Geoeffectiveness of Solar Wind Transients

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Normal Stresses

- **Shape of magnetosphere**
- **Size of magnetosphere**
- **Pressure distribution on magnetopause**

Role of the Bow Shock

Tangential Stresses

- **Viscous stress**
- **Reconnection**
  - **Dungey model**
  - **Poynting flux versus mechanical energy flux**
  - **Importance of the plasma mass density**
  - **Interplanetary electric field**
  - **Angular dependence**
  - **Beta dependence**

Real World Reconnection

- **Where does it occur?**
- **Frequency response of the magnetosphere**
- **Saturation of the auroral and polar regions**
- **Substorms at Earth and Jupiter**
- **Northward IMF triggering of substorms**
- **Summary and Conclusions**

Confinement of a Planetary Magnetic Field by a Flowing Magnetized Plasma

Momentum conservation in a stream tube

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

Consider ratio of first two terms

$$\rho u^2/nkT = u^2/(kT/m_i) = \gamma\mu^2/c_s^2 = \gamma M_s^2$$

Consider ratio of first and third terms

$$\rho u^2/(B^2/2\mu_o) = 0.5\, u^2/(B^2/\mu_o\rho) = 0.5 M_A^2$$

Consider ratio of second and third terms

$$m_i kT/(B^2/2\mu_o) = \beta = (M_A^2/M_S^2)/2\gamma$$

In the solar wind the sonic and Alfven Mach numbers are large and the pressure is dominated by the dynamic pressure.

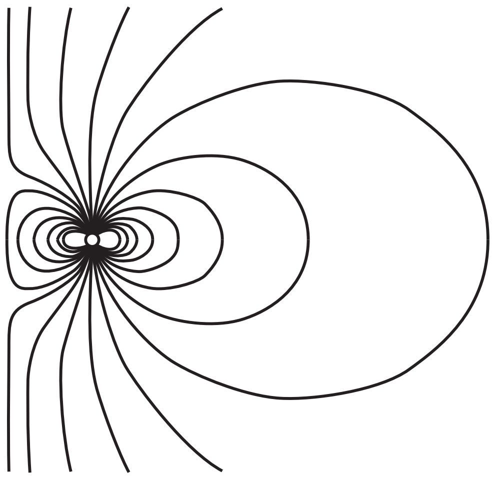
At the magnetopause the dynamic pressure is zero and the static pressure dominates.

The pressure is slightly diminished from the solar wind value because S increases by about 10%.

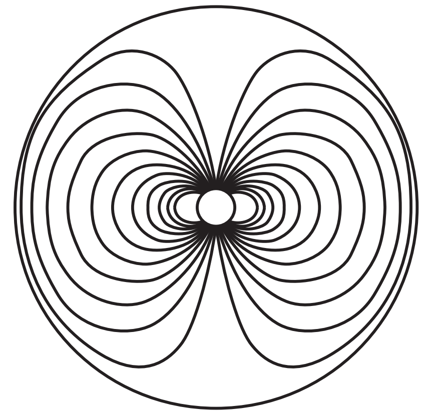
Inside the magnetosphere the pressure is dominated by the magnetic pressure. The strength of this field is (aB_o/L_{mp}^3) where a is a shape dependent parameter. Balancing the magnetic pressure against the solar wind dynamic pressure we obtain

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

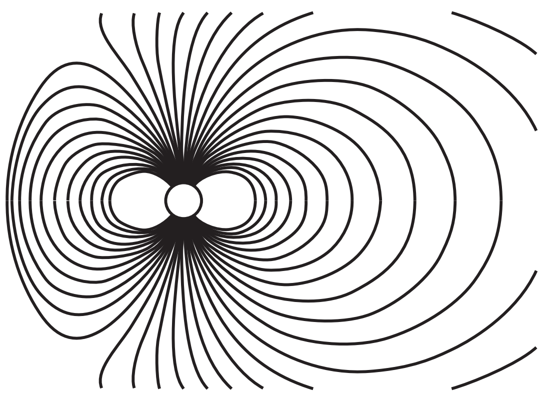
with n_{sw} being the number of proton masses per cm^3 and u_{sw} being the solar wind speed in km/s.



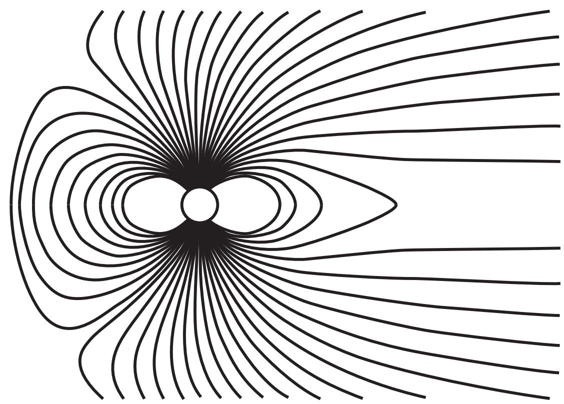
Planar Magnetopause



Spherical Magnetopause

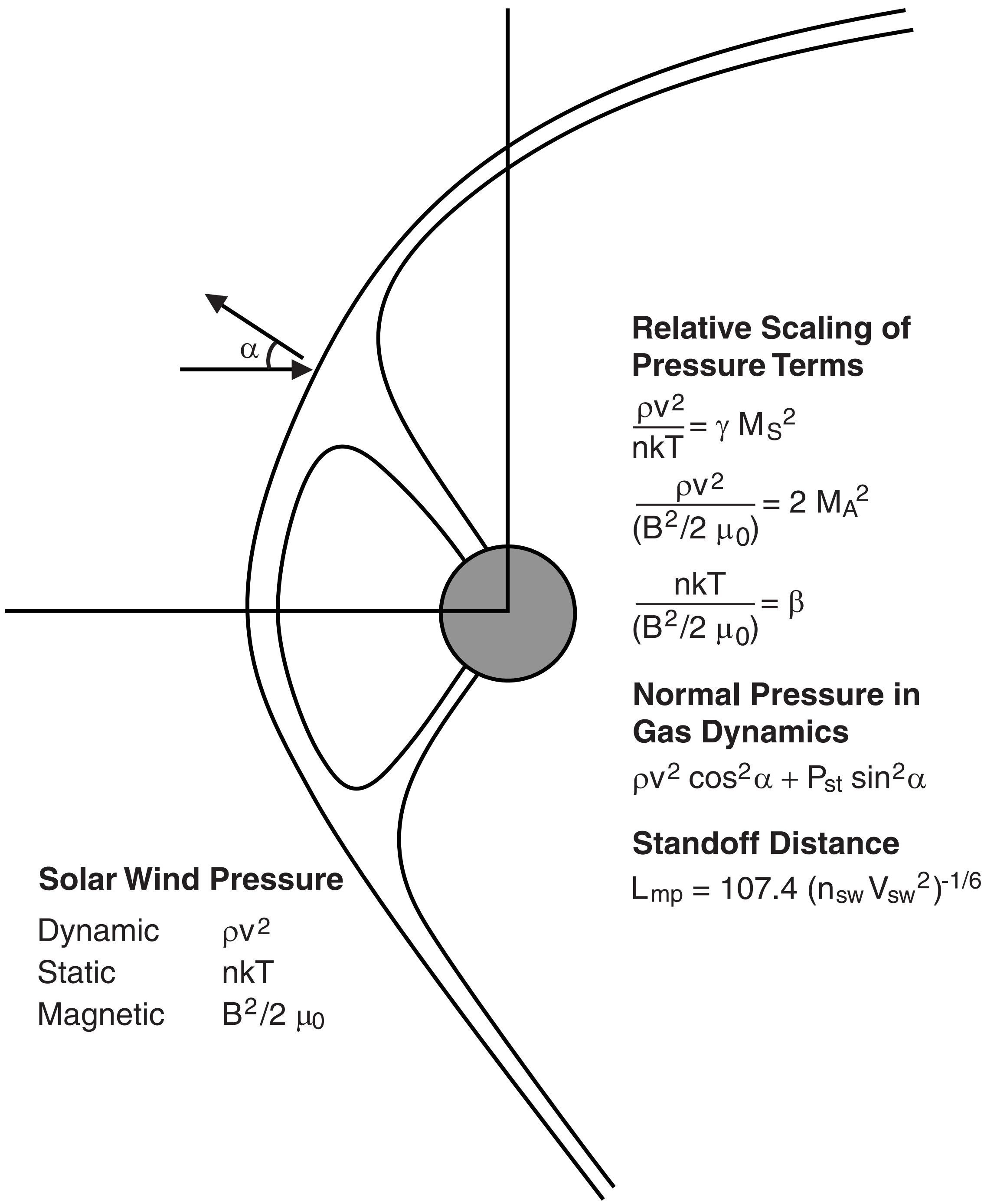


Elliptical Magnetopause



Empirical Magnetosphere

Shape determines magnetic field enhancement at subsolar point
Planar magnetopause -- double dipole field strength
Spherical magnetopause -- triple
Elliptical magnetopause (T89a) -- 2.4
Empirical magnetopause (T89b) -- 2.4



Pressure applied by the solar wind to the magnetopause varies with the angle of the normal to the solar wind flow

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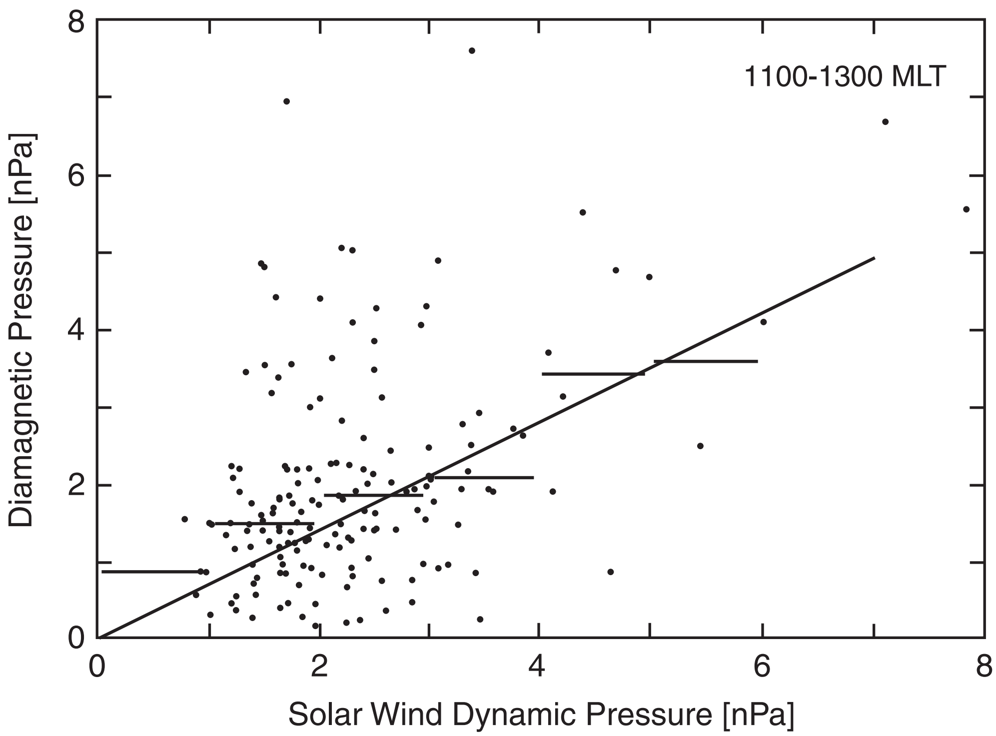
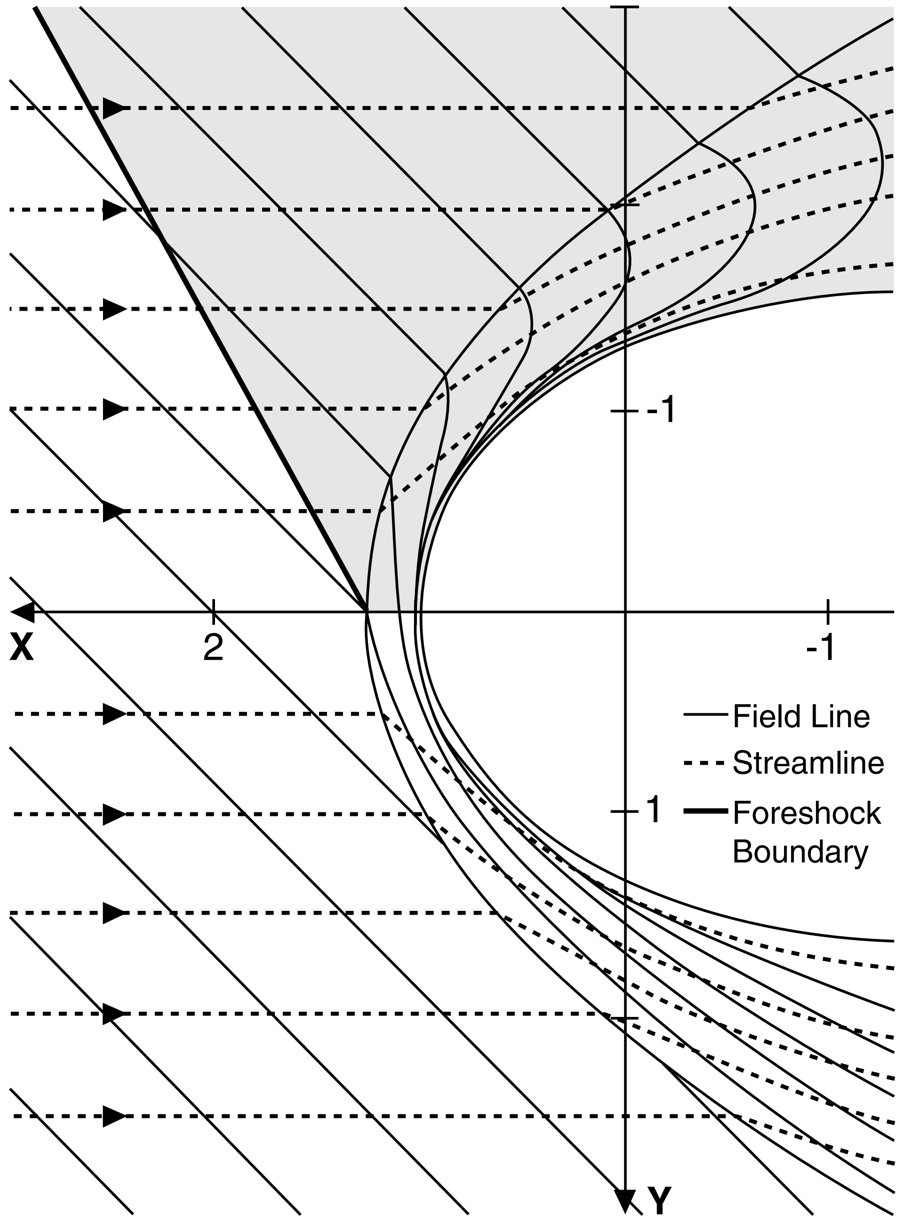
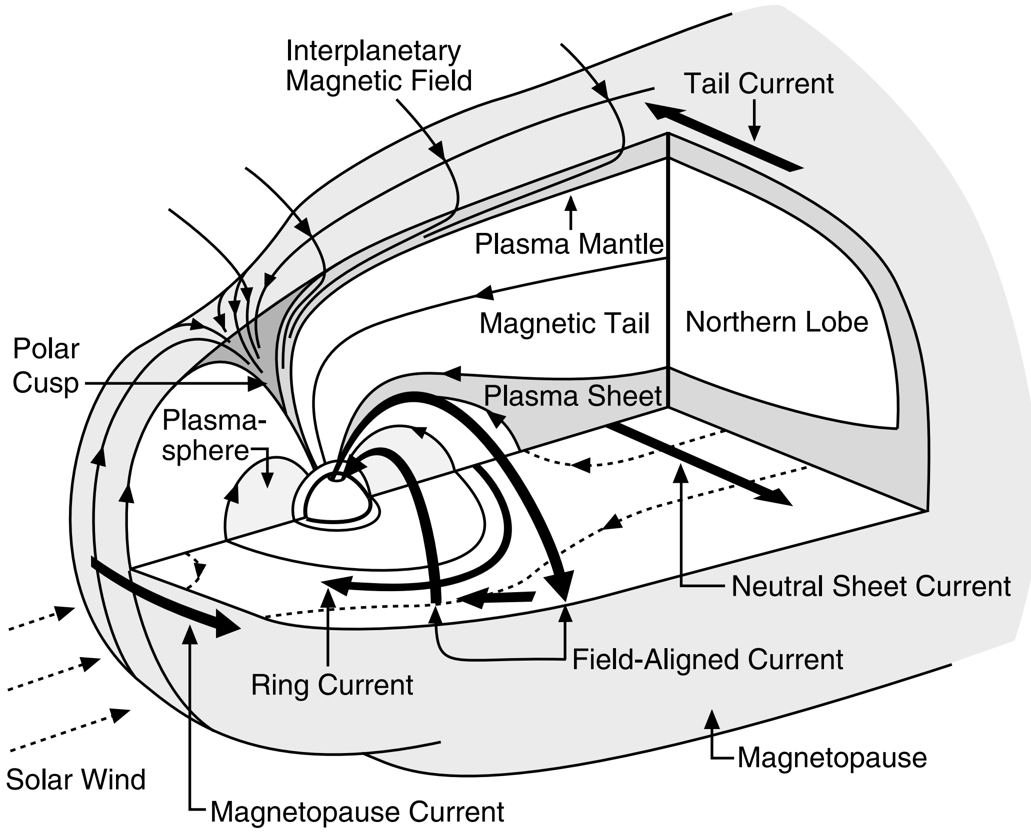


The pressure of the plasma inside the cusp is directly proportional to the dynamic pressure of the solar wind flow. The straight line is the expected pressure given the orientation of the surface of the cusp to the solar wind flow.



The gas dynamic convected field model carries magnetic field lines as if they were threads in the fluid. The shaded foreshock is where ions reflected from the shock move upstream.



This cutaway model of the magnetosphere illustrates the flows and current systems in the magnetosphere. The field aligned currents couple stresses in the outer magnetosphere with those in the ionosphere.

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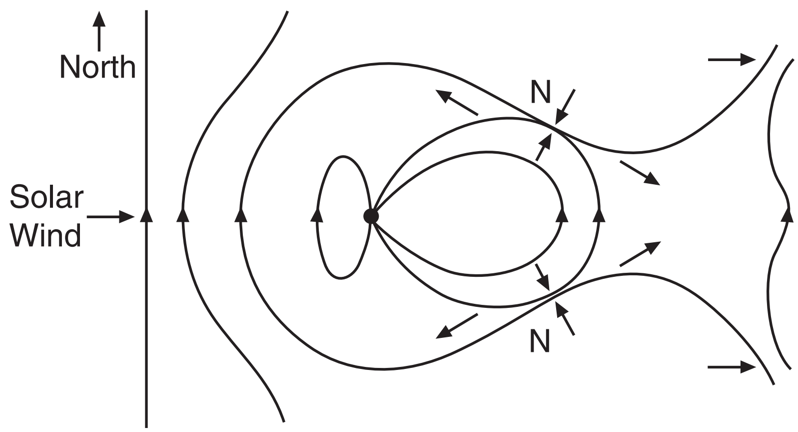
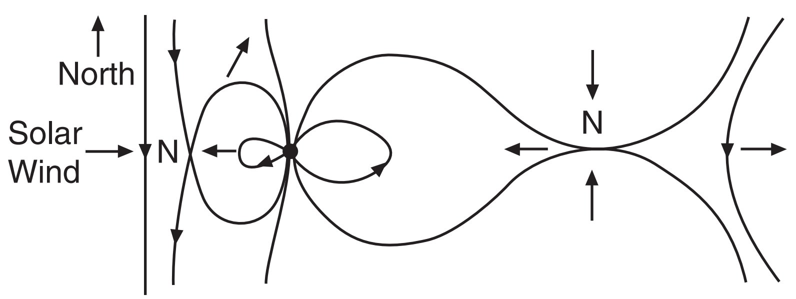
Interplanetary Field Northward

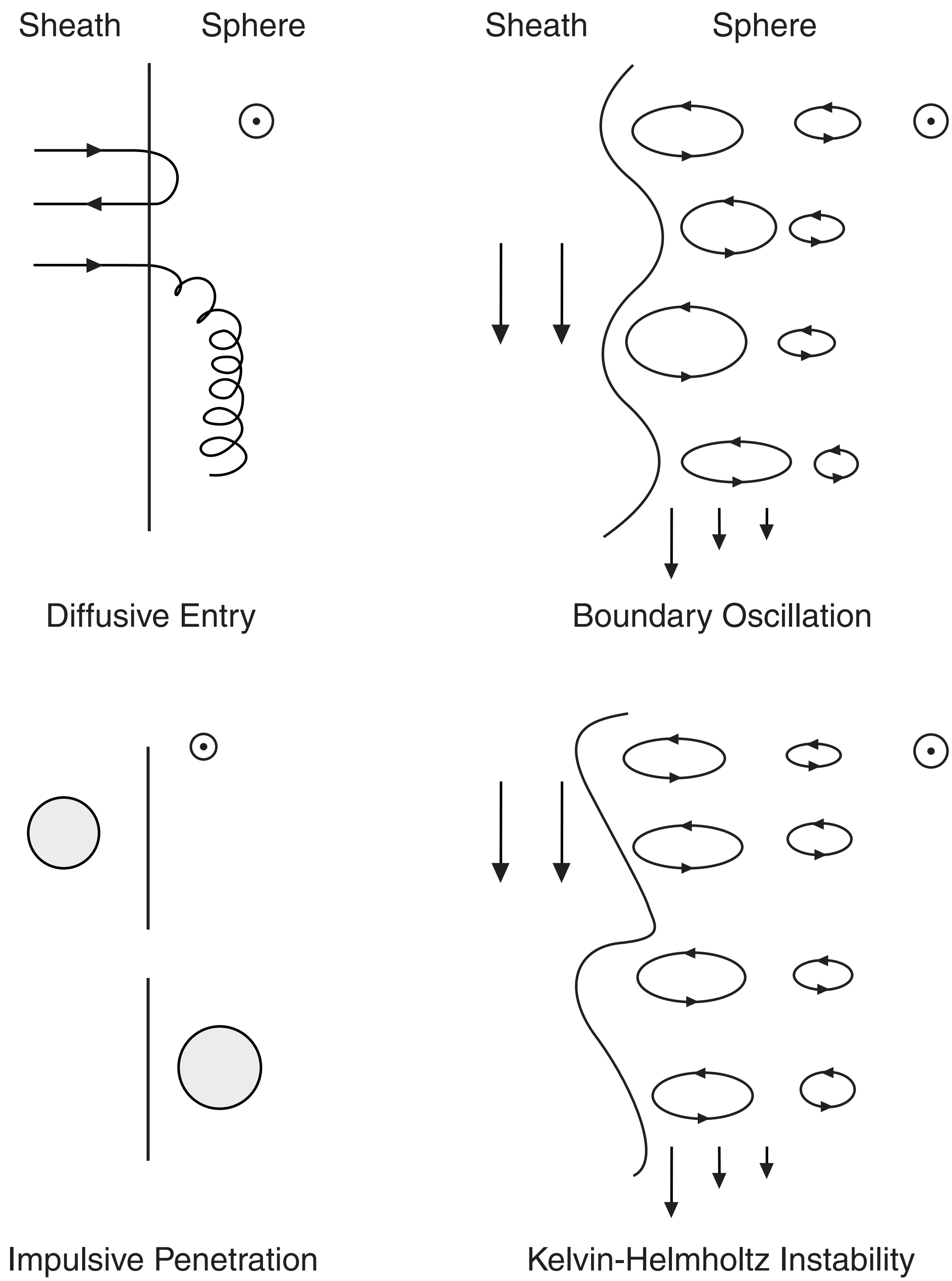


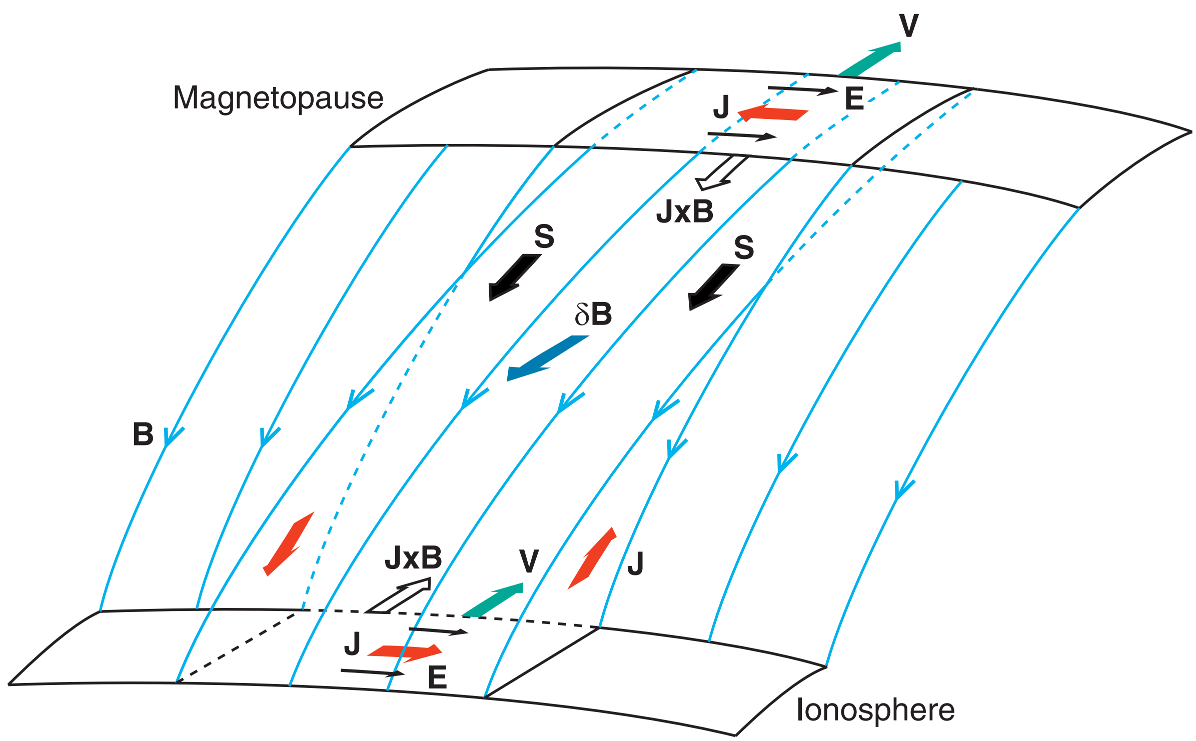
Interplanetary Field Southward



When the interplanetary magnetic field is northward (top), Dungey's 1963 model of the magnetosphere predicts reconnection with tail region, flow over the polar cap toward the sun and flow back to the nightside along the flanks. When the interplanetary magnetic field is southward (bottom), Dungey's 1961 model of the magnetosphere predicts a flow of plasma and the frozen in field over the polar cap and after reconnection in the magnetotail back to the dayside magnetosphere.

Sources of Viscosity at the Magnetopause





A slab of magnetic field is pulled backward at high altitudes creating a shear layer on either side of the slab on which field-aligned electric current flows. The regions of current closure across the magnetic field at high and low altitudes are regions in which momentum is added to the plasma (top) and lost from the plasma (bottom) leading to the terms generator and load respectively for the two regions.

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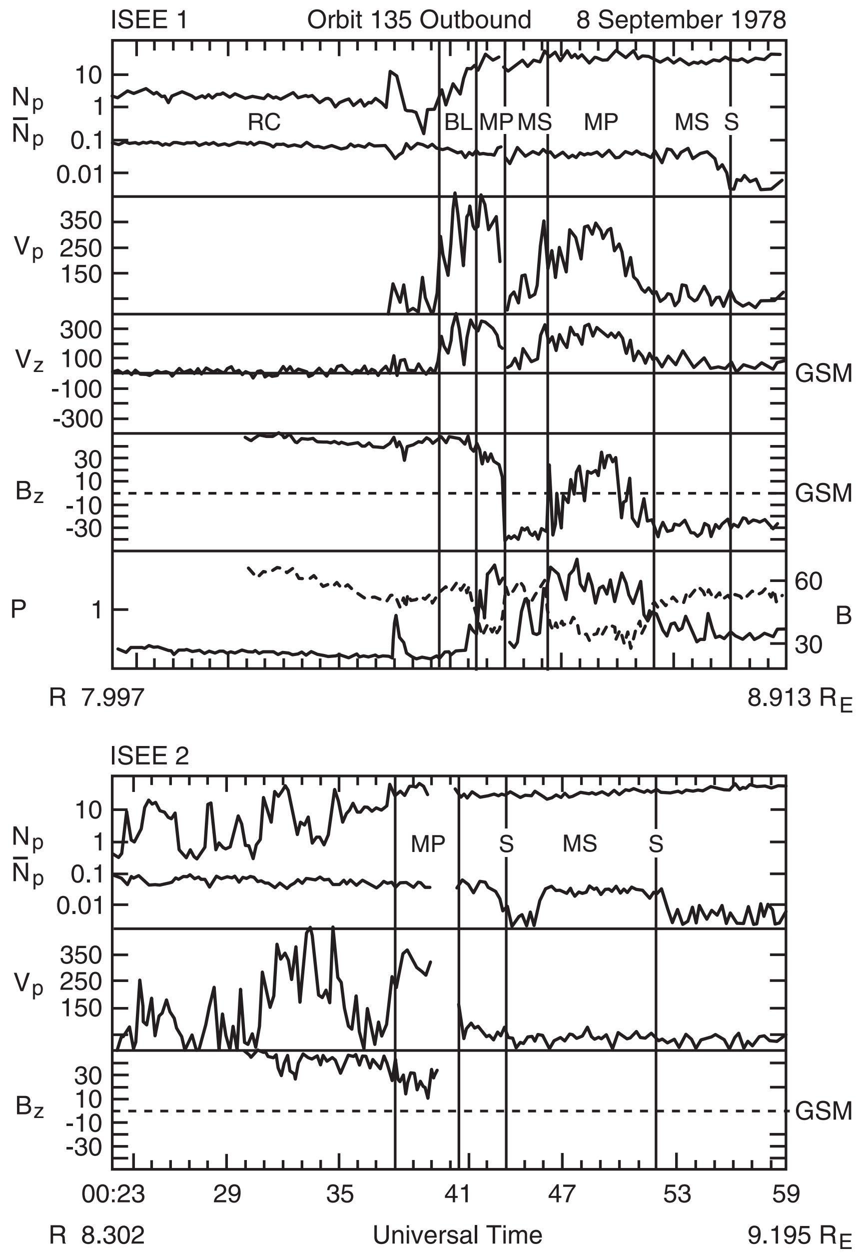
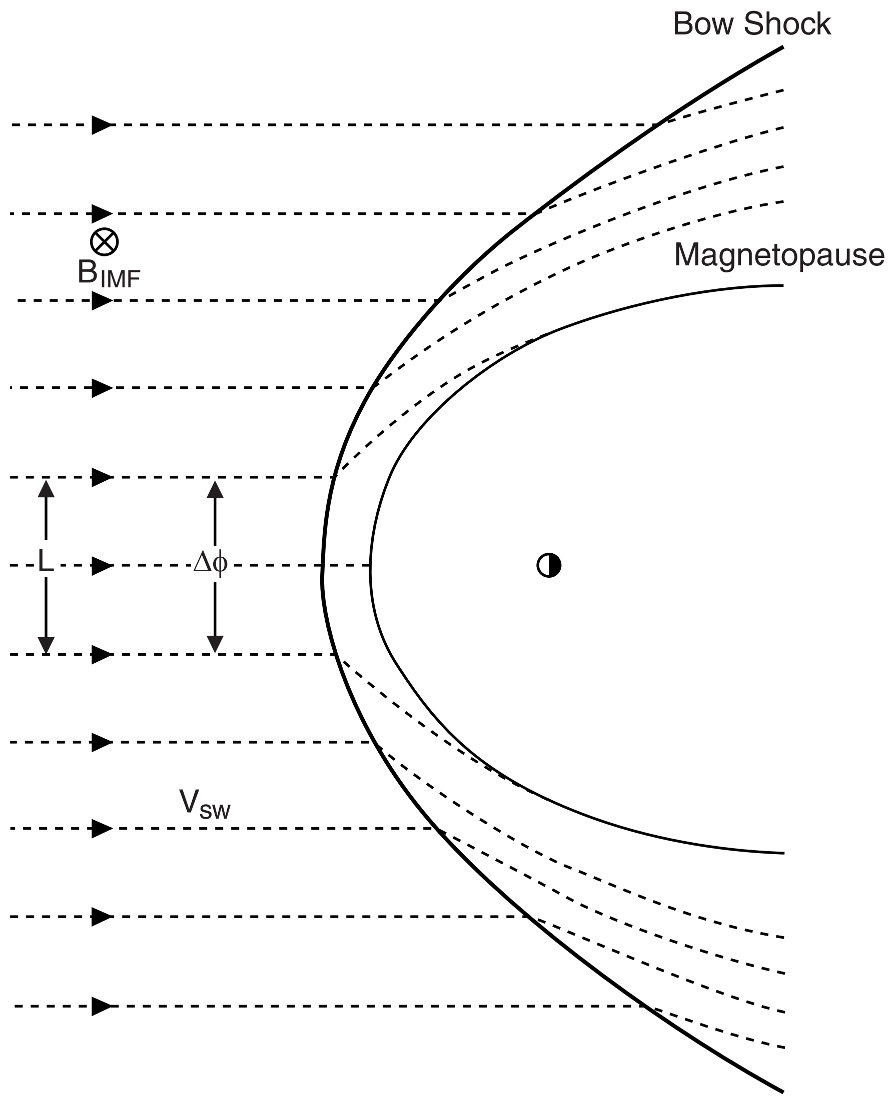
The importance of the Alfven velocity



The ISEE 1 and 2 spacecraft showed that there were persistent accelerated flows at approximately the Alfven velocity as the magnetopause was crossed when the IMF was southward.



Only a thin slab of solar wind plasma of width, L, perpendicular to the IMF and the flow, reconnects with the magnetosphere. In steady state the drop in electric potential across the solar wind slab equals the drop in electric potential across the polar cap.

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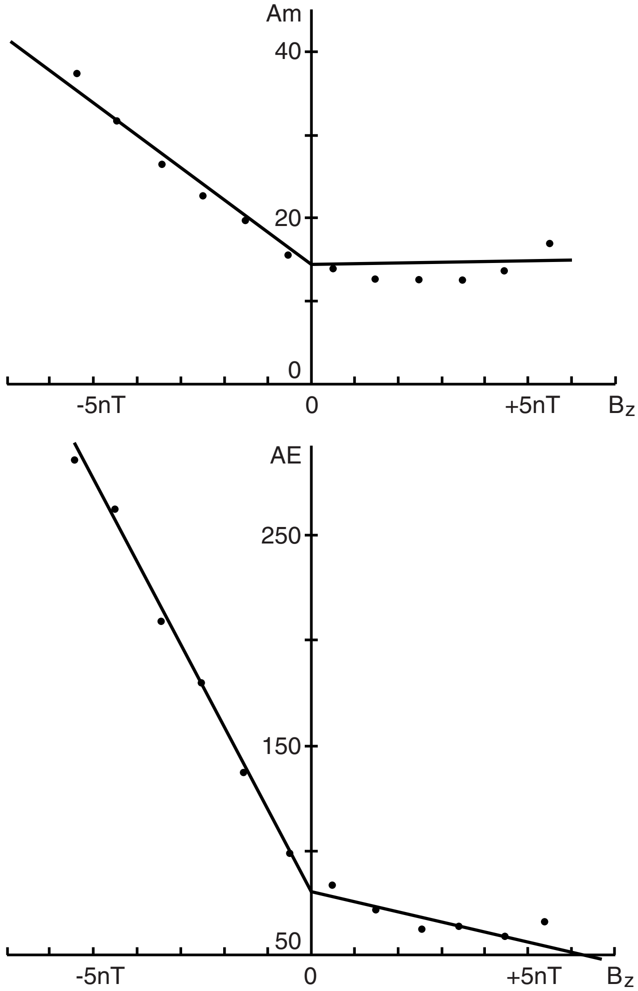
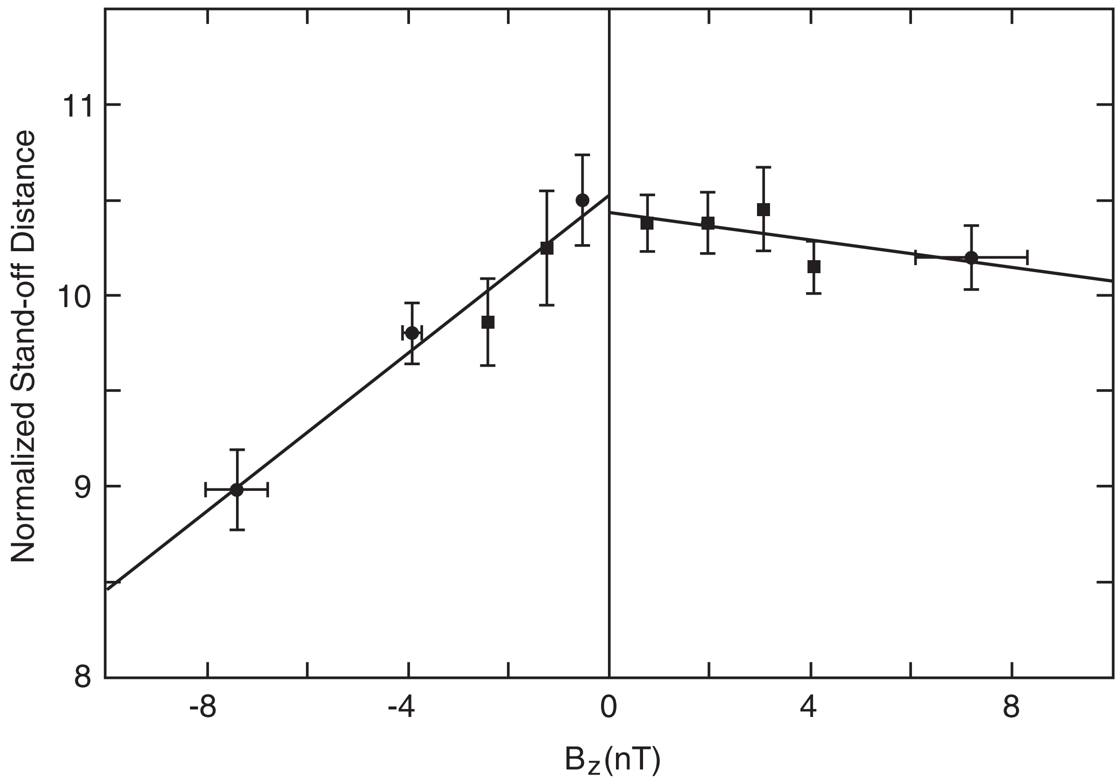
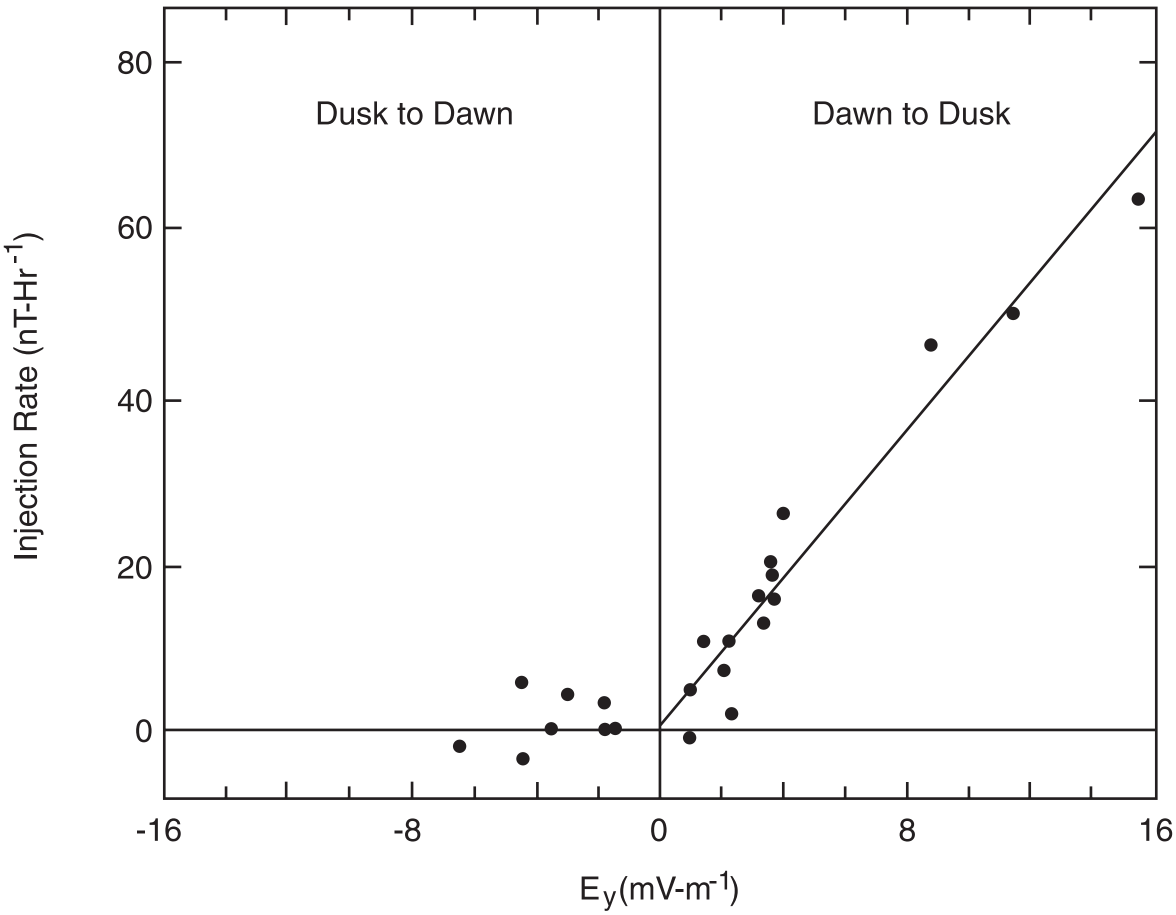


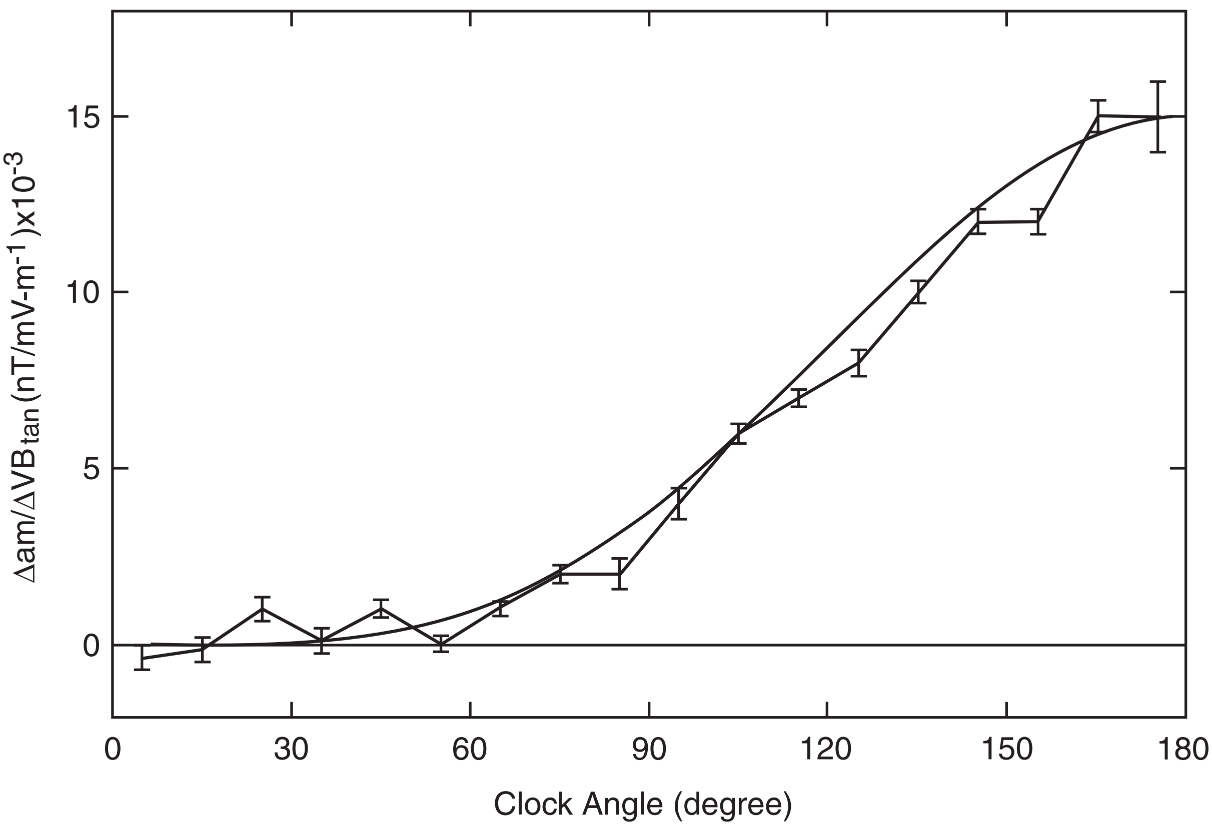
Many geomagnetic indices change slope at zero when plotted versus B_Z IMF (in GSM coordinates). When the IMF is northward, there is little geomagnetic activity.



When the IMF is southward the magnetopause is closer to the Earth than when it is northward. However, there is a weak tendency for the magnetopause to shrink for strong positive B_z as well.



The energy injected into the ring current is proportional to the interplanetary electric field VB_z, the amount of reconnecting magnetic flux carried to the magnetopause per unit time.



Magnetic indices can be used as a proxy for the efficiency of reconnection. Here the efficiency is shown versus the clock angle of the IMF where 0 is northward and 180° southward. The variation is approximately $\sin^4(\theta/2)$.

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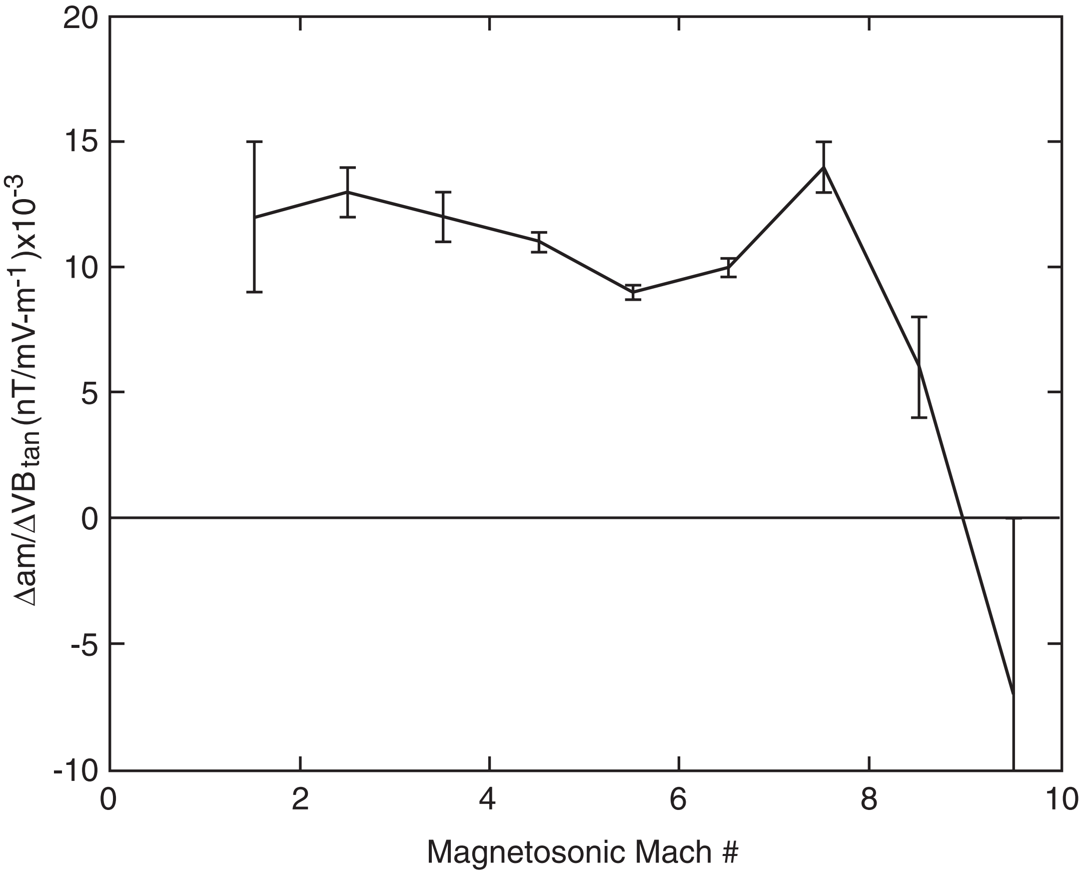

For high Mach number the reconnection efficiency drops to zero.

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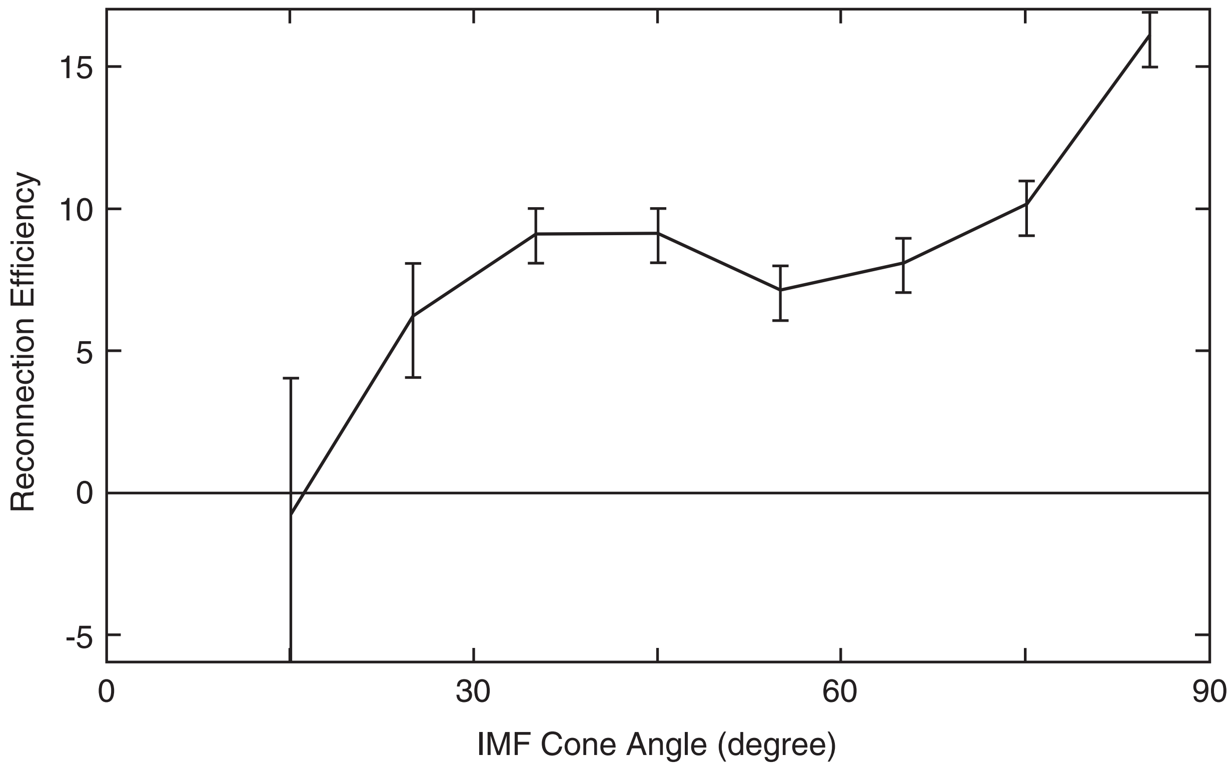

For low cone angles the subsolar reconnection efficiency drops to zero.

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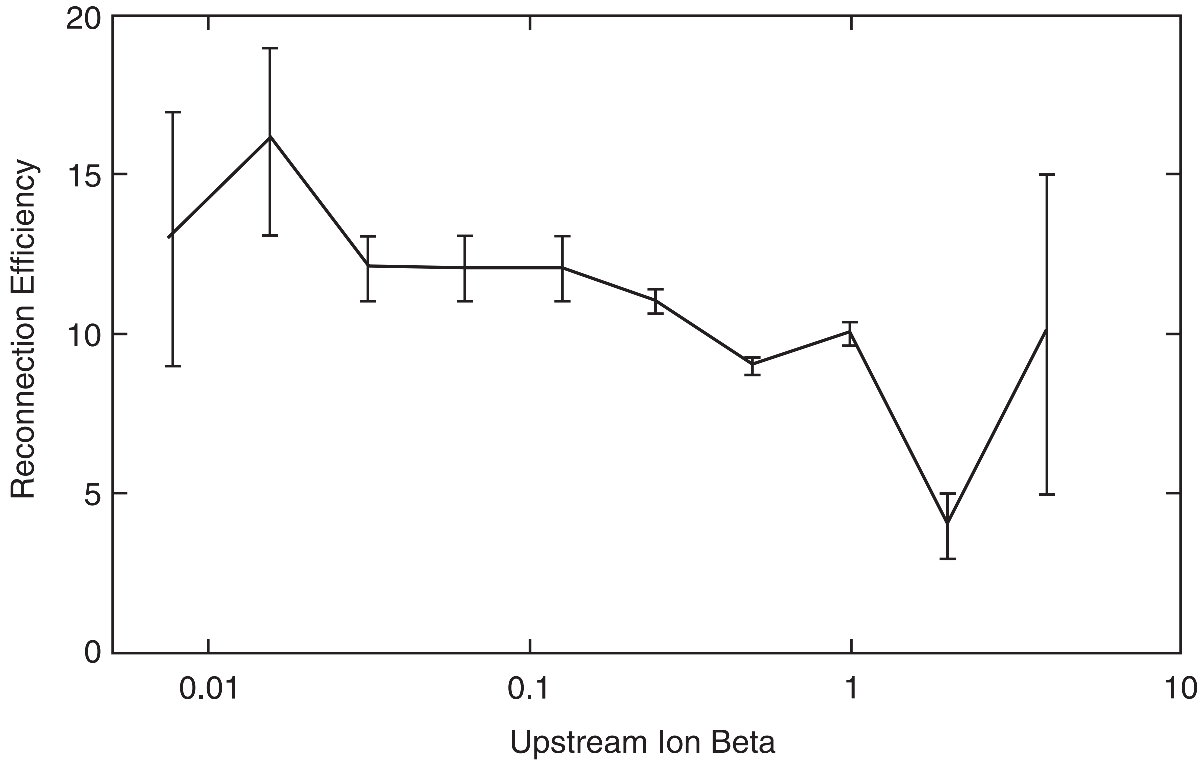
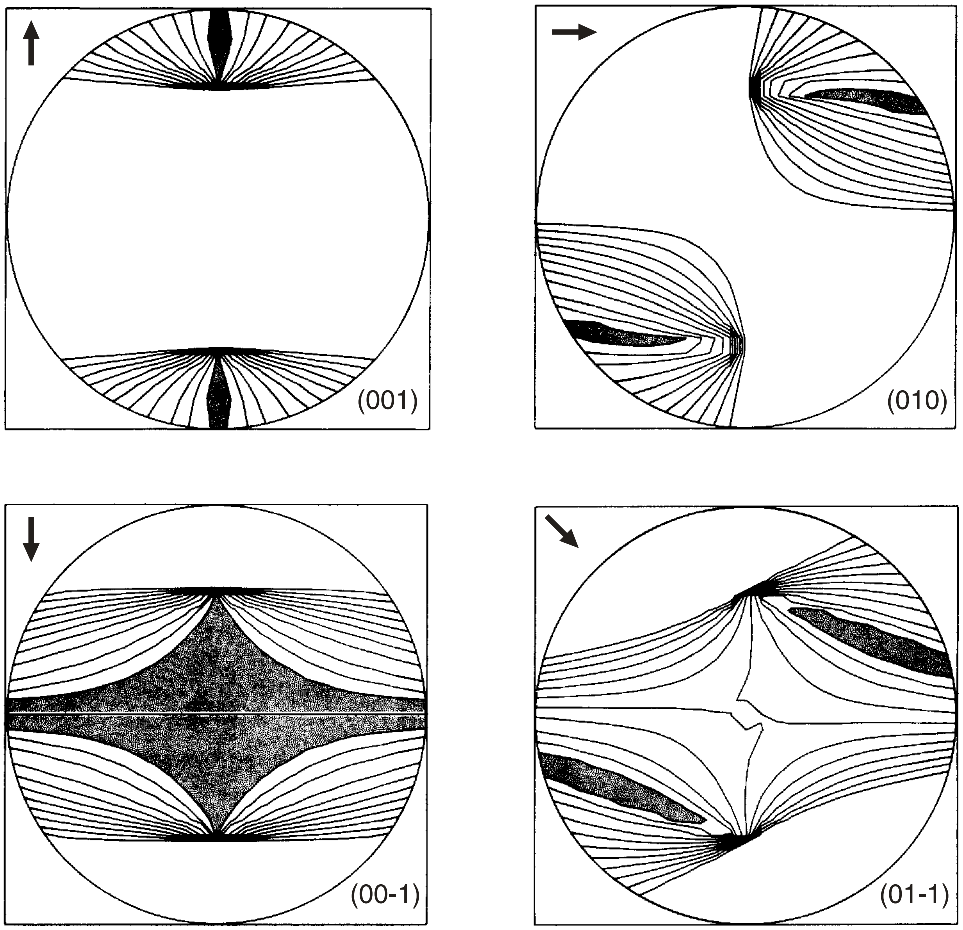


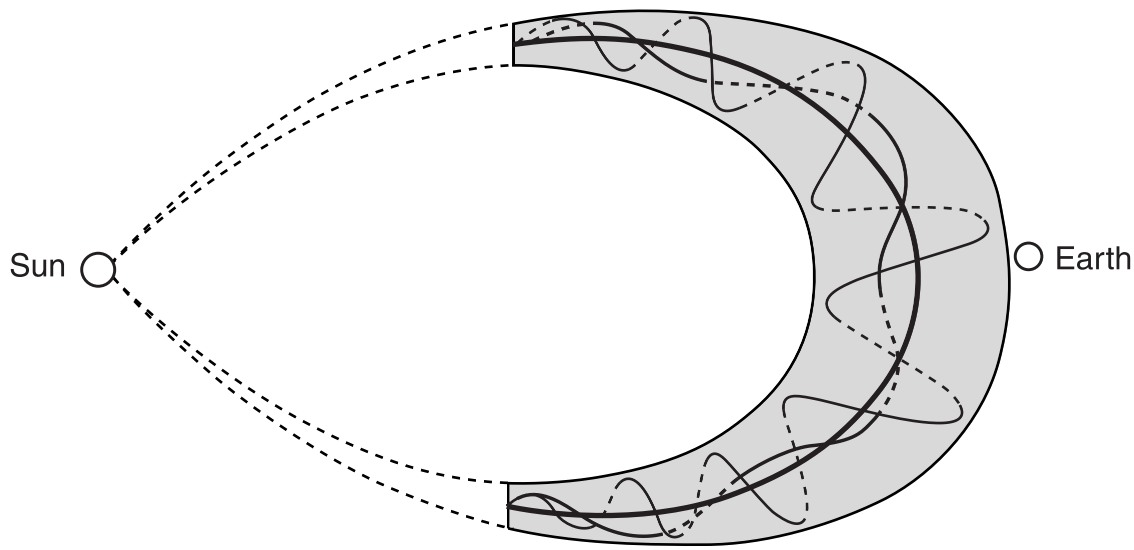
For high solar wind beta the reconnection efficiency drops.

Where does Reconnection occur?

What does it do there?



Using a realistic field model for the magnetic field inside the magnetosphere and the gas dynamic convected fluid outside, one can find the places on the magnetopause where the fields are nearly antiparallel for different IMF directions. This is where reconnection is most likely to occur.



Interplanetary Coronal Mass Ejections

- "Polar" field of sun predicts leading polarity
- Axial field lies along neutral line on source surface but direction not predictable (as yet)
- Structures often appear to be force free (but is model unique?)
- Cross section is probably not cylindrical

The “Burton” Formula

$$dDst/dt = F(Ey) - a\, Dst_o \qquad (1)$$

$$Dst_o = Dst - b(P)^{1/2} + c \qquad (2)$$

$$F(Ey) = d\,(Ey - 0.5) \qquad Ey \geq 0.50 \text{ mV/m} \qquad (3)$$

$$F(Ey) = 0 \qquad Ey < 0.50 \text{ mV/m} \qquad (4)$$

where a = 3.6×10^{-5} s^{-1}, b = 15.8 $nT/nPa^{1/2}$, c = 20 nT; and d = 1.5×10^{-3} $nT/(mv\text{-}m^{-1}\text{-}s)$.

- Equation (1) states that the rate of change of the ring current as represented by the Dst index increases due to an energy coupling function F(Ey), and decreases by a fixed percentage each minute because of loss processes

- Equation (2) states that the observed Dst index consists of a ring current contribution, Dst_o, and magnetopause current proportional to the square root of the dynamic pressure of the solar wind

- The parameter, c, accounts for the fact that the Dst baseline has been chosen to be zero for a typical solar wind pressure, not for zero pressure

- Equation (3) and (4) are the energy coupling functions for southward and northward interplanetary magnetic fields

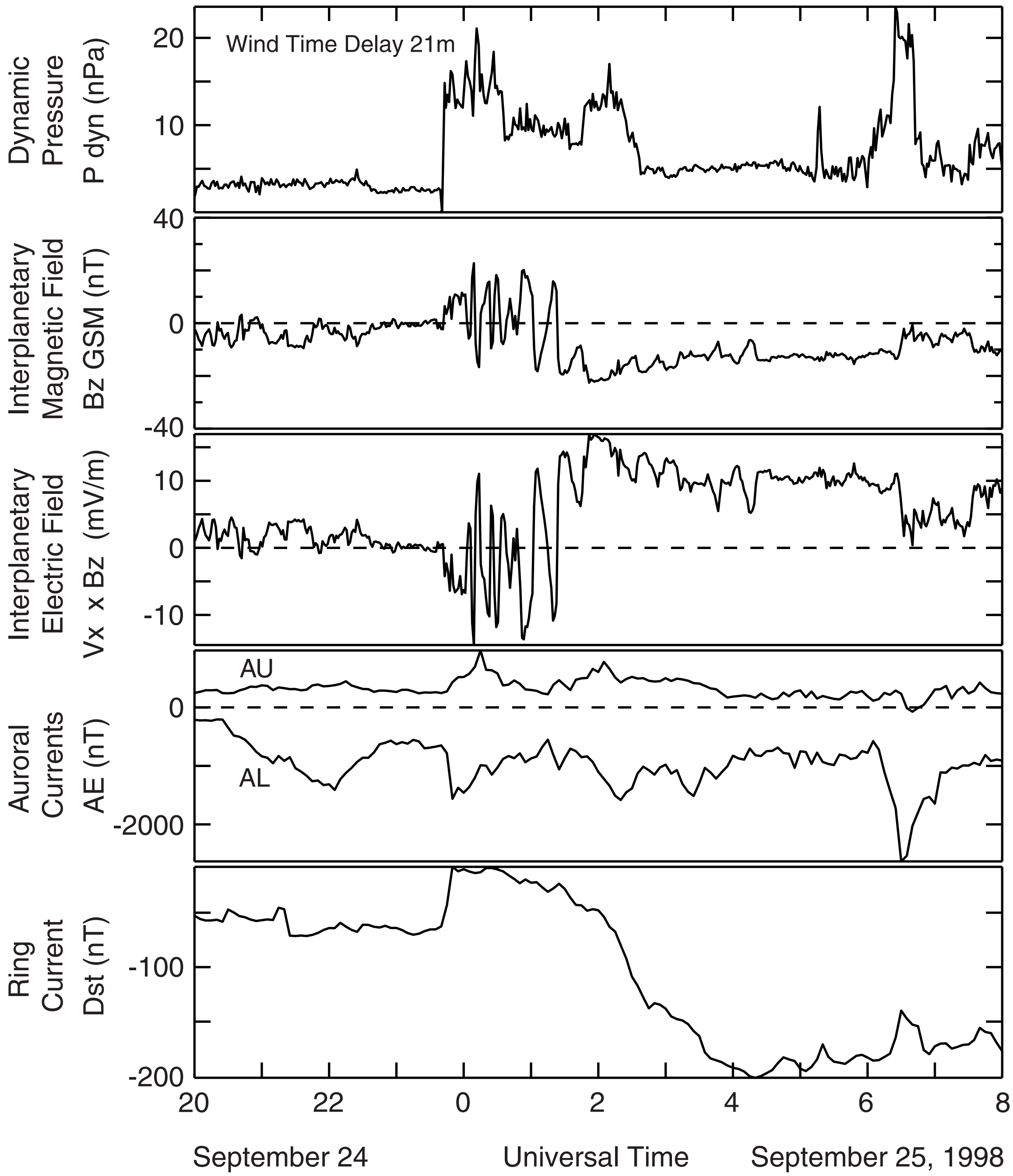
What geomagnetic activity responds to what solar wind input?

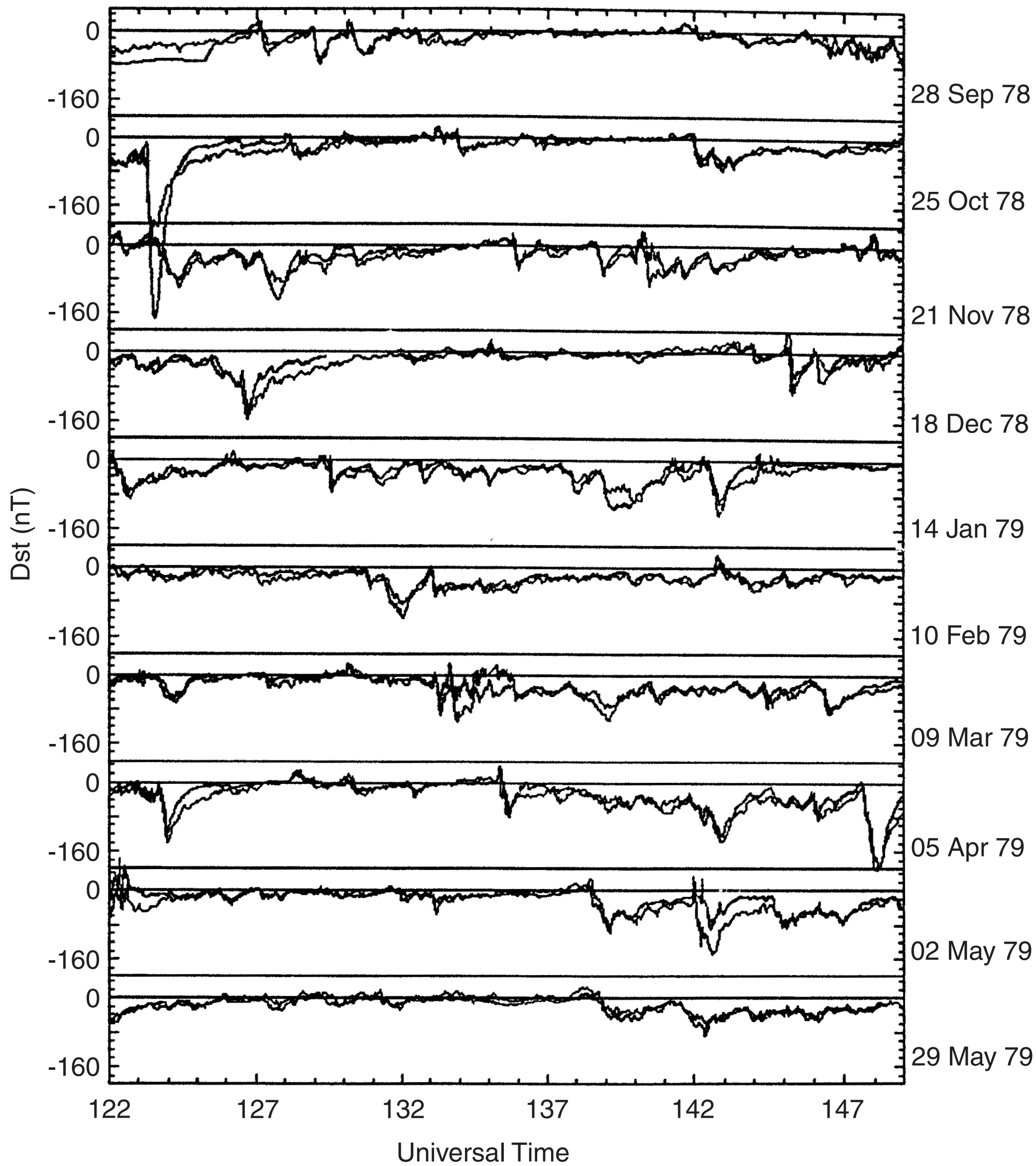
AE roughly the same for weak IEF

oscillating IEF

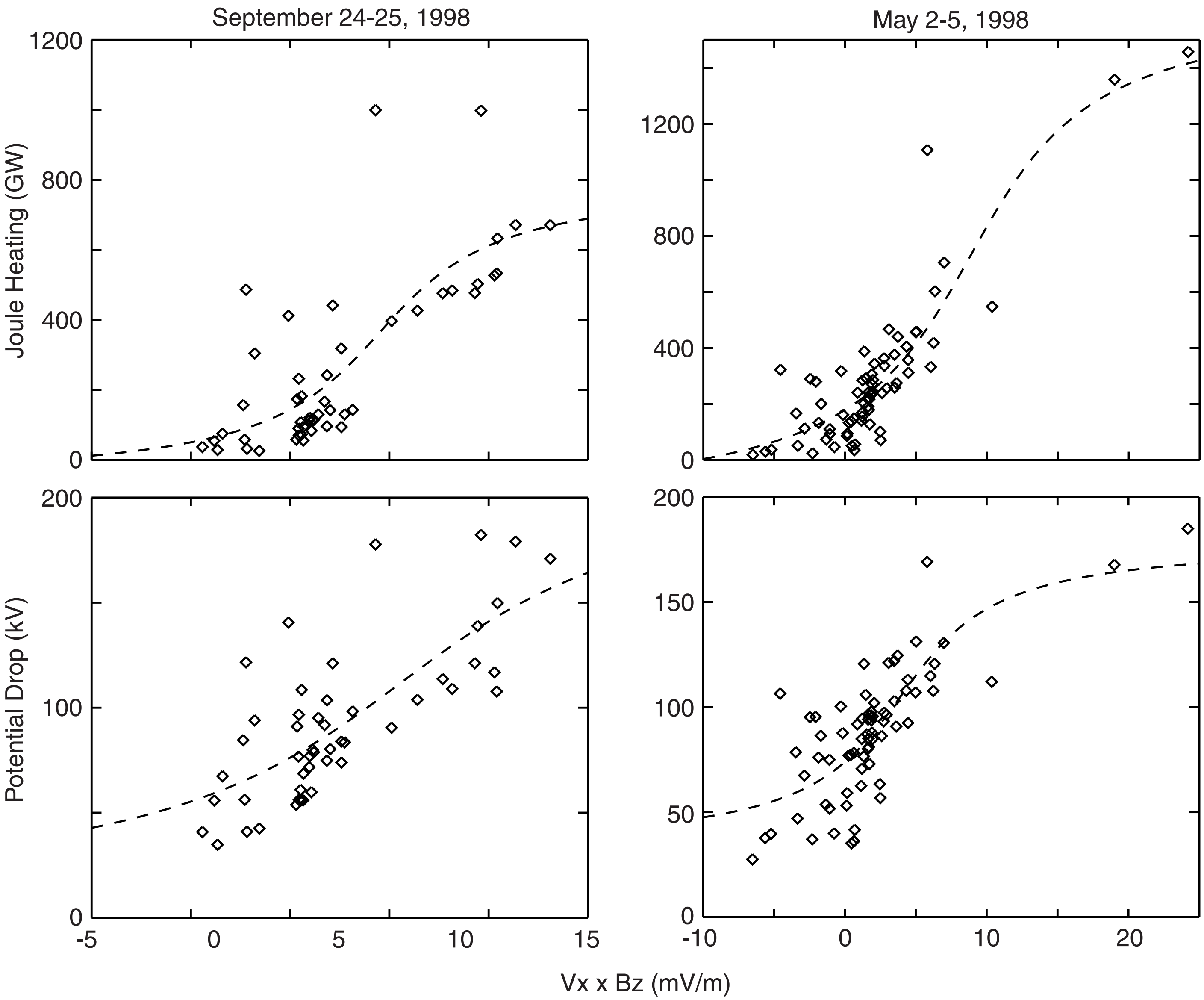
strong IEF

Ring current responds to strong IEF





The Burton formula is not perfect but does well in predicting Dst over a wide range of solar wind parameters.



When the interplanetary electric field increases the potential drop does not follow it linearly if the IEF is large; neither does the Joule heating.

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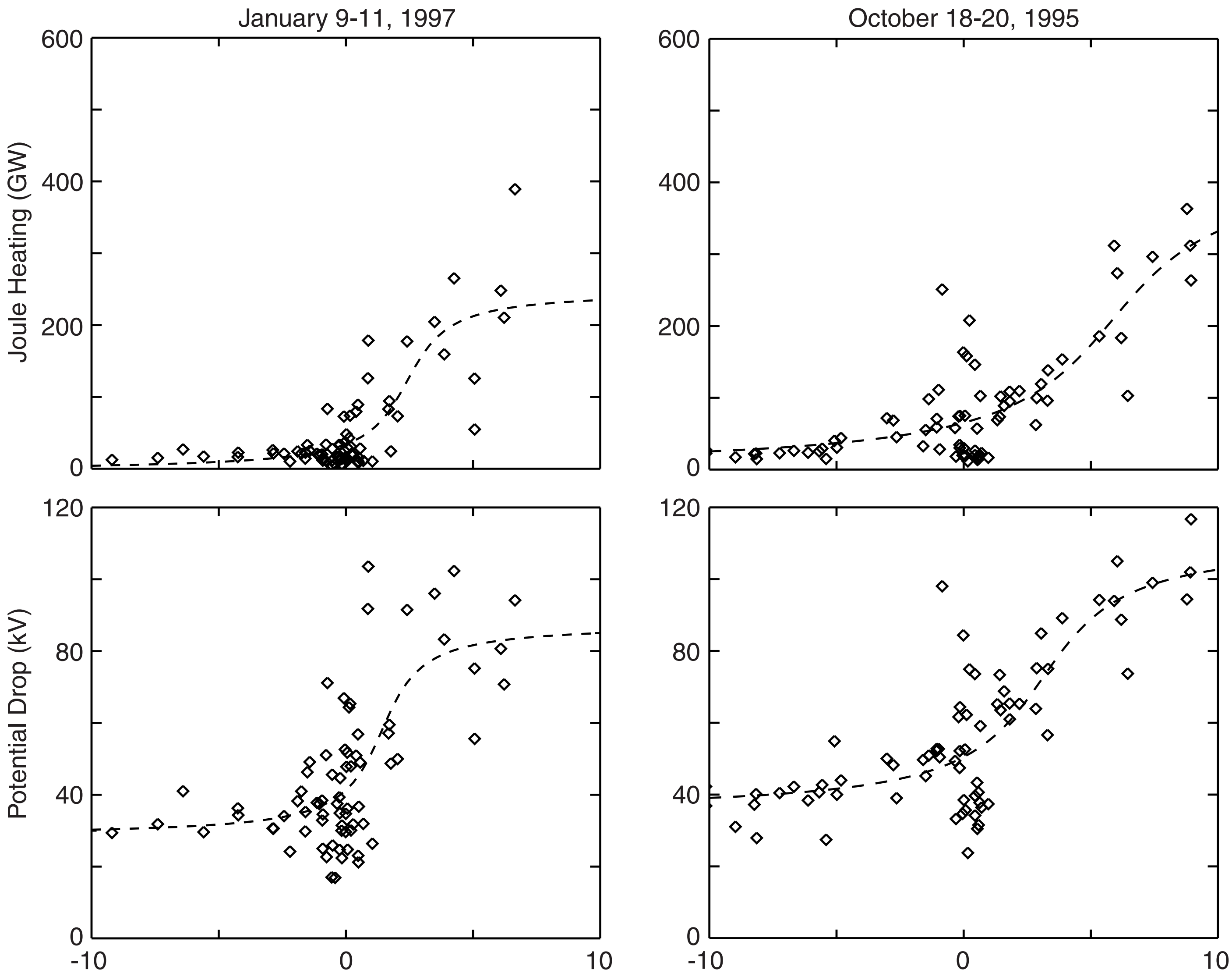
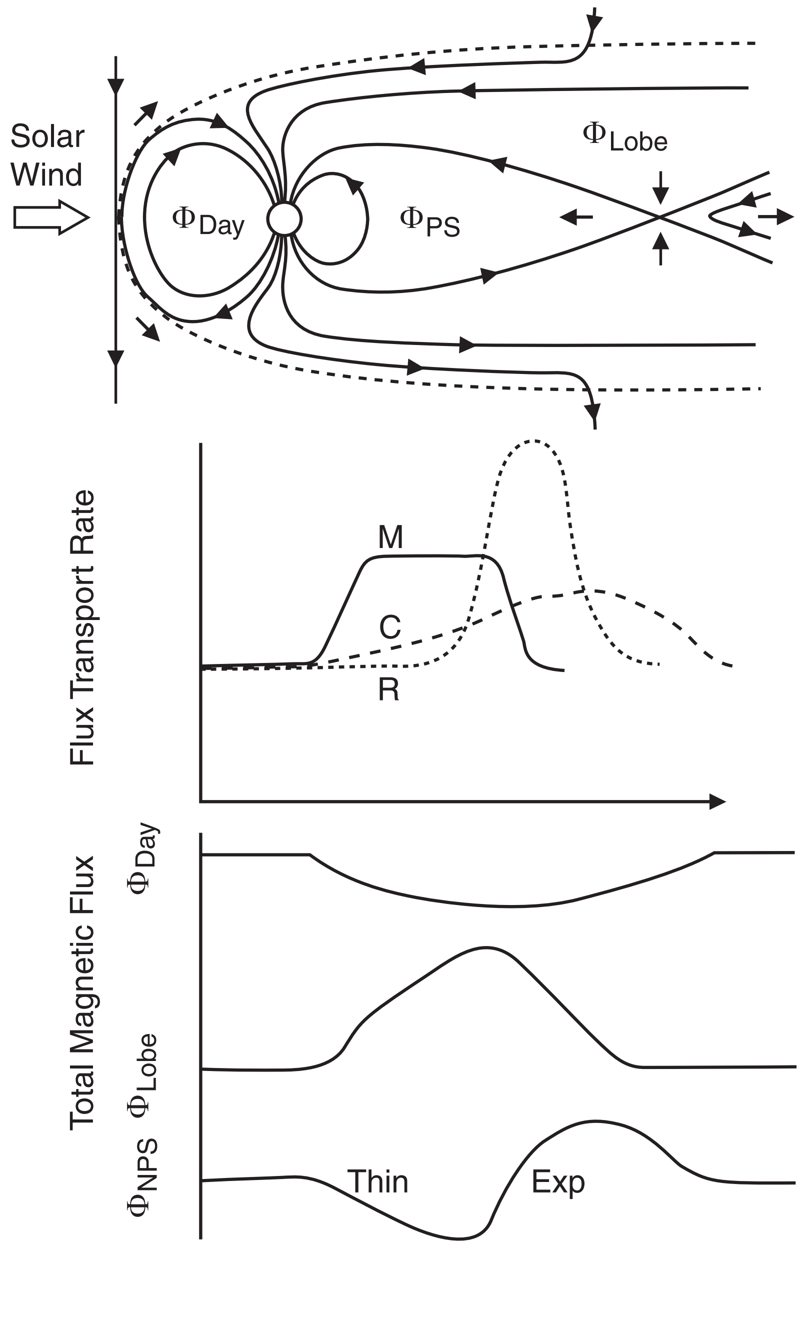
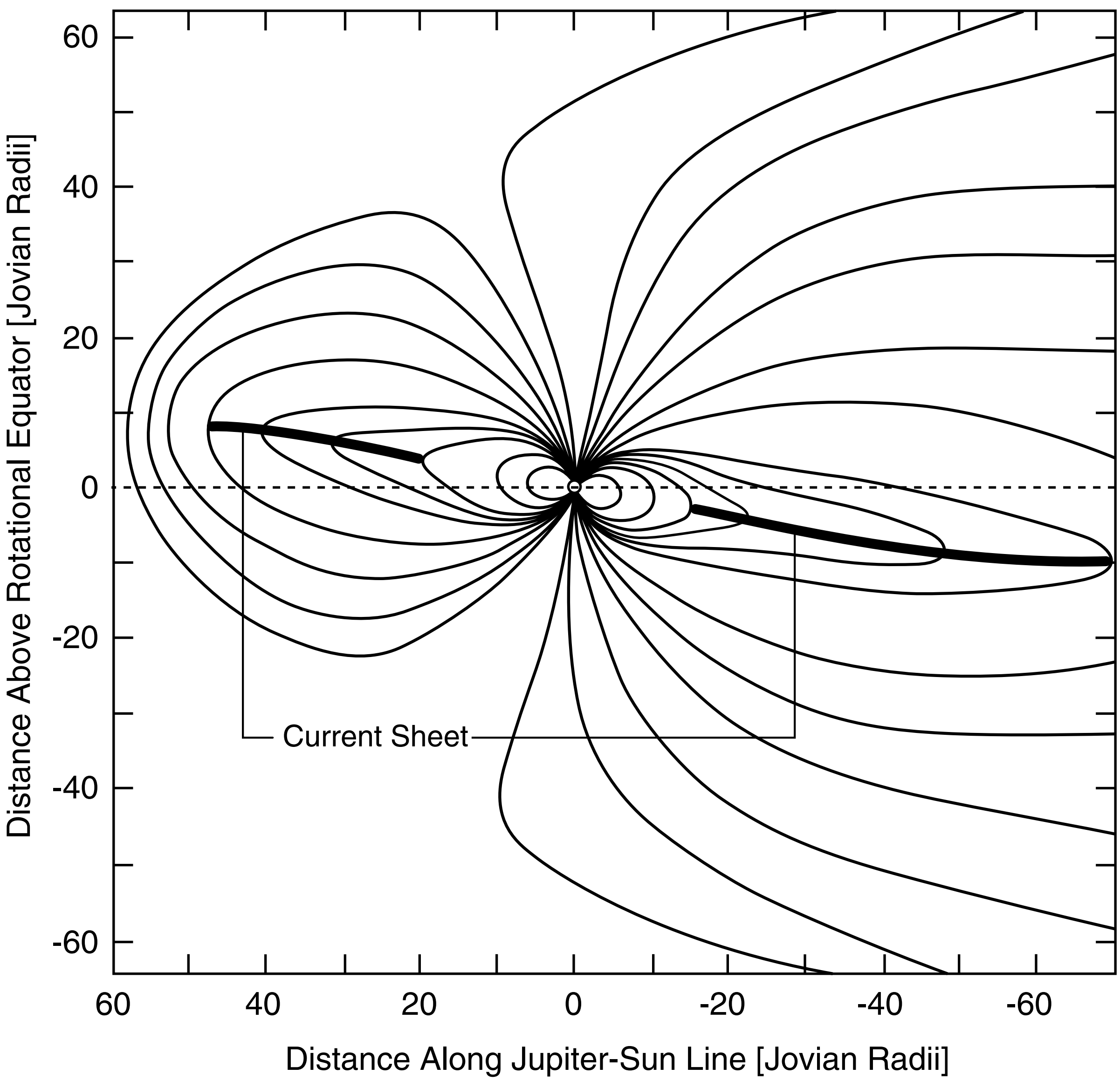


Another pair of examples of the non-linearity of the polar ionosphere currents and the potential drop.

Substorm Model (ca 1973)



An early model of the driving of substorms by a southward turning of the interplanetary magnetic field. A delay of the onset of tail reconnection allows the magnetic flux in the tail to be built up.



Noon midnight meridian view of the Jovian magnetosphere.

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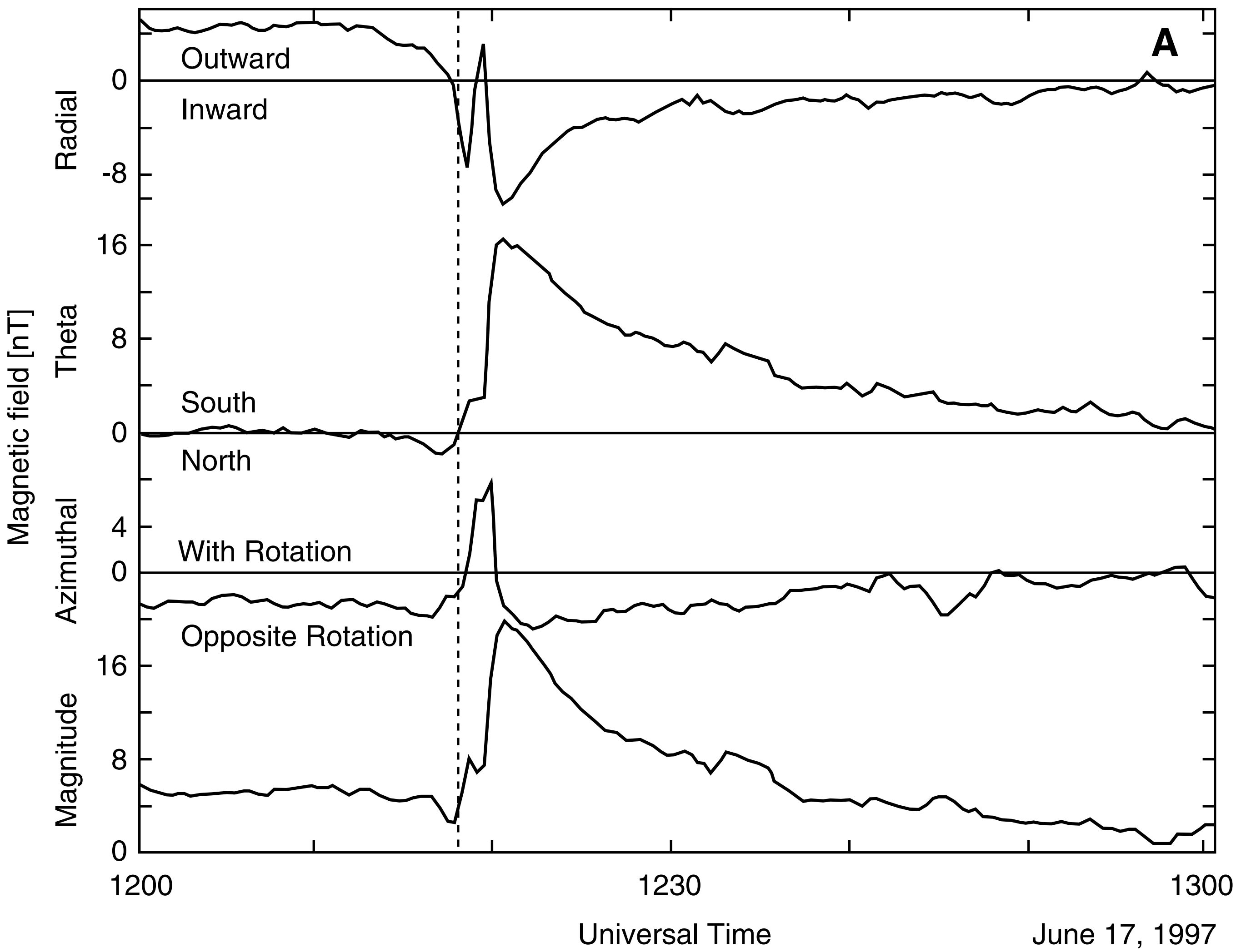

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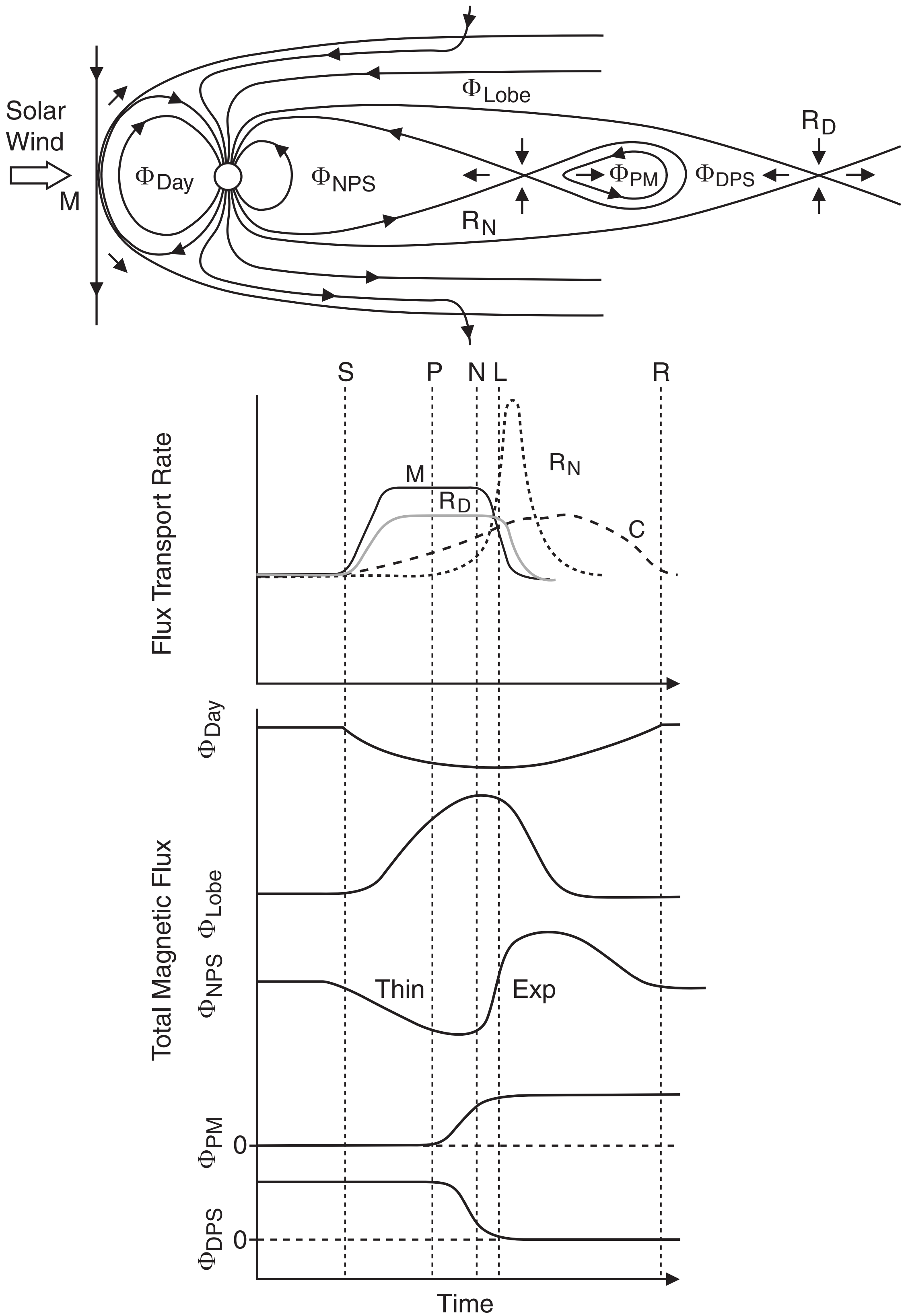
In the near tail of Jupiter sporadic reconnection occurs across the magnetodisk current sheet. The large overshoot in magnetic pressure suggests this process at Jupiter is much stronger than in the terrestrial magnetotail.



A recent model of substorms in the magnetotail that takes note of the existence of two neutral points. This allows two substorm onsets corresponding to the first initiation of reconnection of the near-Earth neutral point and to the time of which this reconnection region manages to reach the open field lines of the lobe. It also explains the triggering of substorms by northward IMF turning.

Figure 16
CR-1509

Summary and Conclusions

- **The solar wind dynamic and static pressures determine the zeroth order size and shape of the magnetosphere**
- **Reconnection both opens the field lines between the solar wind and the magnetosphere and applies tangential stress that transfers magnetic flux and stores magnetic energy**
- **The energy to power geomagnetic activity is derived from the mechanical energy flux of the solar wind not the Poynting flux. The Poynting flux is the agent for transfer first to plasma accelerated at the subsolar magnetopause and also to transfer energy into the tail**
- **The shock changes the plasma conditions at the subsolar magnetopause. Thus the cone angle of the IMF and the Mach number of the flow are important in determining the reconnection rate**
- **The magnetosphere is a good half-wave rectifier of the IEF**
- **Magnetospheric convection seems not to respond to temporal scales shorter than 20 minutes**
- **The AE index maximizes at about 2000 nT. Other quantities such as the potential drop and the Joule dissipation also tend to saturate but may just have a long response time**
- **ICMEs are very geoeffective because they have large IEFs, long time constants and low beta**
- **The explosive phase of substorms can be explained both at Earth and Jupiter by the reconnection point reaching a low density region where the Alfven velocity is large**
- **Northward triggering of substorms can be explained in terms of the modulation of the rate of reconnection at the near Earth neutral point by the supply of plasma from the distant neutral point**