Magnetic Reconnection

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In collaboration with
Joe Olson, Cary Forest and the MPDX team

UW-Madison, WI
Les Houches, March, 2015
Madison Plasma Dynamo eXperiment
Key new hardware for TREX

- **Cylindrical Insert**:
  - Houses internal coils to drive reconnection
  - Results in symmetric, symmetric reconnection and strong guide field reconnection
  - To be pulsed at a 10 s rep rate

**Hugely flexible facility**

→ **User Facility**
Magnetic Reconnection

- A change in magnetic topology in the presence of a plasma

Consider a small perturbation

Plasma carrying a current

Magnetic fields
• A change in magnetic topology in the presence of a plasma

Consider a small perturbation
Magnetic Reconnection

- A change in magnetic topology in the presence of a plasma

Consider a small perturbation

Nearly all the initial magnetic energy is converted into:
1. thermal energy
2. kinetic energy on fast electrons and ions
3. kinetic energy of large scale flows
Coronal Mass Ejections

The most powerful explosions in our solar system

Can power the US consumption of electricity for 10 million years
Outline

- More Pretty Pictures
- Models for Reconnection
- Role of Pressure Tensor
- Electron Heating
- TREX, the Terrestrial Reconnection EXperiment
  ("The" Reconnection EXperiment)
- Conclusions
Coronal Mass Ejections

Movie from NASA’s Solar Dynamics Observatory (SDO)
Outstanding Problems

- Heating
- 3D effects
- Trigger

Arcade as seen from above
The Solar Wind affects the Earth’s environment
The Earth’s Magnetic Shield

Before reconnection

During reconnection

Magnetopause
Cusp
Solar Wind
Bow Shock
Magnetosheath
Magnetotail
Plasmasheet
Plasmasphere
Neutral point
Becoming reconnection

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Magnetic Storms
Aurora Borealis

October 26\textsuperscript{th}, 2011, Nantucket Island, Massachusetts, USA
Aurora Borealis

October 26th, 2011, Kola Peninsula, Russia
Carrington Flare  (1859, Sep 1, am 11:18)

- Richard Carrington (England) first observed a solar flare in 1859.
- White flare for 5 minutes.
- Very bright aura appeared next day in many places on Earth including Cuba, the Bahamas, Jamaica, El Salvador and Hawaii.
- Largest magnetic storm in recent 200 years (> 1000 nT).

Telegraph systems all over Europe and North America failed, in some cases even shocking telegraph operators. Telegraph pylons threw sparks and telegraph paper spontaneously caught Fire. (Loomis 1861)

Magnetic storm and aurora on March 13, that lead to Quebeck blackout (for 6 million people)

Magnetic storm \( \sim 540 \text{ nT} \), Solar flare X4.6.

A Carrington Flare today \( \Rightarrow \) 30 – 70 billion dollars of damage
Occurrence frequency of flares?

1000 in 1 year
100 in 1 year
10 in 1 year
1 in 1 year
1 in 10 years
1 in 100 years
1 in 1000 years
1 in 10000 years

New Kepler data from 83,000 stars for 120 days

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The Magnetosphere as a Laboratory

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MMS Successfully Launched!

Magnetospheric Multiscale Missing

March, 12, 2015
Electromagnetism 101

- Faraday’s law:

\[ EMF = -Area \cdot \frac{dB}{dt} \]

- Faraday’s law for a conducting ring: EMF=0.

- The magnetic flux through the ring is trapped

- This also holds if the ring is made of plasma

\[ \Rightarrow \text{plasma frozen in condition} \]
Magnetic Topology Constant in Ideal Plasma

- Ideal Plasma \( E' = E + v \times B = 0 \)  \( \Rightarrow \) Plasma and B frozen together

Ideal MHD: \( E \cdot B = 0 \),

Excellent for 99.9% of all plasmas, 99.9% of the time.
Philosophical Magazine Series
LXXVI. Conditions for the Occurrence of Electrical Discharges in Astrophysical Systems

By J. W. Dungey
School of Physics, The University of Sydney, Australia*

[Received November 14, 1952, revised March 11, 1953]
Simplest model for reconnection:
\[ \mathbf{E} + \mathbf{v} \times \mathbf{B} = \eta \mathbf{j} \quad [\text{Sweet-Parker (1957)}] \]

\[
- \frac{\partial \Psi}{\partial t} \bigg|_x = E_x = \eta j_x
\]
Simplest model for reconnection:

\[ \mathbf{E} + \mathbf{v} \times \mathbf{B} = \eta \mathbf{j} \quad [Sweet-Parker (1957)] \]

Sweet-Parker: \( L \gg \delta \):

\[
t_{sp} = \sqrt{t_R t_A} = \sqrt{\frac{\mu_0 L^2}{\eta}} \sqrt{\frac{L}{v_A}}
\]

Unfavorable for fast reconnection

Two months for a coronal mass ejections

Outflow speed:

\[ v_A = \frac{B}{\sqrt{\mu_0 n m_i}} \]

(Alfven speed)
Consider flux tube with reflecting boundaries:

Conserved quantities:

\[ \mu = \frac{mv_{\perp}^2}{B} \]

\[ \frac{p_{\perp}}{p_{\perp 0}} = \frac{n}{n_0} \frac{B}{B_0} \]

\[ J = \oint v_{\parallel} dl \]

\[ \frac{p_{\parallel}}{p_{\parallel 0}} = \frac{n}{n_0} \frac{l^2_0}{l^2} = \frac{n^3 B_0^2}{n_0^3 B^2} \]

Flux: \[ A B \]

\[ \frac{l}{l_0} = \frac{n_0}{n} \frac{B}{B_0} \]

\# Partic: \[ n A l \]

CGL-scalings

[Chew, Goldberger, Low, 1956]
Things Good to Know: Whistlers
The collisionless Vlasov equation:

\[
\left( \frac{\partial}{\partial t} + \mathbf{v} \frac{d}{dt} \right) f_j(x, v, t) = 0 \cdot \nabla_v \right) f_j = 0
\]

\[
n_j = \int f_j d^3v \quad \mathbf{J}_j = q_j \int v f_j d^3v
\]

+ Maxwell’s eqs.

Vlasov-Maxwell system of equations

Can be solved numerically (PIC-codes)
Fluid Formulation (Conservation Laws)

mass:

\[ \frac{\partial n}{\partial t} + \frac{\partial (n u_j)}{\partial x_j} = 0, \]

momentum:

\[ mn \left( \frac{\partial u_j}{\partial t} + u_k \frac{\partial u_j}{\partial x_k} \right) + \frac{\partial P_{jk}}{\partial x_k} - en \left( E_j + \epsilon_{jkl} u_k B_l \right) - F_j^{\text{coll}} = 0, \]

energy:

\[ \frac{\partial P_{jk}}{\partial t} + \frac{\partial}{\partial x_l} \left( P_{jk} u_l + Q_{ikl} \right) + \frac{\partial u_{[j}}}{\partial x_{l]} \right) - \frac{e}{m} \epsilon_{[jlm} B_{m} P_{lk]} - G_{jk}^{\text{coll}} = 0. \]

Isotropic (scalar) pressure is the standard closure!

\[ p = n \, T \]

Add Maxwell’s eqs to complete the fluid model.
Two-Fluid Simulation

GEM challenge (Hall reconnection)
\( \mathbf{E} + \mathbf{v} \times \mathbf{B} = \frac{(\mathbf{j} \times \mathbf{B})}{ne} \)  [Birn, … Drake, et al. (2001)]

Out of plane current

Aspect ratio: 1 / 10

\( v_{in} \sim \frac{v_A}{10} \)
Hall Effect documented in Simulations and in MRX

**PIC Simulation**

**Experiment**

The electron diffusion region identified inside the ion diffusion region in a laboratory plasma

[Ren et al, PRL 08, Ji et al GRL, 08, Dorfman et al '10]
Two-Fluid Simulation vs. Kinetic

Isotropic pressure

<i>FLUID: ISOTROPIC PRESSURE</i>

Kinetic Simulation

<i>FULLY KINETIC SIMULATION</i>

Out of plane current

Particle In Cell (PIC) simulation,
Electron Trapped by $\Phi_\parallel$, $B_g = 0.4$

$$\Phi_\parallel(x) = \int_x^\infty \mathbf{E} \cdot d\mathbf{l}$$

$$e\Phi_\parallel / T_e$$
Pressure Anisotropy

WIND Spacecraft Observations in Magnetotail, 60$R_E$

- Measurements within the ion diffusion region reveal:
  **Strong anisotropy in $f_e$**
  \[ p_{\parallel} > p_{\perp} \]
Wind Spacecraft Observations

- Measurements within the ion diffusion region reveal:
  **Strong anisotropy in** \( f_e \)
  \[ p_{||} > p_{\perp} \]

- Simulations: Ion density near uniform
- Quasi neutrality: \( n_e \approx n_i \)
- \( A_2 \approx A_1 \): Parallel compression by \( E_{||} \)
- Trapped electrons dominate, Zero heat transport
  \[ \text{CGL: } p_{||} \propto n^3/B^2, \quad p_{\perp} \propto nB \]
Electrons in an Expanding Flux Tube

Magnetic moment:

$$\mu = \frac{mv_{\perp}^2}{2B}$$

⇒ mirror force:
Electrons in an Expanding Flux Tube

Trapped:
\[ \mathcal{E}_\perp = \mu B = \mathcal{E}_\infty B / B_\infty \]
\[ \implies \mathcal{E}_\infty = \mu B_\infty \]

Passing:
\[ \mathcal{E} = \mathcal{E}_\infty + e\Phi_\parallel \]
\[ \implies \mathcal{E}_\infty = \mathcal{E} - e\Phi_\parallel \]

Drift kinetic equation:
\[ \frac{df}{dt} = 0 \]
\[ f(x, v) = f_\infty(\mathcal{E}_\infty) \]

J. Egedal et al., JGR (2009)
J. Egedal et al., POP (2013)

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Les Houches, March, 2015
EoS Implemented in Two-Fluid Code

- Moments over kinetic model yields fluid closure with anisotropic pressure, $EoS$, $p_\parallel(n, B)$ and $p_\perp(n, B)$ [Le et al., PRL 2009]

- $EoS$ implemented by O Ohia using the HiFi framework developed in part by VS Lukin

\[
\begin{align*}
\frac{\partial n}{\partial t} + \nabla \cdot (n \mathbf{v}_i) &= 0 \\
\frac{\partial \mathbf{v}_i}{\partial t} + \mathbf{v}_i \cdot \nabla \mathbf{v}_i &= \mathbf{J} \times \mathbf{B} - \nabla \cdot \mathbf{P} + m_i n v_i \nabla^2 \mathbf{v}_i \\
\frac{\partial}{\partial t} \left( \frac{p_i}{n^\Gamma} \right) &= -\mathbf{v}_i \cdot \nabla \frac{p_i}{n^\Gamma} \\
\frac{\partial \mathbf{B}}{\partial t} &= -\nabla \times \mathbf{E}' \\
\mathbf{E}' + \mathbf{v}_i \times \mathbf{B} &= \frac{1}{n e} \left( \mathbf{J} \times \mathbf{B}' - \nabla \cdot \mathbf{P}_e \right) + \eta_R \mathbf{J} - \eta_H \nabla^2 \mathbf{J} \\
\mathbf{B}' &= (1 - d_e^2 \nabla^2) \mathbf{B} \\
\mu_0 \mathbf{J} &= \nabla \times \mathbf{B}
\end{align*}
\]

Standard two-fluid equations

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\[
\begin{align*}
\mathbf{P} &= p_i \mathbf{I} + \mathbf{P}_e = p_i \mathbf{I} + p_\perp \mathbf{I} + (p_\parallel - p_\perp) \frac{BB}{B^2}, \\
\tilde{p}_\parallel &= \tilde{n} \frac{2}{2 + \alpha} + \frac{\pi \tilde{n}^3}{6 \tilde{B}^2} \frac{2\alpha}{2\alpha + 1}, \\
\tilde{p}_\perp &= \tilde{n} \frac{1}{1 + \alpha} + \tilde{n} \tilde{B} \frac{\alpha}{\alpha + 1}.
\end{align*}
\]

Here, $\alpha = \tilde{n}^3/\tilde{B}^2$ and $\tilde{Q} = Q/Q_\infty$

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Boltzmann

CGL

Anisotropic pressure model
New EoS Implemented in Two-Fluid Code

Ohia et al., PRL, 2012

Out of plane current

Isotropic pressure

Anisotropic pressure

Kinetic Simulation

FLUID: ISOTROPIC PRESSURE

FLUID: NEW CLOSURE

FULLY KINETIC SIMULATION

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Kinetic simulation results at $m_i/m_e = 1836$, [A Le et al., PRL 2013]
Regimes of the Electron Diffusion Region

Regimes of reconnection vs. $m_i/m_e$ and $B_g$

Unexplored regime of reconnection, relevant to the MMS mission

[Le et al., PRL, 2013]
Role of Collisions for Pressure Anisotropy

\[ \frac{B_g}{B_0} = 0.28 \quad \frac{m_i}{m_e} = 1836 \]

Collisionless if

\[ \tau_{ei} 0.1 \nu_A > di \]

or

\[ S \gtrsim 10 \epsilon (m_i/m_e) \lambda \]

\[ \lambda = L/d_i \quad \epsilon = L_{SP}/L_i \]
Role of Collisions:

\[ S > 10^4 \frac{L}{d_i} \]

Condition for anisotropy

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Phase Diagram for moderate guide fields \((B_g \leq B_r)\)

- Magnetotail
- Magnetopause
- Multiple X-lines
- Solar Wind
- Solar Corona
- Multiple X-lines hybrid
- Single X-line collisional
- Multiple X-lines collisional

\[ \nu_{ei}/\omega_c = 10^{-4} \]


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EoS for anti-parallel reconnection?

The electrons are magnetized in the inflow region:
Electron distributions in the layer  [J. Ng et al., PRL2011]
The electrons are magnetized in the inflow region:

Momentum balance: \[ p_{\parallel}(n, B) - p_{\perp}(n, B) = B^2 \]

With CGL:

\[ \Phi_{\parallel}(x) = \int_{x}^{\infty} E \cdot dI \]
Estimates of $\Phi_{\parallel}$ in the Magnetotail

Cluster Mission  August 21, 2002

Magnetotail data, 18 events

$e\Phi_{\parallel}/T_e \approx 110$
Breakdown of Parallel Adiabaticity

Expect non-adiabatic behavior if $v_{e||} > v_{te} \Rightarrow \beta_{e\infty} < 200 \frac{m_e}{m_i}$

Including role of $E_{||}$ for driving flows \textit{(kinetic model)} \quad $\beta_{e\infty} < \left( \frac{m_e}{100m_i} \right)^{\frac{1}{3}} \approx 0.02$
Simulation with $\beta_e \sim 0.003$

- 320 $d_i$ long, 180 billion particles
Simulation with $\beta_e \sim 0.003$

- 320 $d_i$ long, 180 billion particles!
Strong Double Layer Instability Observed

\[
f_{\parallel}(x, v_{\parallel}) = 2\pi \int v_{\perp} f dv_{\perp}
\]
$\Phi_\parallel$ confines electrons, further energized by $E_\perp$.

Heated by $v_d \cdot E_\perp$,

\[
\frac{d\mathcal{E}}{dt} \approx \mathcal{E}_0 \frac{v_A}{2l}
\]
or
\[
\frac{\partial v}{\partial t} \approx \frac{v_A}{\tau_b}
\]
Generation of Super-Thermals

$\log_{10}(\text{# of electrons with energies above } 1.7mc^2)$

Steady state:

$\log_{10} f(E)$

Continuity Eq. for electrons with $v_1 < |v| < v_2$:

$$4\pi v^2 dv \frac{\partial f}{\partial t} \bigg|_{v=v_1} = - 4\pi v^2 dv f R_{loss} \frac{dt}{\tau_b/2} \bigg|_{v=v_1} - 4\pi v^2 \frac{\partial v}{\partial t} dt f \bigg|_{v=v_1} + 4\pi v^2 \frac{\partial v}{\partial t} dt f \bigg|_{v=v_2}$$

$$v^2 \frac{\partial f}{\partial v} = - \frac{2v^2}{\tau_b} f R_{loss} - \frac{\partial}{\partial v} \left( v^2 \frac{\partial f}{\partial v} \right)$$

Steady state:

$$f = \frac{A}{v^3} \exp \left( - \frac{v R_{loss}}{v_A} \right)$$
Model applicable to solar flares?

Ohm’s law:

\[-enE_\parallel = \hat{b} \cdot (\nabla \cdot p)\]

Before reconnection: \( p = nT_e \rightarrow e\Phi_\parallel \sim T_e \log(n/n_0) \)

During reconnection:

\( e\Phi_\parallel \geq 100T_e \)

\( \rightarrow \) yielding bulk energization

Superthermal tail generated by \( v_d \cdot E_\perp \)

\( \log_{10}[ f(E) ] \)

Advantages:
Role of free-streaming losses addressed
The model is simple, and works with one or more X-lines

Loop top confinement by \( E_\parallel \) explored by [Li, Drake, et al., 2012, 2013, 2014]

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New Giant Simulation with $B_g=1$:
Requirements for Experiment

- Large normalized size of experiment: \( \frac{L}{d_i} \sim 10 \) (high \( n \), large \( L \))

- Low collisionality to allow \( p_\parallel >> p_\perp \): \( \tau_{ei} \ 0.1vA > di \) (low \( n \), high \( T_e \), high \( B \))

- Low electron pressure: \( \beta_e < 0.05 \) (low \( n \), \( T_e \), high \( B \))

- Manageable loop voltage: \( 0.1v_A B_{rec} (2\pi R) < 5kV \) (high \( n \), low \( B \))

- Variable guide field: \( B_g = 0 - 4B_{rec} \)

- Symmetric inflows

Experimental window available in Hydrogen or Helium plasma with

\( n \sim 10^{18} \text{ m}^{-3}, \ T_e \sim 15 \text{ eV}, \ B_{rec} \sim 15 \text{ mT}, \ L \sim 2 \text{ m} \)
Asymmetric reconnection in TREX

- Simple configuration using the HH-coils plus two internal coils
- This will be the first configuration to be implemented
Experimental Setup

Cross-section of TREX implemented in the MPDX facility

- Area covered by probes
- 3 axis B-probes & L-probes
Reaching Target Plasma

- Helium plasma
- 60G Helmholtz field
- -400 V cathode bias
Preliminary Results

\[ \sim 44.5 \, \mu s \text{ after second pulse} \]
**Strong Guide-field Reconnection**

- Pulsed operation of magnetic coils
- \( B_g = 0.25 \text{T at 1m} \)
- 3 min between pulses
- Optimize configuration for maximal length of reconnection layer to explore “turbulent reconnection”
**Strong Guide-field Reconnection**

- Pulsed operation of magnetic coils
- 3 min between pulses
- $B_g = 0.25\,\text{T} \text{ at } 1\,\text{m}$

$$\rho_s = (2m_iT_e)^{1/2}/eB$$

= "ion sound Larmor Radius"

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<table>
<thead>
<tr>
<th></th>
<th>$n_e/[\text{m}^{-3}]$</th>
<th>$T_e/[$eV$]$</th>
<th>$B_r/[\text{T}]$</th>
<th>$B_g/[\text{T}]$</th>
<th>$L/[\text{m}]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>TREX</td>
<td>$10^{17} - 10^{19}$</td>
<td>8 – 40</td>
<td>0 – 0.05</td>
<td>0 – 0.3</td>
<td>0.8 – 2</td>
</tr>
<tr>
<td>MRX</td>
<td>$10^{19} - 10^{20}$</td>
<td>5 – 10</td>
<td>0.03</td>
<td>0 – 0.1</td>
<td>0.7</td>
</tr>
<tr>
<td>VTF</td>
<td>$10^{17} - 10^{18}$</td>
<td>8 – 30</td>
<td>0.01</td>
<td>0.1</td>
<td>0.3</td>
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Conclusion

• Reconnection is still purely understood, but the pressure tensor is important
• The construction of the new Terrestrial Reconnection EXperiment is well under way
• TREX provides huge flexibility in available configurations, and the insert will allow for fast turn-around.
• MPDX/TREX in the process of becoming a user facility