The Theory of Magnetic Reconnection: Past, Present, and Future

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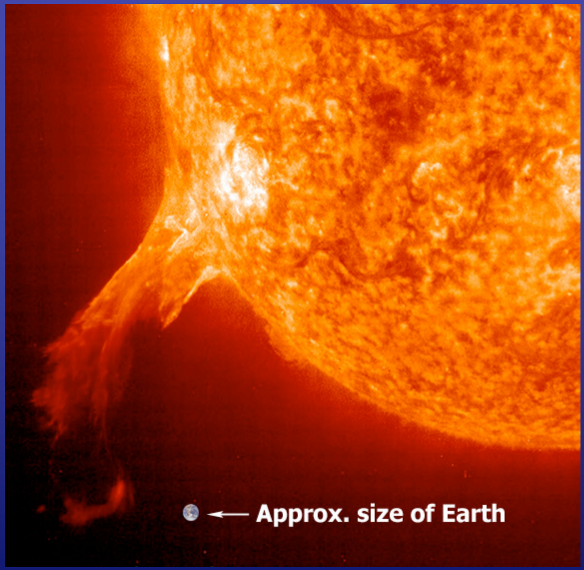
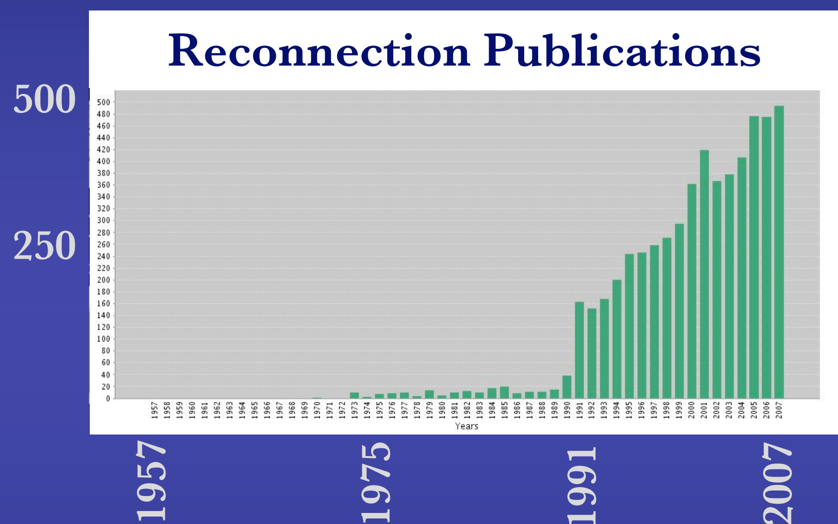
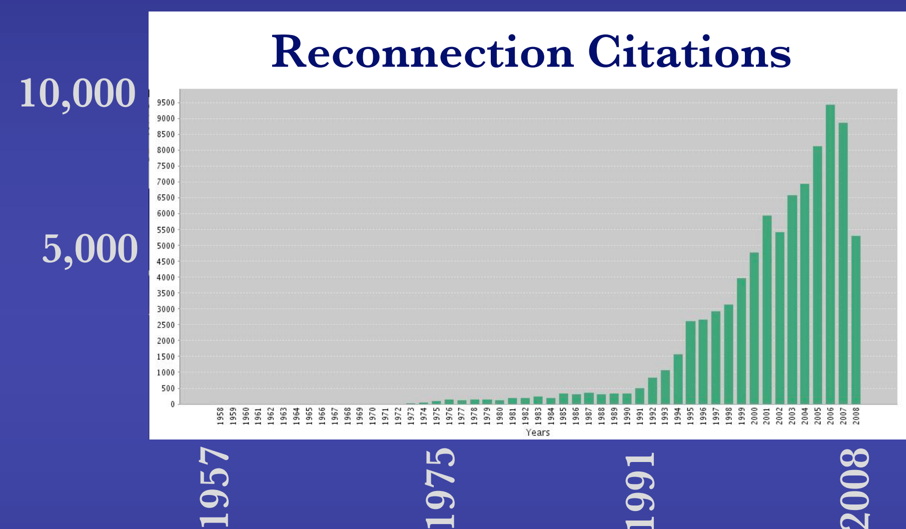


SOHO (ESA & NASA)

Magnetic Reconnection

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





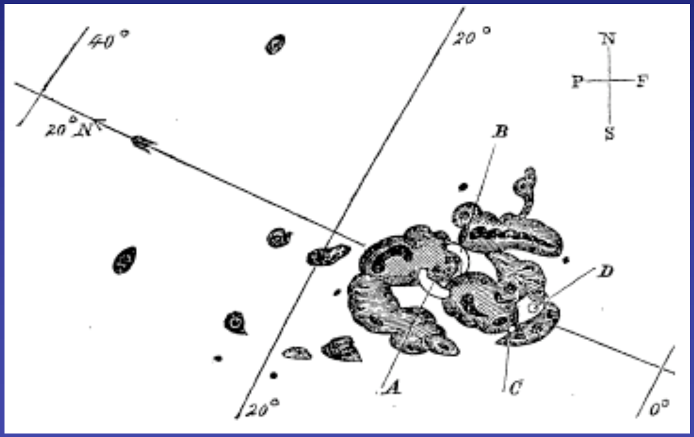
- Focus of this talk: the fundamental theory of reconnection
- To be omitted: observations, experiments, applications (except where relevant)

Outline

- “Considerable astrophysical importance”
  - The Early History of Magnetic Reconnection
- “Other alternatives”
  - A Recent History of Magnetic Reconnection
- The Devil is in the Details
  - The Present and the Future

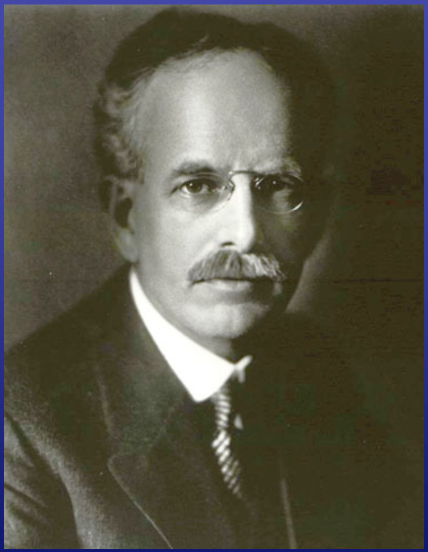
Pre 1930s Solar Astronomy

- **Solar flare history**
  - **Discovered (no later than) 1859** (Carrington, MNRAS, 1859; Hodgson, MNRAS, 1859)
  - **First pictures of a flare taken** (Hale, Astron. Astrophys., 1892)



Carrington, 1859

- **History of solar dynamics**
  - **Vortical flow discovered around sunspots** (Hale, Ap. J., 1908a), **likened to cyclones and tornados on Earth**
  - **Magnetic fields detected in sunspots** (Hale, Ap. J., 1908b)
  - **MHD yet to be discovered** (Alfvén, Nature, 1942)
    - **Sun described by hydrodynamics, not electromagnetism or hydromagnetics**



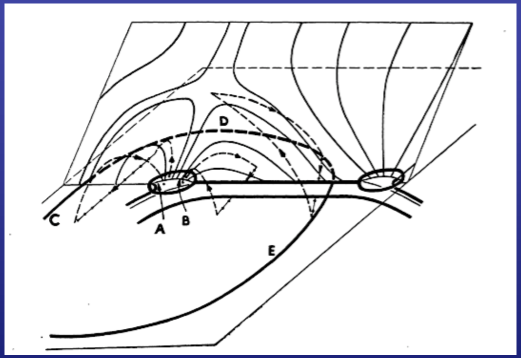
G. E. Hale

Ronald Giovanelli

- **Observational study of flares** (Giovanelli, Ap. J., 1939)**:**
  - **"[M]ost eruptions can be associated with particular spot groups."**

- **New theory of flares** (Giovanelli, MNRAS, 1947)**:**
  - **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!**

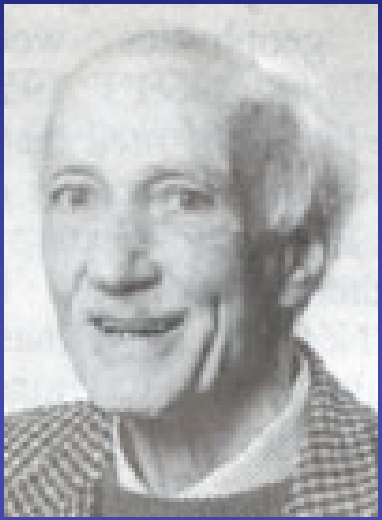


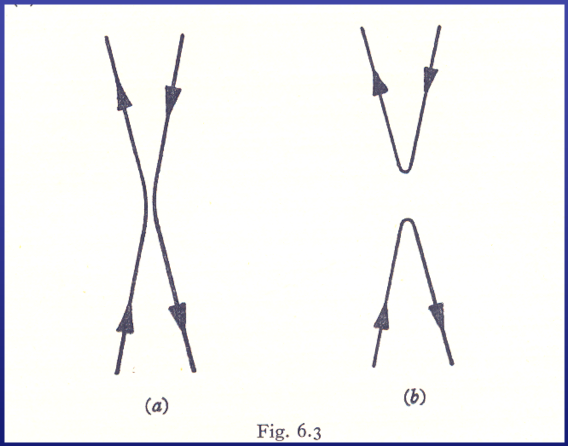
Giovanelli, 1947

James Dungey

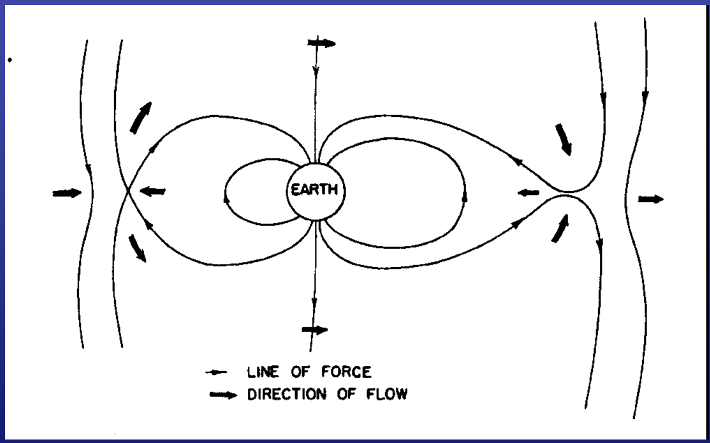
- **Giovanelli discussed his model with Fred Hoyle**
  - **He became interested in it both for flares and auroral applications** (Hoyle, *Some Recent Researches in Solar Physics*, 1949)

- **Hoyle gave the problem to his grad student, Dungey, in 1947**
  - **A non-zero resistivity η 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)



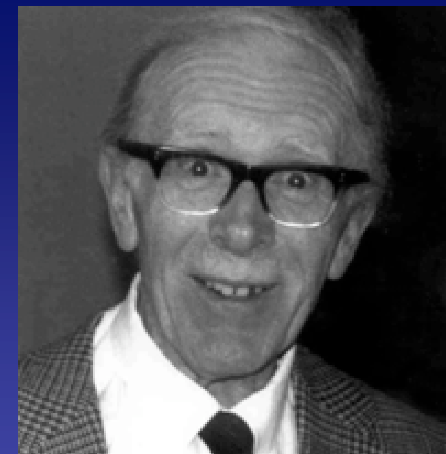


Dungey, 1958



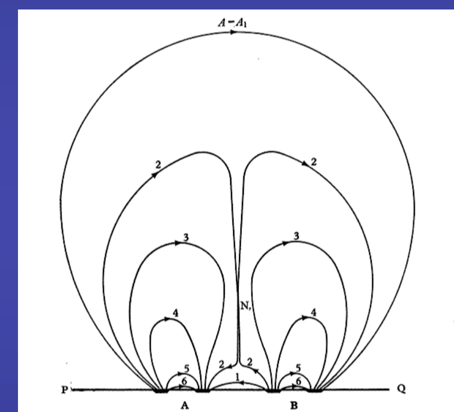
Dungey, 1961

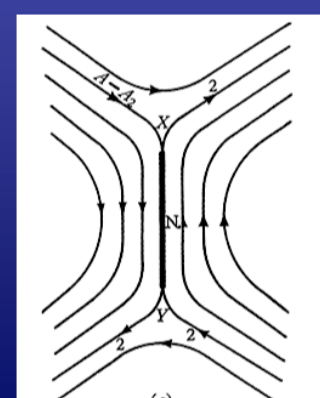
Peter Sweet

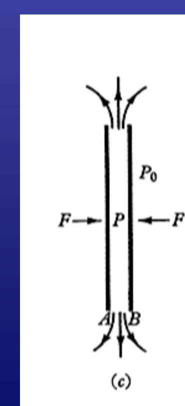


- Gave a solar flare model using Giovanelli/Dungey mechanism
  - Two bipolar regions come together.
  - The field flattens “analogous to the flattening of a motor tyre when loaded.”
  - “A thin collision layer of gas is formed” at the neutral point.
  - Used hydrodynamic analogy of plates forced together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

- Presented at International Astronomical Union Symposium No. 6 (Electromagnetic Phenomena in Cosmical Physics), Stockholm, Sweden, August 27-31, 1956. Proceedings published in 1958.







Sweet, 1958

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

Journal of

GEOPHYSICAL RESEARCH

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Terrestrial Magnetism and Atmospheric Electricity

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SWEET'S MECHANISM FOR MERGING MAGNETIC FIELDS IN CONDUCTING FLUIDS*

BY E. N. PARKER

Enrico Fermi Institute for Nuclear Studies, The University of Chicago, Chicago 37, Illinois

(Received June 4, 1957)

ABSTRACT

Sweet's mechanism for the merging of two oppositely directed magnetic fields in a highly conducting fluid is investigated in a semi-quantitative manner. It is shown that two oppositely directed sunspot fields with scales of 10^4 km could be merged by Sweet's mechanism, if shoved firmly together, in about two weeks; their normal interdiffusion time would be of the order of 600 years. It is suggested that Sweet's mechanism may be of considerable astrophysical importance: It gives a means of altering quickly the configuration of magnetic fields in ionized gases, allowing a stable field to go over into an unstable configuration, subsequently converting much of the magnetic energy into kinetic energy of the fluid.

If l is the characteristic length of the gradient in **B** across the neutral plane, then the decay time of the field in the region of this gradient is of the order of $l^2\sigma/c^2$. The velocity u with which the fields merge is $l/(l^2\sigma/c^2)$,

$$u \cong c^2/l\sigma$$

The fluid expelled along the lines of force over a front of width L achieves a velocity v, where

$$v \cong uL/l$$

based on geometrical considerations. The pressure $B^2/8\pi$ available for squeezing the fluid out along the lines of force leads to the conclusion that

$$\tfrac{1}{2}\rho v^2 \cong B^2/8\pi$$

from energy considerations; hence $v \cong C_0$, where C_0 is the characteristic hydromagnetic velocity $B/(4\pi\rho)^{1/2}$. Therefore, it follows that

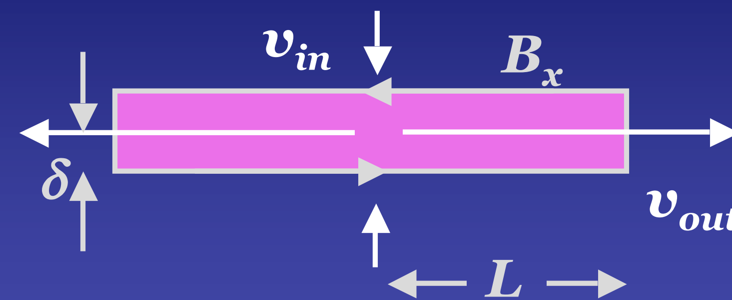
$$u \cong c(C_0/L\sigma)^{1/2}$$

$$l/L \cong c/(C_0L\sigma)^{1/2}$$

Sweet-Parker Scaling

- **A steady-state is reached when field lines convect into the collisional layer at the same rate that they are annihilated**

$$v_{in} \sim \frac{\eta c^2}{4\pi\delta}$$



- **"The pressure available for squeezing the fluid out …" is magnetic ($B^2/8\pi$), so "from energy considerations," the outflow speed is** $v_{out} \sim \frac{B_x}{\sqrt{4\pi\rho}} \sim c_A$
- **Combine with continuity "based on geometrical considerations,"** $v_{in} \sim \frac{\delta}{L} v_{out}$

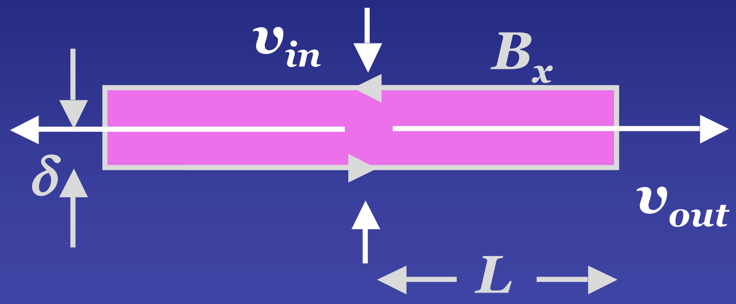
- **The result** (Parker, JGR, 1957)

$$\frac{\delta}{L} \sim \frac{v_{in}}{v_{out}} \sim \frac{cE}{B_x c_A} \sim \sqrt{\frac{\eta c^2}{4\pi c_A L}} \sim S^{-1/2}$$

  - **It is fully nonlinear and (almost) entirely self-consistent**
    - **Based on conservation laws (mass, energy, magnetic flux)**
  - **It has been confirmed by simulations** (Biskamp, Phys. Fluids, 1986) **and experiments** (Ji et al., PRL, 1998) **in certain regimes**

The Sweet-Parker Model

- Drawbacks
  - L is a free parameter which scales with the system size (for the corona, L ~ radius of a flux tube ~ 10^4 km)



  - The model is **MUCH too slow** to explain the observed energy release rates in flares
  - Can Sweet-Parker reconnection be made faster? (Parker, Ap. J. Supp. Ser., 1963)
    - Considered runaway electrons and ambipolar diffusion, concluding it wouldn't work.
    - Need a new mechanism which **decreases L** or **anomalously increases η**

> "The observational and theoretical difficulties with the hypothesis of magnetic-field line annihilation suggest that **other alternatives** for the flare must be explored."
> (Parker, Ap. J. Supp. Ser., 1963)

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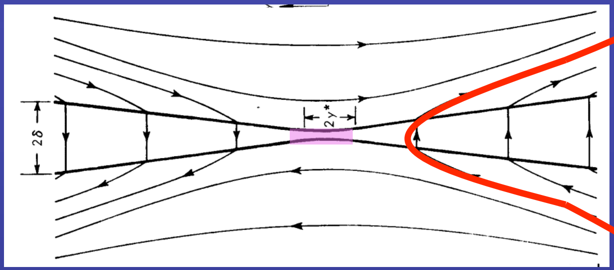
Harry Petschek

- **Gave a talk at AAS-NASA Symposium, Physics of Solar Flares, Greenbelt, Maryland, October 28-30, 1963.**
  - **"[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**

Petschek, 1964

Open outflow region



Small Sweet-Parker region

Standing waves drive outflow

- **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."
- **However, the theory is not self-consistent! It occurs for localized η** (Sato and Hayashi, Phys. Fluids, 1979)**, but not for uniform η** (Biskamp, Phys. Fluids, 1986)

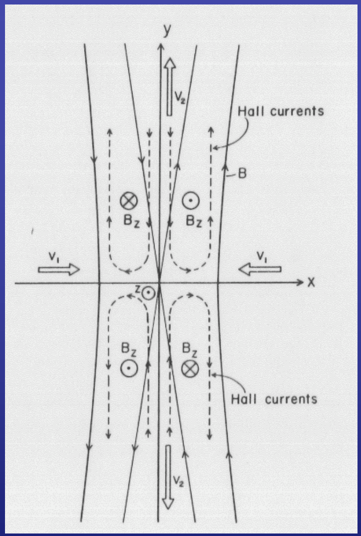
The Hall Effect

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

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

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.**



Sonnerup, 1979

- **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 Reconnection

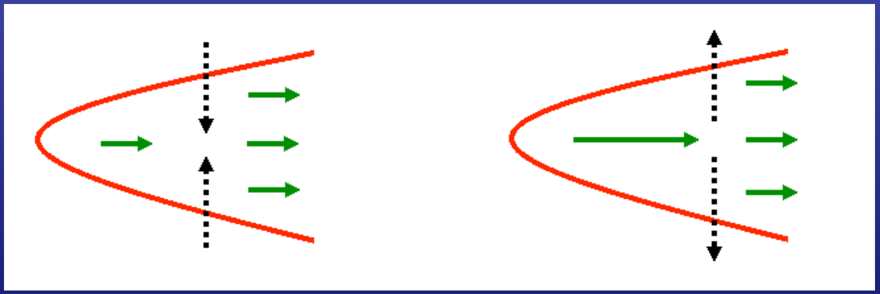
- **Why is Hall reconnection fast?**
  - **Hall effect makes Alfvén waves dispersive (whistlers)** (Dungey, 1954)
  - **Since whistlers are dispersive ($\omega \sim k^2$), the waves driving the outflow are faster at smaller scales** (Mandt et al., GRL, 1994).

$$v_{out} \sim \frac{\omega}{k} \sim k \sim \frac{1}{\delta}$$

so the reconnection rate is independent of dissipation mechanism

  - **Reconnection is fast provided the outflow is driven by dispersive waves** (Rogers et al., PRL, 2001)

Non-dispersive waves

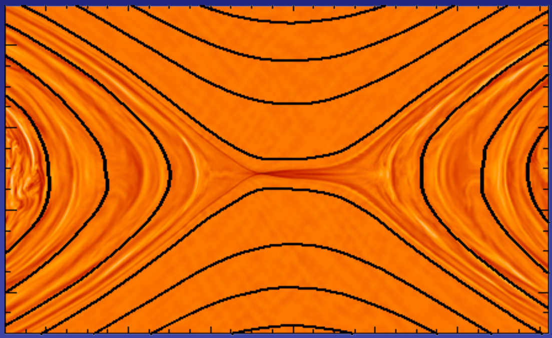


Dispersive waves

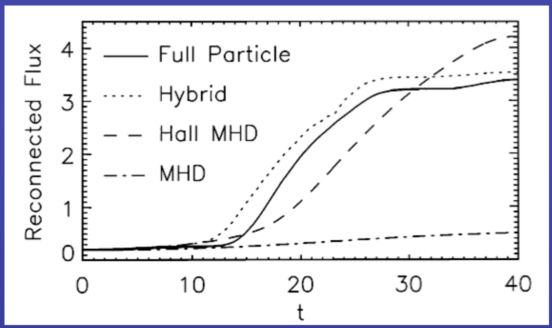
adapted from Drake and Shay, 2007

Hall Reconnection

- **Hall effect (plus dissipation) gives fast reconnection with the Petschek shock structure**
  - **Hall reconnection rate is fast enough to explain energy release rate in flares/substorms** (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** (Cothran et al., GRL, 2005; Ren et al., PRL, 2005; Frank et al., Phys. Lett. A, 2006)



Courtesy of M. Shay



Birn et al., 2001

Hall model is (almost) entirely self-consistent model of fast reconnection, though aspects remain under study.

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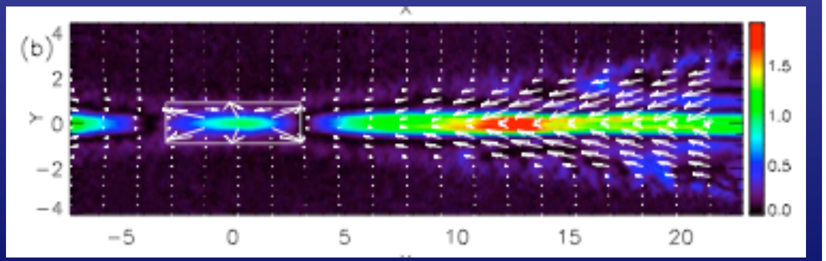
    - Is the Hall Effect Enough?
    - Reconnection Onset and Energy Storage
    - The Role of Reconnection in Particle Acceleration
    - Asymmetric Magnetic Reconnection
    - Additional Topics in Magnetic Reconnection Theory

Is the Hall Effect Enough?

- Open questions
  - What maintains a small *L*?
    - **Secondary island formation** (Daughton et al., Phys. Plasmas, 2006)
    - **The Hall effect** (Drake et al., Phys. Plasmas, 2008)
  - What is the role of the Hall effect?
    - **Contrast with "electron-positron" reconnection in which Hall effect vanishes** (Bessho and Bhattacharjee, PRL, 2005; Hesse and Zenitani, Phys. Plasmas, 2007; Daughton and Karimabadi, Phys. Plasmas, 2007; Swisdak et al., Ap. J., 2008; Zenitani and Hesse, Phys. Plasmas, 2008)
  - What is the dissipation mechanism?
    - **Non-gyrotropic electron pressure** (Hesse et al., Phys. Plasmas, 1999 & 2004; Pritchett, JGR, 2001 & Phys. Plasmas, 2005; Ricci et al., GRL, 2002 & Phys. Plasmas, 2004)
    - **Mixing between incoming and outgoing particles gives effective diffusion at electron Larmor radius scales** (Hesse, Phys. Plasmas, 2006)

- Recent discovery - New results about the electron dissipation region
  - Much longer than previously thought (Daughton et al., Phys. Plasmas, 2006; Fujimoto, Phys. Plasmas, 2006).
  - **Has a two-scale structure** (Shay et al., PRL, 2007; Karimabadi et al., GRL, 2007)
    - **Observed in magnetosphere, >60 ion inertial scales** (Phan et al., PRL, 2007)

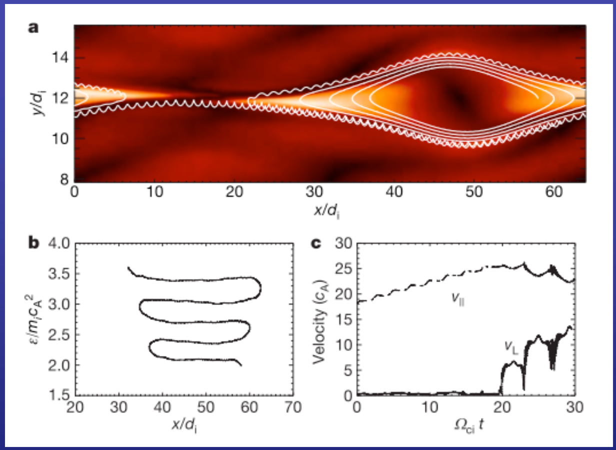


Shay et al., 2007

Particle Acceleration

- **Open question**
  - **Giovanelli's model cannot explain observations because 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, and electrons jumping to multiple islands potentially solves the numbers problem.**
    - **Magnetotail observations found a correlation between accelerated electrons and magnetic islands** (Chen et al., Nature Phys., 2008)

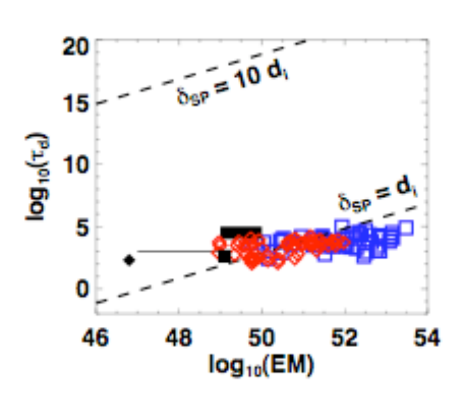


Drake et al., Nature, 2006

Onset and Energy Storage

- **Open questions -**
  - **Why does fast reconnection initiate suddenly?**
    - **Onset of localized anomalous resistivity (example - LHDI threshhold is $v_{ed} > v_{th,i}$)**
    - **Secondary (ideal) instability of Sweet-Parker current layer** (Dahlburg et al., Ap. J., 2005)
    - **After** (Aydemir, Phys. Fluids B, 1992)**, it was suggested that the rapid growth of Hall reconnection could explain onset** (Wang and Bhattacharjee, PRL, 1993).
  - **What prevents fast reconnection before a flare (allowing energy to be stored)?**

- **Recent discovery - Reconnection is bistable** (Cassak et al., PRL, 2005 & 2007)
  - **Both Sweet-Parker and Hall are accessible for given parameters; the system is history dependent**
    - **Sweet-Parker dominates until length scales are comparable to gyro-scales, onset of Hall is catastrophic**
    - **Evidence for this in laboratory plasmas** (Ren et al., PRL, 2005; Egedal et al., PRL, 2007)
    - **Observational data from stellar flares consistent with this condition** (Cassak et al., Ap. J. Lett., 2008)
  - **Two conclusions - Hall effect is important in corona and Sweet-Parker explains energy storage before an eruption**



Cassak et al., 2008

Asymmetric Reconnection

- **Open questions**
  - **How does reconnection proceed in asymmetric conditions (with disparate plasmas on either side of the dissipation region)?**

- **Recent discovery - The Sweet-Parker analysis extended to asymmetric systems** (Cassak and Shay, Phys. Plasmas, 2007)
  - **Based on conservation laws:**

$$\left(\rho_1 v_1 + \rho_2 v_2\right) L \sim \left(\rho_{out} v_{out}\right) 2\delta$$

$$\left(\frac{B_1^2}{8\pi} v_1 + \frac{B_2^2}{8\pi} v_2\right) L \sim \left(\frac{1}{2}\rho_{out} v_{out}^2\right) v_{out} 2\delta$$

$$v_1 B_1 \sim v_2 B_2$$

$$v_{out}^2 \sim \frac{B_1 B_2}{4\pi} \frac{B_1 + B_2}{\rho_1 B_2 + \rho_2 B_1}$$

$$E \sim \frac{1}{c}\left(\frac{B_1 B_2}{B_1 + B_2}\right) v_{out} \frac{2\delta}{L}$$

  - **Various parameter regimes have been simulated** (Borovsky and Hesse, Phys. Plasmas, 2007; Birn et al., Phys. Plasmas, 2008; Pritchett, JGR, 2008)
  - **Theory agrees with global MHD simulations** (Borovsky et al., JGR, 2008)
  - **A first principles solar wind-magnetospheric coupling model gave as good predictive capability as the previous best model** (Borovsky, JGR, 2008)

More Open Questions

- **Is the fast reconnection rate always 0.1? Why?**
- **Can reconnection be steady in time or is it fundamentally bursty?**
- **How do multiple microscopic reconnection events organize into macroscopic events (like flares and substorms)?**
- **What is the nature of reconnection in three-dimensions?**
  - Hornig and Priest, Phys. Plasmas, 2003; Pontin and Galsgaard, JGR, 2007; Pontin and Craig, Ap. J., 2006; Haynes et al., Proc. Roy. Soc. A, 2007; Longcope et al., Ap. J., 2001 & 2005; Linton et al., Ap. J., 2001; Linton and Priest, Ap. J., 2003; Dorelli et al., JGR, 2007; Dorelli and Bhattacharjee, Phys. Plasmas, 2008; Lapenta et al., Phys. Plasmas, 2003; Scholer et al., Phys. Plasmas, 2003; Huba and Rudakov et al., Phys. Plasmas, 2002; Shay et al., GRL, 2003; Yin et al., PRL, submitted; …
- **Does turbulence make reconnection faster?** (Matthaeus and Lamkin, Phys. Fluids, 1986; Lazarian and Vishniac, Ap. J., 1999; Smith et al., GRL, 2004).

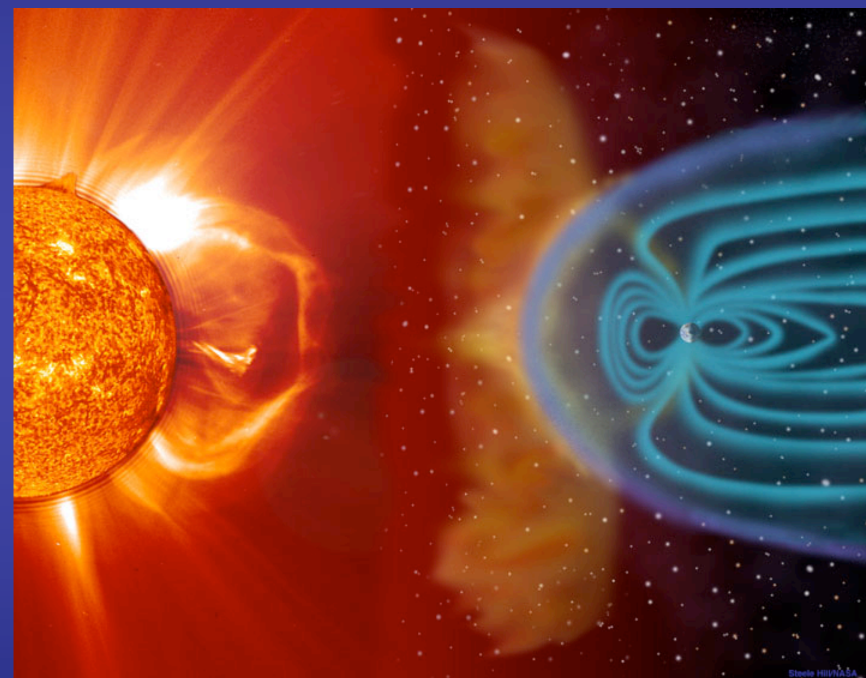
- **Applications of Reconnection**
  - **Solar corona (eruptions and heating) and chromosphere, magnetosphere, astrophysical settings, laboratory experiments, fusion devices, …**

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!**



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- **Thank you!**
  - **Thanks to Bill Daughton, Jim Drake, Jim Klimchuk, Dermott Mullan, Michael Shay, Julie Bryan**