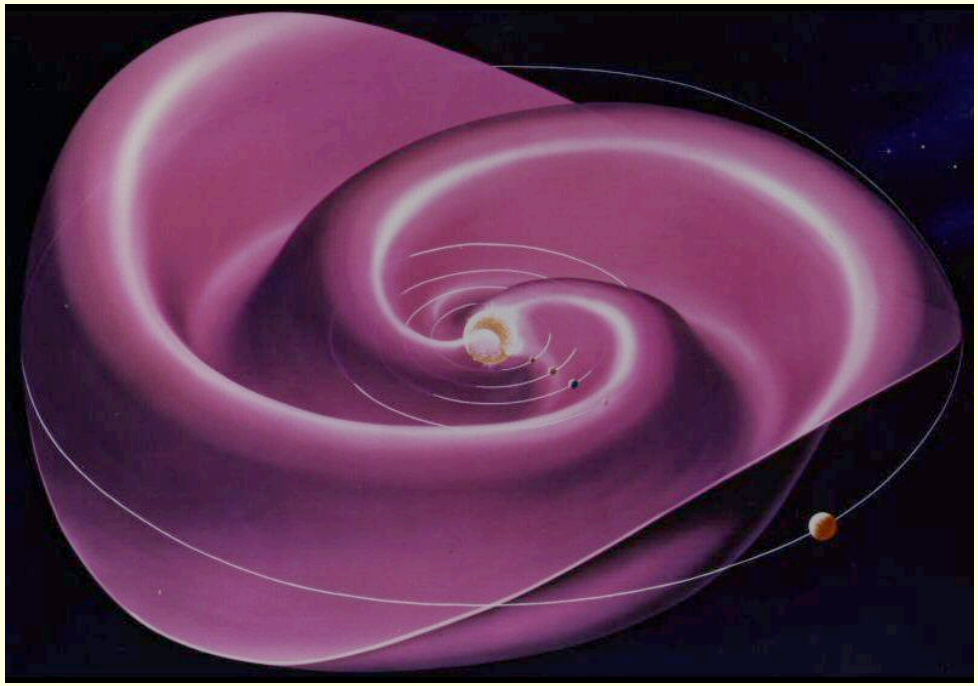
Parker Spiral



- The solar wind flows radially outward at ~ 400 km/s
- Solar rotation period at equator ~25 days
- Results in Parker Spiral
- Left is view looking down on ecliptic
- Magnetic field ~ 45 degrees to Earth-Sun line at 1AU

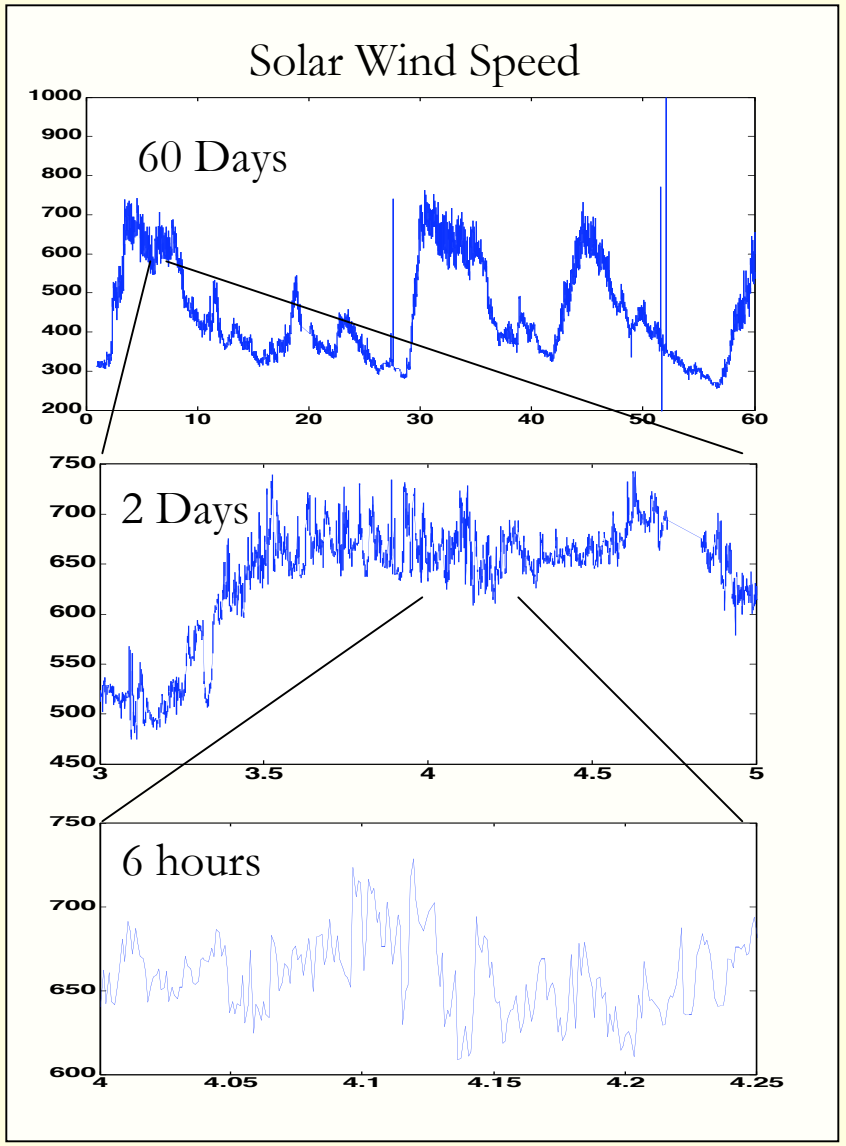
Parker Spiral

- Right: Current sheet shown in purple
- Current sheet separates regions of different magnetic polarity
- Magnetic axis ≠ rotation axis - this creates 'ballerina skirt' effect
- Earth will pass through different regions of magnetic polarity, crossing the current sheet in between



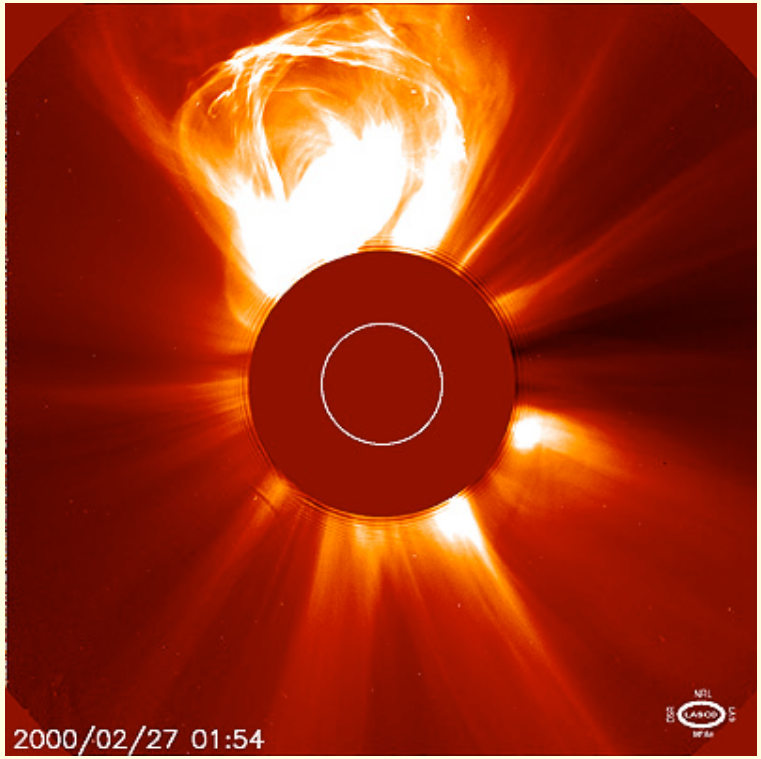
More Things About the Solar Wind

- Previous picture was the general, large scale picture
- On smaller spatial and time scales magnetic field and flow is turbulent
  - Non deterministic flow
  - Fluctuations at range of scale sizes
  - Small scale fluctuations in magnetic field in all directions (this is how we get local southward magnetic field in the solar wind at the Earth for reconnection with the magnetosphere)
  - ΔBz/Bz is largest of components
- Super Sonic and Super Alfvenic (Alfven speed is the speed of a wave propagation along magnetic field line)
- Plasma is collisionless
- Composition
  - Mostly protons and electrons
  - 5% helium ions
  - Small fractions is made up of highly stripped oxygen and other heavy elements



CME and Transients

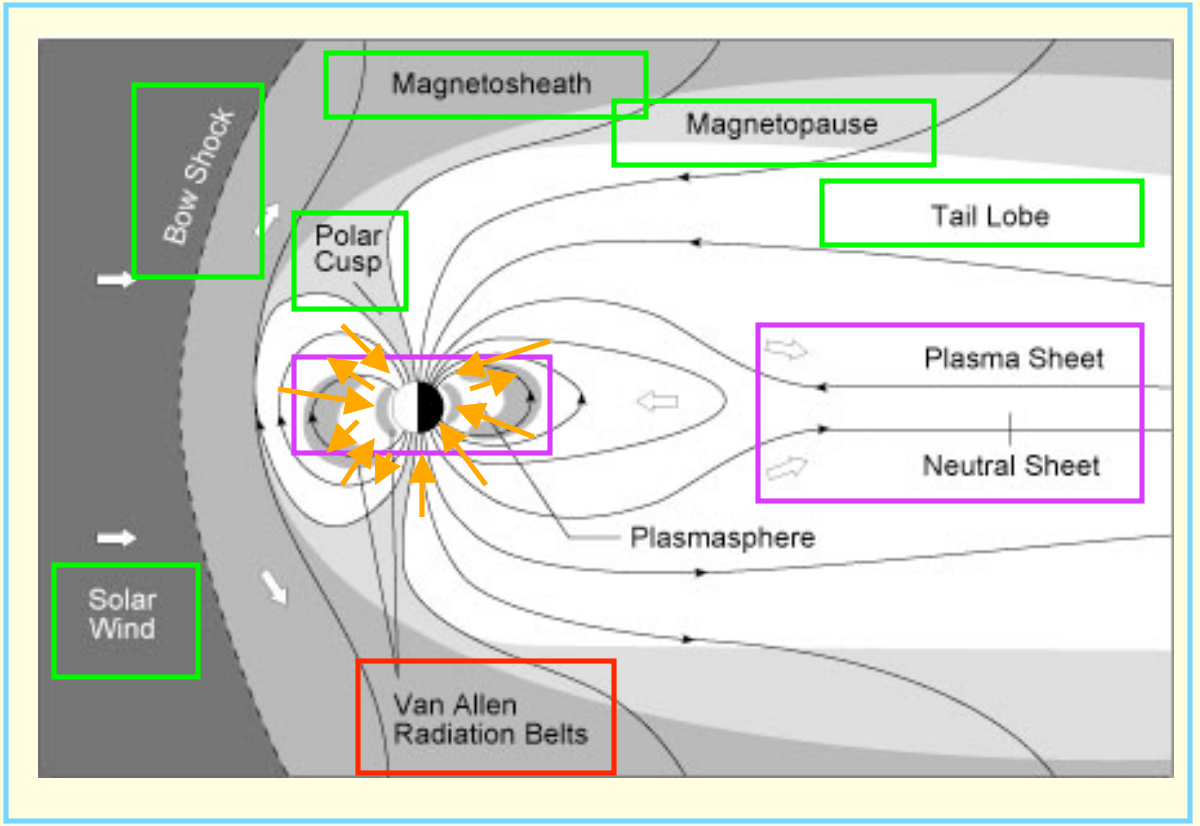
- Coronal Mass Ejections (CMEs)
  - Large eruptions of coronal plasma from the Sun
  - Eruption occurs over several hours
  - Magnetic field is often complex (this is important for interactions with Earth's magnetosphere)
  - Shock front travels ahead of CME (also important for interactions with Earth's magnetosphere)
- The rate of CMEs varies with the sunspot cycle:
  - Solar minimum ~1/week
  - Solar maximum ~ 2-3 /day
- Other Transients:
  - Solar flares-magnetic reconnection events; large energy release (Bursts of x-rays, gamma rays and energetic particles)
  - Solar prominences – Can erupt, resulting in a CME, sometime they remain quiescent



Soho

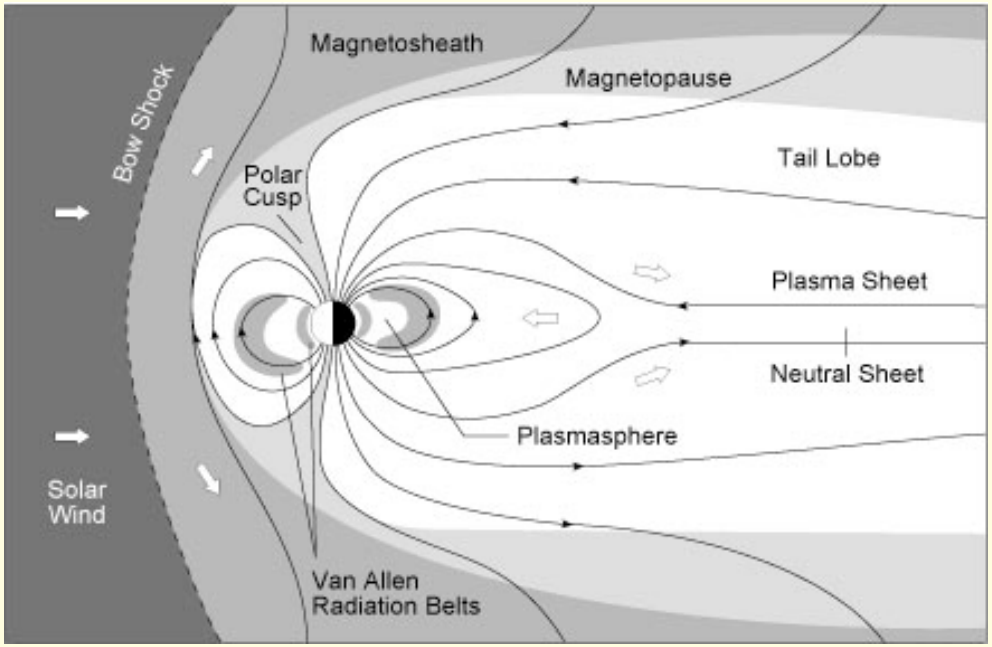
Overview of Topics

- This talk
- Plasma sheet and ring current
- Radiation belt
- MI coupling
- Modeling



Earth's Magnetosphere

- Earth's magnetic field is obstacle in the Solar wind flow
- Solar wind flows past Earth and is deflected around Earth's magnetic field creating the Magnetosphere
    - Solar wind is composed of plasma – charged particles
    - Charged particles don't like to cross magnetic field lines - Lorentz Force
- Near the Earth the magnetic field is roughly a dipole
- Farther out, the solar wind compresses Earth's dipole on the dayside, and stretches it on the nightside



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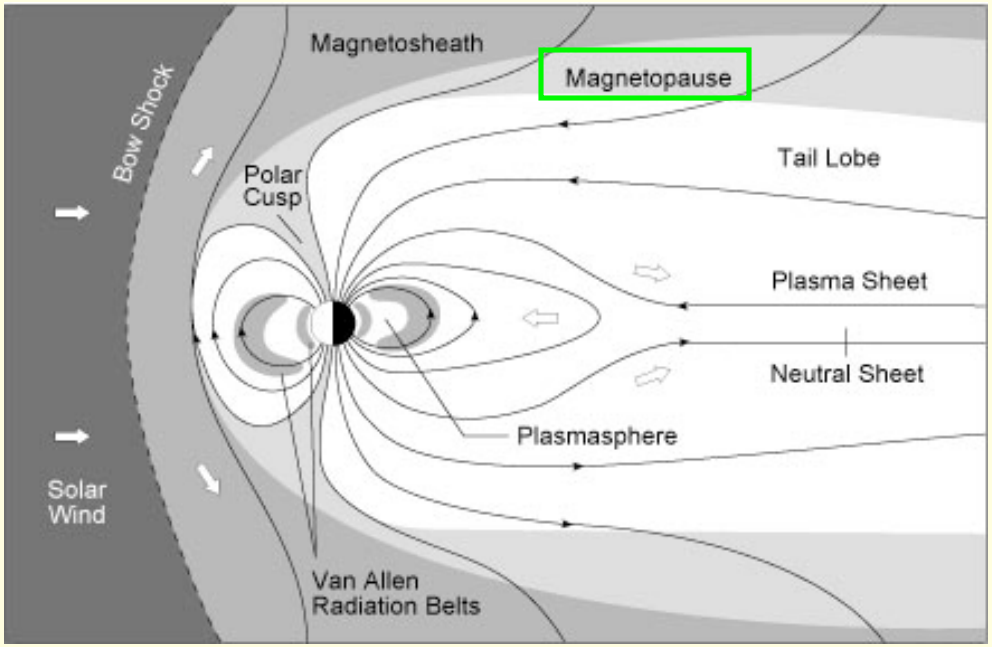
Earth's Magnetopause

- Magnetopause is the boundary that separates the solar wind plasma from the Earth's magnetic field and plasma
- It is the location of pressure balance between the incoming solar wind dynamic pressure and the magnetic pressure in the magnetosphere:
  - $\rho v^2 = B^2/2\mu_o$
- If the solar wind dynamic pressure increases, the magnetosphere is compressed and the magnetic field magnitude in the magnetosphere increases and vice versa
- Magnetopause is ~ 10-12 R_E (Earth Radii) upstream on dayside from Earth



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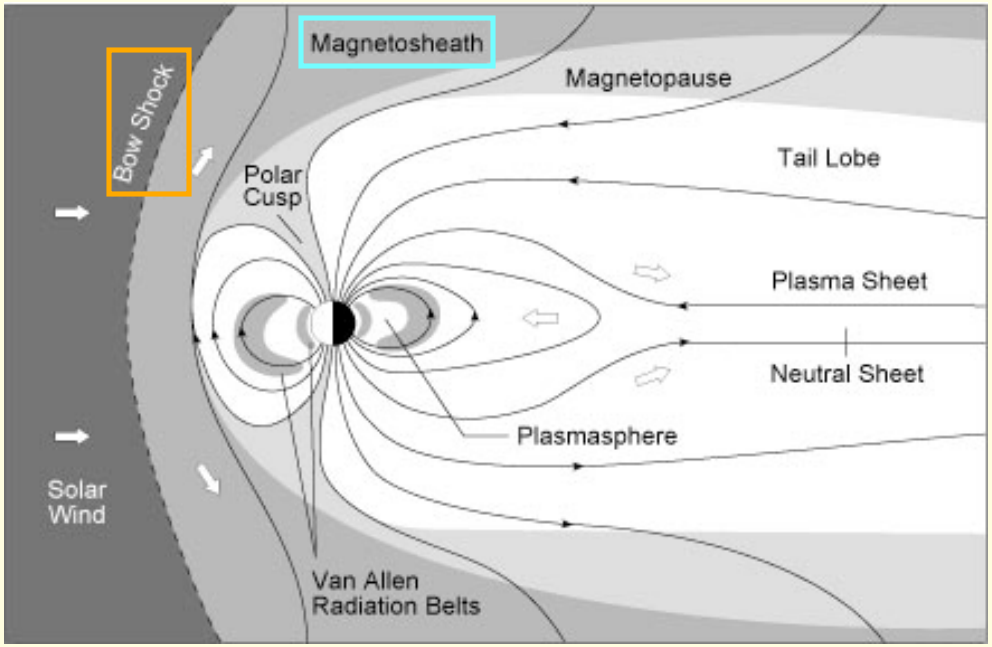
Bow Shock and Magnetosheath

- The solar wind is supersonic - Bow Shock forms upstream of the magnetopause
- Bow Shock ~ 15-20 R_E upstream of Earth
- Bow Shock slows supersonic SW; downstream of Bow Shock the SW is subsonic
- Shock converts flow energy to thermal energy
- Magnetosheath is region between Bow Shock and magnetopause
- Flow in magnetosheath is around the magnetosphere



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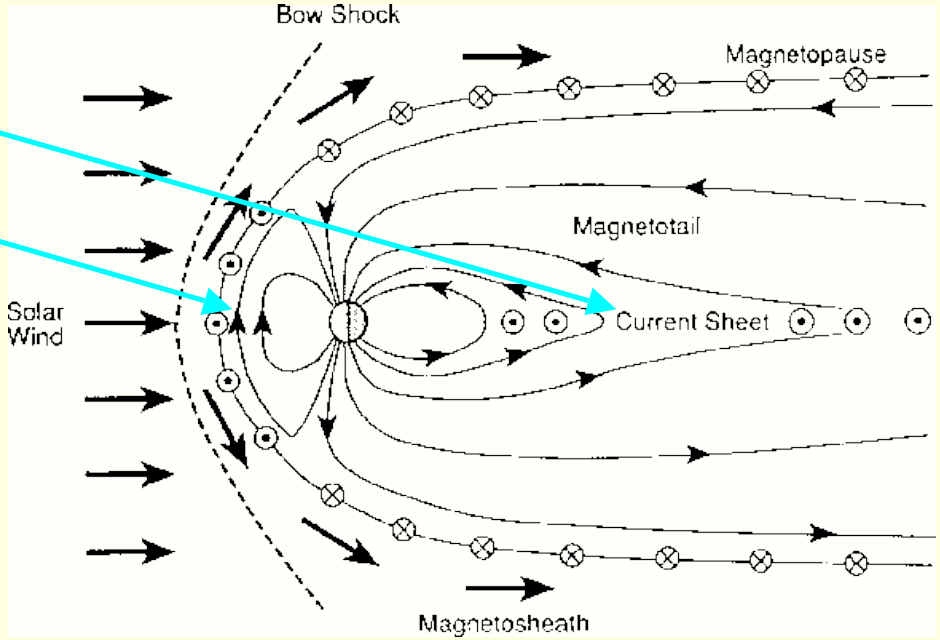
More on the Magnetosphere

- Magnetic field is dipolar in inner magnetosphere
- Outer magnetosphere - dayside magnetic field is compressed and nightside is stretched relative to dipole
  - Current at Magnetopause and cross-tail current (causes ΔB)
- Dayside currents close on tail magnetopause
- In magnetotail there is a plasma sheet, and a current sheet contained within the plasma sheet
- Those currents (cross-tail currents) also close through tail magnetopause
- Plasma sheet is hot plasma and dense
  - n ~ .1-1 cm^{-3}
  - Te ~ 1 kev



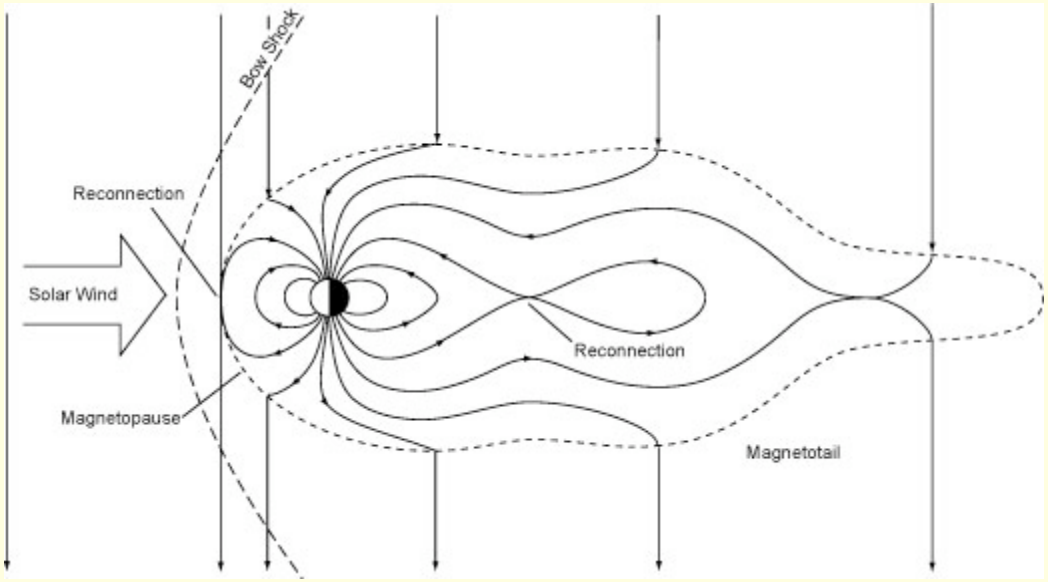
http://www.physics.usyd.edu.au/~cairns/teaching/lecture14/img33.gif

- Cusp
  - Region where magnetopause extends deep into the magnetosphere due to dipole magnetic field topology
  - Magnetosheath plasma has the most direct access to the magnetosphere in this region
- Tail lobes
  - Large magnetic field and low density

Closed Vs Open Magnetosphere

- Closed:
  - Axford and Hines (1961)
  - Also called 'Viscous interaction model'
  - Magnetic field lines of Terrestrial origin are entirely separated from those of the IMF
  - Diffusion of particles across magnetopause
  - Momentum transfer across magnetopause induce a potential drop across magnetosphere and includes convection
  - Considered an applicable description during periods of extended northward IMF and low geomagnetic activity
- Open:
  - Dungey (1961)
  - Magnetic field lines in the polar cap are open and connect with the IMF in the solar wind
  - The reconnection happens where magnetic field lines are oppositely aligned
  - The auroral oval separates regions of open and closed magnetic field lines

Magnetospheric Convection



http://geomag.usgs.gov/images/magnetosphere_simple.jpg

- Dayside reconnection of IMF with magnetospheric magnetic field
- Solar wind flow drags these field lines over the polar cap and down stream to the magnetotail
- Reconnection happens in the tail
- Stretched tail magnetic geometry exerts magnetic tension force – flow is sunward returning flux to the dayside magnetosphere

- Electric field in magnetohydrodynamics (MHD): E = -V x B
  - Solar wind, E = solar wind flow speed x solar wind magnetic field
    - E field maps along the magnetic field lines that have reconnected with Earth's magnetic field lines: result is E field across magnetotail
  - Plasma flow: V= ExB
    - In magnetotail dawn- to-dusk magnetospheric electric field in the tail causes plasma flow towards sun