Time-Varying Reconnection

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GEM, Snowmass

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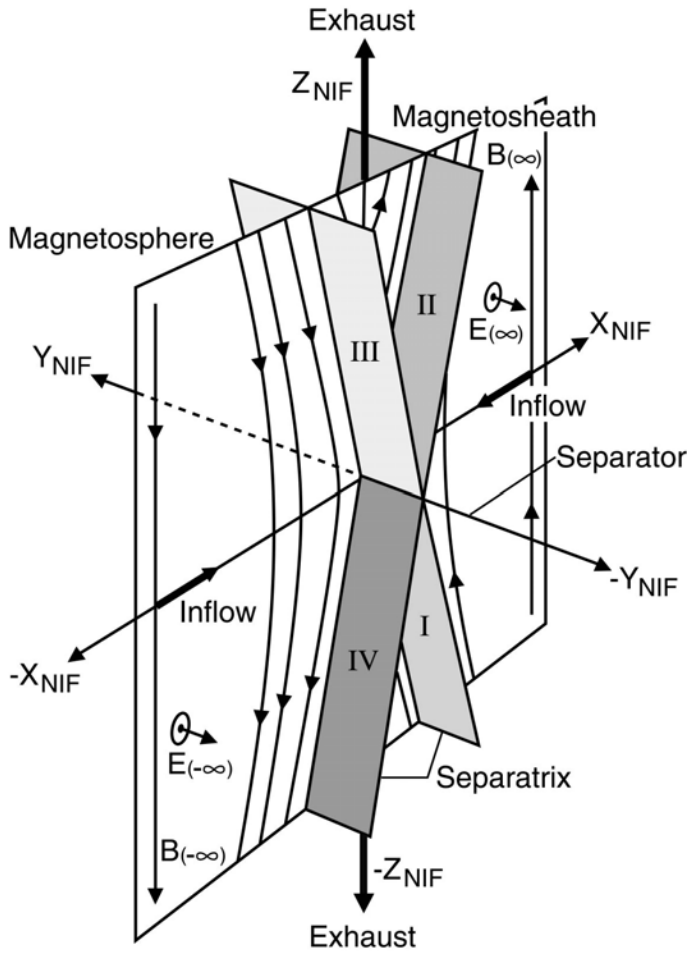
Reconnection: What is it?

Definition

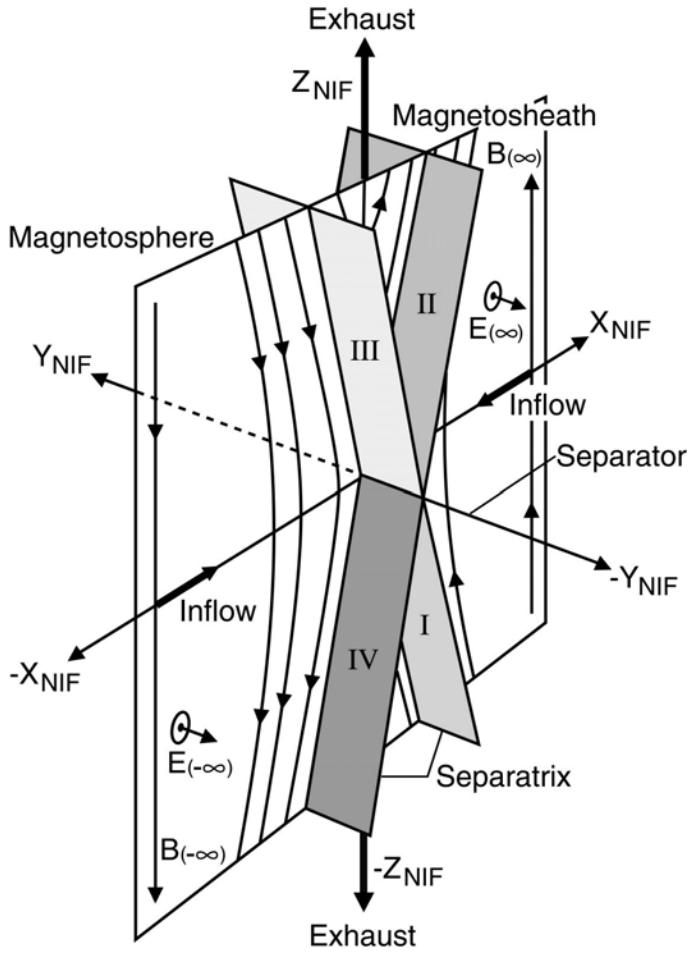
- Reconnection is the process whereby plasma flows across a surface that separates regions containing topologically different field lines. The potential drop along the neutral line, VBL, is the rate of reconnection.



Reconnection: Why do we need it?

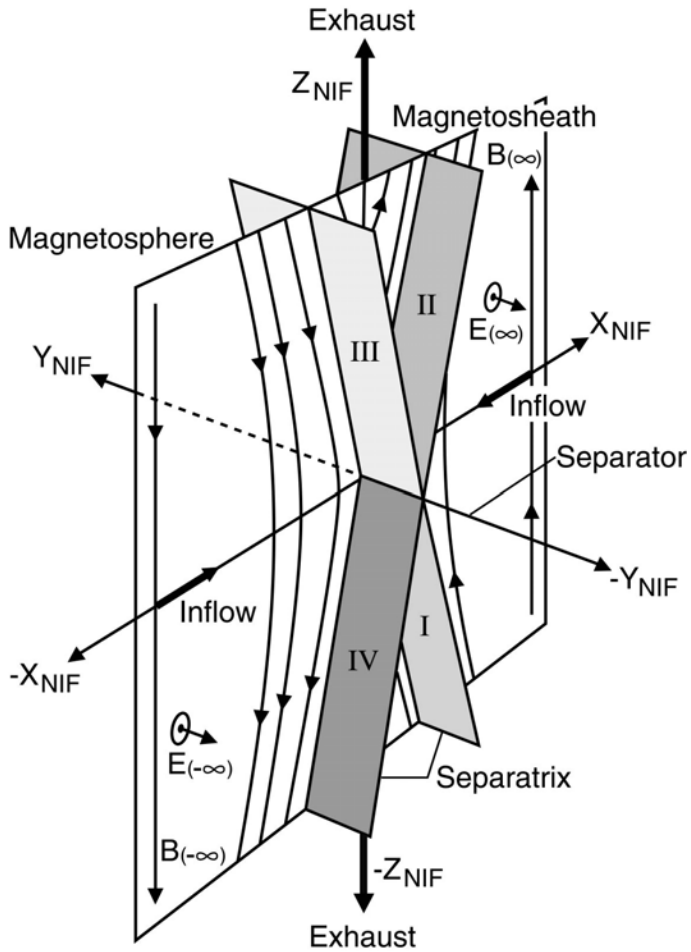
Effects

- Rapid release of energy stored in the magnetic field
- Coupling of fields of different topology enabling transfer of momentum and energy across boundaries

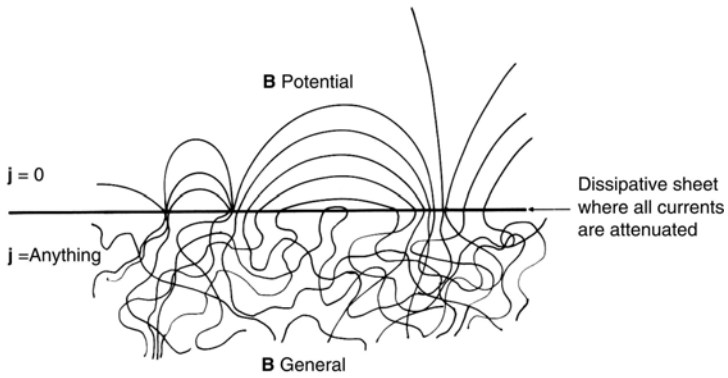


Reconnection: What controls it?

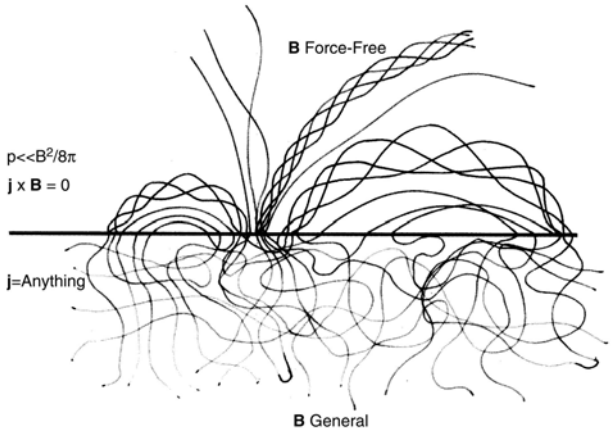
- Arguably the most important example of cross-scale coupling in collisionless plasmas
- Manifestation of the kinetics underlying fluid behavior in magnetized plasmas
- Geometry is important. Problem is to move plasma away from the neutral point so the process can continue
- Diffusion or “frozen-in-flux violation” occurs at x-point but MHD waves provide deflection and acceleration
- Dimension perpendicular to x-plane can adjust to control rate
- Opening angle can also affect flow



Early Motivations and Motivators 1



Gold [1964]



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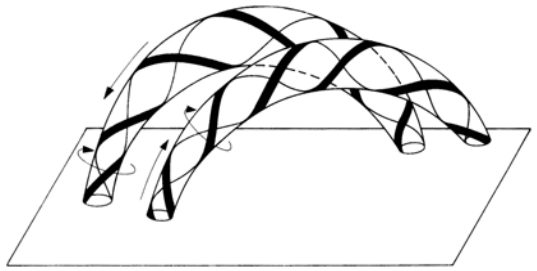
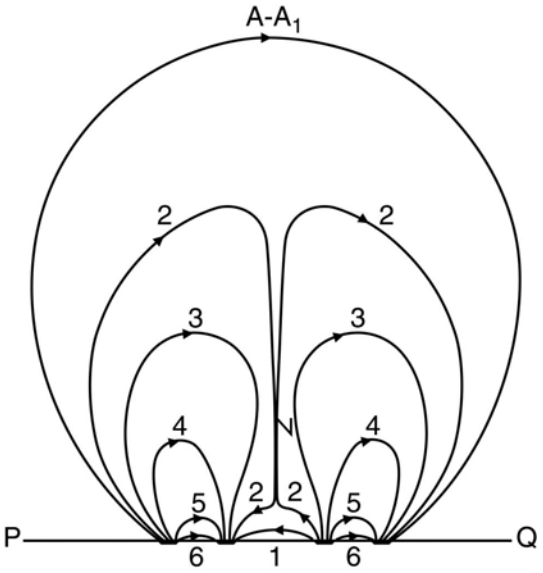


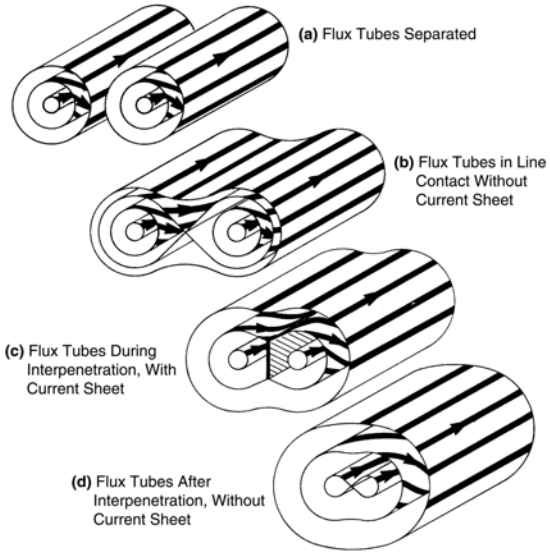
Gold and Hoyle [1960]

- Solar flares represent an enormous rapid release of energy
- The most logical (at the present time) source for that energy is the solar magnetic field
- Tom Gold and Fred Hoyle had surprisingly accurate concepts of the magnetic field in the photosphere and lower corona
- Ron Giovanelli(1947) suggested that neutral points were important

Early Motivations and Motivators 2



Sweet (1958)



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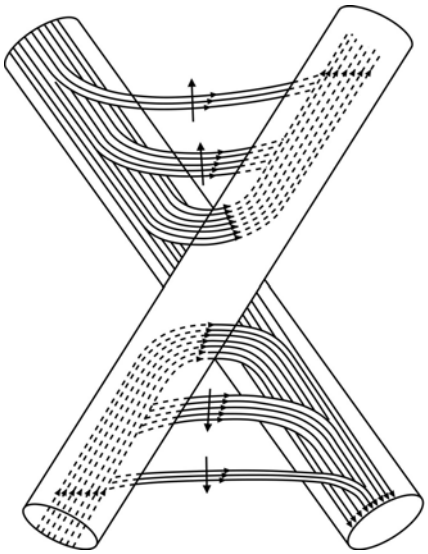
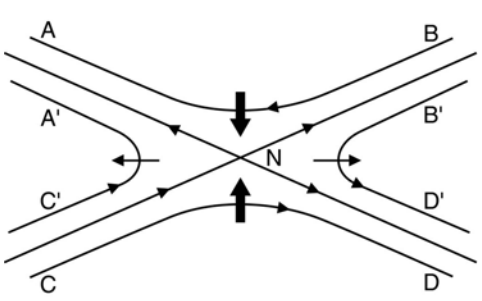


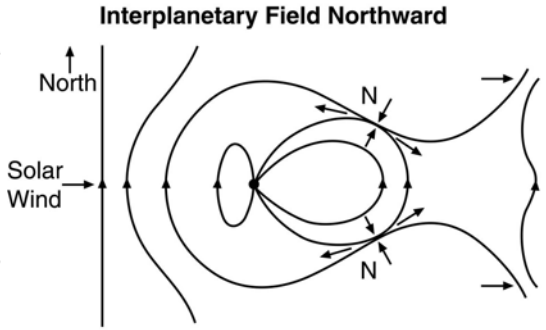
Parker (1957)

- Peter Sweet examined the diffusion across a simple current sheet
- This current sheet would of course arise in colliding flux tubes, even if the tubes were not aligned

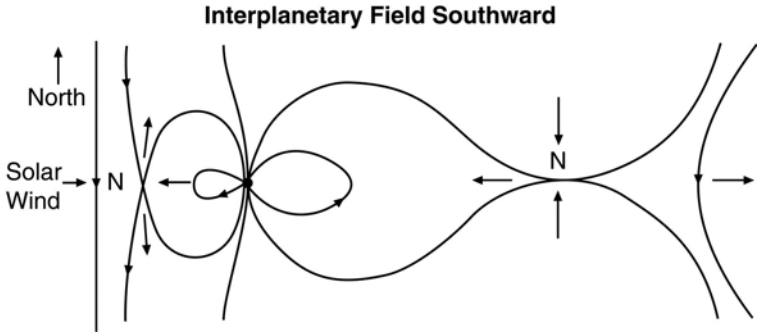
Application to the Magnetosphere



Dungey (1958)



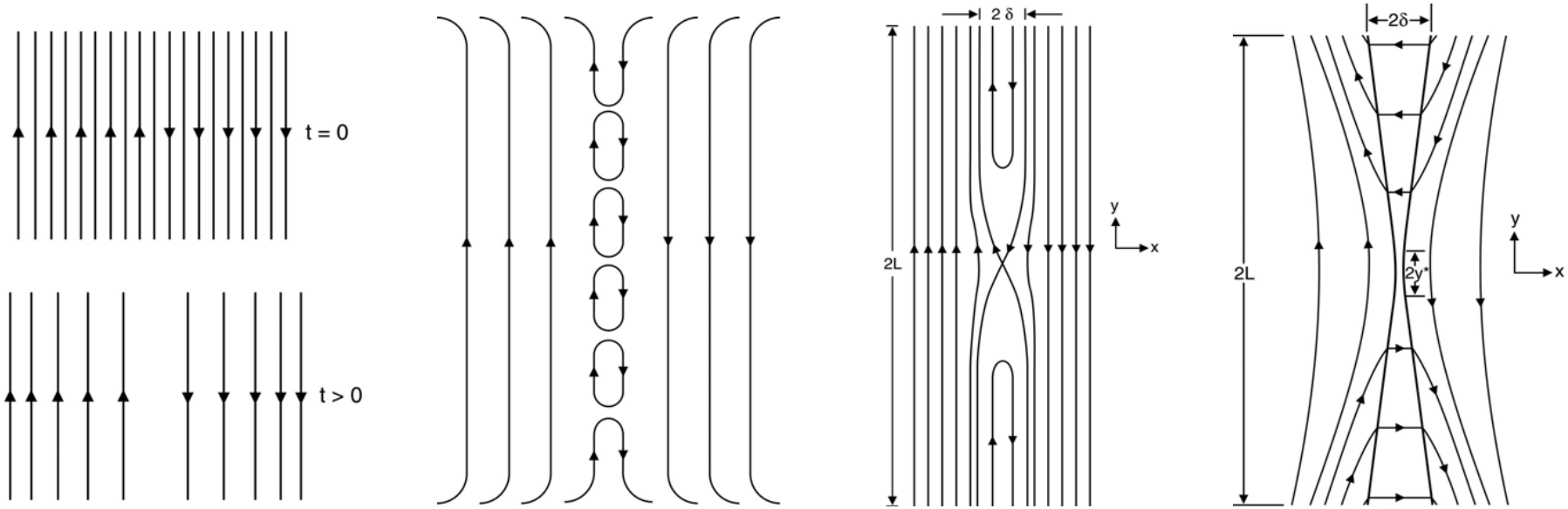
Dungey (1963)



Dungey (1961)

- Fred Hoyle assigned Jim Dungey the task of developing the theory of reconnection and applying it to the aurora as a Ph. D. project
- Jim Dungey focused on neutral lines (and neutral points) rather than sheets, realizing that partner swapping was the important process that could be accomplished in many ways
- Jim graduated and went to post-doc with Giovanelli in Sydney. He submitted his work to MNRS in 1951 and was rejected (Cowling?); revised and resubmitted to Philosophical Magazine (1953) [<200 citations]
- Sitting in a sidewalk café in Montparnasse prior to giving a seminar Dungey finally solved the conceptual problem Hoyle had given him and wrote it up (Dungey, 1961) [>1300 citations]

Current Sheets versus Neutral Lines

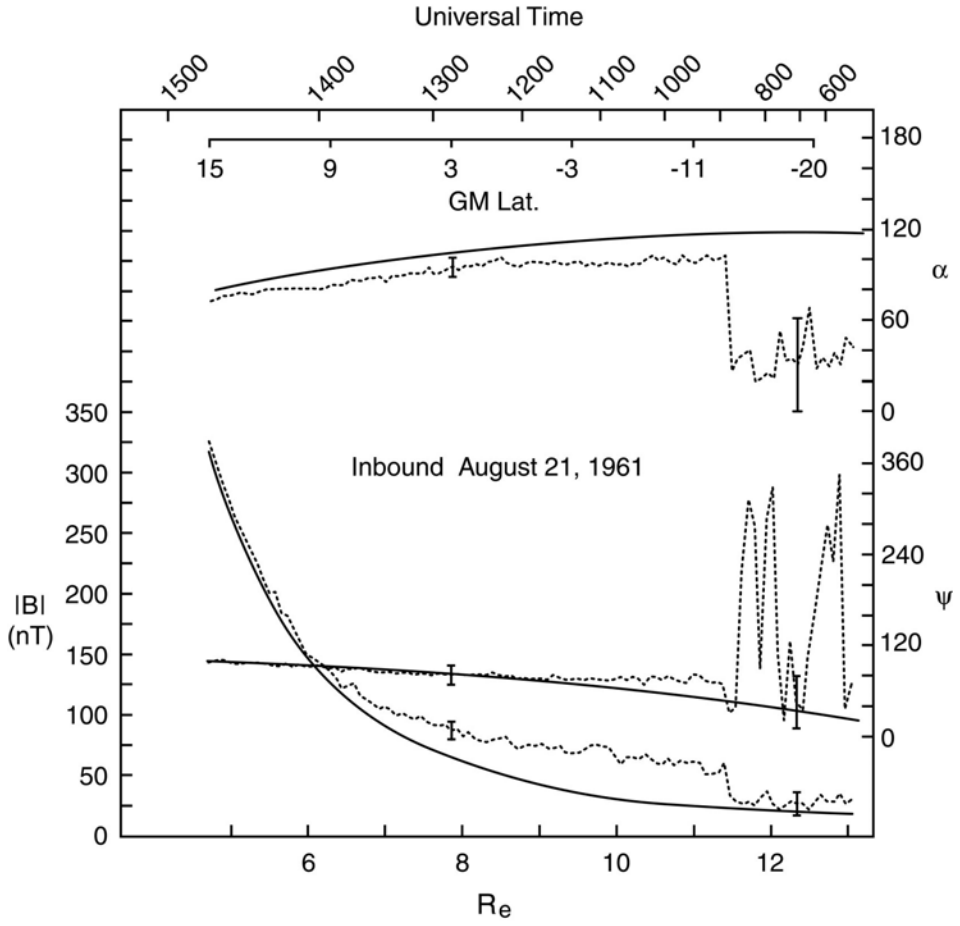


Diffusion | Jaggi (1964) | Parker (1963) | Petschek (1964)

- While Dungey had jumped to the importance of neutral points and lines, the majority in the solar community were toiling over how to speed up reconnection in a sheet
- Diffusion took too long and making the diffusion region smaller by tearing islands or limiting the size of the diffusion region did not help much
- Harry Petschek was the first to show that MHD waves in an x-line geometry would achieve the rates observed to occur

Space Age: In Situ Observations Begin

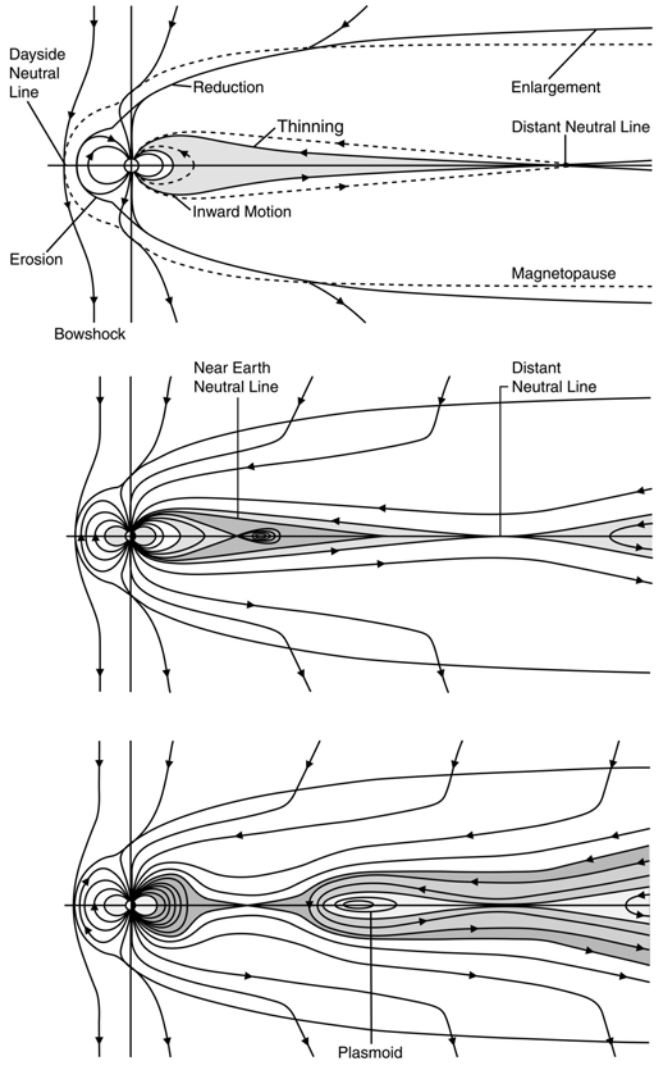
- Launch of Explorer 12 in 1961 into a 13.1 R_E apogee orbit allowed regular sampling of the magnetopause for 4 months
- Jim Dungey asked his graduate student, Don Fairfield, to compare the north-south component of the magnetic field in the magnetosheath with geomagnetic activity
- Fairfield found that a southward field corresponds to ground level disturbances and a northward field with quiet conditions. Concludes Dungey model is most plausible explanation
- Digitization of magnetometer data (± 12 nT) too large to resolve fine scale field at magnetopause. Motion of boundary also a problem



Cahill and Patel (1967)

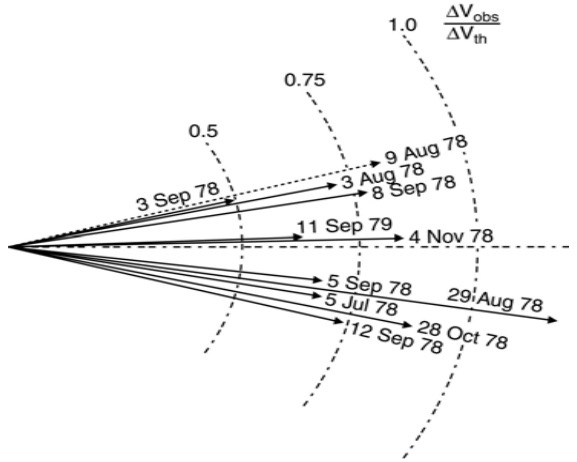
Erosion of the Magnetopause and Flaring of Tail

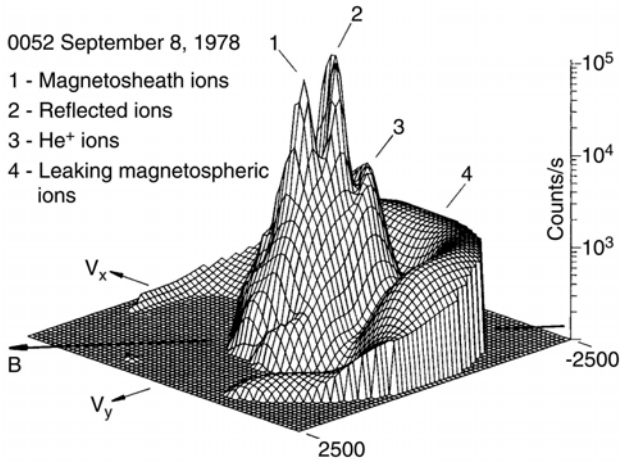
- The Orbiting Geophysical Observatories had annual launches from 1964-1969 with 1, 3, and 5 going to about 23 RE. OGO5 produced much data
- The advent of simultaneous solar wind measurement on Explorer 33 and 35 enabled the UCLA group to study how the magnetopause and tail responded to southward and northward IMF
- When the IMF turned southward, the magnetopause moved in on the dayside and outward on the nightside, verifying Dungey's predicted transport
- Substorms returned the flux to the dayside so they too were caused by reconnection
- A key point is that a neutral point forms on closed field lines in the plasma sheet. This creates a magnetic island or plasmoid that is explosive when reconnection reaches open field lines



Flows Associated with Reconnection at Magnetopause

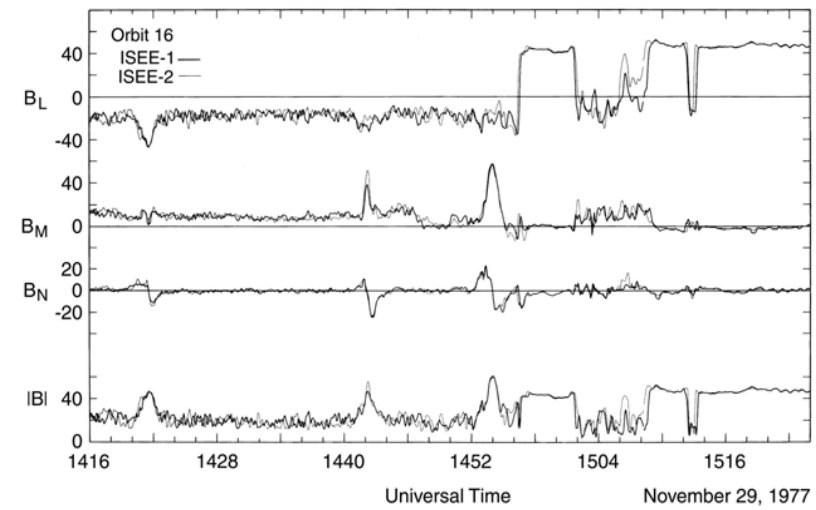
- ISEE 1 had a hot plasma detector that could measure the flow along the spin axis, the direction of the expected flow from reconnection
- The expected flows were observed [Paschmann et al., 1979] and were shown to be steady [Sonnerup et al., 1981] and to have the expected speed
- Some concern that diffusion region was not positively identified but it probably passes very quickly compared to the sample rates of the plasma instruments
- Polar was a single spacecraft but had much improved sampling of the plasma. Scudder et al (2002) have found credible diffusion regions
- Cluster now probing high latitude magnetopause; eventually the Magnetospheric Multiscale mission will probe the subsolar region

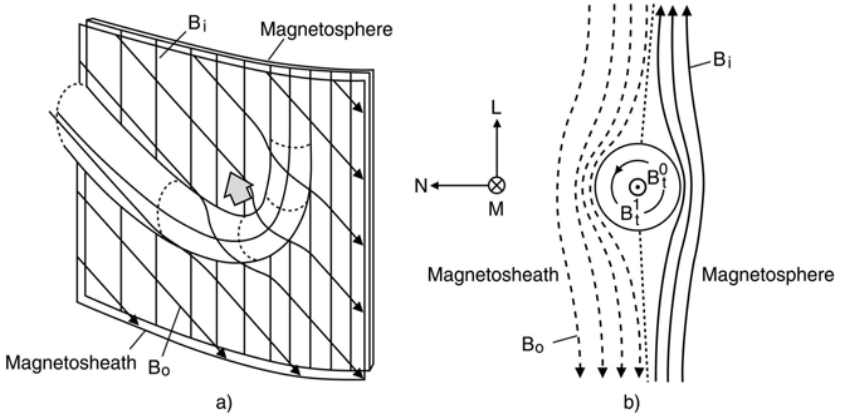




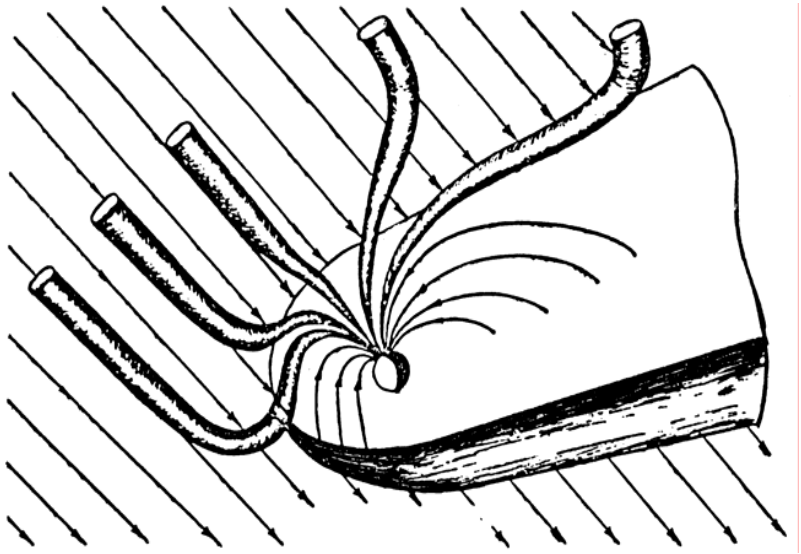
Flux Transfer Events

- In 1977 the co-orbiting ISEE 1 and 2 spacecraft allowed us to measure the velocity of motion of the magnetopause and to distinguish stationary from time-varying features
- Moving flux tubes were found on the magnetopause at low latitudes by ISEE and at high latitudes by HEOS-1
- These were interpreted in terms of time-varying reconnection
- Recent simulations by Raeder suggest that their formation is dependent on dipole tilt

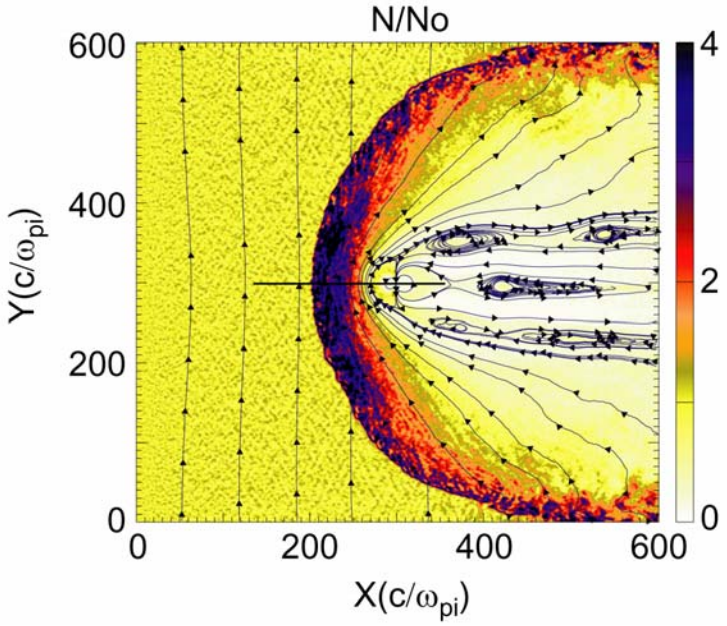




Flux Transfer Events at Mercury



Interpretation of Mariner 10 Observations

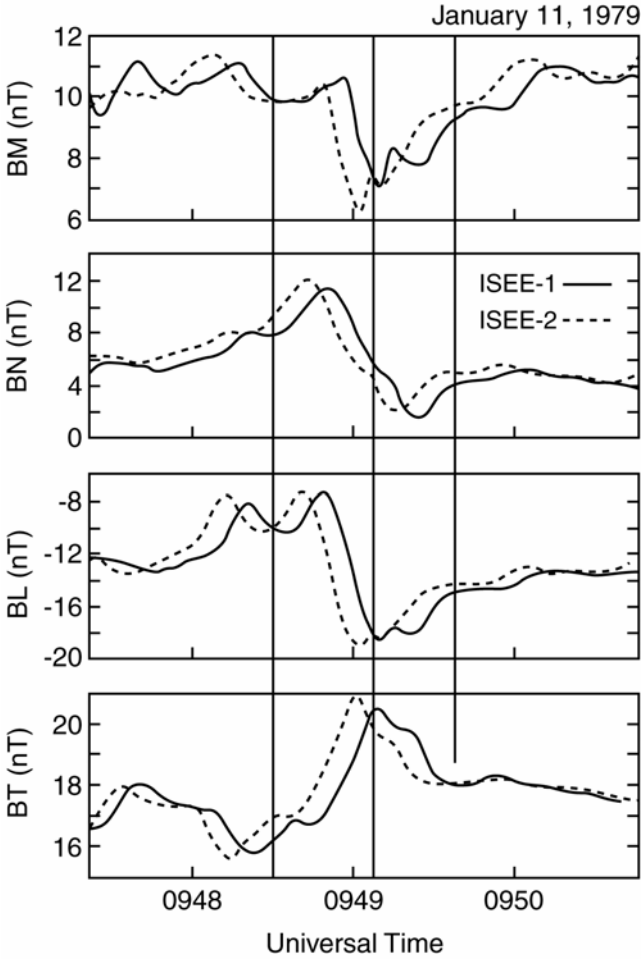


Hybrid Simulation of Mercury Interaction

- Flux transfer events were also found at the Mercury magnetopause
- The differences with the terrestrial FTE are instructive
- Smaller and more frequent and thus scale with the size (curvature) of the obstacle
- Hybrid simulation of Mercury reproduces them

Motion of Flux Transfer Events

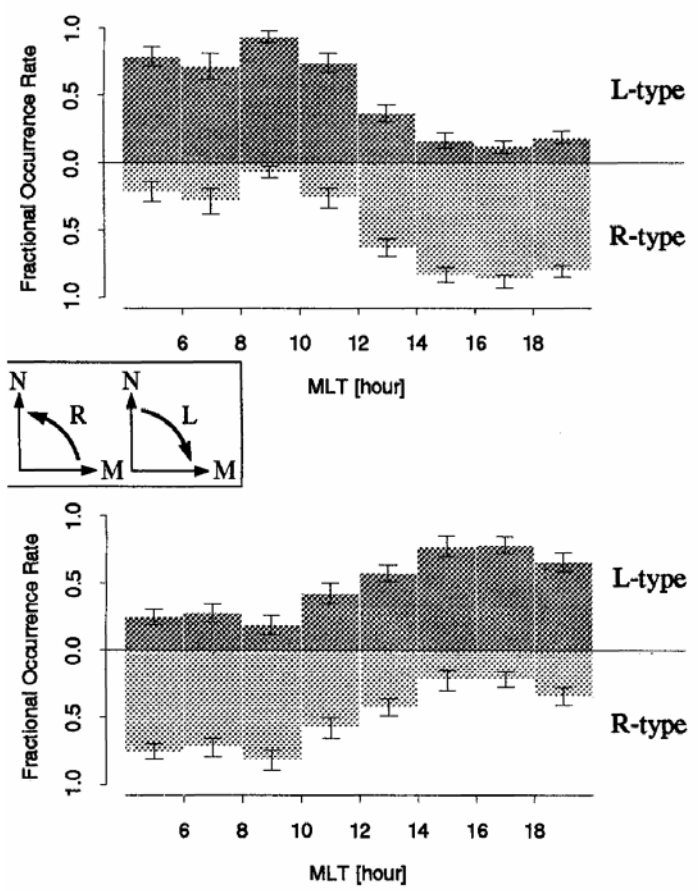
- FTEs in the hybrid simulation move over the top and bottom of the magnetosphere because the magnetosphere is 2D
- In the 3D magnetosphere their motion will be controlled by the flow of the plasma where they are formed and the magnetic tension
- To determine how an FTE moves we can use multiple spacecraft and the time delay or attempt to interpret the time sequence of field changes from single spacecraft



ISEE 1 and 2 measurements of an IFE

Motion of Flux Transfer Events: Single Spacecraft (1)

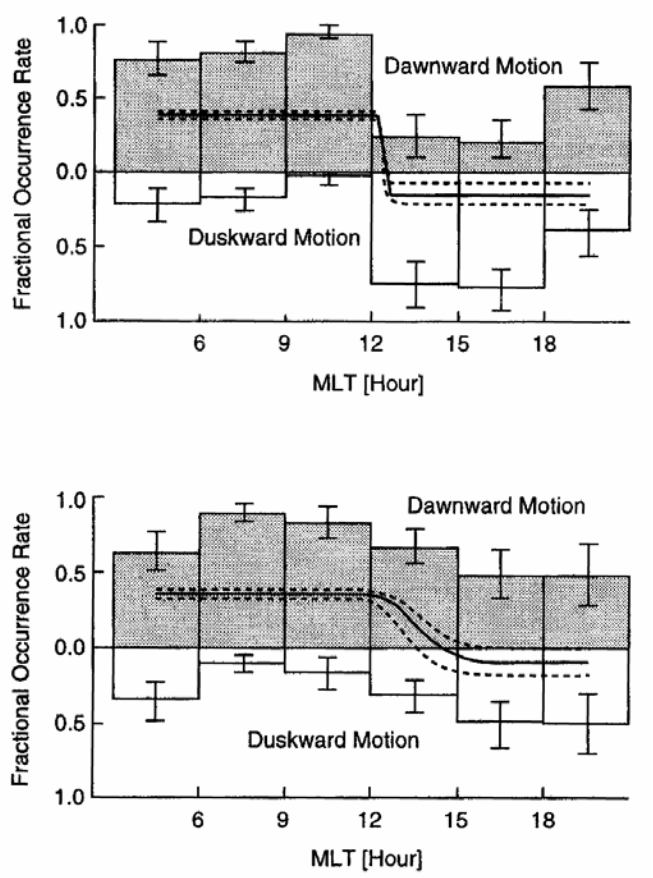
- If IMF is southward and magnetospheric field is northward, then a tube aligned perpendicular to B in the plane of the interface will cause a +/- B_N perturbation (direct) if moving northward and -/+ B_N perturbation (reverse) if moving southward
- There is a tendency to see direct perturbations above the equator and reverse below
- The direction of rotation of the ΔN-ΔM perturbation as the FTE passes should depend on the motion of the FTE and whether it is in the magnetosphere (top) or magnetosheath (bottom)
- The data indicate that the FTE's largely move away from noon



Kawano and Russell (1996)

Motion of Flux Transfer Events: Single Spacecraft (2)

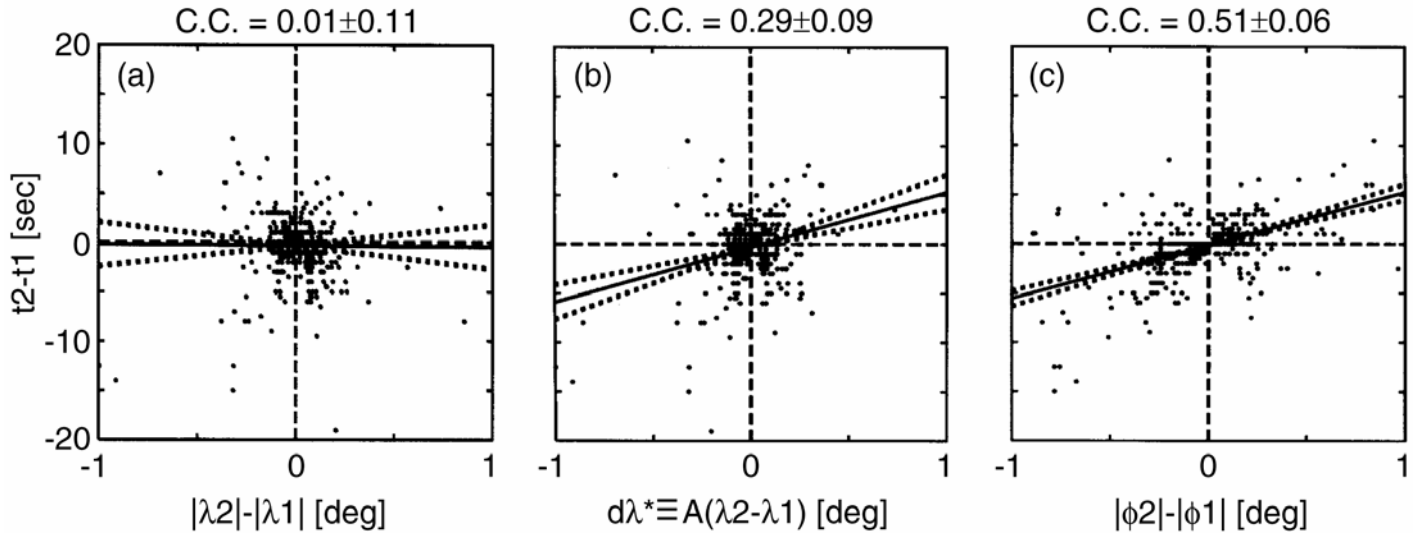
- One can define the occurrence of FTEs that move away from noon and toward noon (sunward) with this rotational parameter and compare with expectations
- If one does this for FTEs seen inside and outside the magnetosphere and separate by weak (top) and strong (bottom) By one gets a split at noon with some violations for weak fields and poor separation across noon for strong fields
- This is an indication that the merging line model through the subsolar point may be incorrect



Kawano and Russell (1997)

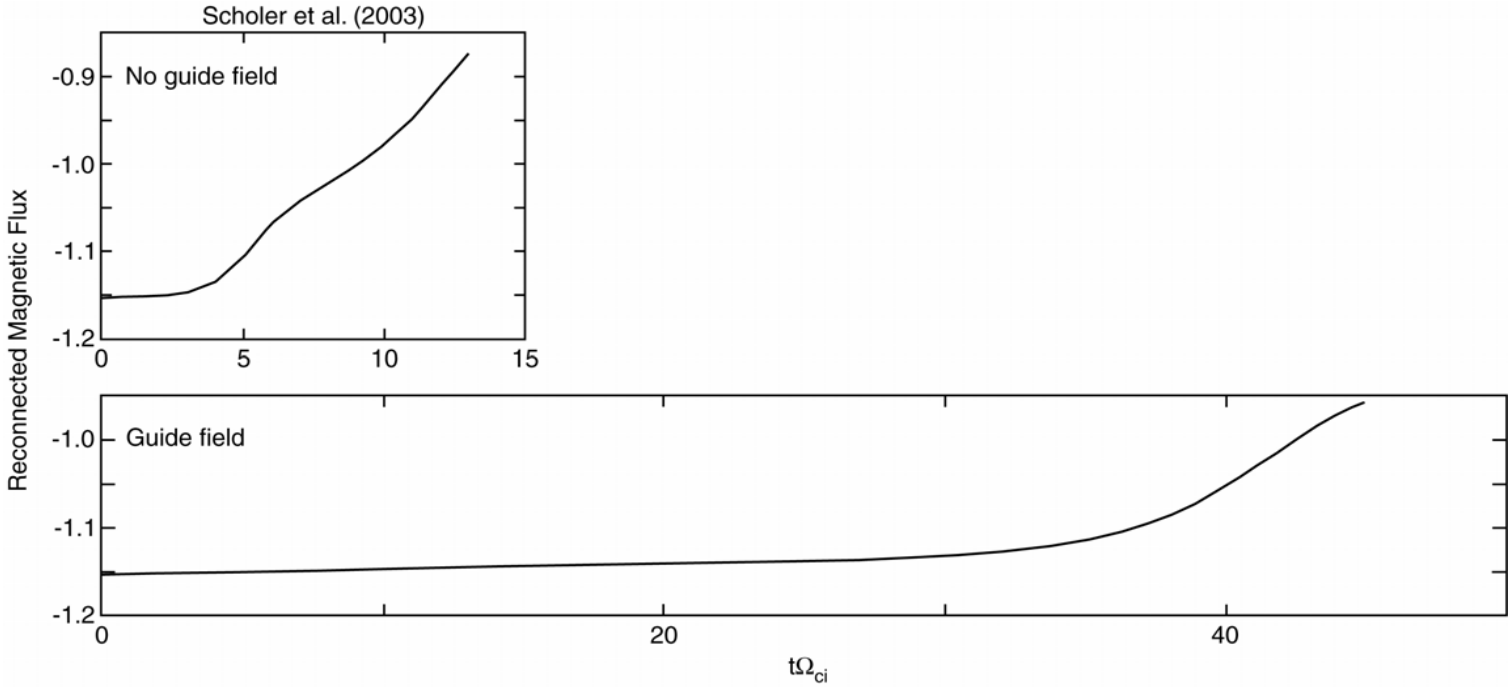
Motion of Flux Transfer Events: Dual Spacecraft

- Kawano and Russell (2005) examined the time delay between successive FTEs and ISEE 1 and 2 and compared with difference in absolute latitude differences, modified latitude (accounting for FTE signature), and absolute longitude difference
- Agrees with the “standard model” of reconnection but with much scatter

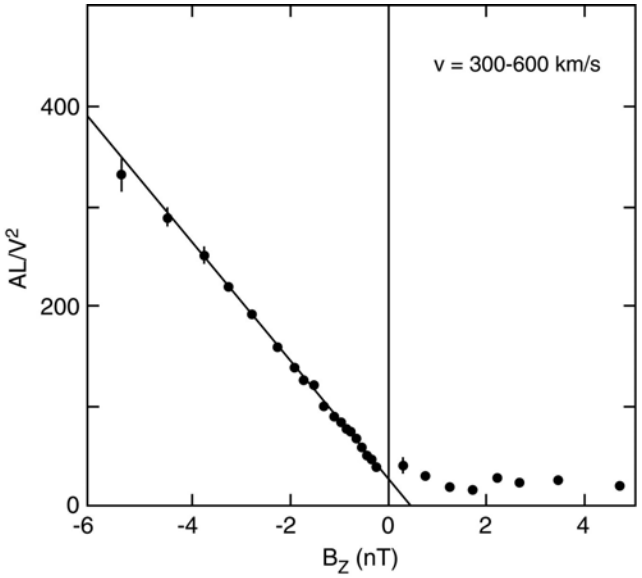


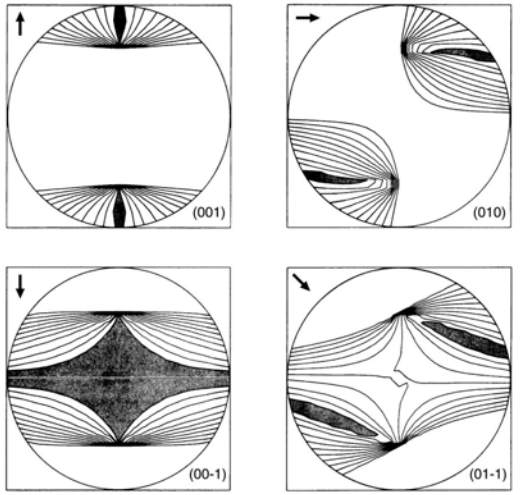
Controversies : Dependence of reconnection on relative orientation, or role of guide field on reconnection

- In kinetic simulations onset of reconnection is rapid with no guide field
- In kinetic simulation with a guide field the onset of reconnection is delayed but once it occurs it proceeds at same rate
- Time to onset is important as it determines the location of the reconnection point



Controversies : Geomagnetic activity dependence on IMF orientation

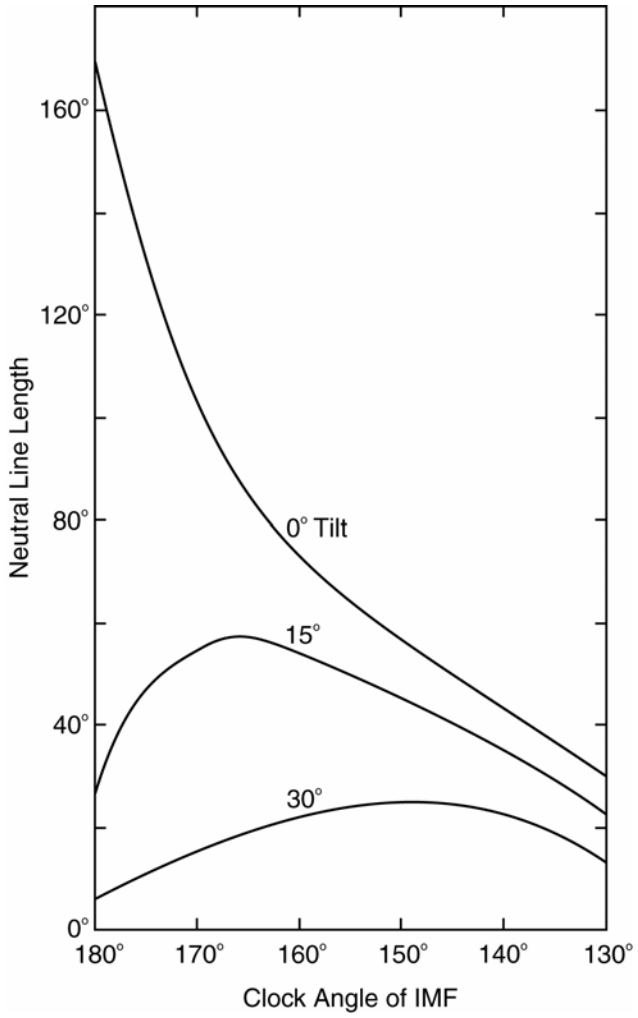




- Geomagnetic activity depends on magnetic flux transport to tail
- There is little geomagnetic activity for northward field
- This behavior can be explained by antiparallel reconnection (no guide field)
- This also leads to an explanation of the semi-annual variation of geomagnetic activity

Dependence of Reconnection on Dipole Tilt

- The size of the region of antiparallel magnetic field on the magnetopause depends strongly on the dipole tilt
- It maximizes in the due southward direction (clock angle 180^o) only for 0^o tilt (flow perpendicular to dipole)
- Depending on tilt of dipole changing of clock angle may affect reconnection rate differently
- Semi-annual variation of geomagnetic activity strongly affected by this dependence



Russell et al. (2003)

Summary and Conclusions

- Neutral points and not current sheets are the key to understanding reconnection
- Reconnection enables (but does not guarantee) rapid energy release
- Reconnection through topology changes enables momentum coupling between flowing plasma and the obstacle
- Coupling is not necessarily steady: Flux transfer events and bursty bulk flows recur without obvious triggers
- Geometry is important in determining the size and occurrence frequency
- Large scatter in statistics and strength of By effects suggests that subsolar merging line is not correct
- Guide field appears to control onset of collisionless reconnection. This affects where reconnection can occur, leads to half wave rectification and dipole tilt control, and enhances the semi-annual variation of geomagnetic activity