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School on the Physics of Equatorial Atmosphere

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Solar-Terrestrial Disturbance Scenario - I: Sun --> Solar Wind --> Magnetosphere

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SOLAR-TERRESTRIAL DISTURBANCE SCENARIO - I: SUN --> SOLAR WIND --> MAGNETOSPHERE

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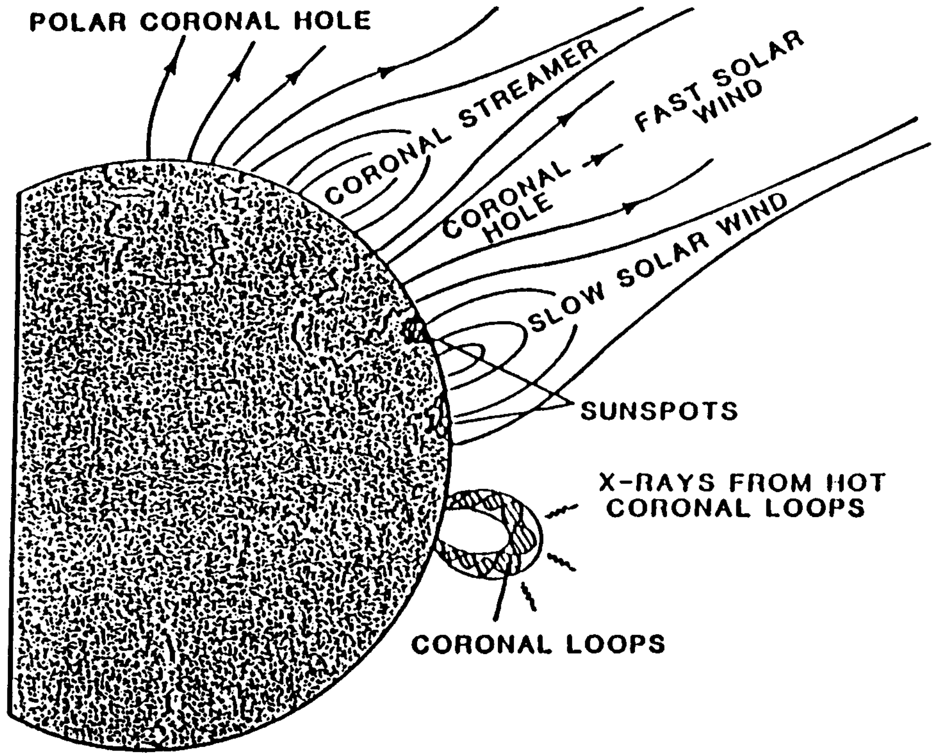
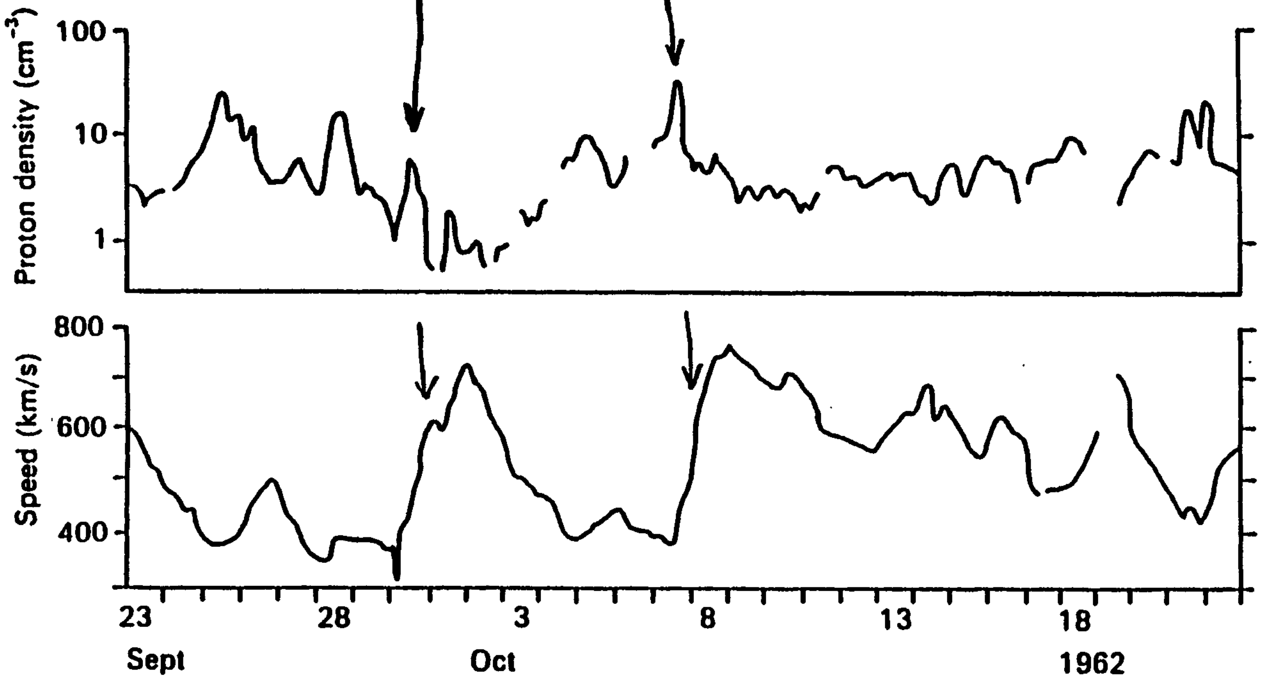
- **Coronal Mass Ejections**
- **Solar Flares**
- **"Immediate" vs. "Delayed" Effects**
- **"Fast" vs. "Slow" Solar Wind Streams**
- **Merging, Reconnection and Particle Transfer**
- **Magnetospheric Circulation**
- **Plasmasphere Plasma Detachment & Flux Tube Refilling**
- **Equatorial Electrojet Signatures**

Open and Closed Field Lines in the Corona

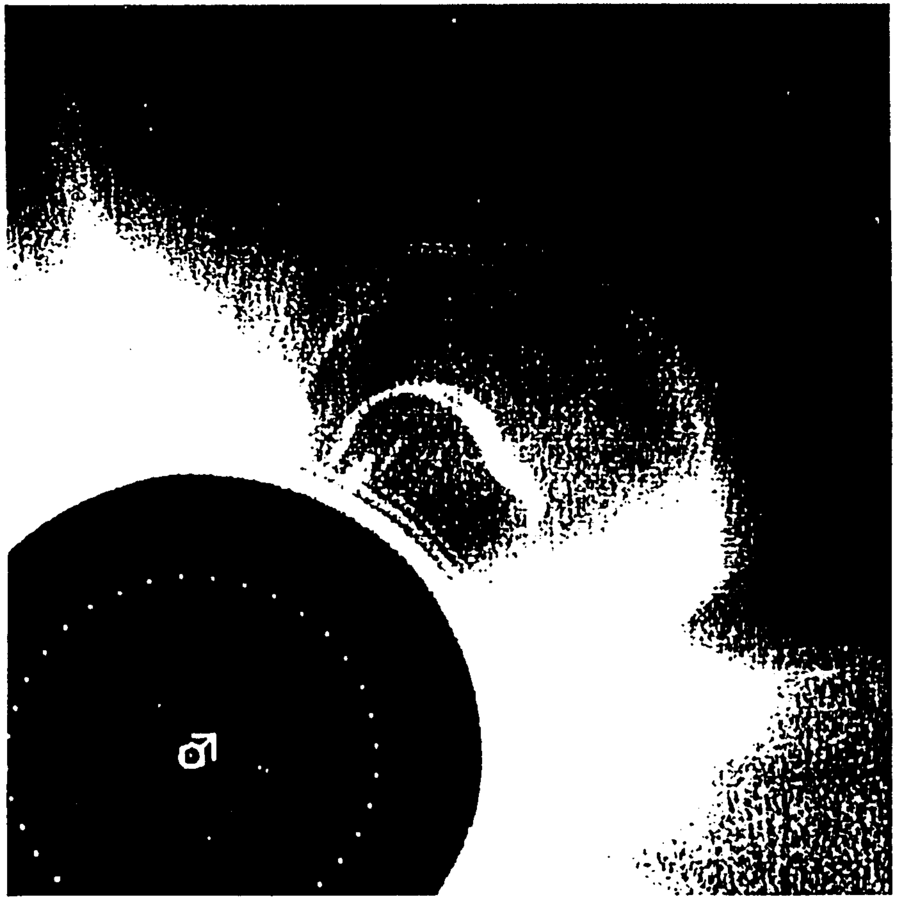


Density and Speed of the Solar Wind over one Solar Rotation in 1962, from Mariner-2

Maybe "fast streams" associated with coronal holes



These features tend to recurr in subsequent 27-day rotations



Coronal

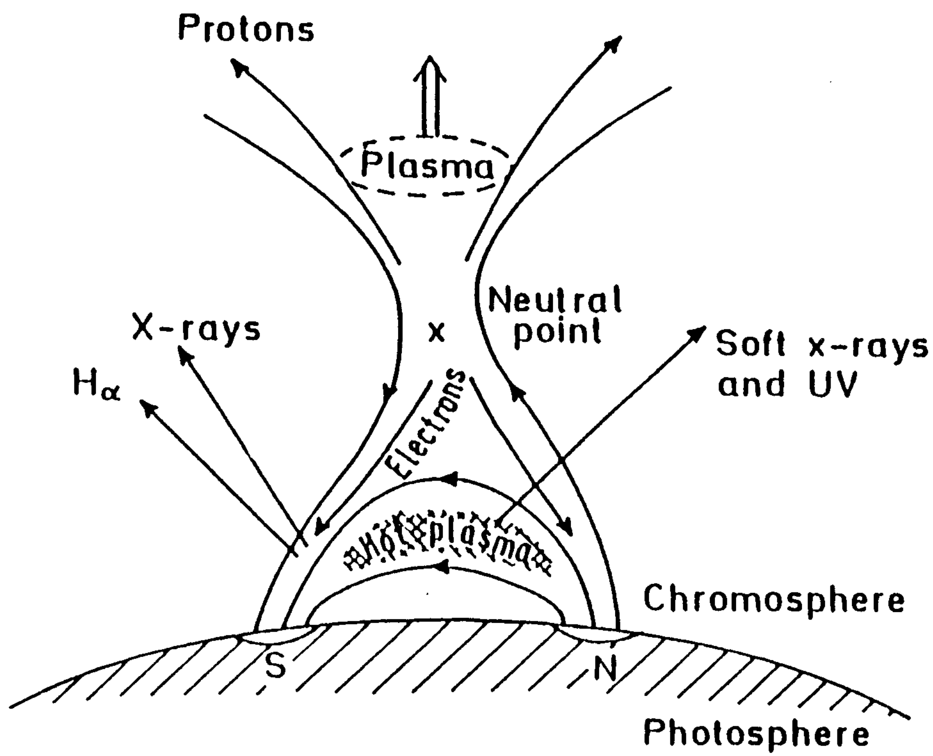
Mass

Ejection

Coronal mass ejection observed on April 14, 1980 with a coronograph on the SMM spacecraft. The two bright, concentric loops at the upper left are seen to move forward in successive images.

SOLAR FLARES

• A <u>Flare</u> is an explosive release of energy, originally in the form of magnetically-confined hot plasma, which appears as a localized brightening in the chromosphere



A model of the solar flare, showing possible sources for some of the known products

- x-ray emissions are greatly enhanced during a flare
  - perhaps 3-4 orders of magnitude;

  - almost immediate effect on the ionosphere;

  - energetic particles also released, and arrive at earth ~ 2 days later.

- Note: "soft" x-rays are 1-10Å ;
  "hard" x-rays are 10 Kev - 1 Mev

- energetic protons (1-10^3 Mev) are sometimes emitted from flares -- these produce PCA events on earth

- significant radio wave emissions also accompany flares, with important operational impacts on earth

OPERATIONAL EFFECTS ASSOCIATED WITH FLARES

IMMEDIATE VS. DELAYED EFFECTS (see schematic)

- **Immediate effects** are caused by flare radiation at X-ray, ultraviolet, and radio wavelengths.

  -- This radiation takes 8.3 minutes to reach the earth.

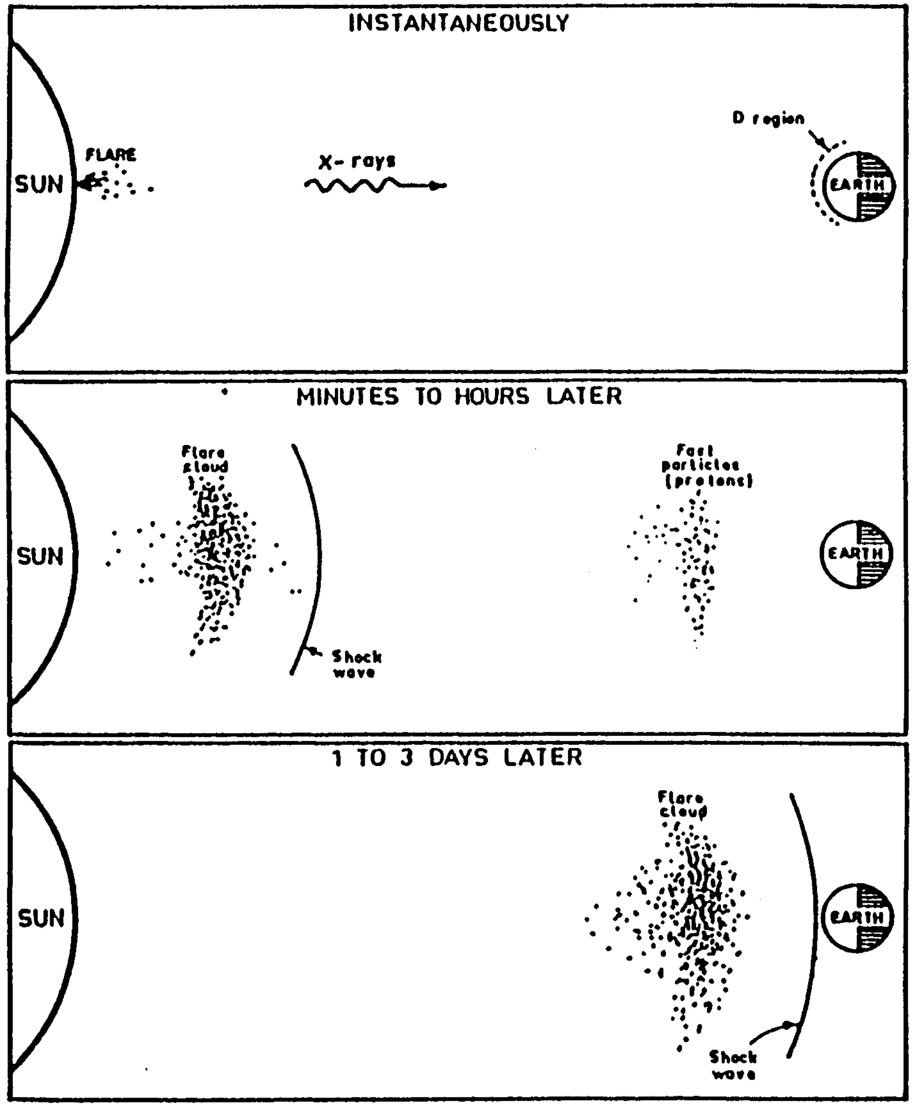
  -- Effects are thus experienced shortly after the flare is noticed visually, and also tend to subside shortly after the flare ends.

- **Delayed Effects** are associated with flare-emitted particles traveling at less than the speed of light.

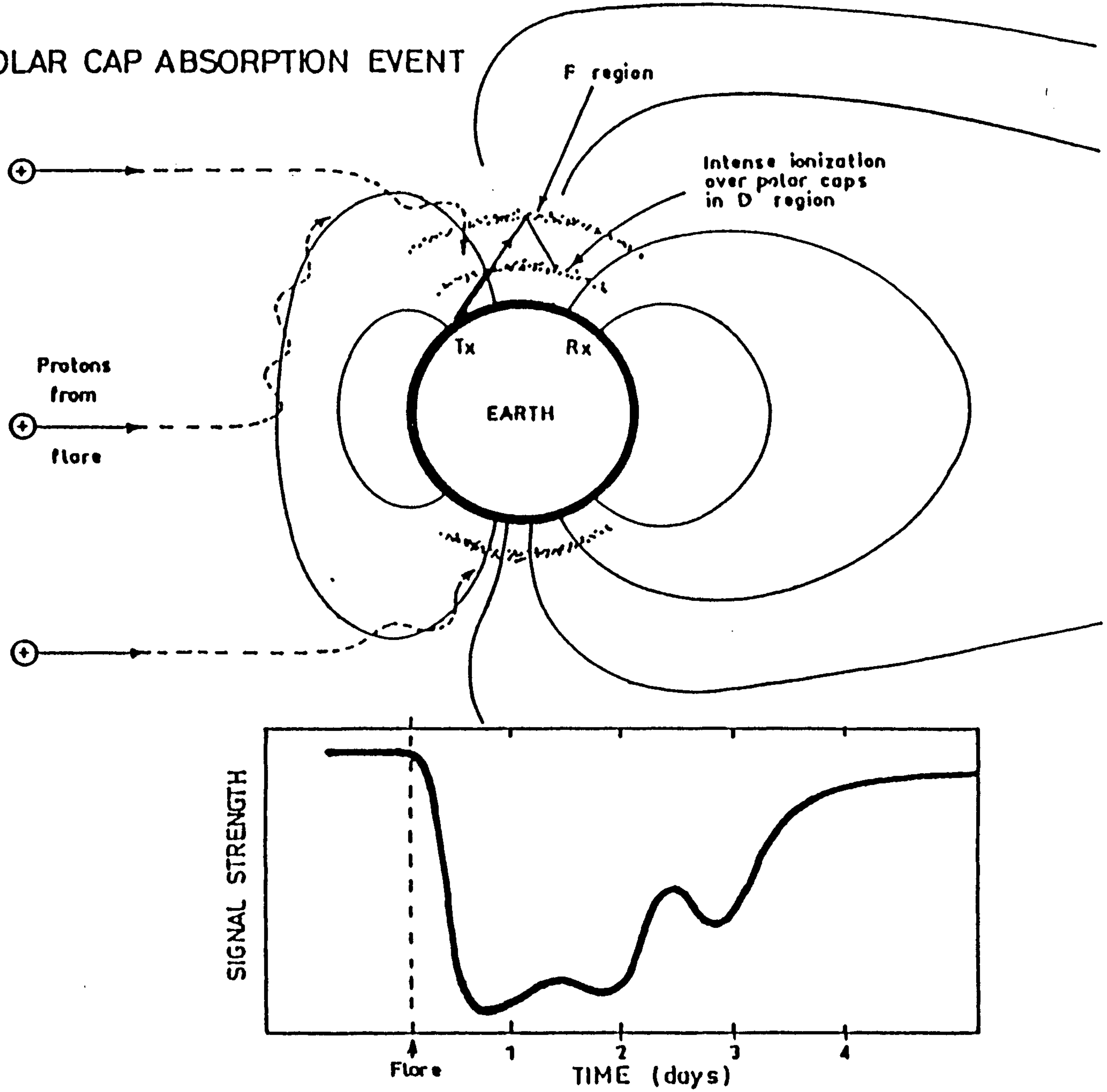
  -- The delay time can range from 15 minutes to 72 hours.

  -- Delayed effects can often be predicted based on the observed characteristics of the flare.

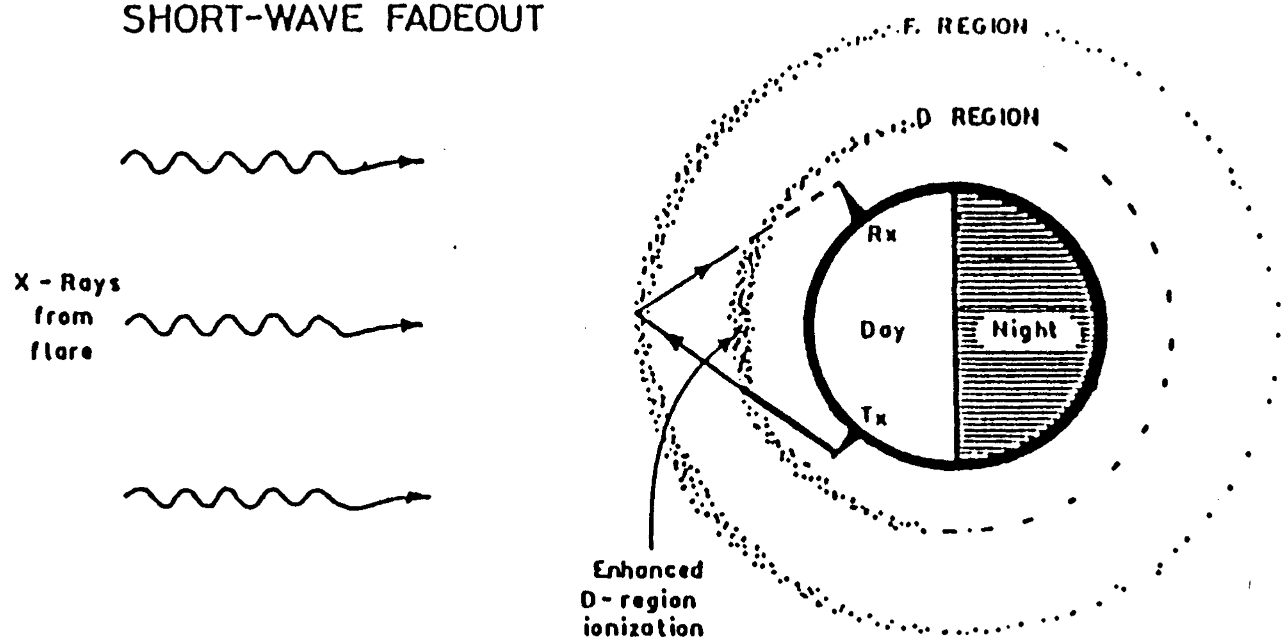
SNAPSHOTS FOLLOWING A LARGE SOLAR FLARE

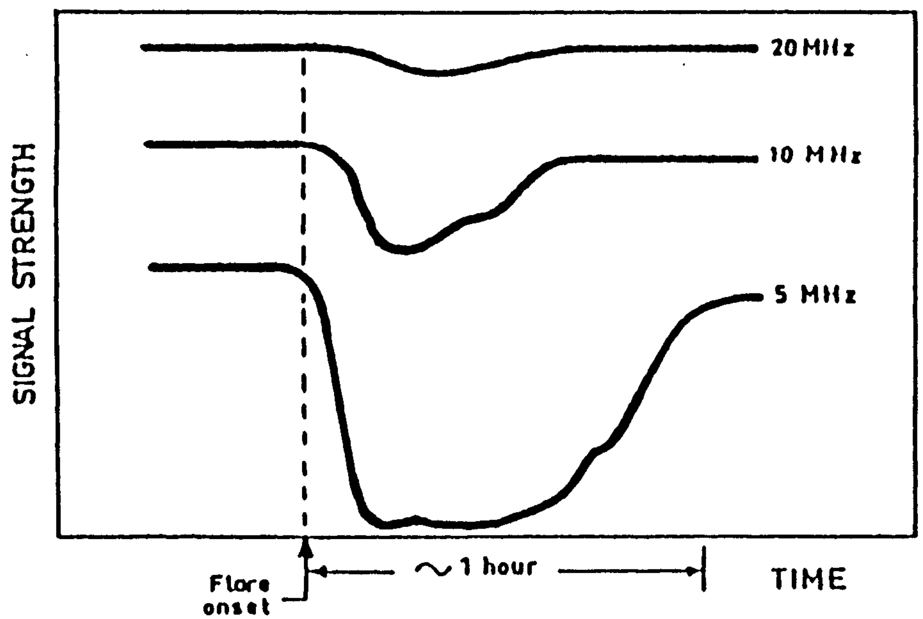


POLAR CAP ABSORPTION EVENT

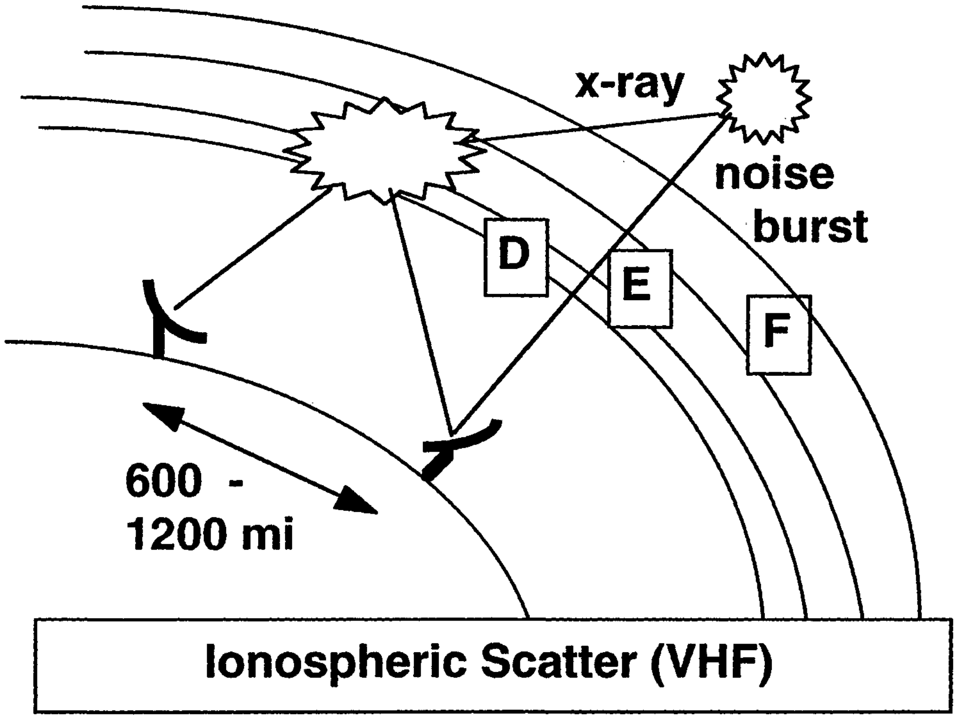


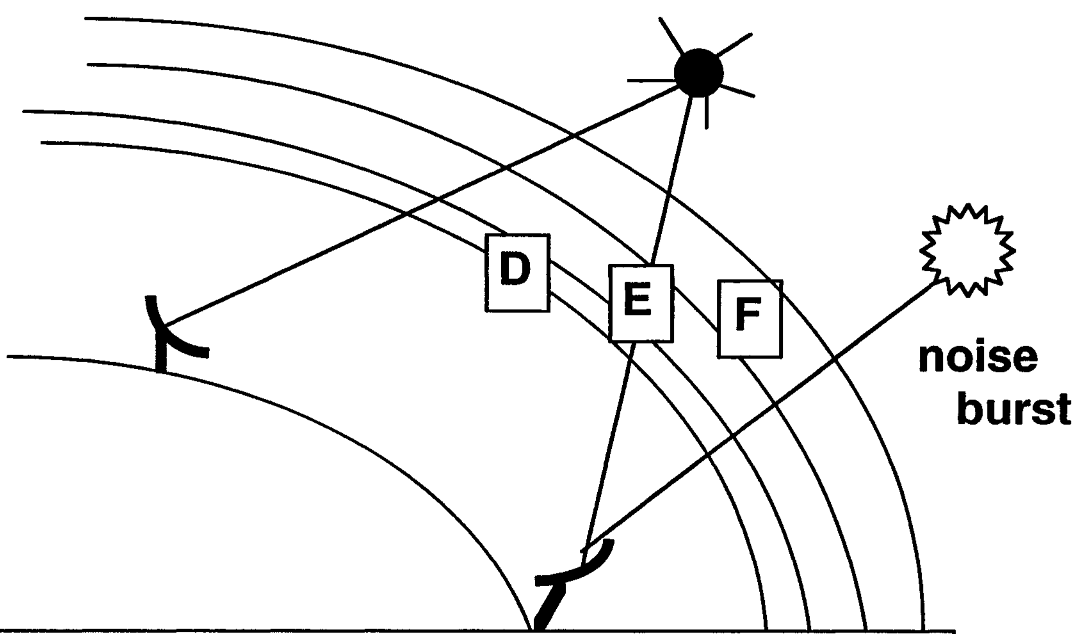
SHORT-WAVE FADEOUT





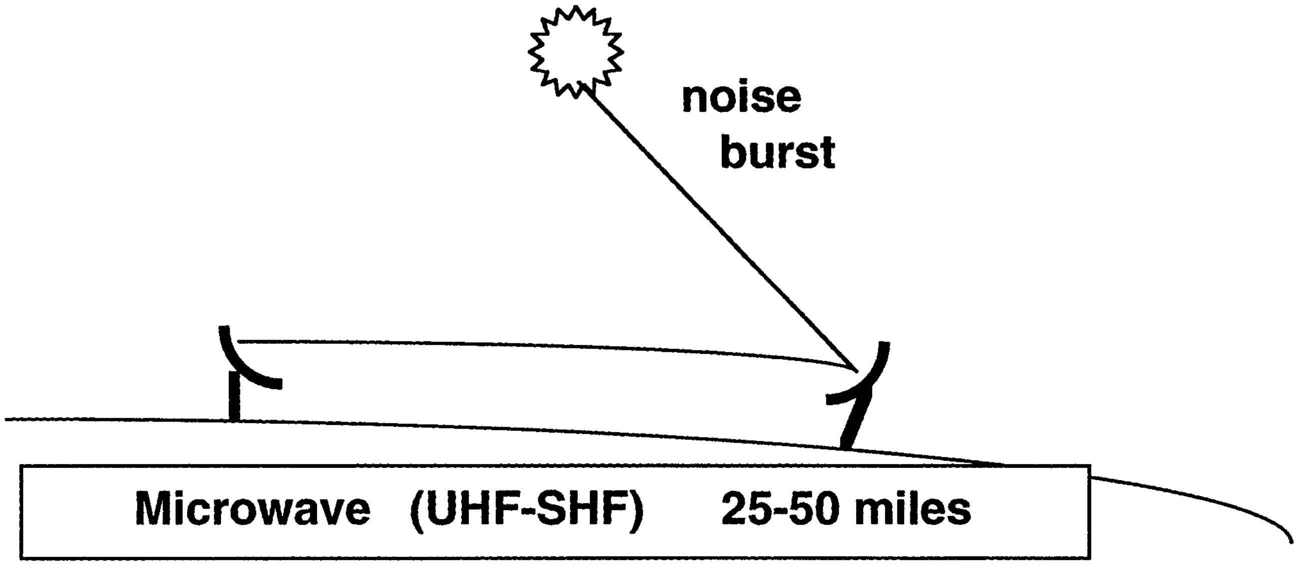
• **Solar Radio Bursts.** Radio wavelength energy is constantly emitted from the sun; however, the amount of radio energy may increase significantly during a solar flare. These bursts may interfere with radar, HF (5-20 MHz) and VHF (30-200 MHz) radio, or satellite communication systems. Radio burst data are also important in helping to predict whether we will experience the delayed effects of solar particle emissions.





Satellite Communications (VHF-UHF-SHF)

Systems in the VHF through SHF range (30 MHz to 30 GHz) are susceptible to interference from solar radio noise. If the sun is in the reception field of the receiving antenna, solar radio bursts may cause Radio Frequency Interference (RFI) in the receiver, as depicted in the types of communications systems depicted.

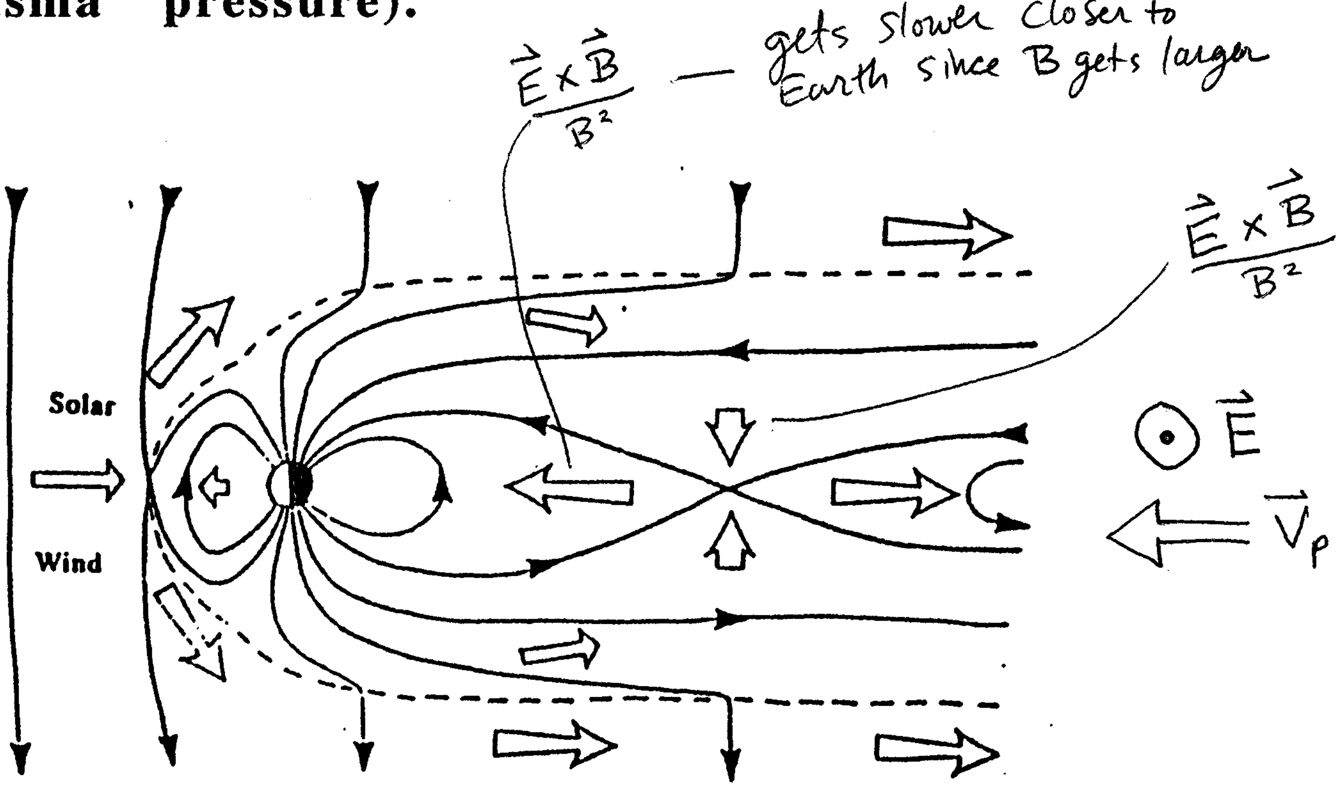


SUBSTORMS

- Recall that coupling between the magnetosphere and solar wind is considerably more efficient during southward IMF ($B_z < 0$) than northward IMF ($B_z > 0$), simply because of the way that magnetic merging occurs in the dayside magnetosphere. A reminder of this process for $B_z < 0$ is shown on the following page.

- During extended periods of northward IMF, the magnetosphere is usually in a quiescent state, unless discontinuities in the solar wind impulsively impact the magnetosphere. In this case there is sure to be an impulsive response of some significance; but the exact scenario through which this occurs is not very well established for $B_z > 0$. We will concentrate on those "storm" events for which $B_z < 0$.

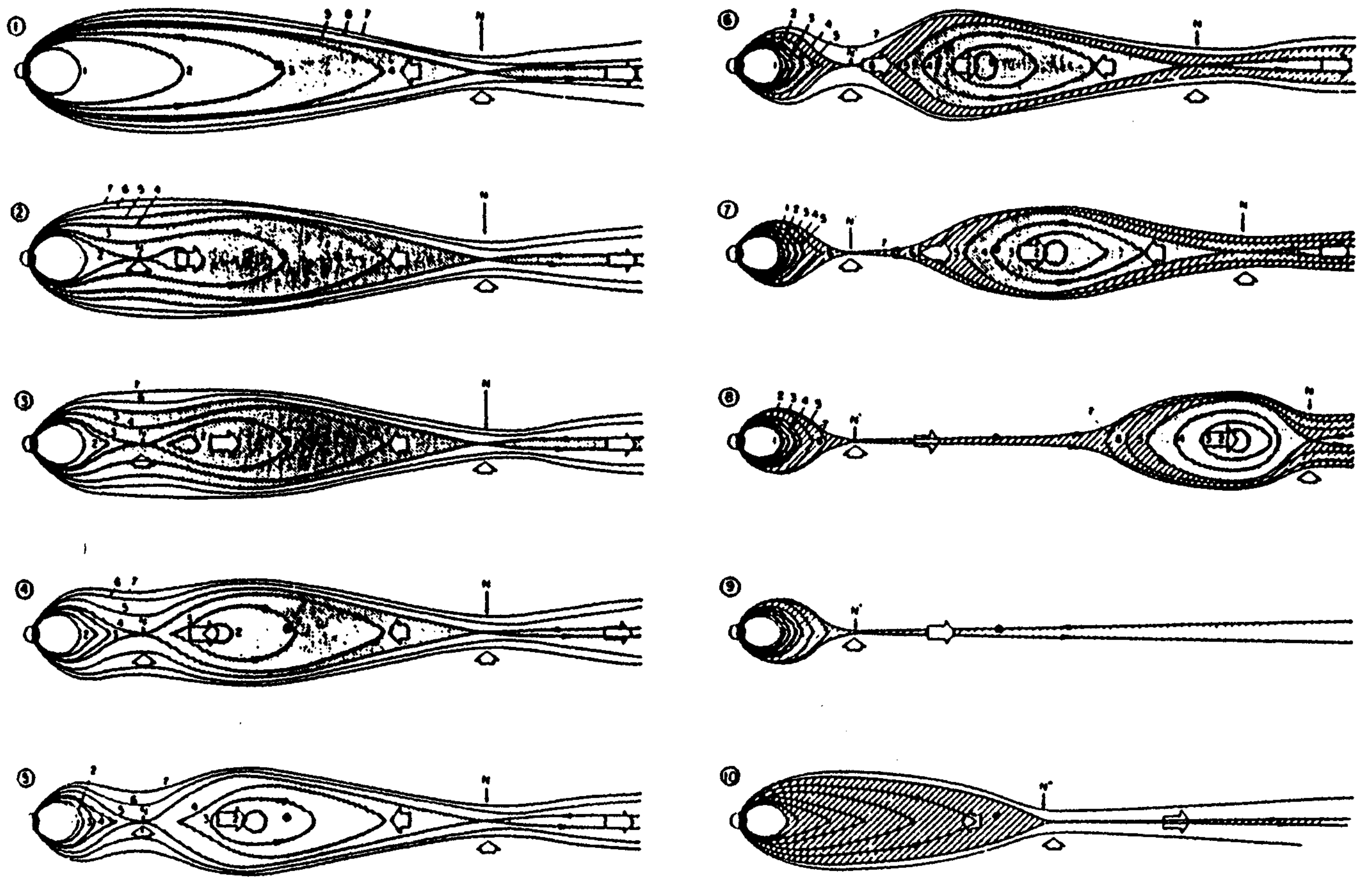
At a <u>southward turning of the IMF</u>, merging on the dayside, day/night transfer of magnetic flux, and reconnection on the nightside are increased. The system is no longer in equilibrium. Potential energy, in the form of stored magnetic flux, builds up in the tail. This leads to a thinning and pinching of the plasma sheet due to the enhanced magnetic flux (now overpowering the plasma sheet plasma pressure).



• This neutral point in the tail now occurs much closer to earth. This buildup occurs over about 1/2 - 1 hour, and is called the initial phase of the substorm. At some point this energy becomes released; particles trapped on the now-closed field line are accelerated and precipitate into the auroral regions; currents flow down the field lines and feed the auroral electrojet; particles are accelerated into the ring current (causing the depression in Dst); and a plasmoid is ejected out the magnetotail (see following figure).

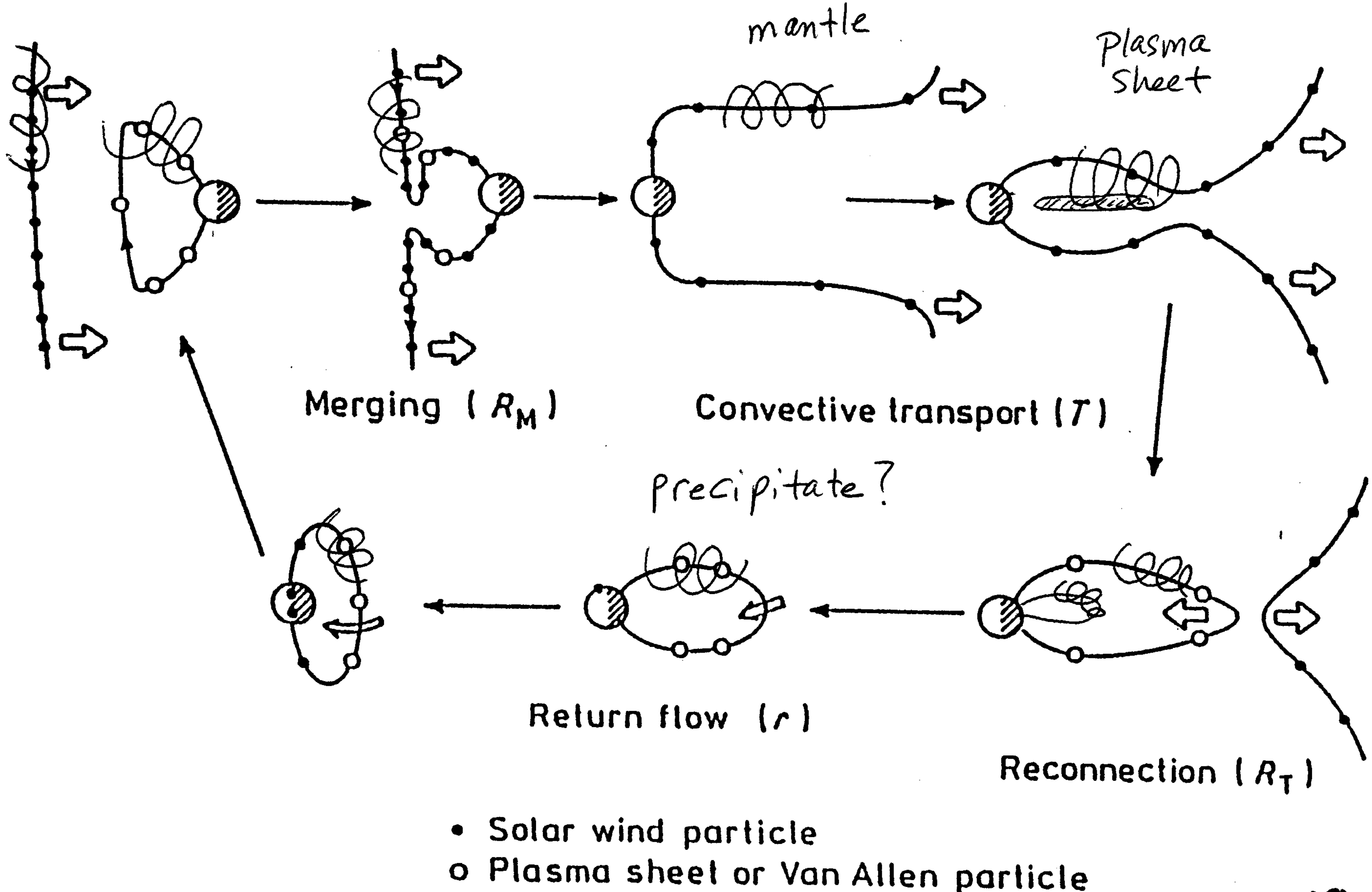
• The flow of current through the ionospheric circuit is completely consistent with the collapse of the tail at the neutral point; the latter can only occur if the cross-tail current is substantially reduced, as it is when being diverted along the field lines into the ionosphere.

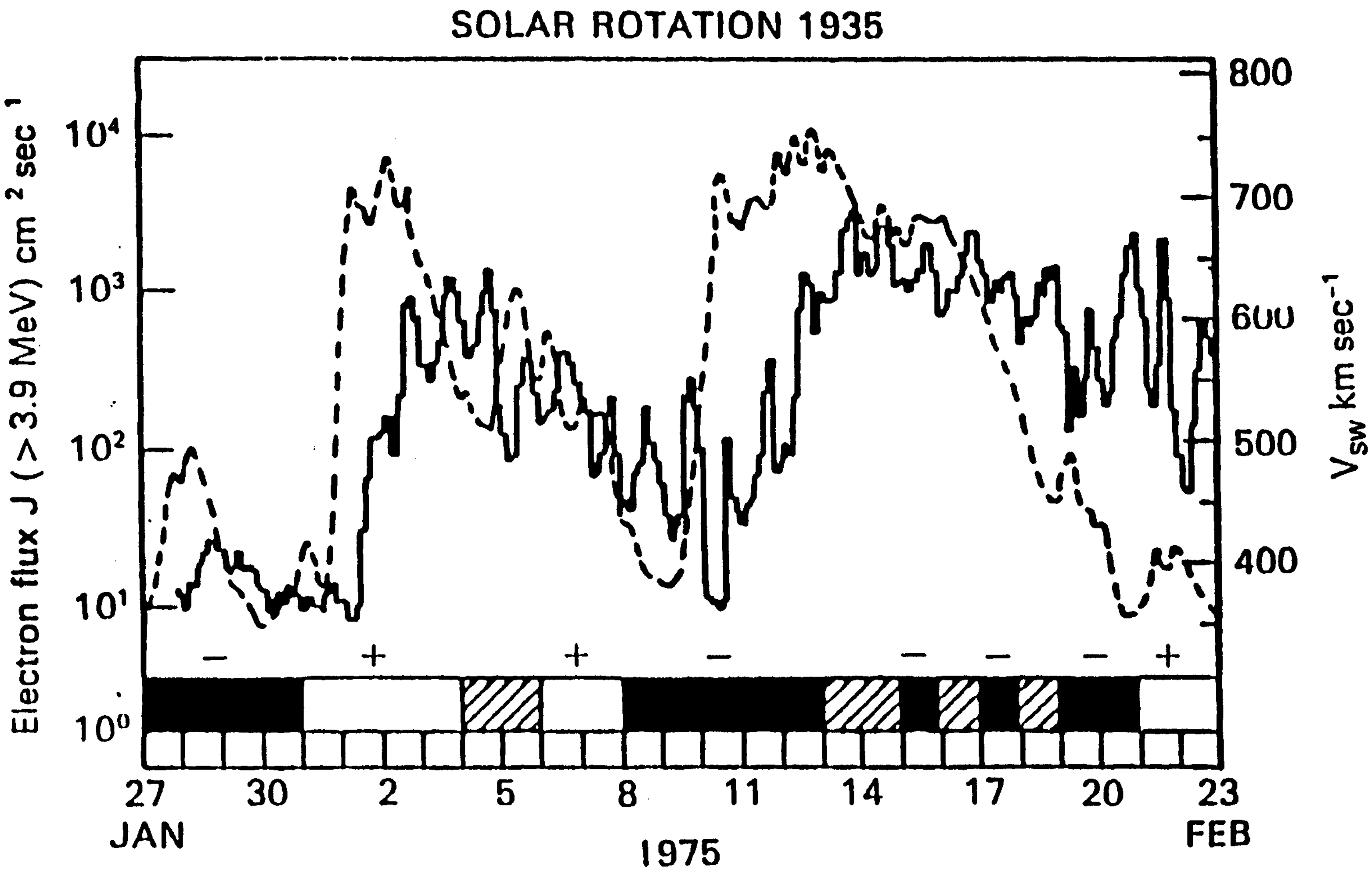
• When the IMF turns northward the rate of flux transfer decreases abruptly. If the IMF remains northward for a considerable time, the potential energy stored in the tail is slowly dissipated and the magnetosphere returns to a quiescent state.



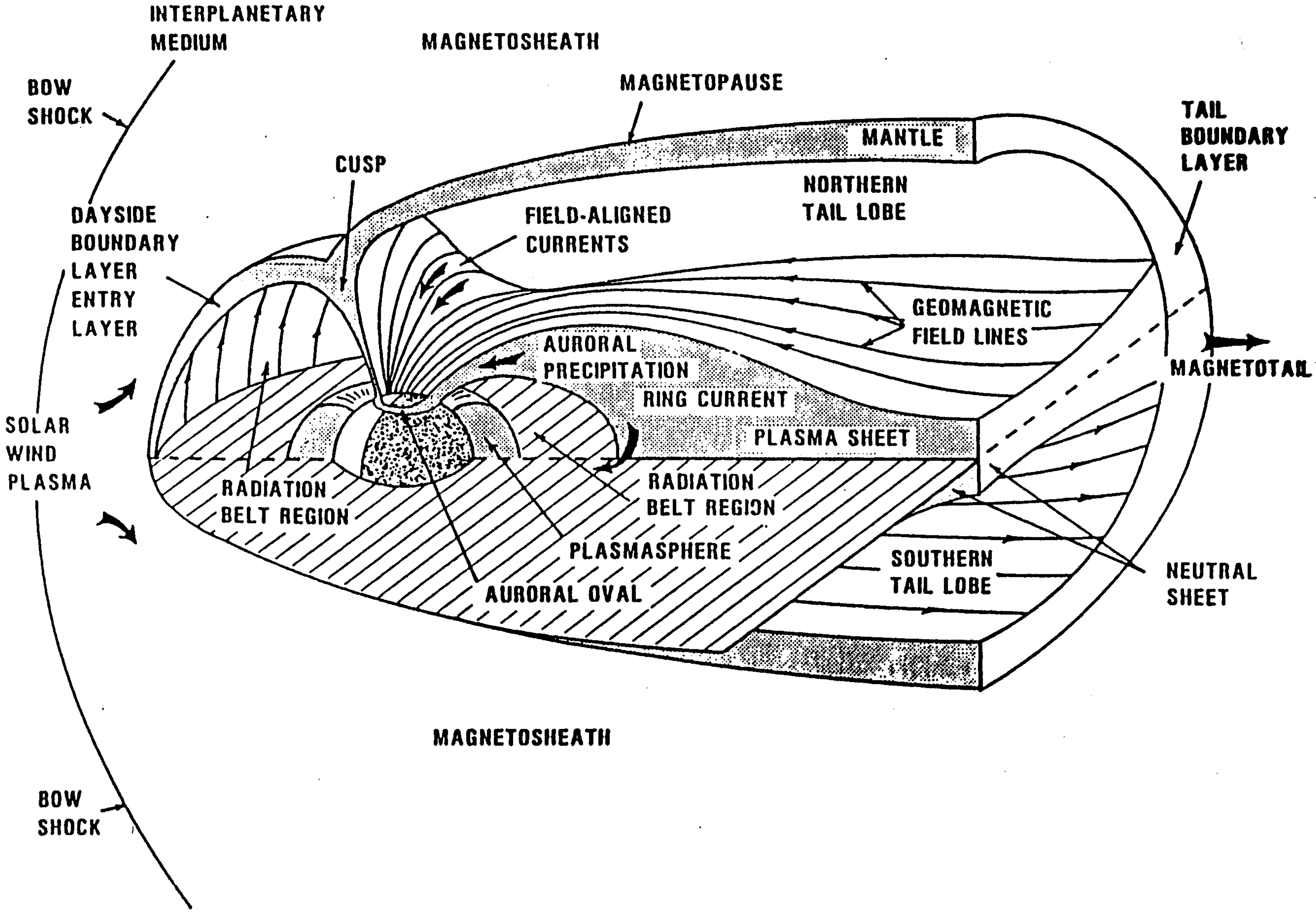
Sequence of events in the magnetotail during a substorm. White arrows indicate plasma flows. The plasma sheet is bounded by field-line 5. N′ is the second neutral line that forms in the substorm, and picture 8 shows the plasmoid being expelled down the tail. (E. W. Hones, in *Magnetic Reconnection* (ed. Hones). A.G.U. Monograph 30, 1984)

Particle Transfer

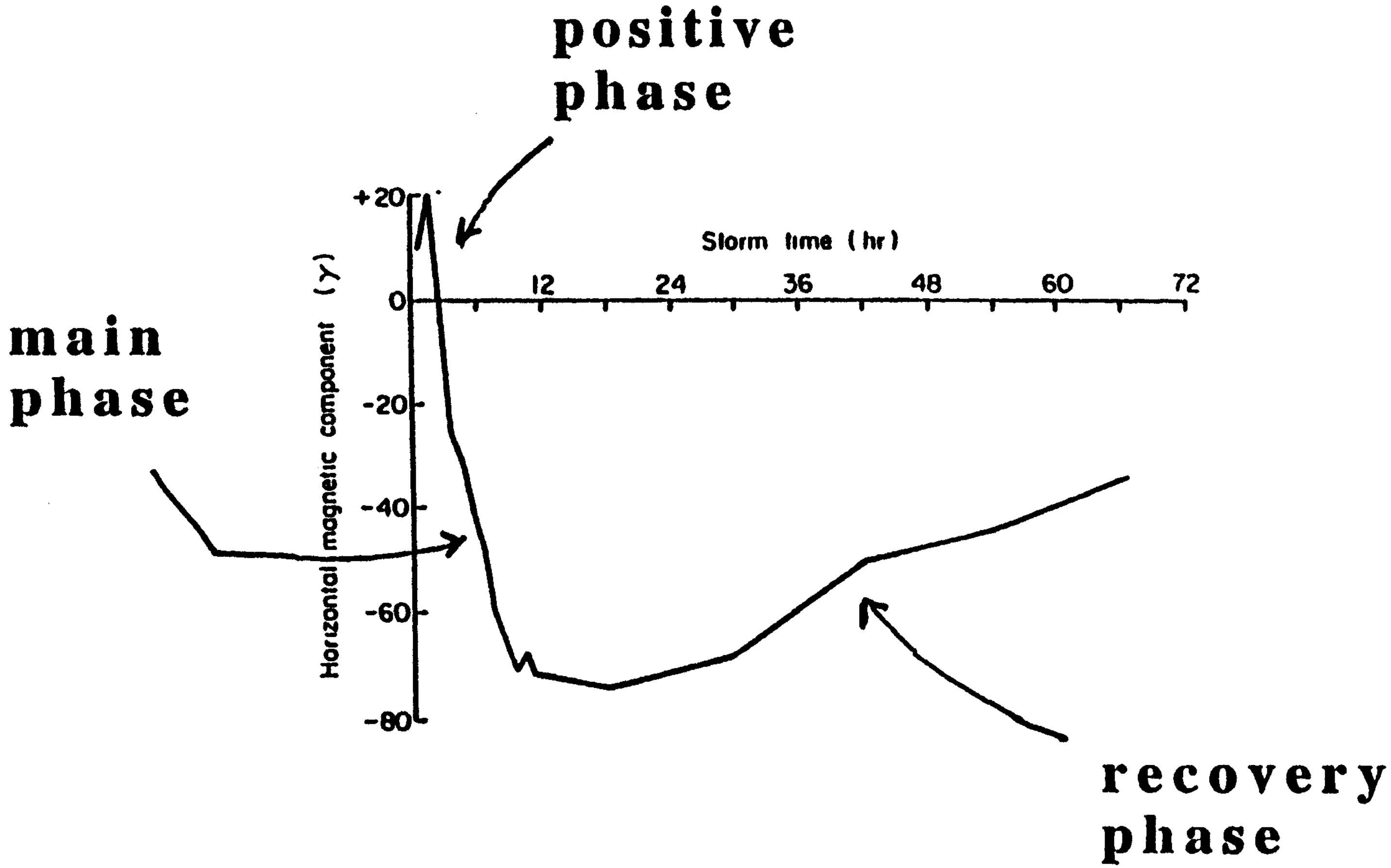




Flux of energetic electrons (solid line) at synchronous orbit and solar wind velocity (dashed line) during one solar rotation. The IMF sectors are indicated. (G. A. Paulikas and J. B. Blake, in *Quantitative Modelling of Magnetospheric Processes* (ed. Olsen). American Geophysical Union, 1979, p. 180)



Cross section of the magnetosphere. For a quiet magnetosphere, geostationary altitudes are between the plasmasphere andplasma sheet (nighttime), and between the plasmasphere and dayside boundary layer (daytime). During active geomagnetic periods, geostationary satellites may become engulfed by the inward moving nighttime plasma sheet, and may pass through the daytime boundary (entry) layer *(after National Research Council, 1981).*



$$H^{+} + H \longrightarrow \underset{\text{(hot)}}{H} + H^{*}$$

dissipation of ring current energy

- However, the plasmapause boundary is very dynamic, and varies between about 3 to 6 R_E, sometimes getting as low as 2 R_E.

- Although not depicted as such in the previous figure, note that the plasmasphere overlaps with a considerable part of the radiation belt region. However, these represent two entirely different particle (energy) populations.

- Now, the co-rotating plasmasphere sets up a "co-rotation" electric field:

$$\vec{E} = -\left(\vec{\Omega} \times \vec{R}\right) \times \vec{B}$$

- Outside the plasmapause the plasma is not co-rotating, and the circulation there is determined by the cross-tail potential.

- Essentially, the plasmapause represents the boundary where these two electric fields are of the same order:

$$E_T \sim \frac{B_E}{L^3} L R_E \Omega$$

where B_E = equatorial magnetic flux density at the surface, L = distance in R_E, and R_E = radius of earth.

- Putting in numbers,

$$E_T \sim \frac{14.4}{L^2} \text{ mVm}^{-1}$$

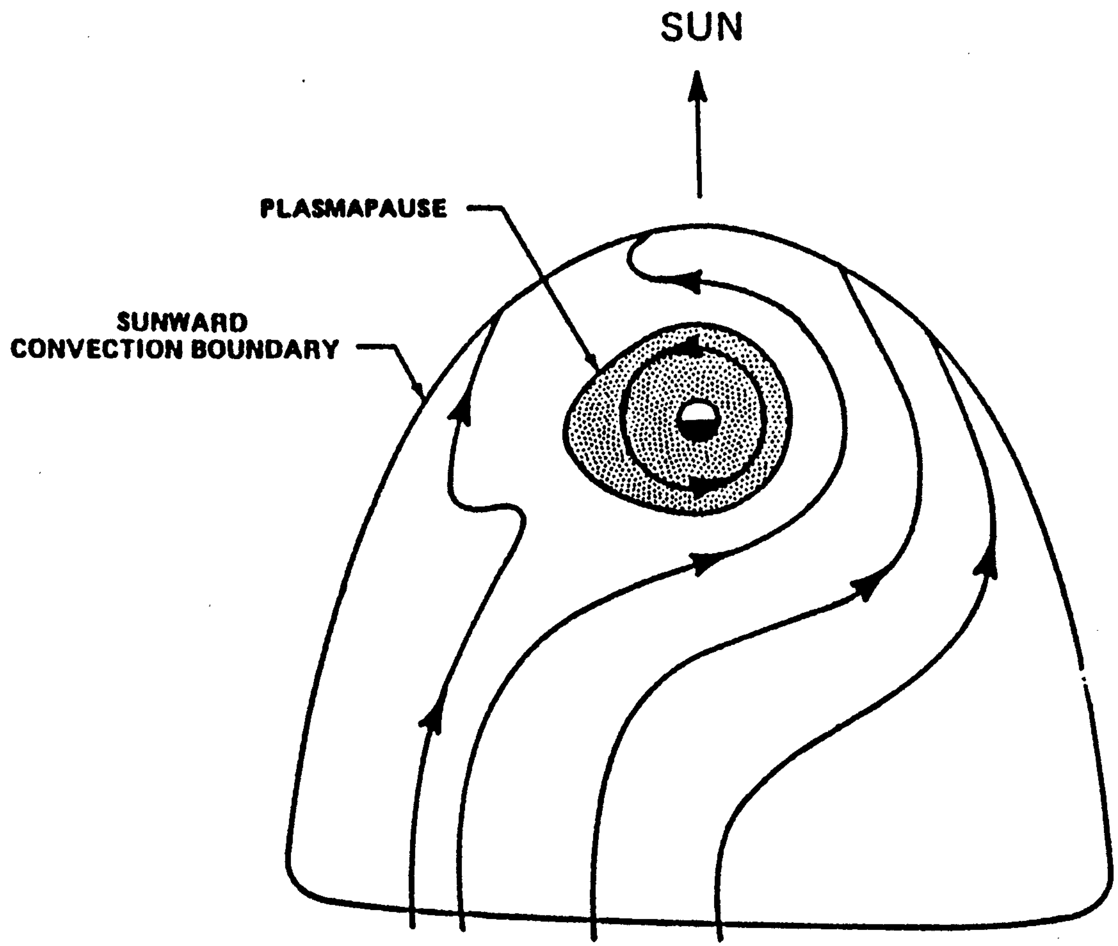
$\sim$ 1 mVm^{-1} at 4 R_E

- Put another way, the plasmapause represents the boundary between the "inner magnetosphere" and "outer magnetosphere" plasma circulation patterns. The former is co-rotating, and the latter is strongly influenced by the solar wind interaction (see following figure):

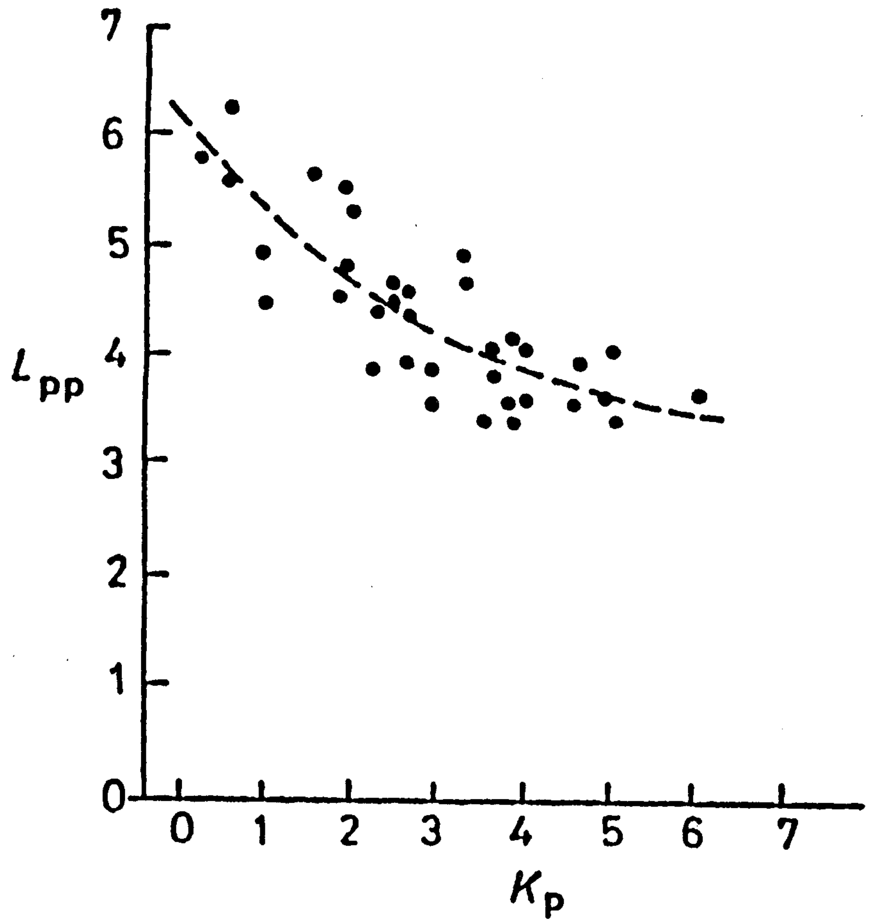
- Viewed this way, one expects intensification of the outer magnetospheric circulation to lead to a contraction of the plasmasphere (inward movement of the plasmapause). This indeed happens (see subsequent figures).

- In fact, it is thought that the intensified outer circulation leads to a peeling off of outer layers of the plasmasphere, which are then lost as detached plasma chunks in the magnetotail and solar wind.

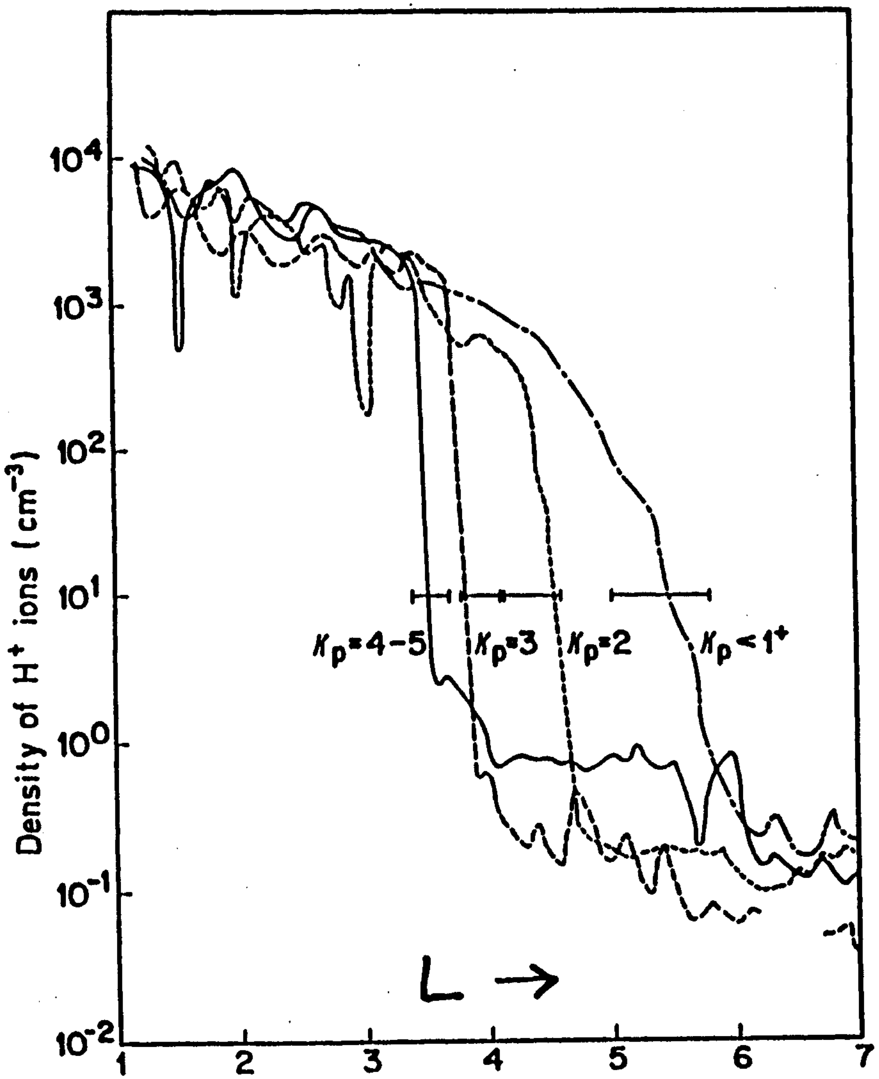
Daily variation of the plasmapause in relation to plasma convection in the magnetospheric equatorial plane



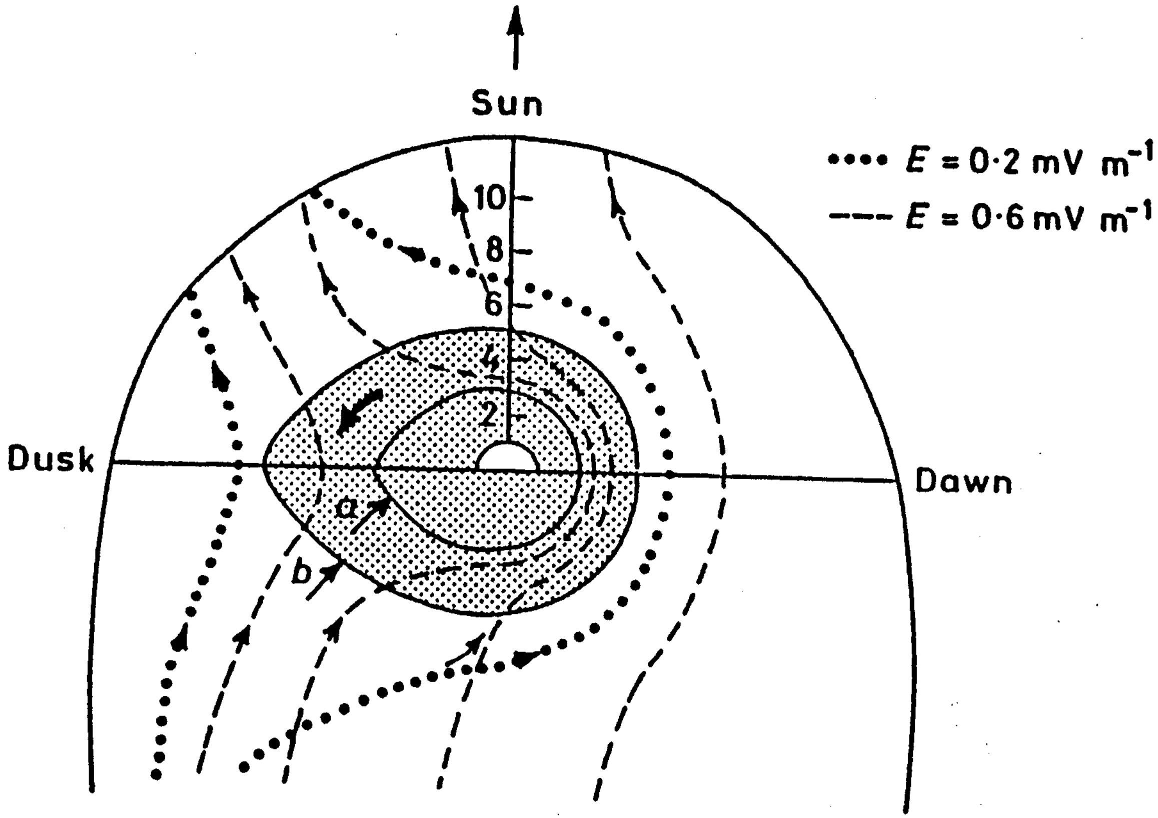
Satellite observations of ion density, showing the plasmapause at several Kp levels



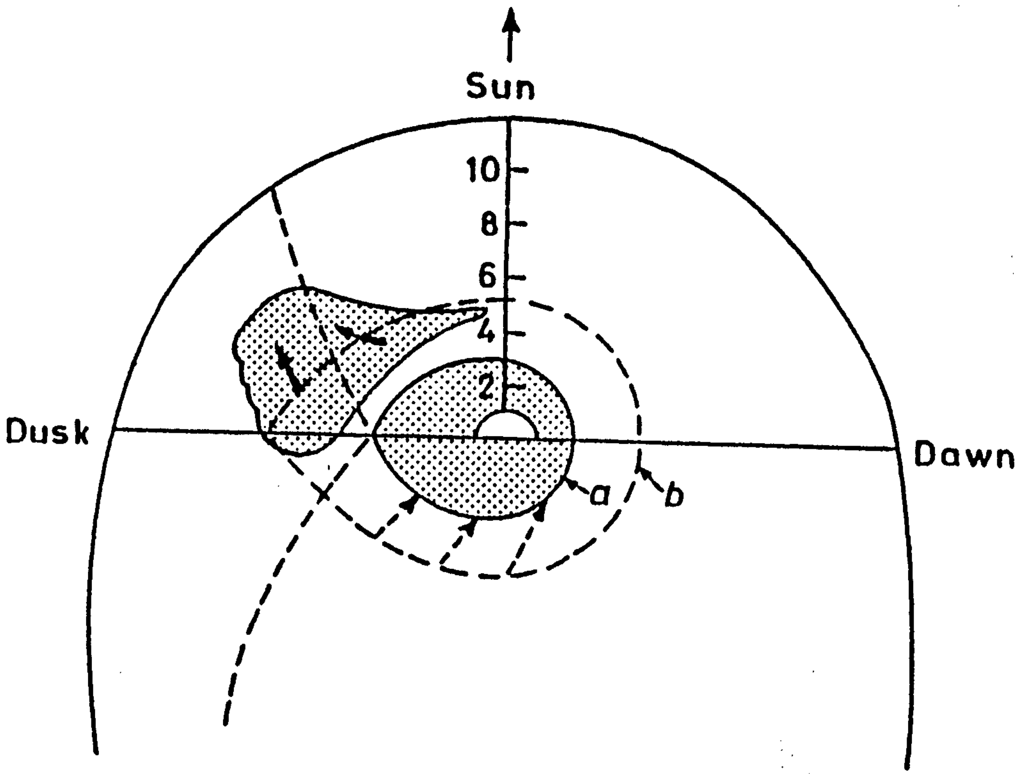
Relationship between plasmapause distance and Kp



Flow patterns for cross-tail fields of 0.2 and 0.6 mV/m



Detaching of plasma due to changing flow patterns during a magnetic storm

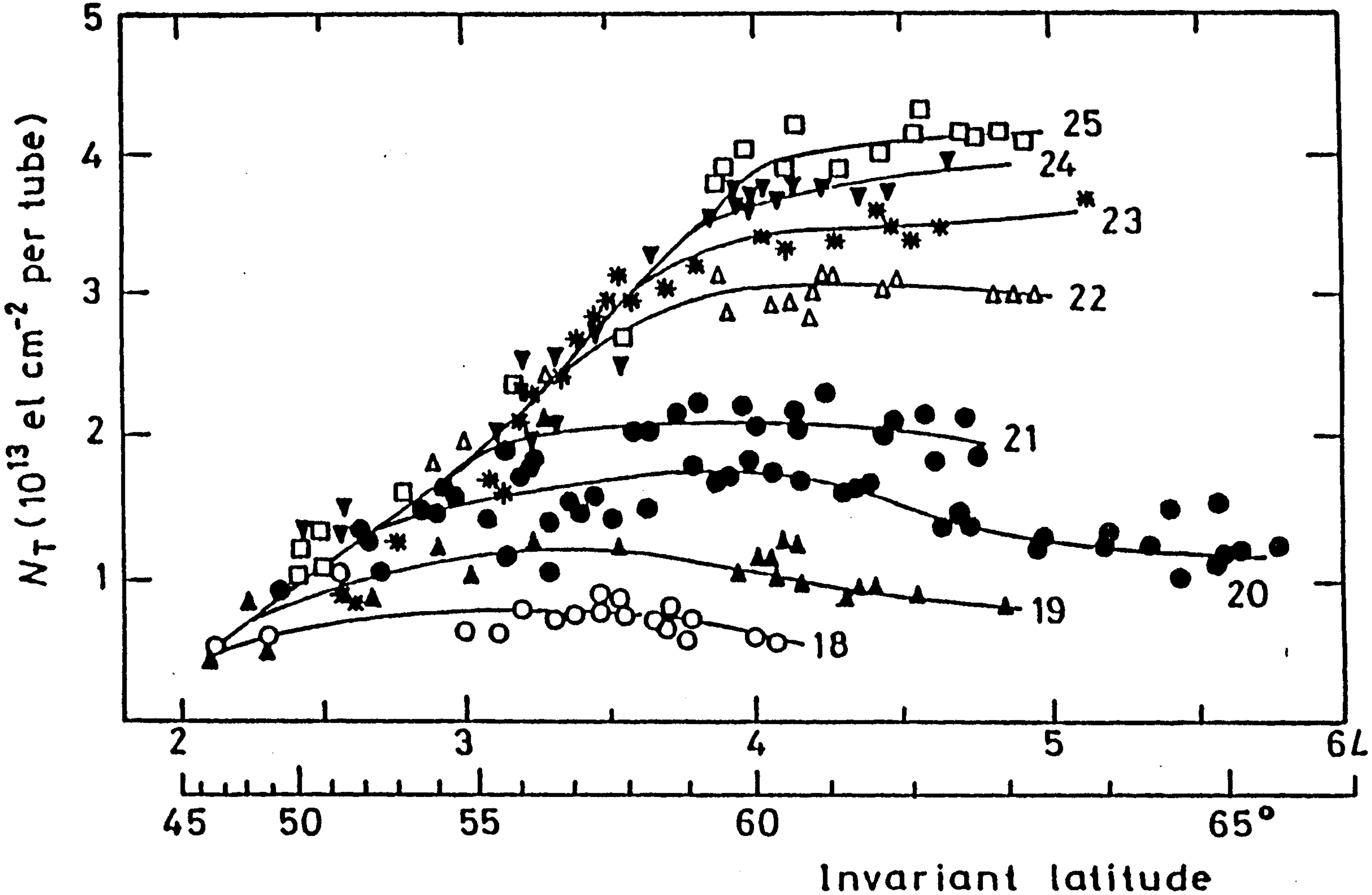


- With the decay of magnetic activity, the magnetospheric circulation and electric fields return to their previous state but now the outer tubes of magnetic flux are devoid of plasma.

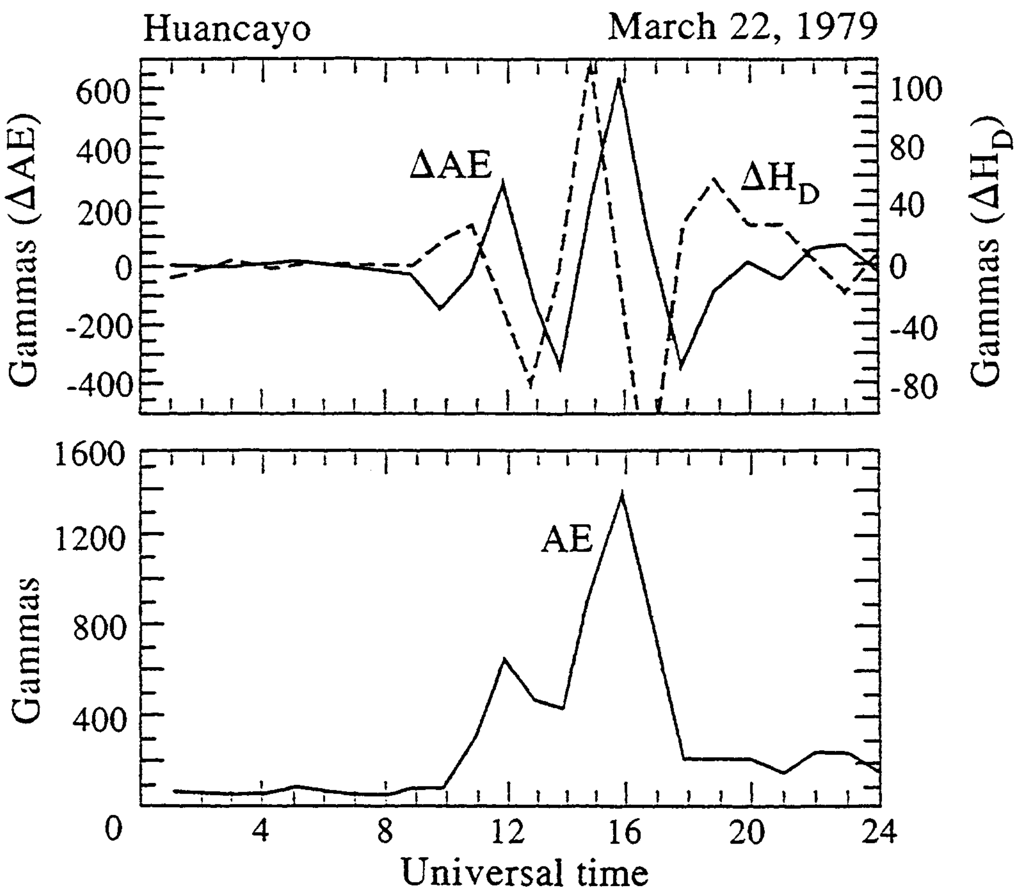
- These gradually refill from the ionosphere over a period of days.

- The rate of filling is determined by the diffusion speed of protons (formed in the upper ionosphere by charge exchange between hydrogen atoms and oxygen ions) coming up along the field, and by the volume of the flux tube which varies as L^4. It therefore takes much longer to refill tubes originating at higher latitude.

- Observations of the filling are shown in the following figure. Since active periods may recurr every few days there will be times when the outer tubes are never full and the plasmasphere has some degree of depletion.



Refilling of the plasmasphere after a storm, 18–19 June 1965. The measurements are of the electron content between conjugate points as a function of L value, by the whistler technique. The content is almost independent of L while the tube is filling, whereas the content of full tubes increases strongly with L. (After C. G. Park, *J. Geophys. Res.* 79, 165, 1974, copyright by the American Geophysical Union)



Top panel: ΔH_D and ΔAE during 22 March 1979.
Bottom panel: AE index during 22 March 1979.