Magnetic Reconnection in Plasmas: a Celestial Phenomenon in the Laboratory

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Magnetic Reconnection

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

Consider a small perturbation
Plasma carrying a current
Magnetic fields
Magnetic Reconnection

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Magnetic Reconnection

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Magnetic Reconnection

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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
• Description of Magnetic Reconnection

• Reconnection in the Versatile Toroidal Facility
  – Closed configuration
  – Open configuration ➔ Trapped Electrons

• Satellite Data from the Magnetotail

• Fixing the Fluid Equations (The Equations of State)

• A New Experiment is Needed

• Conclusions
Coronal Mass Ejections

Movie from NASA’s Solar Dynamics Observatory (SDO)
The Solar Wind affects the Earth’s environment

Space Weather
The Earth’s Magnetic Shield

- Magnetopause
- Cusp
- Solar Wind
- Bow Shock
- Plasmasphere
- Magnetosheath
- Magnetotail
- Neutral point
- Before reconnection
- During reconnection
Aurora Borealis

October 26th, 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 Québec blackout (for 6 million people)

Magnetic storm ~ 540 nT, Solar flare X4.6.

A Carrington Flare today ➔ 30 – 70 billion dollars of damage
Occurrence frequency of flares?

Aschwanden et al. (1999): TRACE 195 Å
Crosby et al. (1993): SMM/HXRBS >25 keV

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
Electromagnetism 101

- Faraday’s law:
  \[ \text{EMF} = -\text{Area} \cdot \frac{dB}{dt} \]

- 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.

  ➔ plasma frozen in condition
Magnetic Topology Constant in Ideal Plasma

– Ideal Plasma \( \mathbf{E}' = \mathbf{E} + \mathbf{v} \times \mathbf{B} = 0 \) \( \Rightarrow \) Plasma and \( \mathbf{B} \) frozen together

Ideal MHD: \( \mathbf{E} \cdot \mathbf{B} = 0 \),
Excellent for 99.9% of all plasmas, 99.9% of the time.
Reconnection: A Long Standing Problem

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]
Reconnection: A Long Standing Problem

Simplest model for reconnection:
\[ \mathbf{E} + \mathbf{v} \times \mathbf{B} = \eta \mathbf{j} \quad [\text{Sweet-Parker (1957)}] \]

\[ - \frac{\partial \Psi}{\partial t} \bigg|_x = E_x = \eta j_x \]
Reconnection: A Long Standing Problem

**Simplest model for reconnection:**

\[ \mathbf{E} + \mathbf{v} \times \mathbf{B} = \eta \mathbf{j} \]  

[Sweet-Parker (1957)]

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

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

Unfavorable for fast reconnection

Two months for a coronal mass ejections
Plasma Kinetic Description

The collisionless Vlasov equation:

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

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

+ Maxwell’s eqs.

Vlasov-Maxwell system of equations

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

mass:

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

momentum:

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

energy:

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

Isotropic (scalar) pressure is the standard closure!

\[ p = nT \]

Add Maxwell’s eqs to complete the fluid model

⇒ Fast Reconnection!
Two-Fluid Simulation

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

Out of plane current

Aspect ratio: 1 / 10

\[ \mathbf{v}_{in} \sim \frac{\mathbf{v}_A}{10} \]
Two-Fluid vs Kinetic Simulations

Isotropic pressure

Kinetic Simulation

Out of plane current

Particle In Cell (PIC) simulation,
Other Outstanding Problems

- Heating
- 3D effects
- Trigger

Arcade as seen from above
Outline

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The Versatile Toroidal Facility (VTF)
VTF Unique for Reconnection Studies

- Large vacuum chamber
- Collisionless plasma
  (long mean-free-path, important for kinetic effects)
- Reproducible
- Flexible magnetic geometries
- Variable guide magnetic field
- Internal probing of $E$, $B$, $n$, $T_e$
The Versatile Toroidal Facility (VTF)

External Coils
Vacuum Vessel
TF Coils
RF-Power
Diagnostics
The Versatile Toroidal Facility (VTF)
Two Different Magnetic Configurations

An open cusp magnetic field. Fast reconnection by trapped electrons.

A closed cusp by internal coil. Passing electrons & spontaneous reconnection events.
Spontaneous Reconnection

Onset of Reconnection is 3D!

Experimentally, $\gamma \sim 1 / (20\mu s \pm 6\mu s)$

3D model, $\gamma \sim 1 / 22\mu s$

- For more info see
  [Katz et al., PRL 2010, POP 2011] &
  [Egedal et al., POP 2011]
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Two Different Magnetic Configurations

An open cusp magnetic field.
Fast reconnection by trapped electrons.

A closed cusp by internal coil.
Passing electrons & spontaneous reconnection events.
Plasma Response to Driven Reconnection
(open configuration)

H2, 17V on CF-bus, Klystron @ 45%, \( l_{\text{cusp}} = 480 \text{ A}, l_0 = 7 \text{ m} \)

- Density: \( 0 - 1 \times 10^{17} \text{ m}^{-3} \)
- Current density: \( 0 - 3 \text{ kA/m}^2 \)
- Floating potential: \(-75 \text{ V to 75 V}\)

\( V_{\text{loop}} \) vs. time

I=0 A
\( t = 6930 \mu\text{s} \)

J Egedal, Jan. - 2002
Kinetic Modeling

- Why is the experimental current density so small?
- Liouville/Vlasov’s equation: $df/dt=0$
- Solved by calculating electron orbits in the measured fields
- Integrate $f(x_0,v_0)$ to get the current profile

Important for later: $p_\parallel > p_\perp$ at the X-line!

Magnetic moment is conserved

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

Cluster observations on 2001-10-01.

Lobe: $T_{e\infty} \sim 0.10$ keV

Inflow: $T_{e\perp} \sim 0.10$ keV, $T_{e\parallel} \sim 1$ keV

Exhaust: $T_{e\perp} \sim T_{e\parallel} \sim 10$ keV = 100 $T_{e\infty}$
Wind Spacecraft Observations in Distant Magnetotail, $60R_E$

- Measurements within the ion diffusion region reveal:
  Strong anisotropy in $f_e$

\[ p_\parallel > p_\perp \]
Wind Spacecraft Observations in Distant Magnetotail, $60R_E$

- Measurements within the ion diffusion region reveal:

  Strong anisotropy in $f_e$

  $p_\parallel > p_\perp$
Electrons in an Expanding Flux Tube

Expanding Flux tube

-μVB

Magnetic moment:

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

⇒ mirror force:
Electrons in an Expanding Flux Tube

Trapped:
\[ E_\perp = \mu B = E_\infty B / B_\infty \]
\[ \implies E_\infty = \mu B_\infty \]

Passing:
\[ E = E_\infty + e \Phi_\parallel \]
\[ \implies E_\infty = E - e \Phi_\parallel \]

Vlasov:
\[ \frac{df}{dt} = 0 \]
\[ f(x, v) = f_\infty(E_\infty) \]

\[ f(x, v) = \begin{cases} f_\infty(E - e \Phi_\parallel) , & \text{passing} \end{cases} \]

J. Egedal et al., JGR (2009)
Formal Derivation using an “Ordering”

The drift kinetic equation:
\[
\frac{\partial f}{\partial t} + (\mathbf{v}_\parallel + \mathbf{v}_D) \cdot \nabla f + \left[ \mu \frac{\partial B}{\partial t} + e(\mathbf{v}_\parallel + \mathbf{v}_D) \cdot \mathbf{E} \right] \frac{\partial f}{\partial \mathcal{E}} = 0
\]

Boundary conditions:
\[
B = B_\infty \quad f = f_\infty(\mathcal{E}_\parallel, \mathcal{E}_\perp)
\]

Ordering:
\[
\nabla_\parallel \sim \frac{1}{L} \quad \nabla_\perp \sim \frac{1}{d} \quad \frac{\partial}{\partial t} \sim \frac{v_D}{d}
\]
\[
\frac{d}{L} \sim \delta \quad \frac{v_D}{v_t} \sim \delta^2 \quad f = f_0 + \delta f_1 + \ldots
\]

\[
f_0(x, \mathbf{v}) = \begin{cases} 
    f_\infty(\mathcal{E} - e\Phi_\parallel), & \text{passing} \\
    f_\infty(\mu B_\infty), & \text{trapped}
\end{cases}
\]
Wind Spacecraft Observations in Distant Magnetotail, $60R_E$

\[
f(x, v) = \begin{cases} 
  f_\infty(E - e\Phi_\|), & \text{passing} \\
  f_\infty(\mu B_\infty), & \text{trapped}
\end{cases}
\]

$\Phi_\| \sim 1 \text{ kV}$
The Acceleration Potential in a Kinetic Simulation

\[ \frac{e\Phi}{T_e} \]
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Kinetic Model $\rightarrow$ Fluid Closure

$$f(x, v) = \begin{cases} f_\infty(E - e\Phi_\parallel), \text{ passing} \\ f_\infty(\mu B_\infty), \text{ trapped} \end{cases}$$

$$\int \ldots d^3v$$

$$\dot{p}_\parallel = p_\parallel(n, B)$$
$$p_\perp = p_\perp(n, B)$$

Smooth transition from Boltzmann to double adiabatic CGL-scaling

$$p_\parallel \propto \frac{n^3}{B^2}$$
$$p_\perp \propto nB$$

A. Le et al., PRL (2009)

[Chew, M Goldberger, F E Low, 1956]
Confirmed in Kinetic Simulations

EoS previously confirmed in 2D simulations, now also in 3D simulations.
New *EoS* Implemented in Two-Fluid Code

Ohia, et al. PRL 2012 (using the HiFi framework by V.S. Lukin)
Analytic Model for Electron Jets

Additional current term:

\[ J_{\perp, \text{extra}} = \left( \frac{p_{\parallel} - p_{\perp}}{B} \right) \mathbf{b} \times \mathbf{b} \cdot \nabla \mathbf{b} \]

The magnetic tension is balanced by pressure anisotropy:

\[ p_{\parallel}(n, B) - p_{\perp}(n, B) = \frac{B^2}{\mu_0} \]

Use EoS to get scaling laws:

\[ \beta_{e, \infty} = \frac{\text{plasma pressure}}{\text{magnetic pressure}} \]
Observed Electron Heating

Cluster observations on 2001-10-01.

Lobe: \( T_{e\infty} \sim 0.10 \text{ keV} \)

Inflow: \( T_{e\perp} \sim 0.10 \text{ keV}, T_{e\parallel} \sim 1 \text{ keV} \)

Exhaust: \( T_{e\perp} \sim T_{e\parallel} \sim 10 \text{keV} = 100 T_{e\infty} \)

Bi-directional Jets

Flat-top

Need \( e\Phi_{\parallel} \sim 100 T_{e\infty} \)

In the simulation \( e\Phi_{\parallel} \) only up to \( 8T_e \)!

But…

\( \beta_{e,\text{cluster}} \sim 0.003 \)
Observed Electron Heating

Cluster observations, 2001-2005. (Thanks to A. Borg)
New simulation with $\beta_e \sim 0.003$

- 320 $d_i$ long, 180 billion particles!
New simulation with $\beta_e \sim 0.003$

- 320 $d_i$ long, 180 billion particles!

J. Egedal et al., Nature Physics (2012)
Flare heating by parallel E-fields?

**Ohm’s law:**

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

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

During reconnection: \( p_\parallel \propto \frac{n^3}{B^2} \)

\[\Rightarrow e\Phi_\parallel \approx T_e \frac{(n/n_0)^2}{(B/B_0)^2}\]

\((n/n_0) \approx 10, \quad (B/B_0) \approx 0.5\)

\[e\Phi_\parallel \approx 400T_e\]
Requirements on New Experiment

- Large normalized size of experiment: \( L / d_i \sim 10 \) (high \( n \), large \( L \))
- Low collisionallity to allow \( p_\parallel >> p_\perp \): \( \tau_{ei} v_A > d_i \) (low \( n \), high \( T_e \), high \( B \))
- Low electron pressure: \( \beta_e < 0.05 \) (low \( n \), \( T_e \), high \( B \))
- Manageable loop voltage: \( 0.1 v_A B_{rec} (2\pi R) < 5kV \) (high \( n \), low \( B \))
- Variable guide field: \( B_g = 0 - 4 B_{rec} \)
- Symmetric inflows

Experimental window available in Hydrogen or Helium plasma with

\[ n \sim 10^{18} \text{ m}^{-3}, \quad T_e \sim 15 \text{ eV}, \quad B_{rec} \sim 15 \text{ mT}, \quad L \sim 2 \text{ m} \]
Possible Experimental Geometry
Conclusions

• The Versatile Toroidal Facility built at MIT to study the reconnection process has provided a wealth of information and insights into the reconnection process.

• The laboratory experiments have helped identity a key physics process, trapping, so that a more relevant analytical model could be constructed. The existence of large amplitude electric fields supported by trapping had not been postulated before.

• The model has also helped explain satellite observations. The mere fact that there are large potential drops in the reconnection region, without which one cannot understand observations, has run counter to the standard models for plasma.

• The results from the model have been confirmed through comprehensive numerical simulations and provides a breakthrough to the electron heating problem.

• Thus, by capturing the ubiquitous phenomena of celestial magnetic reconnection in the laboratory we have begun to unravel the complexities of this exciting process.