

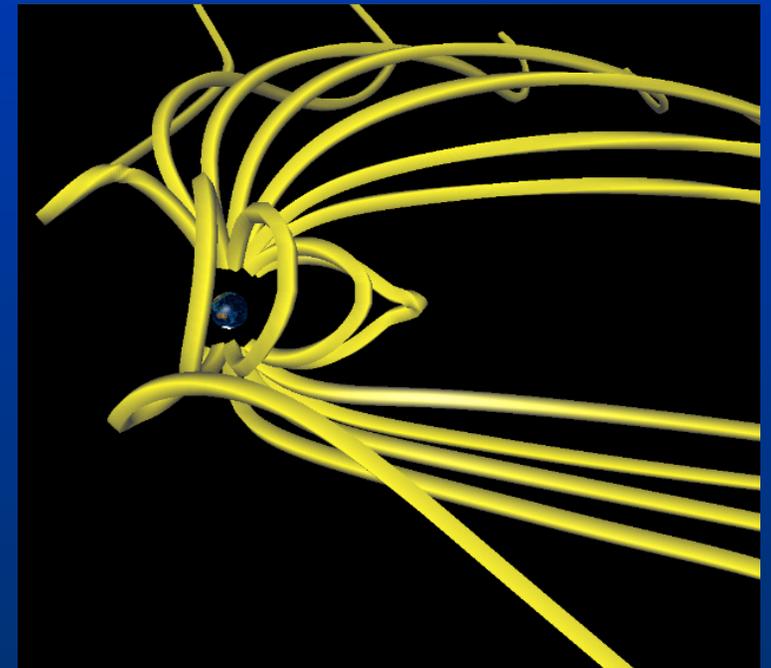
Theory of Magnetic Reconnection for Magnetospheric Applications

or

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

Paul Cassak
West Virginia University
2012 GEM Workshop
June 21, 2012

Thanks to - Slava Merkin, Stan Sazykin and the GEM
Steering Committee; Masha Kuznetsova, David Berrios,
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Megan Cartwright; Richard Denton; John Dorelli;
Jim Drake; Homa Karimabadi; Tai Phan; Earl Scime;
Michael Shay; Brian Sullivan; Marc Swisdak



Outline

- **Early History of Magnetic Reconnection**
 - 1930s through 1981
- **Middle History of Magnetic Reconnection**
 - 1979 through 2001
- **Recent History of Magnetic Reconnection**
 - Magnetospheric Applications, 2000 - present
- **The Future**

H. Alfvén, Keynote Address, Proceedings from NASA Workshop on Double Layers, Huntsville AL, March 17-19, 1986.

Referring to “magnetic merging”:

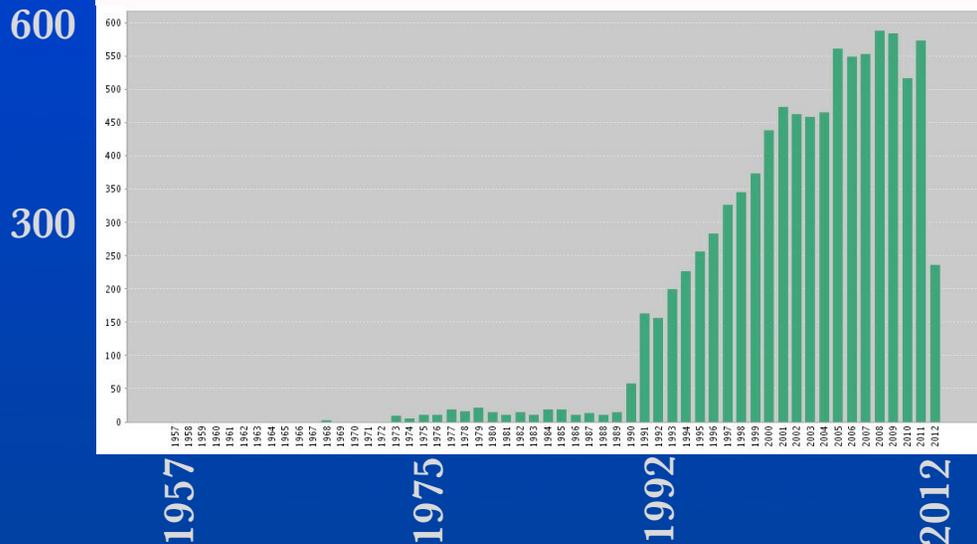
“I was naïve enough to believe that such a pseudo-science would die by itself in the scientific community, and I concentrated my work on more pleasant problems. To my great surprise the opposite has occurred: ‘merging’ pseudo-science seems to be increasingly powerful. Magnetospheric physics and solar wind physics today are no doubt in a chaotic state, and a major reason for this is that part of the published papers are science and part pseudo-science, perhaps even with a majority in the latter group.”



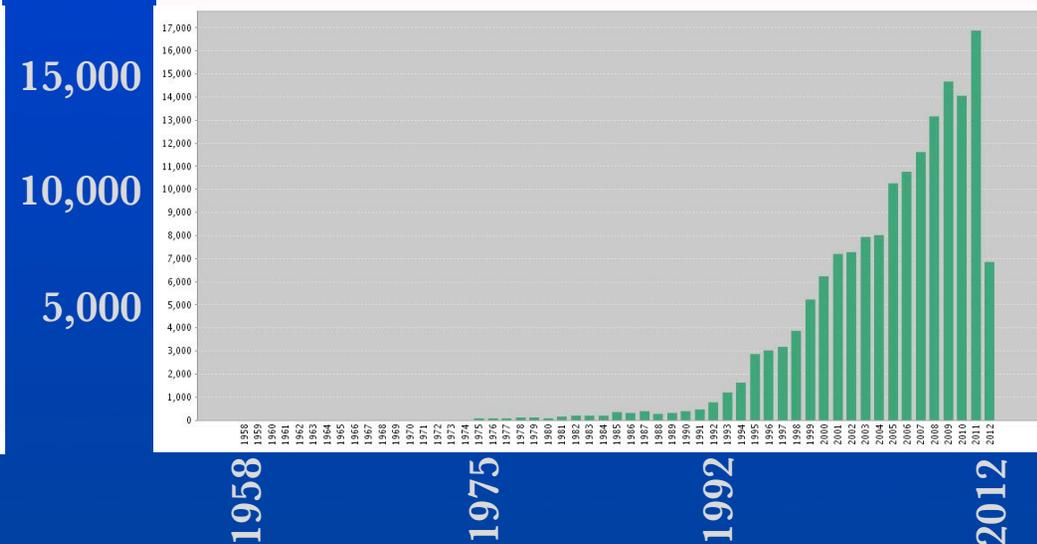
Magnetic Reconnection

- An ISI search (06/2012) found >9,100 papers from 1957-2012 on reconnection (h-index = 132)

Reconnection Publications



Reconnection Citations



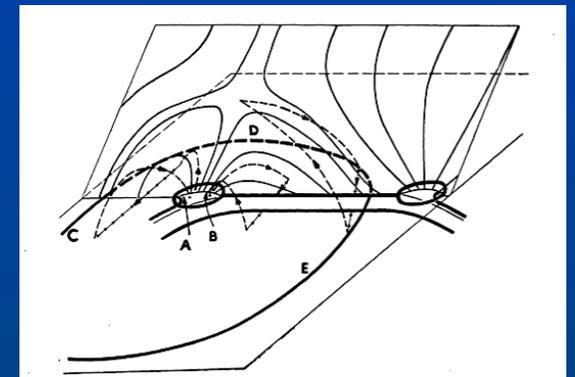
- Focus of this talk: History and fundamental physics of reconnection
How fundamental reconnection physics enters magnetospheric applications
- Biases: Mine
- To be omitted: Copious references, observations, experiments, other applications
(except where relevant)

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.”

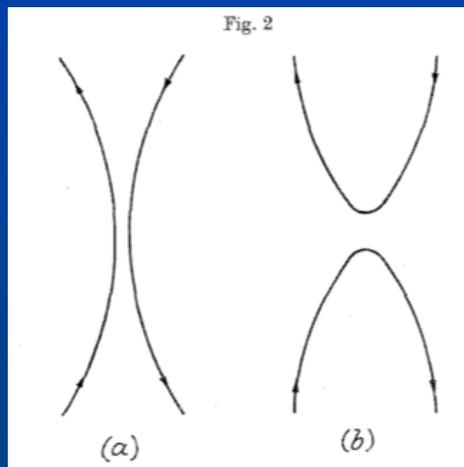
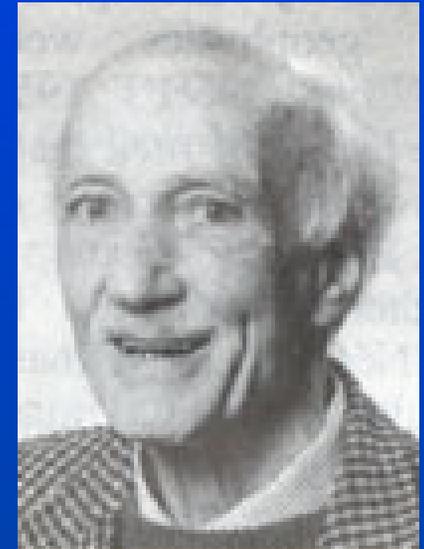
This theory of flares is electromagnetic,
not hydrodynamic!



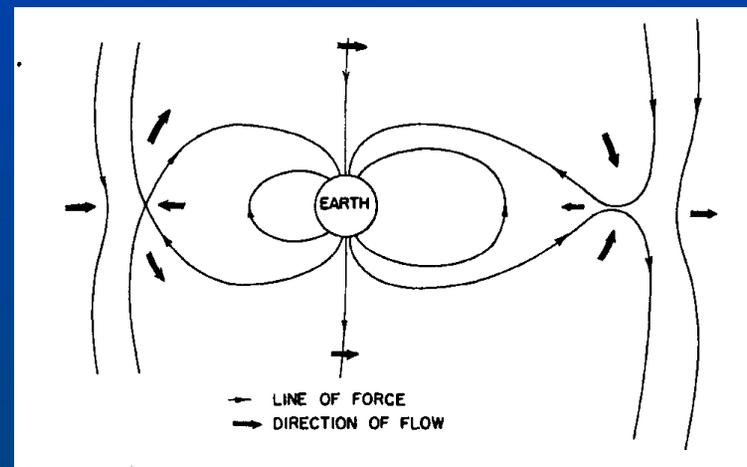
Giovanelli, 1947

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**
 - MHD, frozen flux had been developed by then
 - 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)



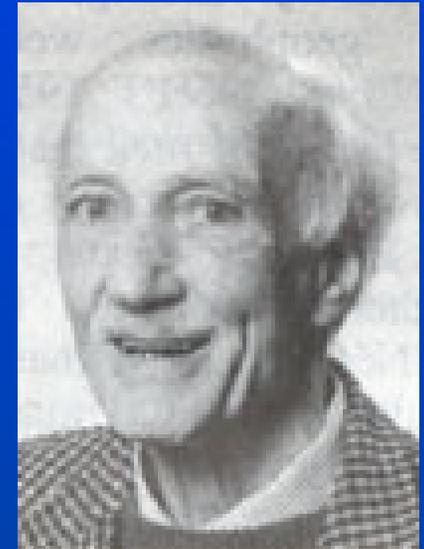
Dungey, 1953



Dungey, 1961

James Dungey

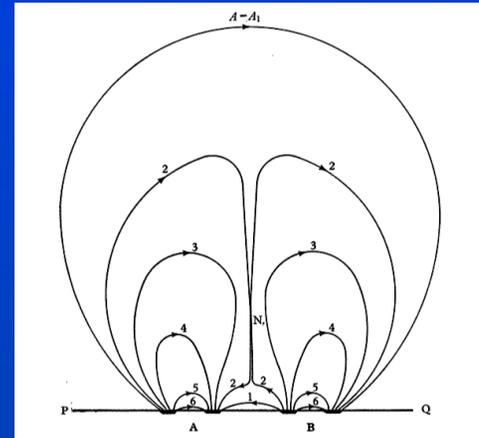
- **On the 1953 paper**
 - **“One reason against publishing [diagrams of reconnection in the magnetosphere] was the rejection of my reconnection paper by the Royal Astronomical Society, though it was published in the *Philosophical Magazine*.”**
- **On the 1961 paper (1,834 citations)**
 - **The origin of this paper conformed to the classic model. The publication was precipitated by a flash of vision, but this was preceded by 13 years of intermittent head-scratching, conscious and subconscious. My wife thought I would go bald. The flash came in the classic way, while preparing a talk, in a classic place: I was sitting at a sidewalk café in Montparnasse.”**
 - **“Initially, the reconnection model seems to have been regarded as an entertaining fiction, but a prediction was successful and a controversy developed. [...] Reconnection remained out of favour throughout the 1970s, but improved observations with the International Sun-Earth Explorers swung opinion the other way. This is written as I fly back from a conference, where the opposition was described as a vocal minority.”**



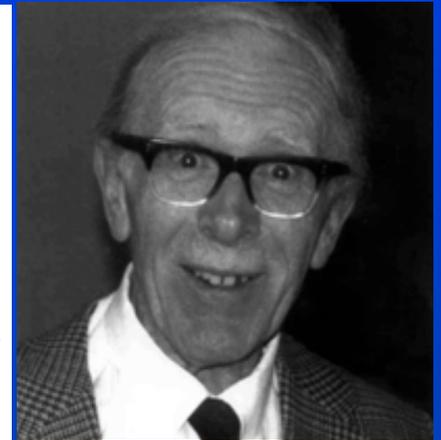
Quotes from “This Week’s Citation Classic,”
ISI, December 5, 1983

Peter Sweet/Eugene Parker

- Sweet - a former student of Hoyle (*before* Dungey)
- Gave a solar flare model using Giovanelli/Dungey mechanism
- Presented at International Astronomical Union Symposium No. 6 (Electromagnetic Phenomena in Cosmical Physics), Stockholm, Sweden, August 27-31, 1956. Proceedings published, 1958.
 - Parker was at the meeting to present “On the Variations of Cosmic Ray Intensity”



Sweet, 1958

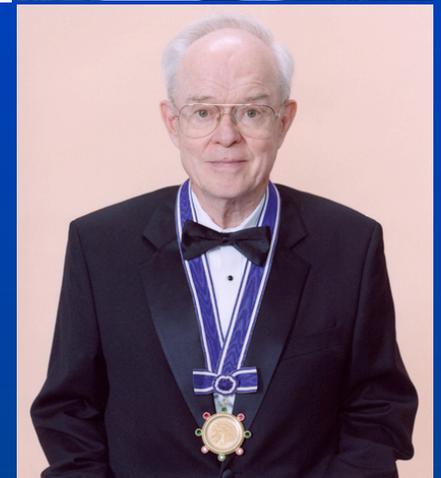


- Parker came up with solution on the way back to the United States

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

S = Lundquist number, E' = 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)
- 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)



Parker, 1957

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 $l/(\tau^2\sigma/c^2)$,

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

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

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

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

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

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

All was good - for six years...

Failure of Sweet-Parker

- For solar flares, $S \approx 10^{14}$, so the Sweet-Parker prediction is

$$E'_{SP} \sim S^{-1/2} \simeq 10^{-7}$$

- Inferred $E'_{SP} \ll E_{observed} \approx 0.1!!!$
(Parker, Ap. J. Supp. Ser., 1963)

- It is even worse in the magnetosphere:

- Very low collisionality - Sweet-Parker reconnection would never happen!

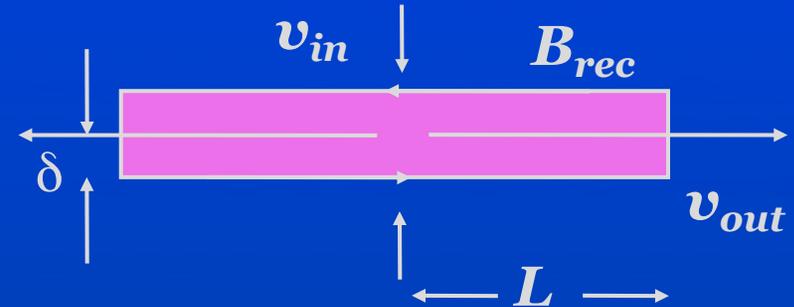
- Why is Sweet-Parker so slow?

- $\delta \sim L / S^{1/2}$; 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)

- Can Sweet-Parker reconnection be made fast? (Parker, Ap. J. Supp. Ser., 1963)

- 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 η



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

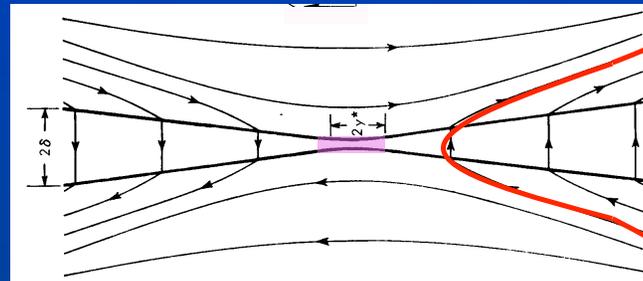
(Parker, Ap. J. Supp. Ser., 1963)

Harry Petschek

- An aeronautical engineer by training
 - Introduced to reconnection problem by Kantrowitz
- 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



Open
outflow
region



Small Sweet-Parker region

Petschek, 1964

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.”

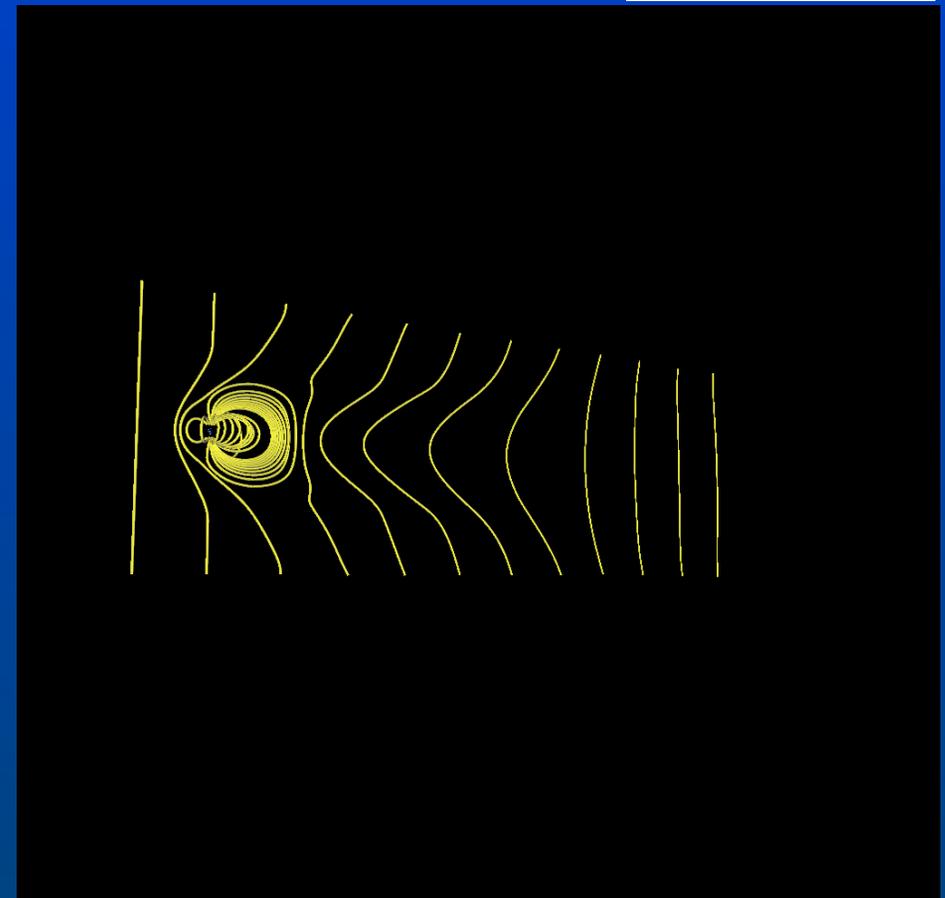
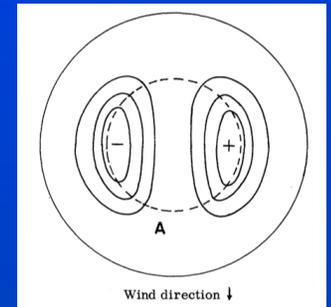
All was good - for 22 years...

Observational Evidence

- **Ramification of reconnection on the dayside is convection pattern at the polar caps** (Dungey, PRL, 1961)
 - **Flows had been observed with ground based magnetometers, but attributed to viscosity**
- **Indirect evidence of reconnection model**
 - **Direction of IMF correlated with auroral and geomagnetic activity** (Fairfield and Cahill Jr., JGR, 1966)
 - **Southward IMF implies magnetopause erosion** (Aubry et al., JGR, 1970)
 - **Energetic particles from the sun reach the field lines at the polar cap first** (Fennell, JGR, 1973)
- **Direct evidence (ISEE measurements)**
 - **Plasma acceleration at a rotational discontinuity** (Paschmann et al., Nature, 1979)
 - **Non-zero component of B field normal to the magnetopause** (Sonnerup et al., JGR, 1981)

Overwhelming evidence for magnetospheric reconnection!

Dungey, 1961



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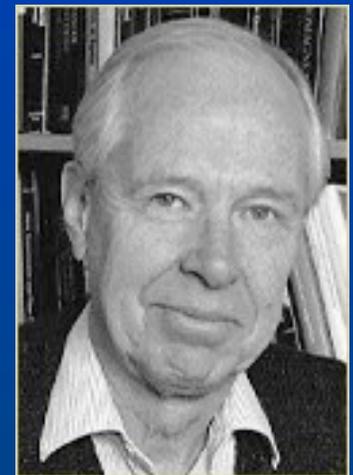
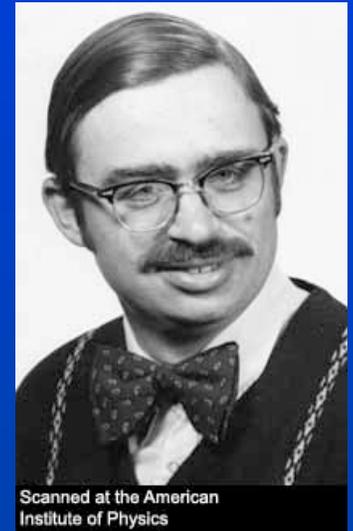
Collisionless Reconnection and the Hall Effect

- **Petschek theory is not self-consistent**
 - **No physical mechanism given for localization of diffusion region**
 - If η is localized, Petschek-type reconnection occurs (Sato and Hayashi, Phys. Fluids, 1979)
 - If η is uniform, it does not (Biskamp, Phys. Fluids, 1986)
- **If resistivity is not important, what allows reconnection? Consider the generalized Ohm's law (Vasyliunas, Rev. Geophys. Space Phys., 1975):**

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

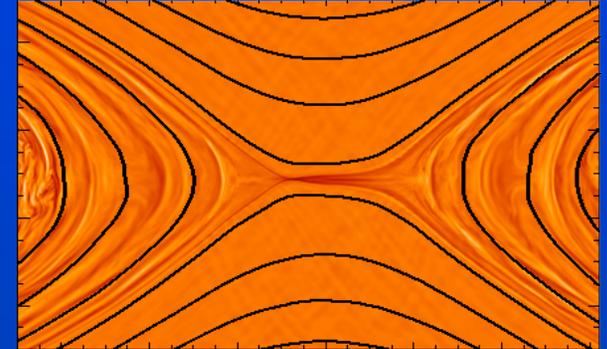
Convection Resistivity Hall effect Electron pressure Electron inertia

- **The Hall effect alone does not allow for reconnection; dissipation is necessary for the field lines to break.**
 - Not thought to be important (yet!)
 - **Electron pressure and inertia can break frozen-in condition even without resistivity**
- **The Hall effect alters the structure between the ion and electron gyro-scales (Sonnerup, 1979).**

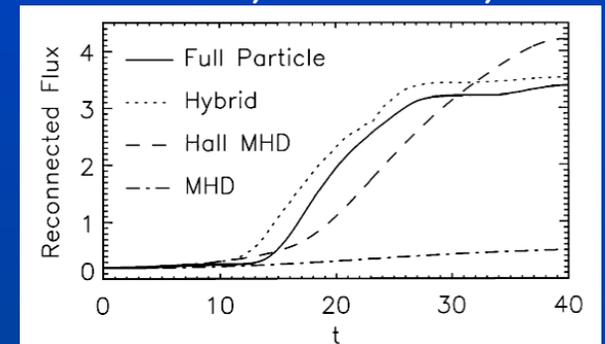


The GEM Reconnection Challenge

- **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 effect (plus some dissipation) gives fast reconnection ($E' \sim 0.1$)** (Ma and Bhattacharjee, GRL, 1996; Shay et al., JGR, 1998)
- **Remains fast for large systems** (Shay et al., GRL, 1999)
- **GEM Challenge** (Birn et al., JGR, 2001):
Same simulation run with multiple codes by multiple members of the community
 - **Conceived at a GEM meeting**
 - **Met the following year to compare results for the first time**
 - **All codes with Hall term had fast reconnection**
 - **11th most cited reconnection paper (473 citations)**
 - **3rd most cited JGR-SP paper**



Courtesy of M. Shay



Birn et al., 2001

JGR | Journal of Geophysical Research
Space Physics

Most Cited | Most Viewed | Just Published | Editors' Highlights

The AGU "Most Cited" count includes only primary, peer-reviewed sources provided by the more than 3800 publishers who participate in CrossRef. The count is updated every Monday for the previous week... [More]

(566) Extension of the MSIS Thermosphere Model into the Middle and Lower Atmosphere

(441) Large-Amplitude Alfvén Waves in the Interplanetary Medium, 2

(411) Geospace Environmental Modeling (GEM) Magnetic Reconnection Challenge

(382) Magnetic Loop Behind an Interplanetary Shock: Voyager, Helios, and IMP 8 Observations

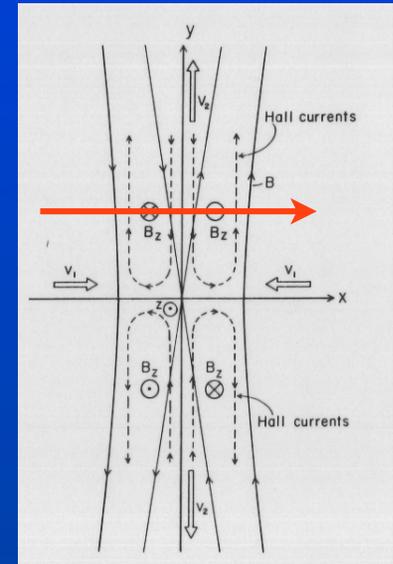
(373) MSIS-86 Thermospheric Model

13
View More

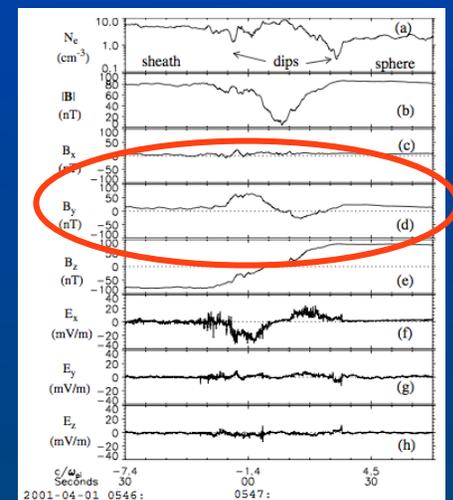
Observations of Hall Reconnection

- **Hall reconnection is marked by a quadrupole out-of-plane magnetic field** (Sonnerup, 1979)
 - **Attributed to in-plane current**
 - **Can also be thought of as dragged out of the page by electrons** (Mandt et al., GRL, 1994)
 - **Similar to physics of whistler wave**
 - **Fast reconnection can occur when dispersive waves in system** (Rogers et al., PRL, 2001)
- **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)

Hall reconnection is the relevant reconnection model in the magnetosphere



Sonnerup, 1979



Mozer et al., 2002

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- **Early History of Magnetic Reconnection**
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 - **Magnetospheric Applications 2000 - present**
 - Dayside - Solar Wind-Magnetospheric Coupling
 - Dayside - Flux Transfer Events
 - Signatures/Microphysics of Reconnection
 - Nightside - Particle Acceleration
 - Nightside - Dipolarization Fronts
- **The Future**

Solar Wind-Magnetospheric Coupling

- A major goal of space weather (and GEM!) research
 - Predicting geomagnetic activity from conditions in the solar wind
- Long history (Newell et al., JGR, 2007)
 - By late 70s, it was thought to be related to solar wind electric field
 - “Axford conjecture”: solar wind convection electric field determines the reconnection electric field (Axford, Rev. Geophys., 1969)
- Attempts to quantify this started simple
 - Modern studies use observed data to fit to reasonable functional forms and get a best fit
 - “Empirical” approach, promoted by B. McPherron in 2008(?) GEM Tutorial
 - Can achieve ~75% correlation!

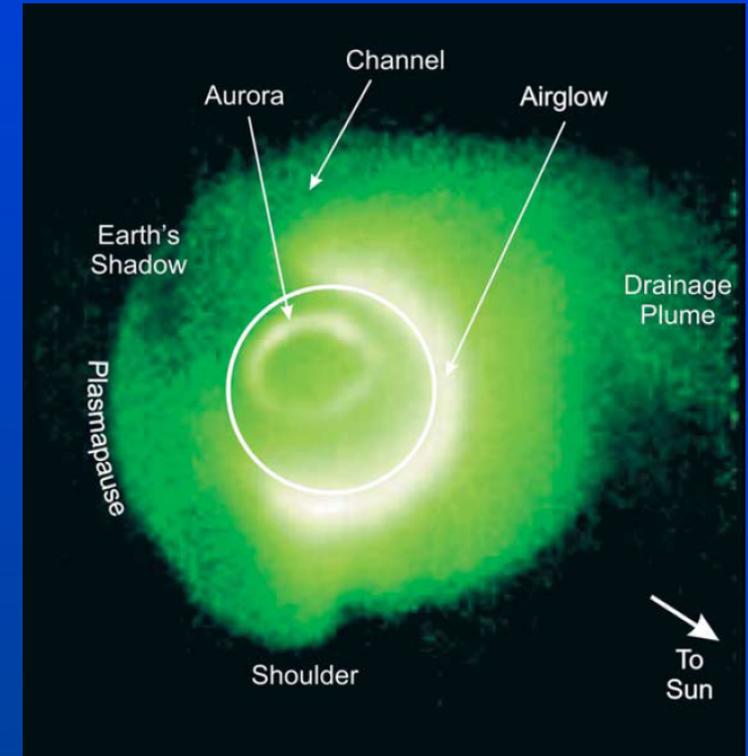
Table 1. Twenty Candidate Solar Wind-Magnetosphere Coupling Functions and Their Origins in Roughly Historical Order

Name	Functional Form	Reference
B_z	B_z	Dungey [1961]
Velocity	v	Crooker et al. [1977]
Density	n	
p	$nv^2/2$	Chapman and Ferraro [1931]
B_s	$B_z (B_z < 0);$ $0 (B_z > 0)$	
Half-wave rectifier	vB_s	Burton et al. [1975]
ϵ	$vB^2 \sin^4(\theta_c/2)$	Perrault and Akasofu [1978]
ϵ_2	$vB_T^2 \sin^4(\theta_c/2)$	Variant on ϵ
ϵ_3	$vB \sin^4(\theta_c/2)$	Variant on ϵ
Solar wind E-field	vB_T	
E_{KL}	$vB_T \sin^2(\theta_c/2)$	Kan and Lee [1979]
$E_{KL}^{1/2}$	$[vB_T \sin^2(\theta_c/2)]^{1/2}$	Variant on the Kan-Lee electric field
E_{KLV}	$v^{4/3} B_T \sin^2(\theta_c/2) p^{1/6}$	Vasyliunas et al. [1982]
E_{WAV}	$vB_T \sin^4(\theta_c/2)$	Wygant et al. [1983]
E_{WAV}^2	$[vB_T \sin^4(\theta_c/2)]^2$	Variant on E_{WAV}
$E_{WAV}^{1/2}$	$[vB_T \sin^4(\theta_c/2)]^{1/2}$	Variant on E_{WAV}
E_{WV}	$v^{4/3} B_T \sin^4(\theta_c/2) p^{1/6}$	Vasyliunas et al. [1982]
E_{SR}	$vB_T \sin^4(\theta_c/2) p^{1/2}$	Scurry and Russell [1991]
E_{TL}	$n^{1/2} v^2 B_T \sin^6(\theta_c/2)$	Temerin and Li [2006]
$d\Phi_{MP}/dt$	$v^{4/3} B_T^{2/3} \sin^{8/3}(\theta_c/2)$	This paper

Newell et al., 2007

Recent Developments

- **Borovsky and Denton (GRL, 2006)** studied effect of “**plasmaspheric drainage plumes**” on SW-MS coupling
 - They occur when pulse in SW make reconnection faster, pulls in material from plasmasphere
 - Borovsky showed SW-MS coupling becomes less efficient when a plume reaches dayside magnetopause
 - Higher density decreases the Alfvén speed, makes reconnection slower



Sandel et al., Space Sci. Rev., 2003
via R. Denton's GEM tutorial, 2011

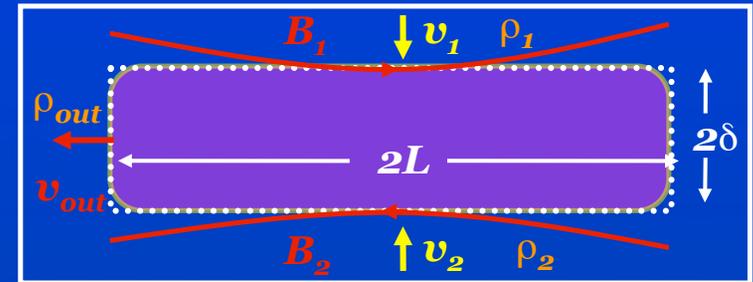
- SW-MS coupling influenced by local reconnection physics
- Calls Axford conjecture into question

Quantifying the Coupling

- “Borovsky conjecture:” local dayside reconnection physics controls

SW-MS coupling (Borovsky, JGR, 2008)

- Must predict reconnection efficiency (rate) as a function of parameters at the dayside
- The dayside is usually asymmetric (different B and n)
- Need a Sweet-Parker-type analysis for asymmetric reconnection (Cassak and Shay, Phys. Plasmas, 2007)



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

Reconnection Rate

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

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

Outflow speed

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

$$v_1 B_1 \sim v_2 B_2$$

Outflow density

$$\rho_{out} \sim \frac{\rho_1 B_2 + \rho_2 B_1}{B_1 + B_2}$$

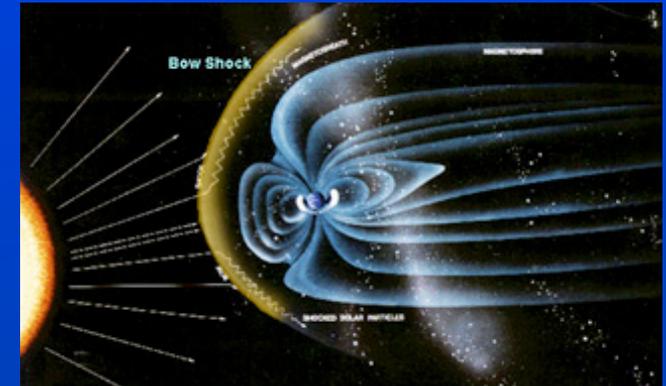
- This follows from first principles!
- Independent of dissipation mechanism, generalizes $E \sim (1/c) B_{CA} (\delta / L)$
- Scaling in 2D rectangular box has now been well tested numerically (Birn et al., 2008; Cassak and Shay, GRL, 2008; Phys. Plasmas, 2009; Malakit et al., 2010)
 - Scaling in magnetospheric geometry tests well for southward IMF (Borovsky et al., JGR, 2008; Sullivan et al., 2010), but has not been established for any other conditions

The Borovsky Coupling Function

- Start with expression for reconnection rate (in SI units, “ms” = magnetosphere, “sh” = magnetosheath) (Borovsky, JGR, 2008)

$$E \sim \frac{2B_{sh}B_{ms}}{B_{sh} + B_{ms}} v_{out} \frac{\delta}{L}$$

$$\sim \frac{2B_{sh}B_{ms}}{B_{sh} + B_{ms}} \sqrt{\frac{B_{sh}B_{ms}}{\mu_0} \frac{B_{sh} + B_{ms}}{\rho_{sh}B_{ms} + \rho_{ms}B_{sh}}} \frac{\delta}{L}$$



Courtesy of NASA

- Next, relate local quantities to properties of solar wind

- Use arguments on pressure balance, shock theory, some semi-empirical relations, assume $\delta/L \sim 0.1$

$$E_x : \frac{B_{ms}^2}{8\pi} \sim \frac{B_{sh}^2}{8\pi} + P_{sh} \sim \frac{B_{SW}^2}{8\pi} + P_{SW} + \frac{1}{2}\rho_{SW}v_{SW}^2$$

$$E \sim 0.4\mu_0^{1/2} \sin(\theta/2)\rho_{SW}v_{SW}^2(1 + 0.5M_{ms}^{-2})(1 + \beta_{sh})^{-1/2}$$

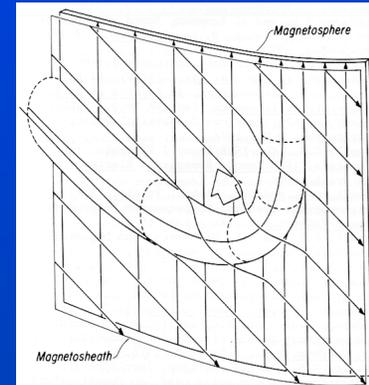
$$\left[C\rho_{SW} + (1 + \beta_{sh})^{-1/2}\rho_{ms} \right]^{-1/2} \left[(1 + \beta_{sh})^{1/2} + 1 \right]^{-1/2}$$

- Tested result with OMNI2 data, correlated at 75% level (Borovsky, JGR, 2008)
 - Comparable to the best previous empirical fitting result (Newell et al., JGR, 2007), but comes (mostly) from first principles!

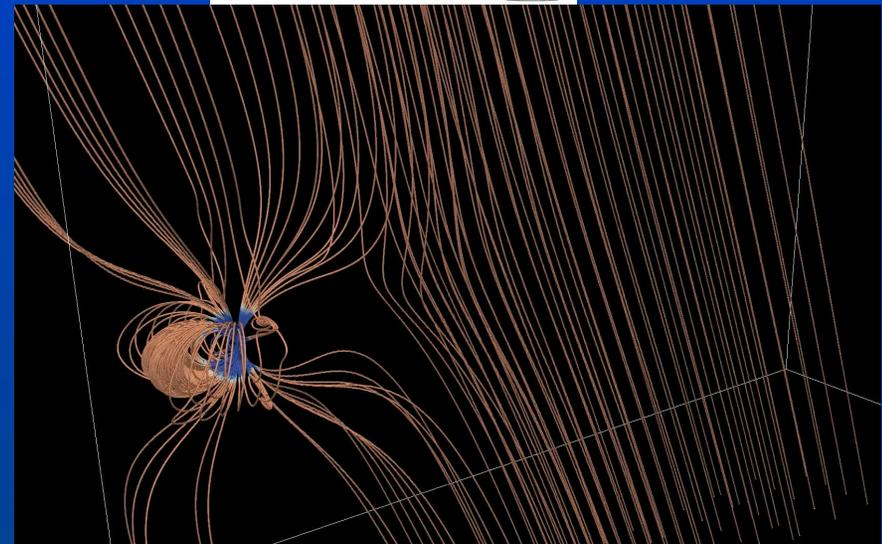
Many assumptions that require testing, but this suggests first principles - and fundamental reconnection physics - can be important to SW-MS coupling!

Dayside - Flux Transfer Events

- **Closed tubes of magnetic flux are observed at the dayside, called Flux Transfer Events** (Russell and Elphic, Space Sci. Rev., 1978)
 - Widely thought to be a result of **non-steady (bursty) reconnection on the dayside**
 - How FTEs are manifested becomes a fundamental physics question about reconnection
- **Burstiness appears even in 2D reconnection**
 - Occurs in collisional (Sweet-Parker) reconnection when $S > S_{crit} \sim 10^4$ (Biskamp, Phys. Fluids, 1986)
 - Also occurs in collisionless PIC simulations (Daughton et al., Phys. Plasmas, 2006)
 - Are the two manifestations the same?
- **Large-scale global hybrid simulations [1 trillion (!) particles] reveal copious production of FTEs** (Karimabadi et al., 2010)



Russell and Elphic, 1979

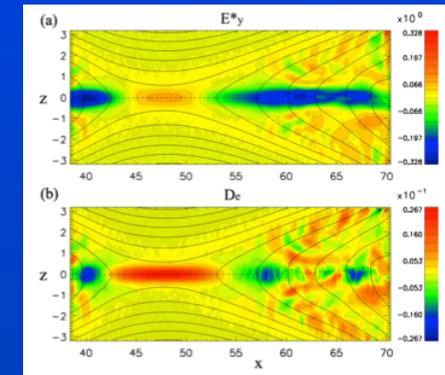


Courtesy of H. Karimabadi

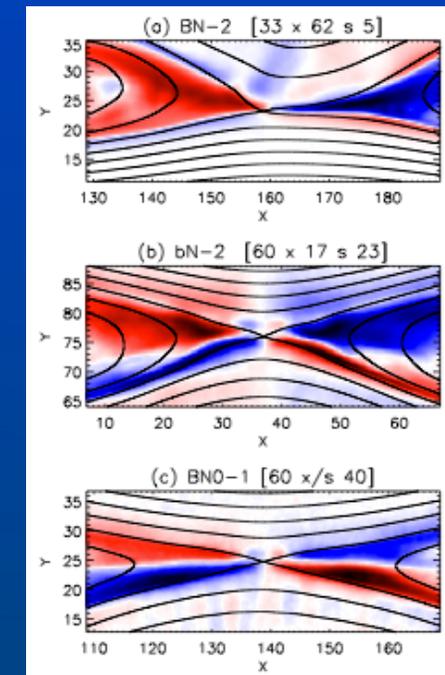
Development of large-scale *kinetic* simulations allow unprecedented opportunity to study production and effects of FTEs in collisionless systems

Signatures and Microphysics

- **Observations of magnetospheric reconnection require knowledge of its micro- and meso-scale signatures**
 - **Example 1 - Two-scale structure of electron diffusion region**
 - **Electron layer longer than originally thought** (Daughton et al., Phys. Plasmas, 2006; Shay et al., PRL, 2007; Karimabadi et al., GRL, 2007; Klimas et al., Phys Plasmas, 2008)
 - **Electron layer has two scales, inner layer known already and outer layer that does not cause a bottleneck**
 - **Outer layer is frozen-in in different reference frame; diamagnetic effects are important in the outer region** (Hesse et al., Phys. Plasmas, 2008)
 - **New measure of frame-independent dissipation; confirmed outer layer is not dissipative** (Zenitani et al., PRL, 2011)
 - **Example 2 - “Quadrupole” structure of Hall B fields**
 - **Hall magnetic fields are quadrupolar** (Sonnerup, 1979)
 - **Becomes more bipolar when there is a strong asymmetry, as is expected at the dayside** Karimabadi et al., JGR, 1999; Mozer et al., GRL, 2008; Tanaka et al., Ann. Geophys., 2008)
 - **Structure of Hall field is related to the substructure of the dissipation region in asymmetric reconnection (relative location of X-line and stagnation point)** (Malakit et al., in prep)



Zenitani et al., 2011

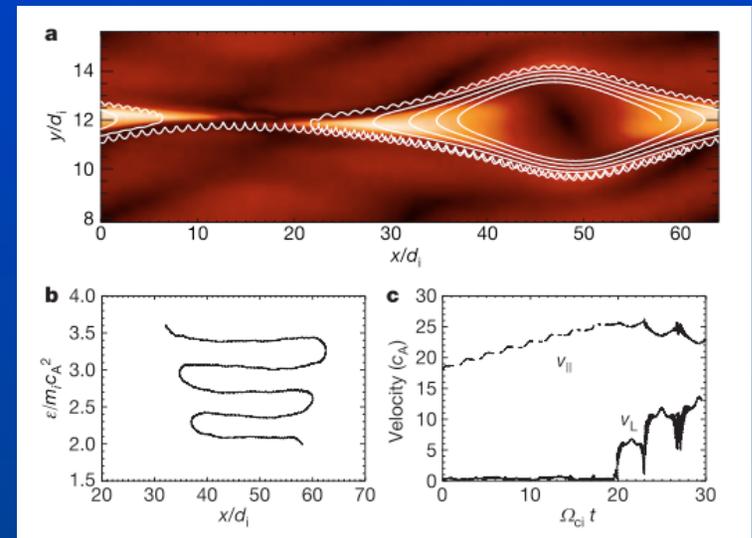


Malakit, 2012

Studies of fundamental physics of reconnection can help determine observable properties in magnetosphere

Particle Acceleration

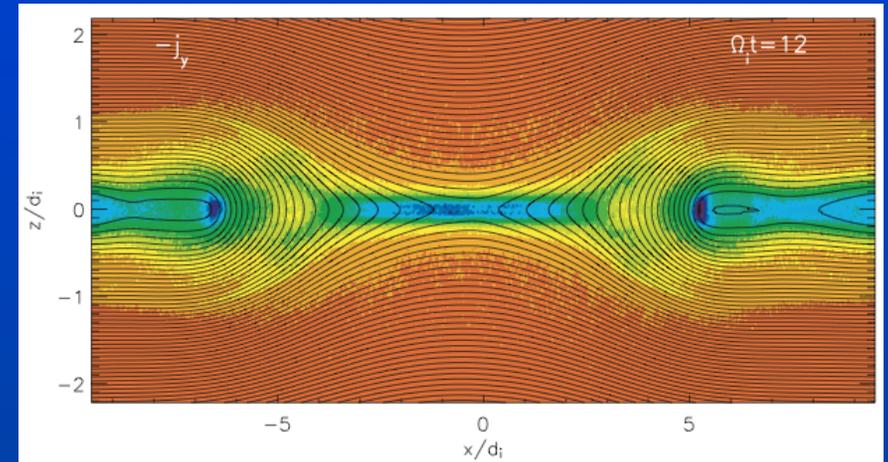
- **What is the role of magnetic reconnection in particle acceleration?**
 - **Giovanelli argued particles are accelerated by the reconnection electric field**
 - **The dissipation region is very small; only few particles would accelerate**
 - **Is acceleration near reconnection sites caused by the physics 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; theory** (Drake et al., Nature, 2006) **and observations** (Chen et al., Nature Phys., 2008)
 - **Island coalescence** (Oka et al., ApJ, 2010)
 - **Parallel electric field in islands** (Oka et al., JGR, 2010)
 - **Parallel electric field caused by an electron temperature anisotropy due to trapped electrons in inflow region** (Egedal et al., JGR, 2008; Nature Phys., 2012)



Drake et al., Nature, 2006

M'Tail - Dipolarization Fronts

- **Substorms and bursty bulk flows lead to a dipolarization of the terrestrial magnetic field** (e.g., Baumjohann et al., JGR, 1990; Angelopoulos et al., JGR, 1992; Ohtani et al., JGR, 2004)
 - **Originally thought to be the effect of material running into magnetospheric field**
 - **Recent simulations** (Sitnov et al., JGR, 2009) **and observations** (Runov et al., GRL, 2009; JGR, 2011) **suggest it is a generic feature of reconnection as newly reconnected field lines straighten, which explains why they occur in many locations in the magnetotail**



Sitnov et al., 2009

- **Compresses normal magnetic field, this may be important as a seed location for ion and electron heating**
- **Manifests differently depending on equilibrium fields** (Sitnov and Swisdak, JGR, 2011)
- **Related to retreat of reconnection site in magnetotail** (Oka et al., GRL, 2011)
- **Propagation speed scales with Alfvén speed, faster DFs reflect ions** (Wu and Shay, GRL, 2012)

Outline

- **Early History of Magnetic Reconnection**
 - 1930s through 1981
- **Middle History of Magnetic Reconnection**
 - 1979 through 2001
- **Recent History of Magnetic Reconnection**
 - Magnetospheric Applications 2000 - present
- **The Future**

Open Questions

- **Solar wind-magnetospheric coupling**
 - How does micro-scale physics couple to the macro-scale?
 - Do local reconnection models apply to the magnetopause? Does the Borovsky coupling function describe SW-MS coupling? Under what conditions?
 - **Observations** (Turner et al., JASTP, 2009; Guo et al., JGR, 2010; Spencer et al., JGR, 2011) **and numerics** (Lopez et al., Ann. Geo., 2011)
- **Flux Transfer Events**
 - What is their dependence on dissipation mechanism?
 - **Collisionless vs. collisional vs. numerical**
 - What is their role in mass and energy transfer from the solar wind to the magnetosphere (SW-MS Coupling)? In particle acceleration?
- **Signatures and Microphysics**
 - What are the signatures of reconnection in magnetospheric settings?
 - What are effects of asymmetries, flow, 3D effects?
 - What effects, if any, do the outer dissipation region have on reconnection?
- **Particle acceleration**
 - What are the dominant acceleration mechanism(s) for a given setting?
 - How much acceleration can be expected from a single reconnection site? Multiple reconnection sites?
- **Dipolarization fronts**
 - What qualifies as a dipolarization front and how they propagate?
 - How do DFs and BBFs contribute to substorm phenomena (Lyons et al., JGR, 2012)? Are they a window on onset?
 - How do DFs play a role in particle acceleration?
- **Other topics**
 - How does reconnection proceed in fully 3D settings, and how can it be quantified (e.g., Dorelli et al., JGR, 2007)
 - What is the nature of reconnection in turbulent media such as the solar wind or magnetosheath (Servidio et al., PRL, 2009)?
 - Can kinetic effects on reconnection be captured by additions to fluid codes (Kuznetsova et al., JGR, 2007; Le et al., PRL, 2009)?



Near Future - MMS Mission

- **Magnetospheric Multi-Scale (MMS) Mission**

- NASA Mission scheduled for 2014

- Similar to Cluster (4 satellites),
but closer together

- Goal is to understand micro-scale
(electron) physics of reconnection

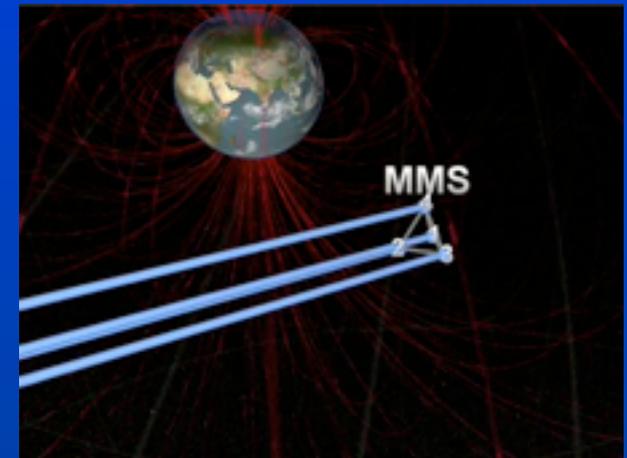
- **Will afford unprecedented
spatio-temporal resolution**

- Excellent opportunity to test
theory/simulation

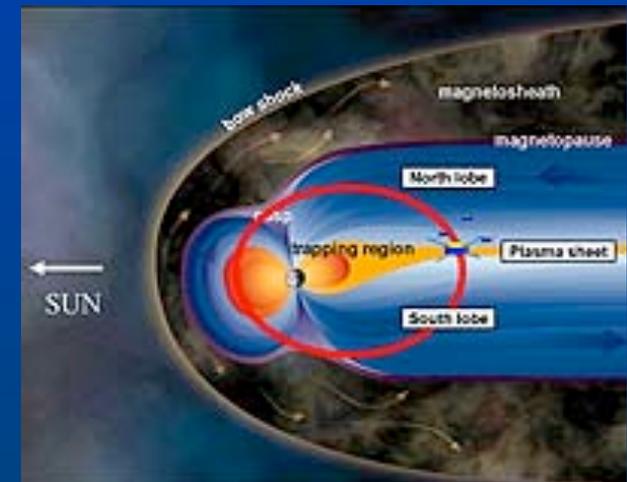
- **Much theoretical work needs
to be done to prepare**

- Example - signatures of reconnection

The next few years will be an
exciting time for reconnection!

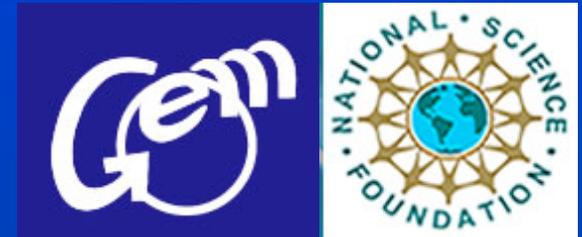


Courtesy of MMS



An Appeal

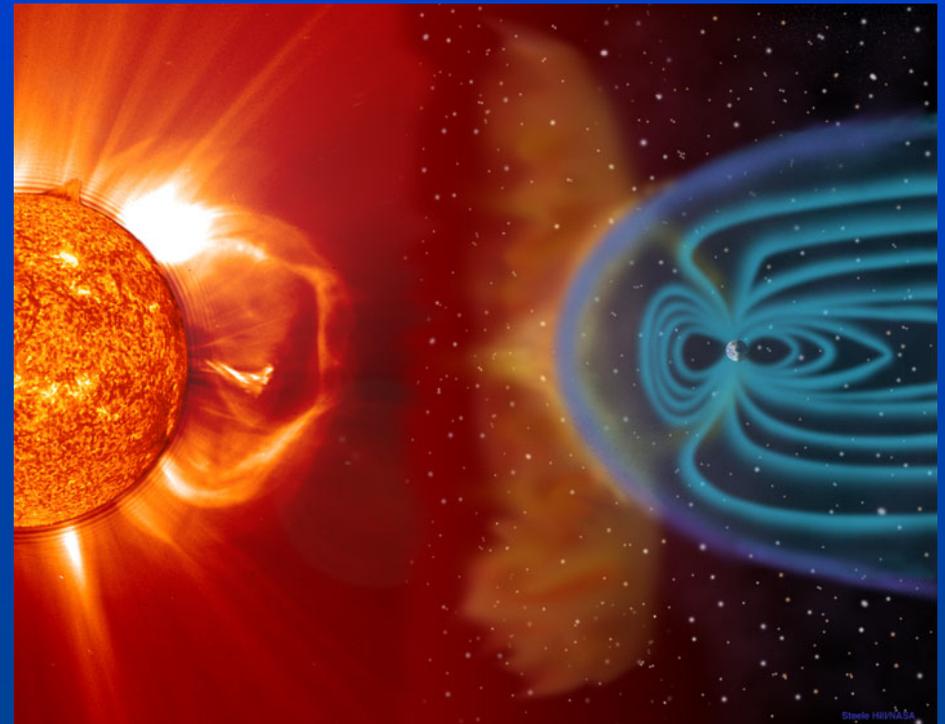
- **Despite a very successful past, there is currently no GEM Focus Group on fundamental reconnection physics (previous one ended in 2010)**
 - Aspects arise in many existing focus groups (> 8 out of 12!)
 - Near Earth Magnetosphere
 - Plasmasphere-Magnetosphere Interactions
 - Substorm Expansion Onset: The First 10 Minutes
 - Modes of Solar Wind-Magnetosphere Energy Transfer
 - The Magnetosheath
 - Metrics and Validation
 - Tail-Inner Magnetosphere Interactions
 - Transient Phenomena at the Magnetopause and Bow Shock and Their Ground Signatures
- **Many open questions would benefit by being addressed as fundamental physics!**
 - Micro- to macro-scale, SW-MS coupling, FTEs, 3D reconnection (a new GEM challenge?), how to parametrize in global fluid codes, the march toward global kinetic modeling, particle acceleration, ...
- **Need to encourage interaction between observers, theorists, and modelers**
 - Especially important with impending launch of MMS



Please contact me at Paul.Cassak@mail.wvu.edu if you would like to be on the mailing list for a potential reconnection Focus Group!

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
- Reconnection has a rich history, and it’s still being written!
- Thank you!



<http://www.msfc.nasa.gov/>

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