Time-Varying Reconnection

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GEM, Snowmass
June 2006
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

- 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
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.
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

• 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 ($\pm$ 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

- 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 $\Delta N-\Delta M$ 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 the same rate.
- Time to onset is important as it determines the location of the reconnection point.

![Graph showing reconnected magnetic flux over time with and without guide field](image)
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°) only for 0° 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 $B_y$ 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.