The Magnetosphere and Its Problems

Joe Borovsky
Space Science Institute

1. Overview of the Earth's magnetosphere

  How it is driven

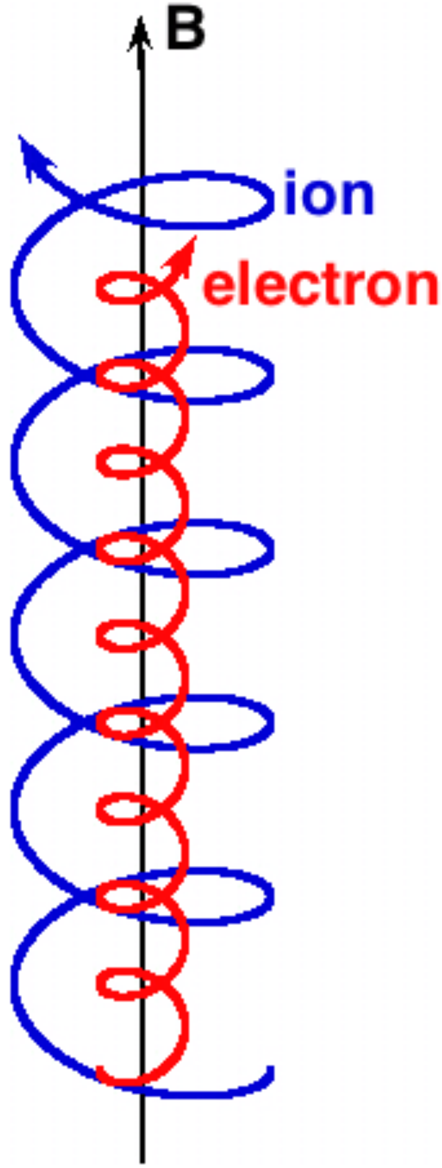
  Geography of its plasmas

2. How the magnetospheric system is measured

3. Outstanding scientific problems

4. The aspects that are "space weather"

Magnetic Field and Charged Particles



A "plasma" is a gas made up of positive and negative charged particles.

Charged particles move easily along magnetic field lines, but the Lorentz $\underline{v}\times\underline{B}$ force prevents them from moving across field lines.

Hence a plasma has difficulty moving across a magnetic field.

A. A plasma can be trapped by a strong magnetic field (radiation belt).

B. A plasma can carry magnetic field lines with it as it flows (solar wind).

Typical Solar-Wind Properties at Earth

(properties vary from day to day)

96% H^+, 4% He^{++}

age = 100 hr

$n = 6\ cm^{-3}$

v = 400 km/s

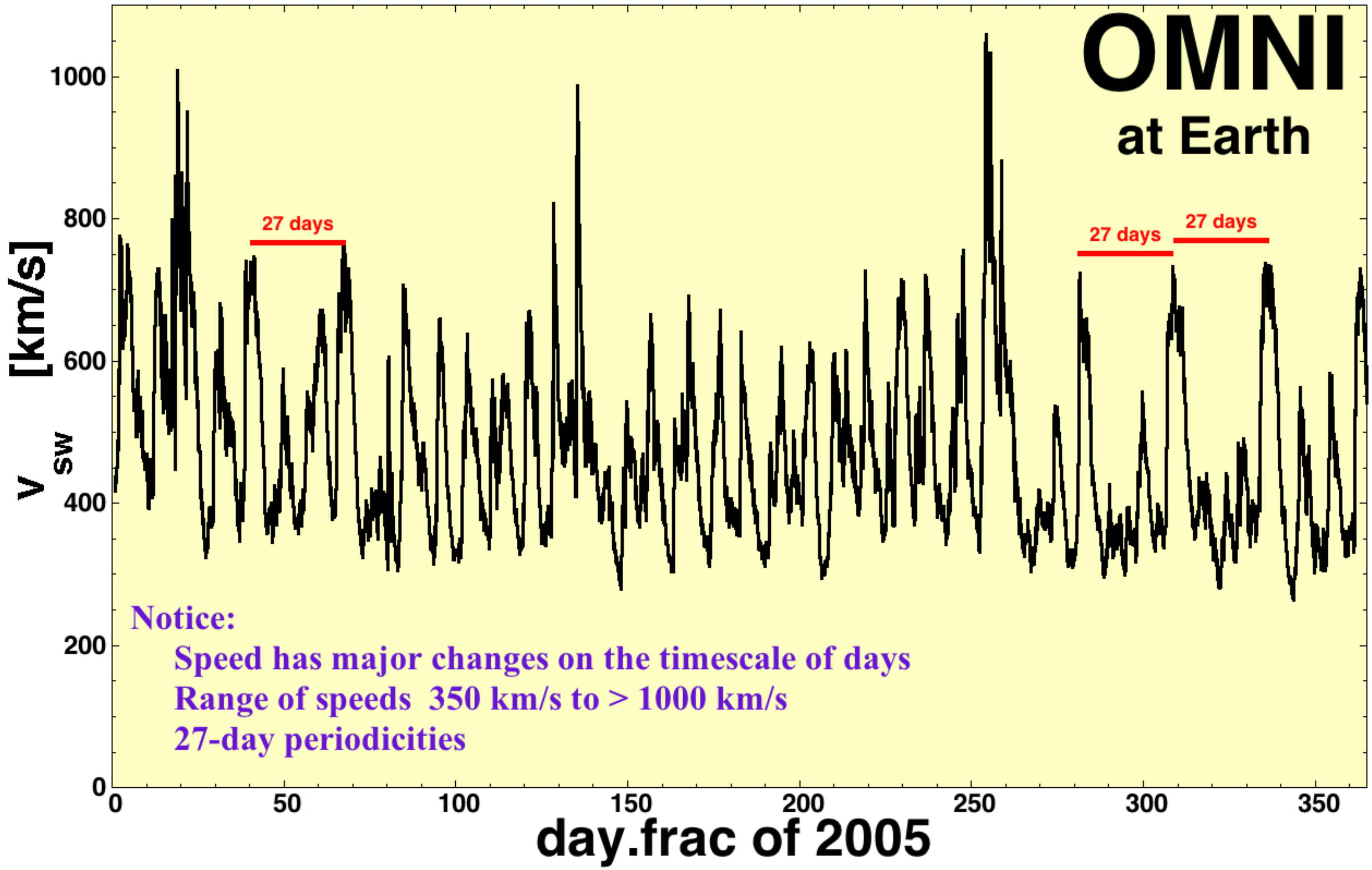
$T_i = 7$ eV

$T_e = 15$ eV

B = 6 nT

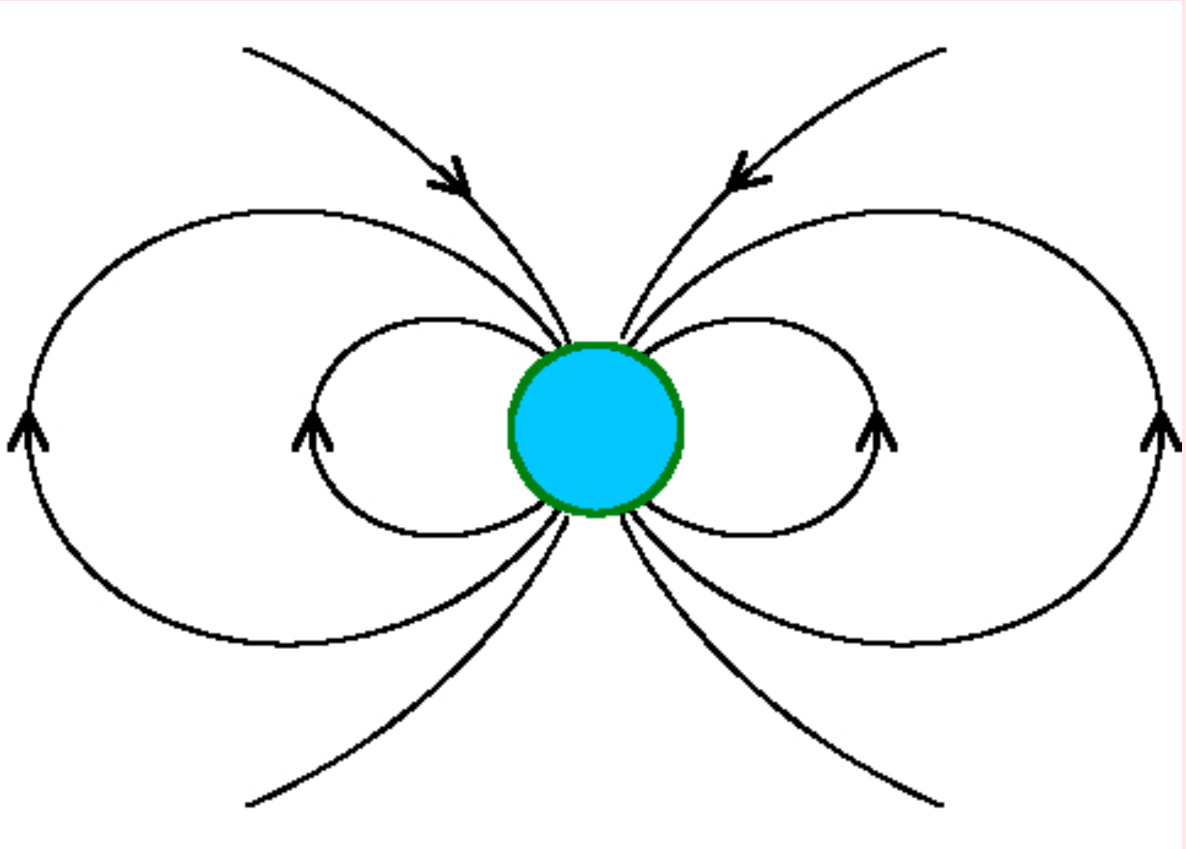
Mach number = 8

The Solar-Wind Speed



Earth's Dipole

The planet Earth has a dipole magnetic field:



Dipole tilt is ~11^o w.r.t. Earth's spin axis.

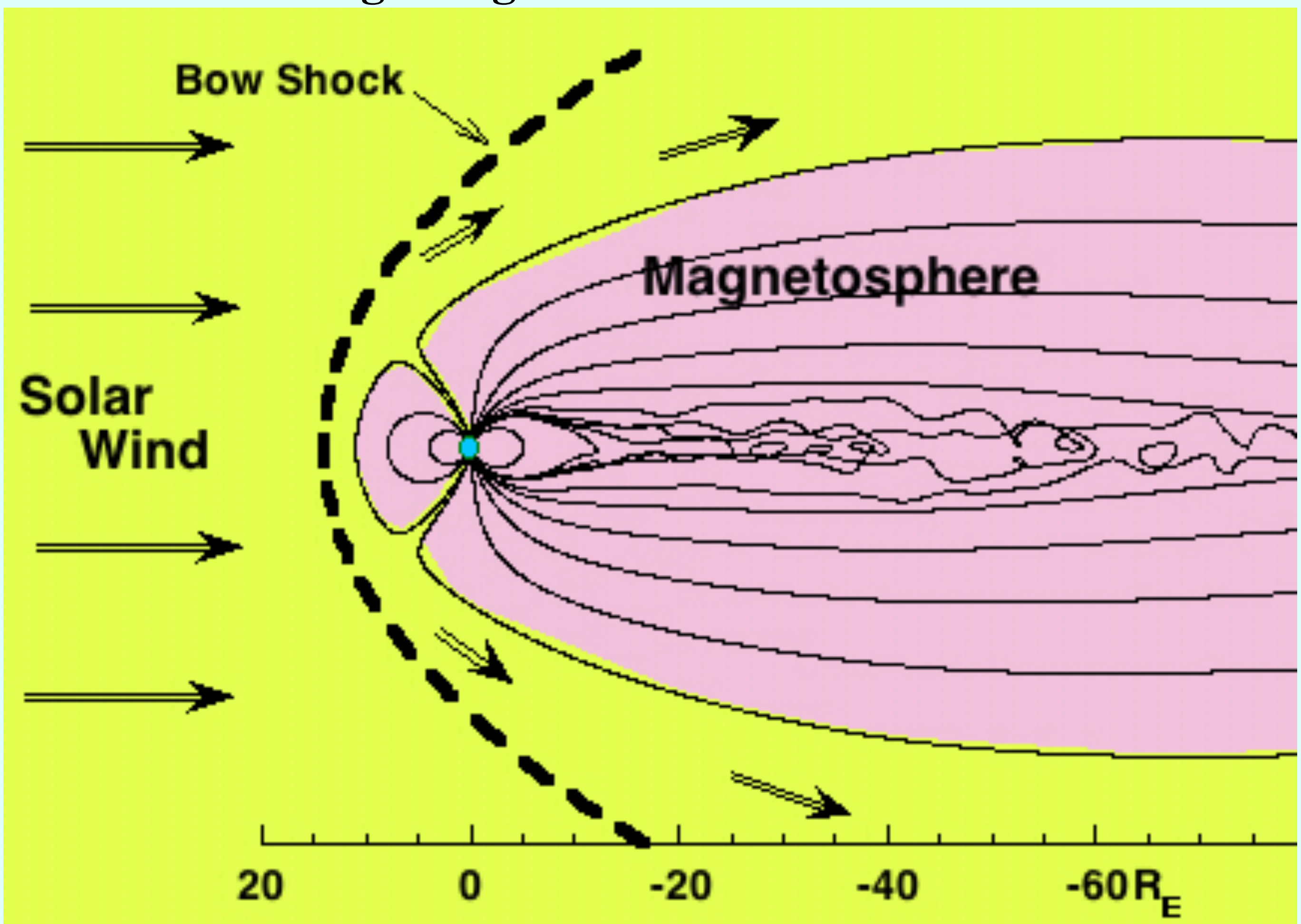
Tilted towards Hudson Bay in the North.

$\mathbf{B \propto r^{-3}}$

The Solar Wind and the Magnetosphere

The solar wind interacts with the outer portions of the Earth's dipole, where the dipole field strength is weak: $B \propto r^{-3}$.

The solar wind compresses the dayside magnetosphere and draws the nightside magnetosphere out into a long "magnetotail".



Magnetic-Field-Line Reconnection

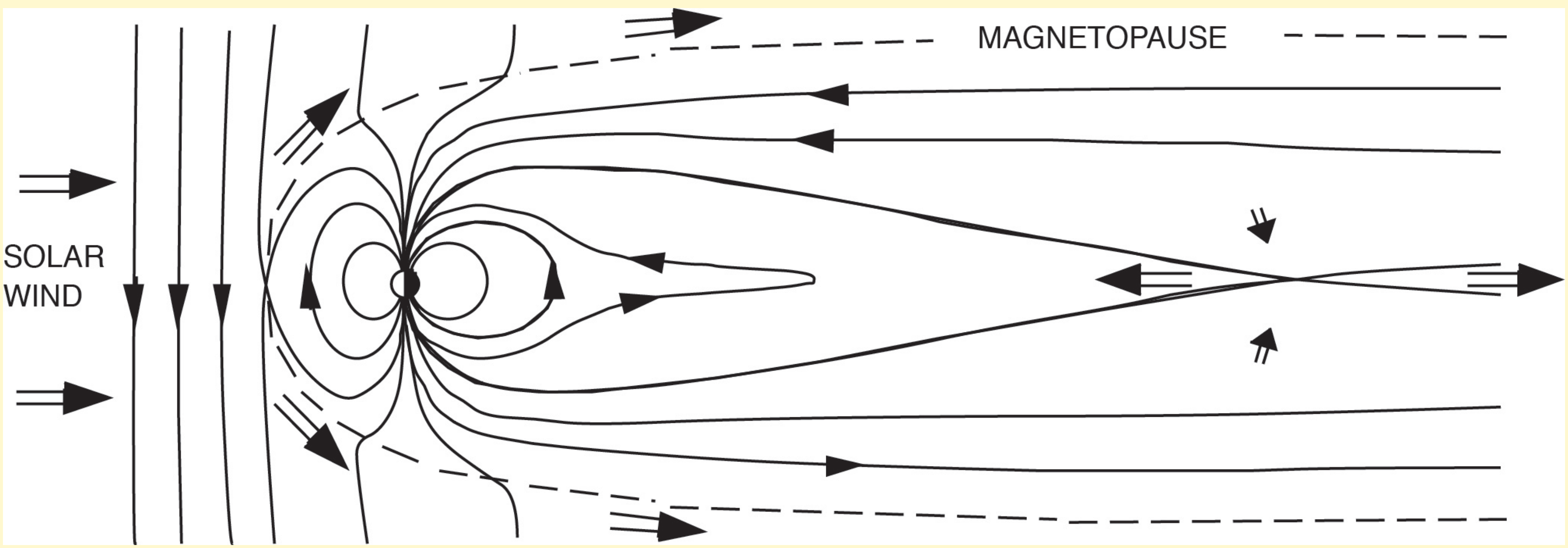
Reconnection is the dominant mechanism by which the solar-wind drives the magnetosphere.

1. Reconnection on the dayside connects the solar wind to the magnetosphere.

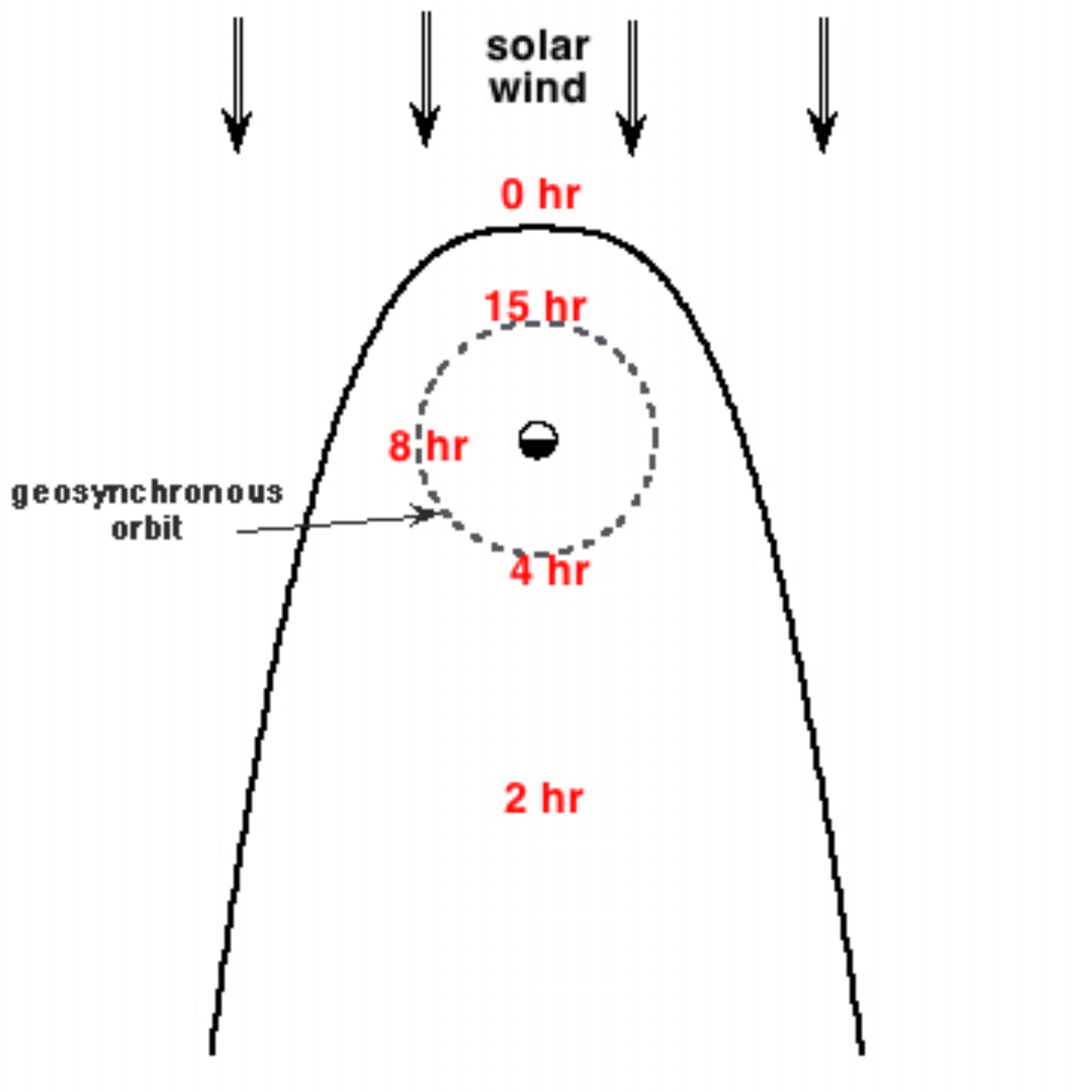
2. The moving solar wind drags magnetic flux into the magnetotail.

3. Reconnection in the tail disconnects the solar wind and allows magnetic flux to convect from the nightside to the dayside.

Reconnection allows plasma to enter and it drives magnetospheric (and ionospheric) convection. Convection energizes the plasmas in the Earth's magnetosphere.



Magnetospheric Circulation Times



Tracking the movement of plasma from the solar wind into and through the magnetosphere.

Magnetospheric Storms and Substorms

The driving of the magnetosphere by the solar wind is not steady.

When the driving is strong, magnetospheric substorms can occur.

- **Sudden Earthward surges in the internal magnetotail convection.**
- **Duration is about an hour.**
- **These occur about 5 times per day on average.**

When driving is very strong, a geomagnetic storm can occur.

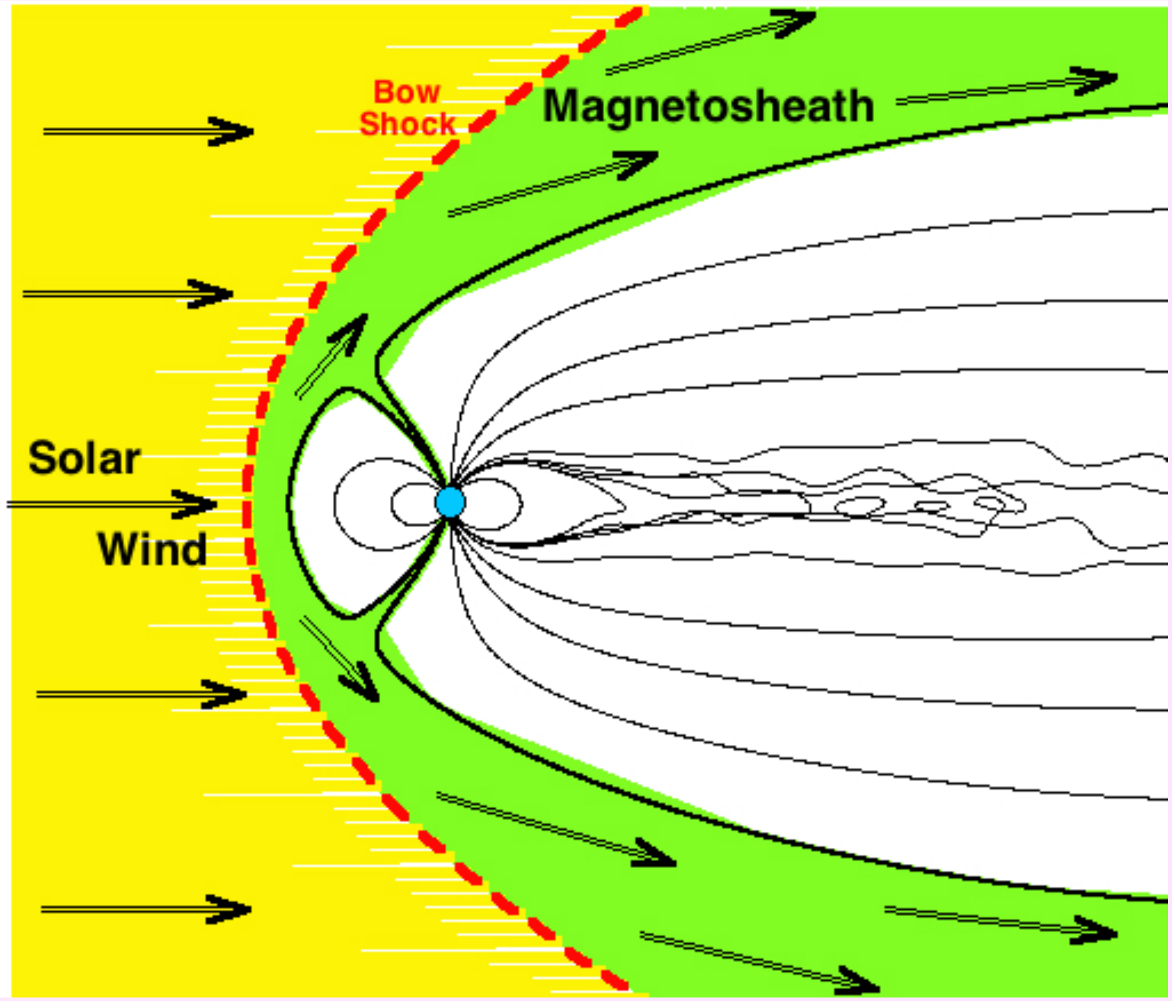
- **Intervals of greatly enhanced global convection.**
- **Duration many hours to several days.**
- **Lead to hazardous space weather.**

The Magnetosheath

number density
$n \sim 4\ n_{sw}$

ion temperature
$k_B T_p \sim 0.5\ m_p\ v_{sw}^2$
~ 1 keV

electron temperature
$T_e \sim T_p/6$



The solar wind contacts the magnetosphere via the magnetosheath!

Two Sources for Magnetospheric Plasma

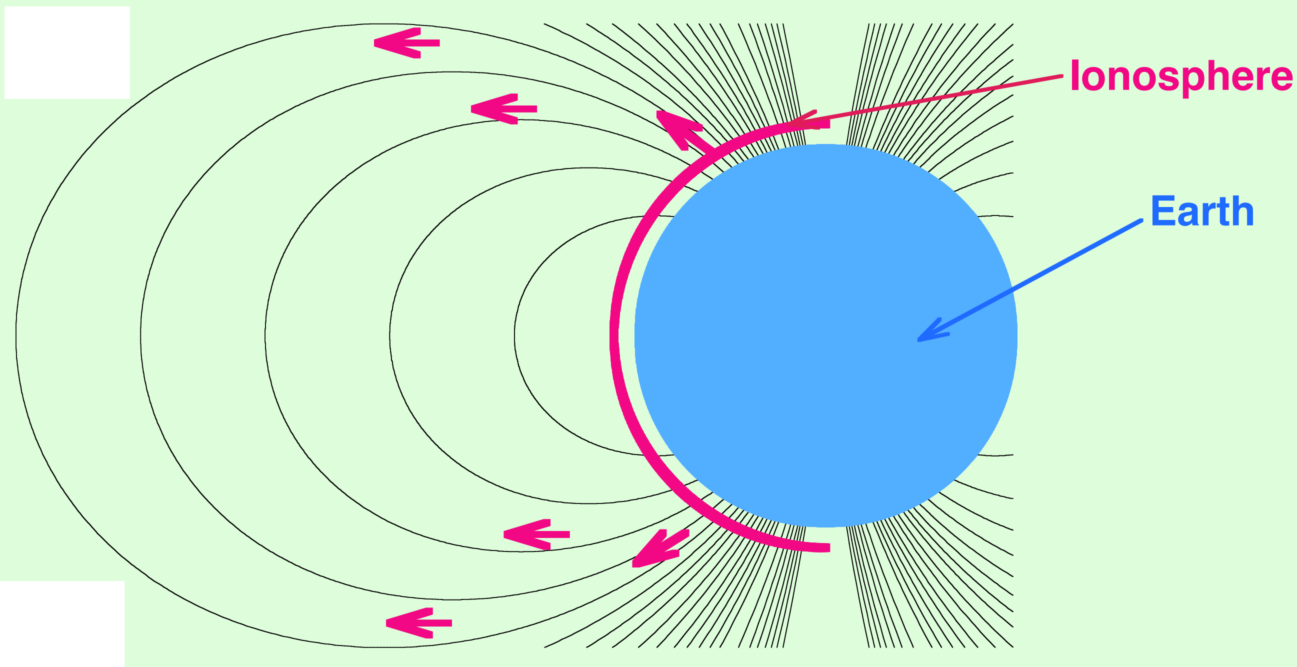
1. The Solar Wind

   H^+, He^{++}

2. The Ionosphere

   H^+, O^+, He^+

The Ionospheric Source of Particles

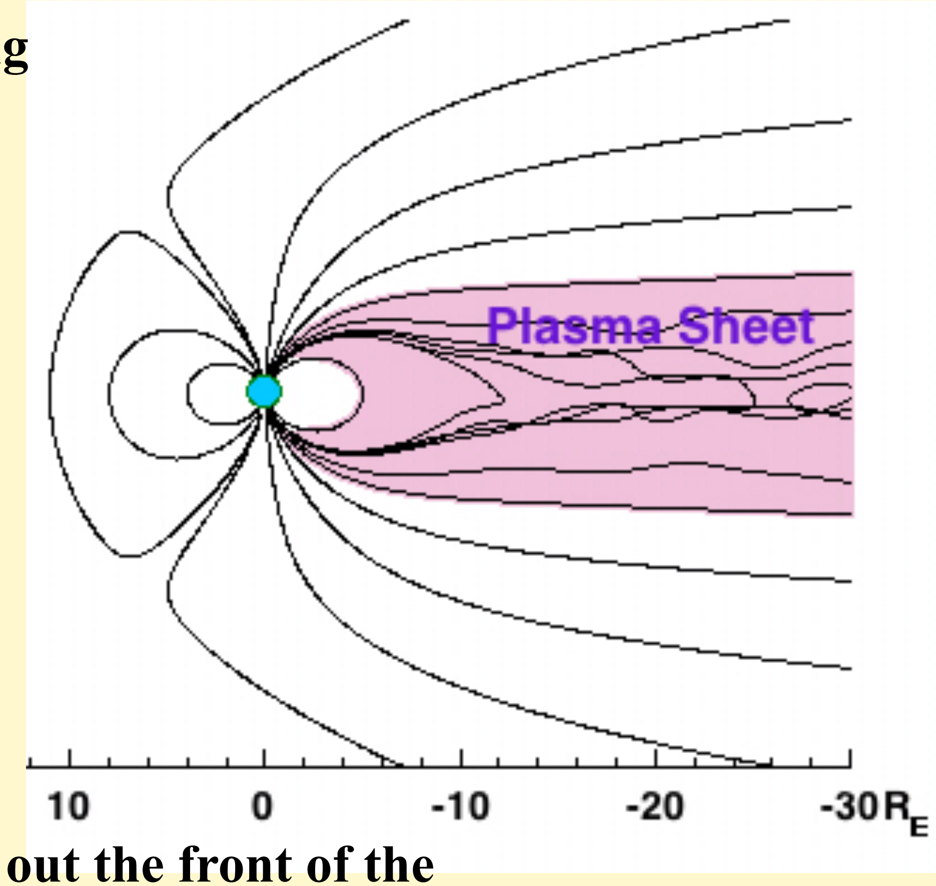


1. UV light from the sun ionizes the upper atmosphere, breaking the molecules into ions and electrons.

2. The very fast electrons are not gravitationally bound, they produce a charge-separation electric field that pulls some of the ions out against gravity.

3. “Plasma waves” can also be important for the uplift of ions.

The Ion and Electron Plasma Sheet



Source: Mostly the solar wind, but during active times the ionosphere contributes.

$n \sim 1\ cm^{-3}$
$T_i \sim$ few keV
$T_e \sim T_i/6$

The ion plasma sheet comes into the dipole deeper than the electron plasma sheet does.

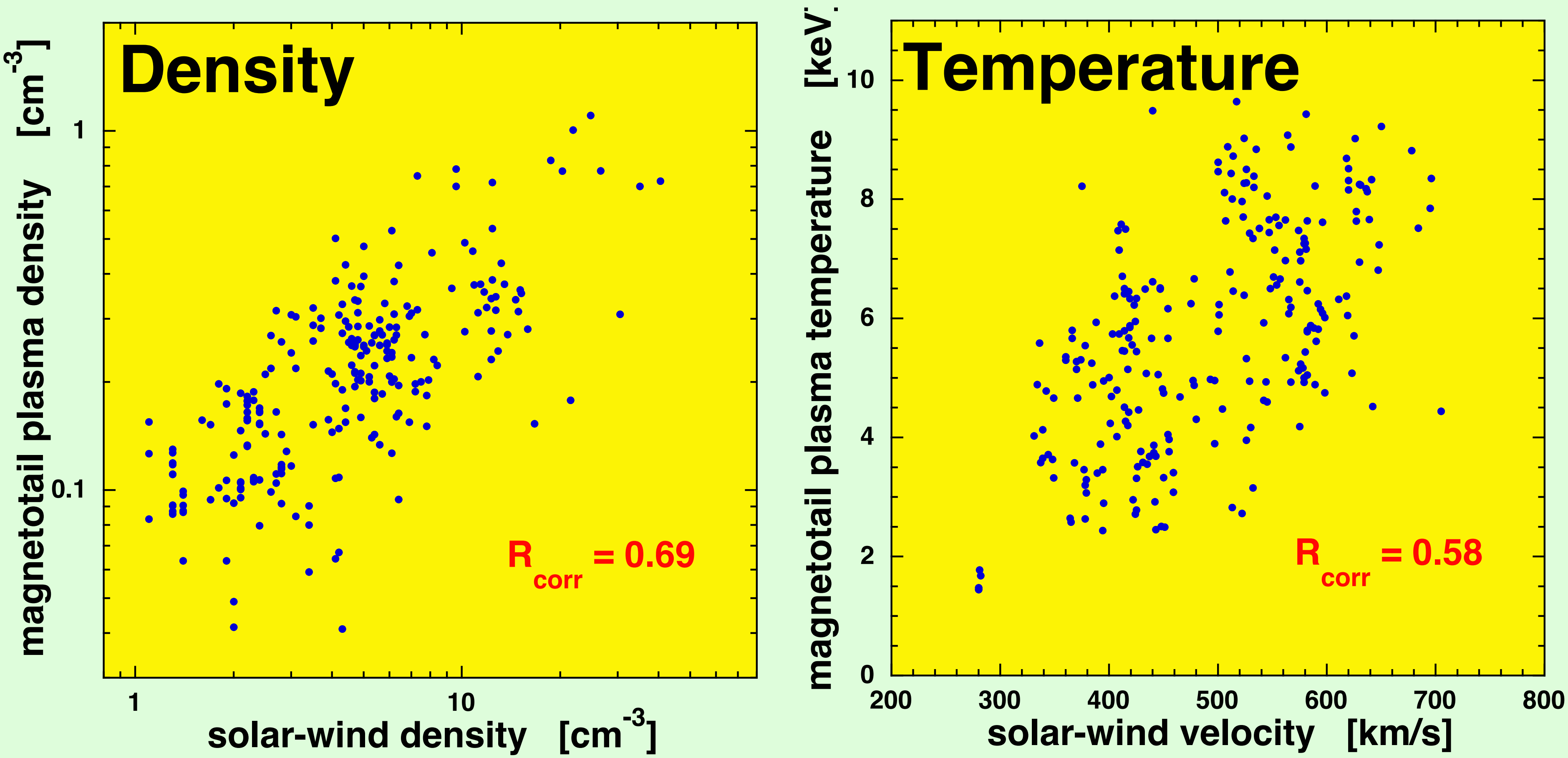
In the dipole, the ion plasma sheet is called the ring current.

The plasma sheet exhausts downtail and out the front of the magnetosphere, and it also precipitates into the atmosphere.

The hot plasma of the plasma sheet produces dangerous levels of spacecraft charging.

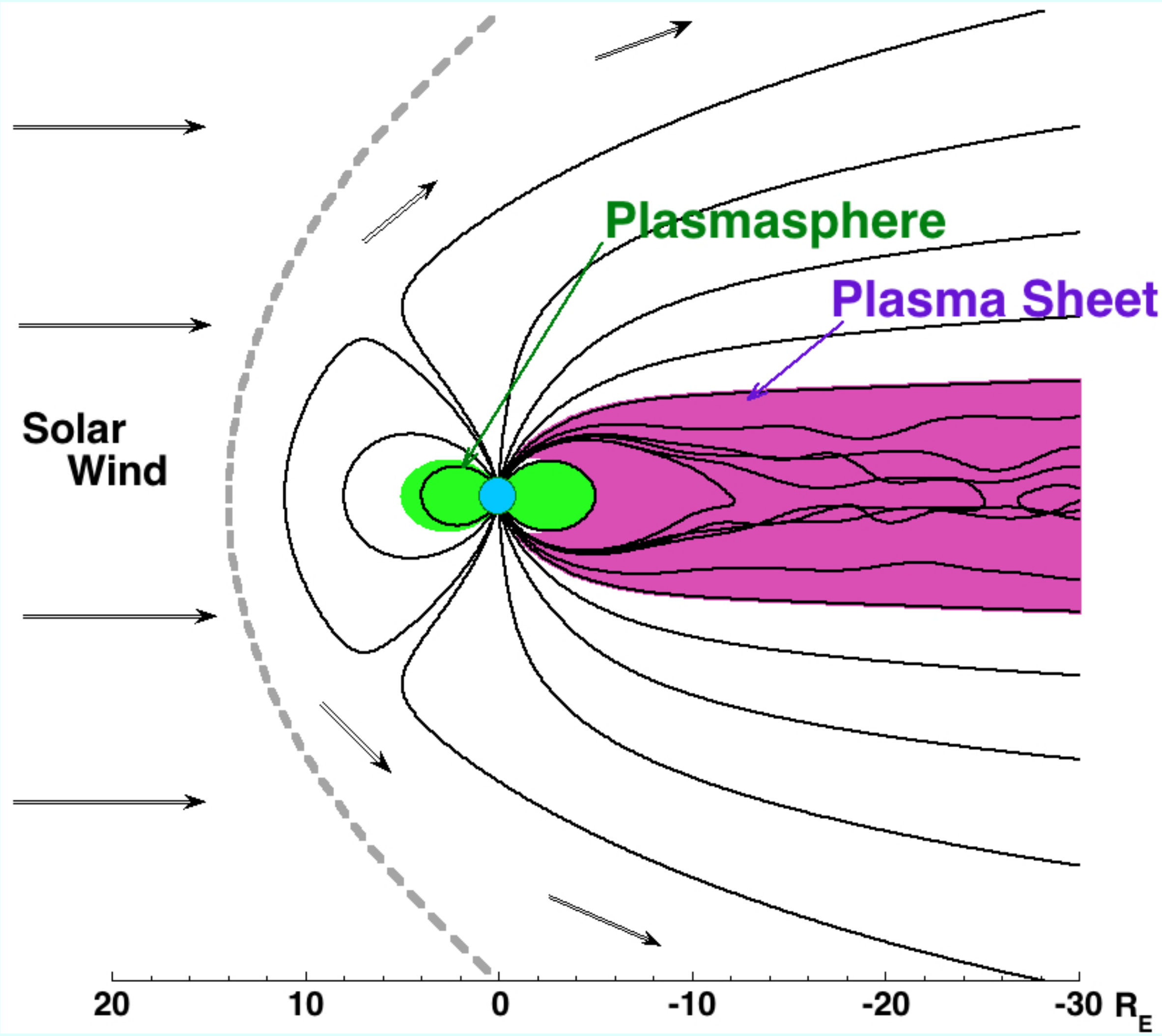
The plasma sheet = the auroral zone.

The Plasma Sheet and the Solar Wind



- The properties of the plasma change as the solar wind changes.
- When the wind speed is high, the magnetotail electrons are hot.

The Plasmasphere



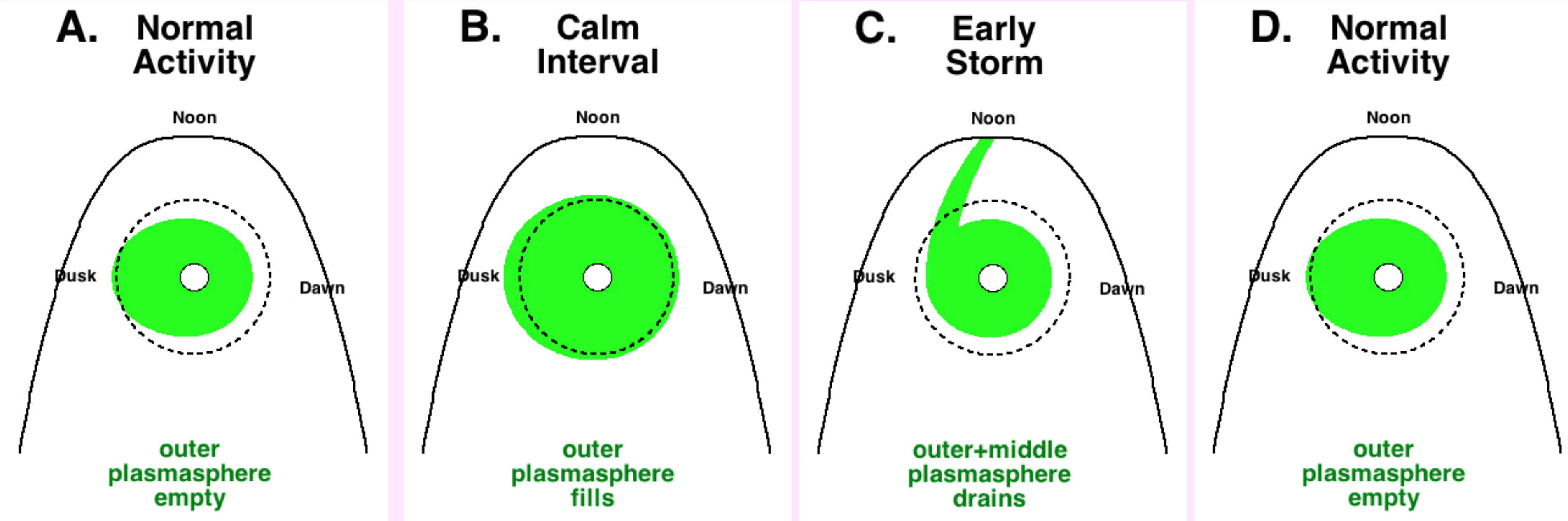
The plasmasphere is a build up of plasma outgassed from the ionosphere.

$n = 50 – 2000\ cm^{-3}$

$T_i = T_e \sim 1$ eV

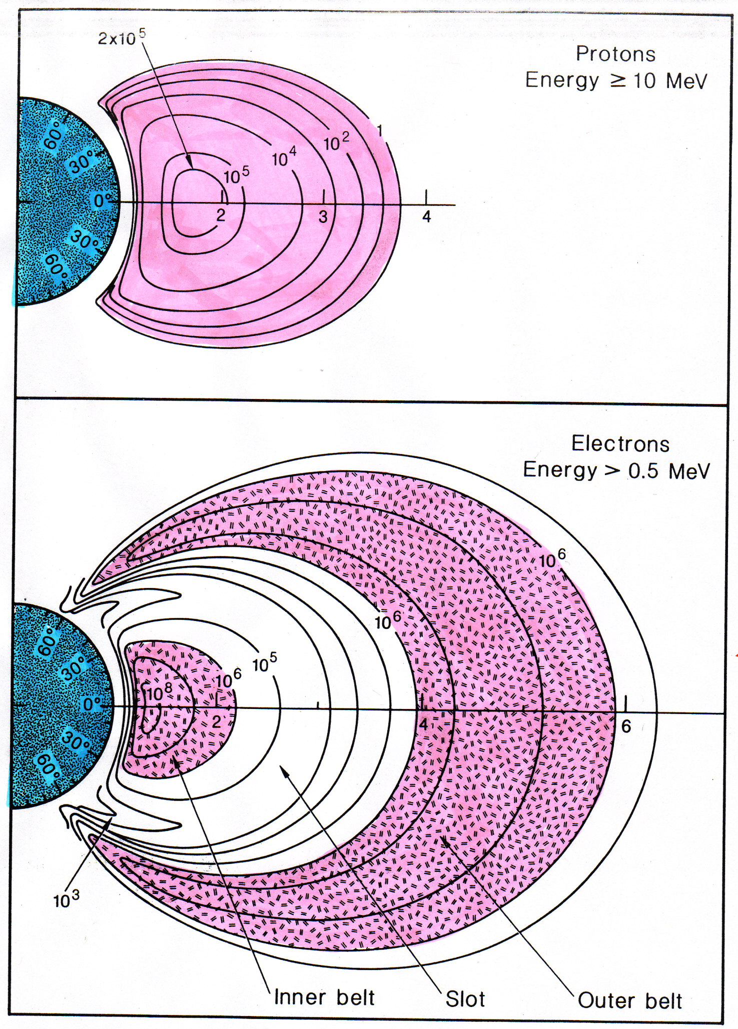
H^+, He^+, O^+

The Plasmapheric Drainage-and-Refilling Cycle



The plasmasphere drains via a sunward-flowing "plume" of plasma.

The Ion and Electron Radiation Belts

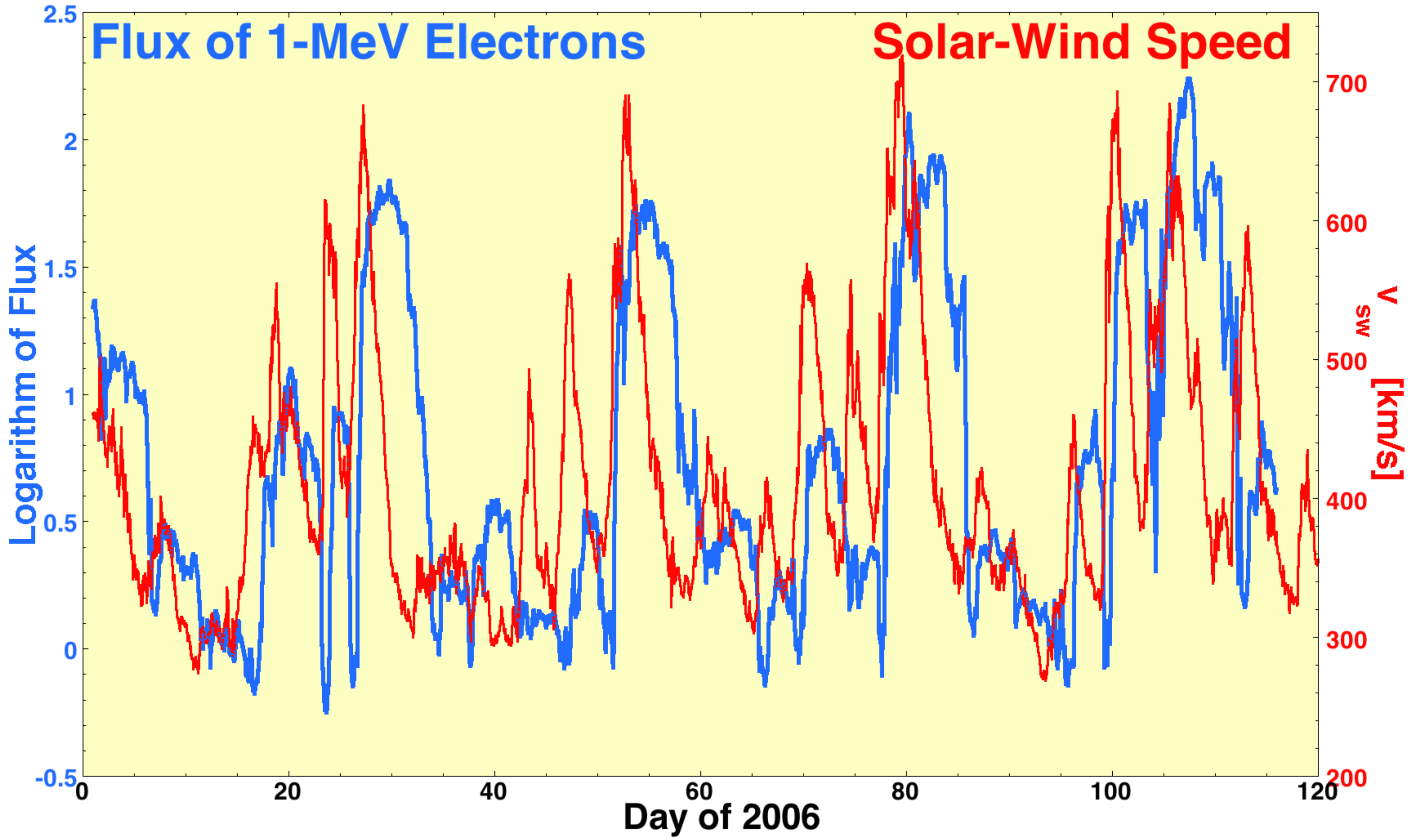


The ion belt and the inner electron belt are relatively stable.

The outer electron belt is very dynamic.

These maps outline regions where the particles can penetrate through 1 mm of aluminum. Top picture is ions, bottom picture is electrons.

The Outer Electron Radiation Belt is Very Dynamic



Note the control by the solar wind!

The Plasmas Are Coupled via Plasma Waves

Plasmasphere

- **Controls where chorus, hiss, and EMIC can exist**
- **Traps hiss**

Electron Plasma Sheet and Substorm-Injected Electrons

- **Drives chorus**
- **Is scattered by chorus**

Ion Plasma Sheet and Substorm-Injected Ions

- **Drives EMIC**
- **Drives ULF**
- **Is scattered by EMIC**

Electron Radiation Belt

- **Is energized by chorus**
- **Is scattered by chorus**
- **Is scattered by EMIC**
- **Is transported by ULF**

audio conversion:
http://www.astrosurf.com/luxorion/audiofiles-geomagnetosphere.htm

Measuring the System 1

The solar wind plasma is measured by instruments on spacecraft upstream of the Earth:

speed
vector flow direction
number density
ionic composition
magnetic-field strength
magnetic-field direction
temperature
fluctuation properties
and more....

OMIN2 data set 1963-present

https://omniweb.gsfc.nasa.gov

Measuring the System 2

Geomagnetic Indices

Ground-based magnetometers measuring various magnetospheric and ionospheric currents

- **AE, AL, AU --- measure strength of auroral activity**
- **Kp --- measures strength of magnetospheric convection**
- **Dst --- measures plasma pressure in the dipolar magnetosphere**

OMIN2 data set 1963-present

https://omniweb.gsfc.nasa.gov

Measuring the System 3

Other Available Measurements:

ULF Wave Activity

Pi-2 Wave Power

Polar-Cap Size

Amount of Magnetotail Stretching

Hot Plasma Properties (density, temperature, pressure)

Radiation-Belt Properties (fluxes, density, temperature)

Substorm occurrence rate

Substorm-Injected Electron Properties (fluxes)

Hemispheric Particle-Precipitation Power

Outstanding Problems/Questions

1. Can we get a fuller understanding of solar-wind/magnetosphere coupling?
2. How does plasma enter into the magnetosphere?
3. What are the pathways of plasma transport into the magnetotail?
4. How does polar-cap potential saturation work?
5. What is the energy-conversion process that drives auroral arcs?
6. What is the distribution of mass density in the magnetosphere?
7. Can we parameterize ionospheric outflows: when, where, at what rate?
8. How does the fine-scale structure of currents affect ionospheric Joule heating?
9. What is the role of turbulence in the magnetotail?
10. What controls the electron-radiation-belt seed population?
11. What is the cause of the 3-hr periodicity of substorm recurrence?
12. Can we predict the occurrence of substorms?
13. Can we calculate the evolution of the electron radiation belt?
14. How well do we understand extreme events?

Some Aspects of Space Weather

Solar Flare X-rays

Radio communication disruption

Solar Energetic-Particle Events

Radiation damage to spacecraft and radiation dose for airliners

Intensification of the Outer Electron Radiation Belt

Radiation damage and spacecraft electronic upsets

Extra-Hot Plasma-Sheet Electrons

Spacecraft surface charging and spacecraft electronic upsets

Geomagnetically-Induced-Currents

Sudden changes in auroral currents induce voltages in high-latitude electrical power grids

Issues:

1. **Predict solar activity**
2. **Evolution of plasma structures from the Sun to the Earth**
3. **Production and transport of energetic particles**
4. **Reaction of the Earth to solar-wind structures**

My Research

Data analysis of solar-wind structure

Solar-wind driving of Earth: First-principles-physics point of view

Solar-wind driving of Earth: Statistical data analysis

Creation of new Earth indices

Use of CCA as a “systems-science” tool.

Canonical Correlation Analysis (CCA)

CCA looks at correlation patterns between two sets of variables.

CCA creates a set of new solar-wind variables S_1, S_2, S_3, ... that are each linear combinations of the original solar-wind variables and CCA creates a set of new Earth variables E_1, E_2, E_3, ... that are each linear combinations of the original Earth variables.

S_1 is the "driver function" for E_1.

S_2 is the "driver function" for E_2. Etc.

S_k and E_k are correlated with each other.

S_k has zero correlation with all other S_i and E_i unless i=k.

E_k has zero correlation with all other S_i and E_i unless i=k.

CCA can find new modes of reaction of the Earth to the solar wind and identify what in the solar wind drives those modes.

Systems-Science Workshop

Sometime in the Summer of 2018 a workshop "Exploring Systems-Science Techniques for the Magnetosphere" will be held in Los Alamos, USA.

If you are interested, contact Joe Borovsky, Enrico Camporale, Jeff Thayer, Juan Valdivia, or Simon Wing.