Theory of Magnetic Reconnection for Solar Applications

or

“Why are we still talking about reconnection after 50 years?!?”

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Acknowledgments - David Alexander and the SHINE Steering Committee, Bill Daughton, Jim Drake, Terry Forbes, Jim Klimchuk, Dermott Mullan, Michael Shay

SOHO (ESA & NASA)
Magnetic Reconnection

- An ISI search found >5,500 papers from 1957-2007 on reconnection

**Reconnection Publications**

**Reconnection Citations**

- Focus of this talk: History and fundamental physics of reconnection
  How fundamental reconnection physics enters solar applications

- Biases: Mine

- To be omitted: Copious references, observations, experiments, other applications, anything outside a little box around reconnection site
  (except where relevant)
Outline

• The Early History of Magnetic Reconnection
  – Pre-1930 through 1964

• The Middle History of Magnetic Reconnection
  – 1986 through 2001

• Solar Applications
Pre 1930s Solar Astronomy

• Solar flare history
  – Discovered (no later than) 1859
  – First pictures of a flare taken
    (Hale, Astron. Astrophys., 1892)

• History of solar dynamics
  – Vortical flow discovered around sunspots (Hale, Ap. J., 1908a), likened to cyclones and tornados on Earth
  – MHD yet to be discovered (Alfvén, Nature, 1942)
    • Sun described by hydrodynamics, not electromagnetism or magnetohydrodynamics!
Ronald Giovanelli

  - “[M]ost eruptions can be associated with particular spot groups.”

  - The magnetic field due to a sunspot cancels the dipole field at a “neutral point.”
  - Electric fields near neutral points can accelerate particles and drive currents.
    “The localization of these phenomena in the neighbourhood of sunspots suggests a basis of an explanation of solar flares.”
  - This theory of flares is **electromagnetic**, not hydrodynamic!
James Dungey

- Giovanelli discussed his model with Fred Hoyle
  - He became interested in it both for flares and auroral applications (Hoyle, Some Recent Researches in Solar Physics, 1949)

- Hoyle gave the problem to his grad student, Dungey, in 1947
  - MHD, frozen flux had been developed by then
  - A non-zero resistivity $\eta$ allows the topology of the magnetic field to change near a neutral point (Dungey, Phil. Mag., 1953)
  - Suggested the same effect occurs in the magnetosphere, coined the phrase “magnetic reconnection” (Dungey, 1950s)

Dungey, 1958

Dungey, 1961
Peter Sweet

• Another former student of Hoyle (though before Dungey)

• Gave a solar flare model using Giovanelli/Dungey mechanism
  – Two bipolar regions come together.
  – The field flattens “analogous to the flattening of a motor tyre when loaded.”
  – “A thin collision layer of gas is formed” at the neutral point, reconnection occurs.
  – Used hydrodynamic analogy of plates *forced together* with a fluid in between.

Eugene Parker

- Parker was at the meeting to present “On the Variations of Cosmic Ray Intensity”
  - Came up with his solution on the way back to the United States

- The result (Parker, JGR, 1957)
  \[
  \frac{\delta}{L} \sim \frac{v_{in}}{v_{out}} \sim \frac{cE}{B_{rec}c_A} \sim E' \sim \sqrt{\frac{\eta c^2}{4\pi c_A L}} \sim S^{-1/2}
  \]
  \(S = \text{Lundquist number, } E' = \text{Reconnection rate}\)
  - Mechanism is much faster than straight diffusion, may be important for flares
  - It is fully nonlinear and (almost) entirely self-consistent
    - Based on conservation laws (mass, energy, magnetic flux)
    - It has been confirmed in certain regimes by simulations (Biskamp, Phys. Fluids, 1986) and experiments (Ji et al., PRL, 1998; Trintchouk et al., Phys. Plasmas, 2003; Furno et al., Phys. Plasmas, 2005)

All was good - for six years...
The Problem - Observations!

• Time scale for impulsive release of energy:
  – \( \sim 10 \text{ sec} \)

• Representative large flare parameters:
  \( B \sim 100 \text{ G}, n \sim 3 \times 10^9 \text{ cm}^{-3}, \)
  \( T \sim 10^6 \text{ K}, R \sim 10^9 \text{ cm}, h \sim 10^{10} \text{ cm} \)
  \( \Rightarrow S \sim 4 \times 10^{13} \) (assuming Spitzer resistivity)

• Inferred rate of reconnection

\[
\frac{d\Phi_M}{dt} = -c \int E \cdot ds
\]

\[
\frac{B \pi R^2}{t} \sim cEh
\]

\[
E \sim \frac{B \pi R^2}{cht} \Rightarrow E' \sim \frac{cE}{Bc_A} \sim \frac{\pi R^2}{c_Aht}
\]

\[
E' \sim \frac{\pi(10^9 \text{cm})^2}{(4 \times 10^8 \text{ cm/s})(10^{10} \text{ cm})(10 \text{ s})} \sim 0.1
\]

Consistent with more modern determinations of \( E' \) (Jiong Qiu, talk yesterday)
Failure of Sweet-Parker

- Sweet-Parker Prediction: Since $L \sim R$,
  $$E_{SP}' \sim S^{-1/2} \sim 10^{-7}$$
  - $E_{SP}' \ll E_{observed}!!!$ (Parker, Ap. J. Supp. Ser., 1963)

- Why is Sweet-Parker so slow?
  - $\delta \sim L / S^{1/2}$
  - Bottleneck causes slow inflow

- Definitions: “fast” reconnection - $E' \sim 0.1$ (usually independent of $S$)
  “slow” reconnection - $E' \ll 0.1$ (usually dependent on $S$)

  - Considered runaway electrons and ambipolar diffusion, concluding they wouldn’t work.
  - Need a new mechanism which effectively decreases $S$,
    by decreasing $L$ or anomalously increasing $\eta$

“The observational and theoretical difficulties with the hypothesis of magnetic-field line annihilation suggest that other alternatives for the flare must be explored.”
An Assist from Fusion

- Fusion requires plasma confinement
  - Develop toroidal configuration that is (linearly) stable in MHD
  - Set up experiment
    - Result - It didn’t work!

- Furth et al., Phys. Fluids, 1963
  - (Linear) stability analysis including resistivity (Dungey!)
  - Called “tearing mode”
    - Explains “disruptions” in tokamaks
  - Crux - perturbation can lower the free energy, resistivity allows field to break
    - Tension force is the key
  - Nonlinear phase of tearing mode is magnetic reconnection!
Harry Petschek

- An aeronautical engineer by training
  - “[P]revious analyses overlooked standing magneto-hydrodynamic waves as a possible mechanism for converting magnetic energy to plasma energy.”
  - Waves become switch-off (slow) shocks if compressible
  - Reconnection rate fast enough to explain solar flares

- Quote from Peter Sweet in the discussion period:
  “I am in favor of your theory, which I thoroughly approve. Dr. Parker and I have been living with this problem for several years and have got the feel of it. Your solution struck me at once as the solution for which we have been seeking.”

All was good - for 22 years...
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• The Early History of Magnetic Reconnection
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Problems with the Theory

• Petschek theory is not self-consistent
  – No physical mechanism given for localization of diffusion region
    • If $\eta$ is localized, Petschek-type reconnection occurs (Sato and Hayashi, Phys. Fluids, 1979)
    • If $\eta$ is uniform, it does not (Biskamp, Phys. Fluids, 1986)

• Misconception - Flares can be explained entirely by MHD with a Spitzer resistivity
  – Dreicer collision theory - Spitzer description breaks down when $E > E_D$:
    \[
    E_D \sim 0.43 \left( \frac{2\pi ne^3}{k_B T} \ln \Lambda \right)
    \]
    \[
    E'_{D} \sim \frac{cE_D}{c_A B} \sim 1.07 \times 10^{-7}
    \]
  – Inferred reconnection electric field $E' \sim 0.1$ during a flare exceeds $E'_D$
  – Spitzer resistivity not meaningful for these parameters!

Need non-Spitzer ("anomalous") resistivity or physics beyond resistive MHD to get fast reconnection!
The Hall Effect

- The Hall effect enters through the generalized Ohm’s law (Vasyliunas, Rev. Geophys. Space Phys., 1975):

\[
\vec{E} + \frac{\vec{v}_i \times \vec{B}}{c} = \eta \vec{J} + \frac{1}{nec} \vec{J} \times \vec{B} - \frac{1}{ne} \nabla \cdot \vec{p}_e - \frac{m_e}{e} \frac{d\vec{v}_e}{dt}
\]

  - Convection  Resistivity  Hall effect  Electron pressure  Electron inertia

- The Hall effect alone does not allow for reconnection; dissipation is necessary for the field lines to break.

- The Hall effect alters the structure at and below ion gyro-scales (Sonnerup, 1979).

- Help from the fusion community:
  - Reconnection is much faster than Sweet-Parker at length scales below the ion gyro-radius (Aydemir, Phys. Fluids B, 1992).
Hall (Collisionless) Reconnection

- Hall effect (plus some dissipation) gives fast reconnection ($E' \sim 0.1$) with Petschek type structure (Shay et al., GRL, 1999)

- **GEM Challenge** (Birn et al., JGR, 2001):
  Same simulation run with multiple codes; **Hall effect** sufficient to make reconnection fast

- Signatures of Hall reconnection observed in the magnetosphere (Nagai et al., JGR, 2001; Deng and Matsumoto, Nature, 2001; Oieroset et al., Nature, 2001; Mozer et al., PRL, 2002) and in laboratory experiments (Ren et al., PRL, 2005; Cothran et al., GRL, 2005; Frank et al., Phys. Lett. A, 2006)

![Image](image-url)
Hall Reconnection

• Why is Hall reconnection \textit{fast}? 
  – Hall effect makes Alfvén waves dispersive (\textit{whistlers}) \cite{Dungey1954}.
  – Since \textit{whistlers} are dispersive ($\omega \sim k^2$), the waves driving the outflow are faster at smaller scales \cite{Mandt1994}.

\[
v_{out} \sim \frac{\omega}{k} \sim k \sim \frac{1}{\delta}
\]
so the reconnection rate is independent of dissipation mechanism.

– Reconnection is fast provided the outflow is driven by \textit{dispersive waves} \cite{Rogers2001}.

Non-dispersive waves

\begin{minipage}{0.5\textwidth}
\begin{center}
\includegraphics[width=0.8\textwidth]{non_dispersive_waves.png}
\end{center}
\end{minipage}

\begin{minipage}{0.5\textwidth}
\begin{center}
\includegraphics[width=0.8\textwidth]{dispersive_waves.png}
\end{center}
\end{minipage}

adapted from Drake and Shay, 2007

Hall model is (almost) entirely self-consistent model of fast reconnection, though aspects remain under study.
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  – Onset of Eruptions (Energy Release)
  – Energy Storage before Eruptions
  – Particle Acceleration
Energy Storage and Release in Eruptions

• Large flares give off $\sim 10^{32}$ ergs
  – A reservoir of stored energy
    • Magnetic Energy (100 G)
  – An energy conversion mechanism
    • Magnetic reconnection
  – A trigger mechanism
  – Something to set off the trigger

• Misconception:
  – Reconnection requires forcing
    • Sweet’s model assumes forcing
    • Certainly can happen due to forcing
  – Tearing instability means forcing not necessary
    • Plasma wants to get to lowest energy state
Reconnection Onset

- The fastness of Hall reconnection could not only explain the rate of energy release, but also onset! (Ma and Bhattacharjee, GRL, 1996; Bhattacharjee, ARA&A, 2004)
  - Reconnection is *slow* until thickness of diffusion region falls below kinetic scale

- How does this work?
  - The onset of Hall reconnection catastrophic because reconnection is *bistable* (Cassak et al., PRL, 2005 & 2007). *(The system is history dependent.)*
    - Sweet-Parker dominates until length scales are comparable to gyro-scales
  - Evidence for catastrophe in laboratory plasmas (Ren et al., PRL, 2005; Egedal et al., PRL, 2007)
Secondary Islands

- Parker assumed Sweet-Parker scales to coronal $S$
  - Diffusion regions long and thin - unstable to secondary island formation
  - Occurs when $S > S_{\text{crit}} \sim 10^4$
    (Biskamp, Phys. Fluids, 1986)
  - Secondary islands ubiquitous in corona
  - Changes reconnection process, but how?

- Secondary islands make Sweet-Parker reconnection faster

- Definitions
  - *Fast* reconnection - Reconnection rate $E$ independent of $S$ (system size and dissipation mechanism), with $E' \sim 0.1$
  - *Slow* reconnection - $E = E(S)$ (dependent on system size and dissipation mechanism), $E' \ll 0.1$
    - Is reconnection with secondary islands fast or slow?
Why We Care

• Energy storage and reconnection onset in flares
  – If reconnection is *slow*
    • Storage could still occur during “Sweet-Parker” phase before flare
      – Onset occurs sooner; is there enough time to store energy?
    • Models of flare/CME onset which require current sheets before eruption remain tenable
  – If reconnection is *fast*
    • Secondary islands are ubiquitous; reconnection fast at onset
      – Stored energy at onset would be released quickly
      – Onset mechanism less clear
    • Models of flare/CME onset must not allow current sheets before eruption

Progress made (Loureiro, Daughton, Bhattacharjee, Fermo, …), but it remains an open question!
Steady vs. Unsteady

- Reconnection events are often bursty
  - Is this a fundamental property of reconnection or is it externally controlled?
  - Do steady-state models (Sweet-Parker, Petschek, Hall) apply?

- In solar wind - reconnection events extend ~400 Earth radii and persist for hours (Phan et al., Nature Lett., 2006)
  - Reconnection is not fundamentally bursty, at least when detected downstream of the dissipation region

- Observations of flares - structure as low as 1/10th of a second (Fletcher talk, Wednesday)
  - Bursty on time scale of system Alfvén time $L_{\text{system}} / c_A \sim 1-10 \text{ sec}$
  - Not bursty on microphysical time scale $L_{\text{Hall}} / c_A \sim 1 \mu\text{s}$
Particle Acceleration

• What is the role of magnetic reconnection in particle acceleration?
  – In flares, up to half the energy can go into energetic electrons (Lin and Hudson, 1971)
  – Giovanelli argued particles are accelerated by the reconnection electric field
    • This cannot explain observations of flares because the dissipation region is so small that only few electrons would accelerate (the “numbers problem”).
      – Is the acceleration caused by the physics of reconnection or a secondary mechanism?

• Recent models -
  – Collision of outflow jet with plasma in island (Hoshino et al., JGR, 2001)
  – Parallel electric fields in density cavities (Drake et al., PRL, 2005; Pritchett, JGR, 2006).
  – Contracting magnetic islands
    • As newly formed islands contract, electrons feel a kick at the end of the island (Fermi mechanism) (Drake et al., Nature, 2006)
    • All electrons participate, so it could potentially solve the numbers problem if electrons jump to multiple islands
    • Magnetotail observations found a correlation between accelerated electrons and magnetic islands (Chen et al., Nature Phys., 2008)

Drake et al., Nature, 2006
Ion Acceleration


- Ions behave like pick-up particles (Drake et al., JGR, 2009; Ap. J. Lett., 2009)
  - With no out-of-plane (guide) field, $\mu$ conservation broken as ions enter outflow jet, gain thermal energy proportional to bulk flow energy
  - With large out-of-plane (guide) field, only heavier ions gain energy
    - Energy gain proportional to mass
    - Can gain $\sim 0.1$ MeV from this mechanism
    - Not enough to explain observations, but can seed ions to undergo Fermi acceleration like the electrons
Other Open Questions

- **Corona and below**
  - How do multiple microscopic reconnection events organize into macroscopic events (like flares and substorms)?
  - What is the role of reconnection in CMEs?
    - Cause, effect, neither or both?
  - What is the role of reconnection in coronal heating?

- **Solar Wind and Corona**
  - What is the nature of reconnection in a turbulent medium? (Servidio et al., PRL, 2009)
    - How do turbulent motions affect reconnection and vice versa?
Conclusion

• “So the physics of rapid reconnection has come a long way in the half-century since it was first proposed.” (Parker, Conversations on Electric and Magnetic Fields in the Cosmos, 2007)

• Contributors to magnetic reconnection theory:
  – solar observers, plasma theorists, solar theorists, aeronautical engineers, fusion experimentalists, fusion theorists, magnetospheric observers, astrophysicists, reconnection numericists and experimentalists

• Much more to be learned about reconnection!

• Thank you!

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