Magnetic Explosions in Space:
Magnetic Reconnection in Plasmas

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Opportunity

• I’m new here.

• I’m looking for students.
  – I have some funding available.

• Contact me if you are interested.
One Heck of a Bang

• Magnetars: Isolated neutron stars with:
  – \(B \sim 10^{15}\) Gauss
  – Strongest B-fields in universe.

• Giant Flare (SGR 1806-20)
  – Dec. 27, 2004, in our galaxy!
  – Peak Luminosity: \(10^{47}\) ergs/sec.
  – Largest supernova: \(4 \times 10^{43}\) ergs/sec.
  – Cause: Global crust failure and magnetic reconnection.
  – Could be a source of short duration gamma ray bursts.

Rhessi data: Hurley et al., 2005
What is a Plasma?

<table>
<thead>
<tr>
<th>Solid</th>
<th>Liquid</th>
<th>Gas</th>
<th>Plasma</th>
</tr>
</thead>
<tbody>
<tr>
<td>Example Ice</td>
<td>Example Water</td>
<td>Example Steam</td>
<td>Example Ionized Gas</td>
</tr>
<tr>
<td>$H_2O$</td>
<td>$H_2O$</td>
<td>$H_2O$</td>
<td>$H_2 \rightarrow H^+ + H^++ + 2e^-$</td>
</tr>
<tr>
<td>Cold $T&lt;0^\circ C$</td>
<td>Warm $0^\circ C &lt; T&lt;100^\circ C$</td>
<td>Hot $T&gt;100^\circ C$</td>
<td>Hotter $T&gt;100,000^\circ C$</td>
</tr>
<tr>
<td>Molecules Fixed in Lattice</td>
<td>Molecules Free to Move</td>
<td>Molecules Free to Move, Large Spacing</td>
<td>Ions and Electrons Move Independently, Large Spacing</td>
</tr>
</tbody>
</table>
The Wide Range of Plasmas

PLASMAS - THE 4th STATE OF MATTER

Temperature (°C)

Number Density (Charged Particles / m³)

- Magnetic fusion reactor
- Solar wind
- Interstellar space
- Solar corona
- Neon sign
- Aurora
- Fluorescent light
- Flames
- Solids, liquids, and gases
- Stars and dense for classical plasmas to exist.

Solar core

- Lightning
- Inertial confinement fusion

Nebula

- Interstellar space
- Flares

- Interstellar space
- Flares
Magnetic Field Energy

• Magnetic fields can store a lot of energy!

\[ \beta = \frac{\text{Plasma Thermal Energy}}{\text{Magnetic Field Energy}} \]

• \( \beta_{\text{magnetosphere}} \geq 0.003 \)
• \( \beta_{\text{surface of Earth}} \approx 3 \cdot 10^7 \)
• \( \beta_{\text{sun}} \geq 0.01 \)
Plasmas Respond to B-Fields

Regular Gas

Plasma
Basic Plasma Equations - MHD

- Magnetohydrodynamics (MHD):
  - Describes the slow, large scale behavior of plasmas.

\[
m_i n \frac{d}{dt} \mathbf{V} = \frac{\mathbf{B} \cdot \nabla \mathbf{B}}{4\pi} - \nabla \left( nT + \frac{\mathbf{B}^2}{8\pi} \right)
\]

\[
\frac{\partial}{\partial t} \mathbf{B} = -c \nabla \times \mathbf{E}
\]

\[
\frac{\partial}{\partial t} n = -\nabla \cdot n \mathbf{V}
\]

\[
\mathbf{E} = -\frac{\mathbf{V}}{c} \times \mathbf{B}
\]
Frozen-in Condition

- In a simple form of plasma, the plasma moves so that the magnetic flux through any surface is preserved.
Magnetic Fields: Rubber Tubes

- Use Conservation of Magnetic flux, incompressible:
  - Magnetic energy release $\sim B^2/8\pi$
  - $1/2 \, m \, n \, V^2 \sim B^2/8\pi$
  - $V^2 \sim B^2/(4\pi \, m \, n) = (Alfven\, speed)^2 = c_A$
Magnetic Field Lines Can’t Break
Everything Breaks Eventually
Field Lines Breaking: Reconnection

Process breaking the frozen-in constraint determines the width of the dissipation region, $\delta$. 

$\delta$
Field Lines Breaking: Reconnection

Fluid Simulations

$J_z$ and Magnetic Field Lines
Questions about Reconnection

- How fast does it release energy?
- When/where/how does it initiate?
- Where does the magnetic energy go?
- What about 3D?
- What about turbulent systems?
The Sun is a Big Ball of Plasma

Solar Flare
1971 October 10

Big Bear Solar Observatory

http://science.msfc.nasa.gov/ssl/pad/solar/flares.htm
Reconnection in Solar Flares

- X-class flare: $\tau \sim 100$ sec.
- Alfven time:
  - $\tau_A \sim L/c_A \sim 10$ sec.
  - => Alfvenic Energy Release
- Half of B-energy => energetic electrons!
Space Weather

- Plasma streams away from the sun and hits the Earth.
  - Astronaut safety.
  - Satellite disruptions.
  - Communication disruptions.
Reconnection drives convection in the Earth’s Magnetosphere.

Kivelson et al., 1995
Controlled Fusion: Tokamaks

- Compress and heat the plasma using magnetic fields.
Outside the Solar System

- Clumps of matter gradually compress due to gravity and heat.
  - Star formation.
  - Must decouple plasma from B-field.
Accretion Disks

- When matter collects onto an object, it tends to form a disk.
- Difficult for matter to accrete:
  - Plasma Turbulence is key.
Simulating Reconnection

• Reconnection simulations are not an end in themselves.
  – Must understand how the results apply to the real world.

• Strong feedback between analytical theory and simulations.
Reconnection is Hard

• Considered a **Grand Challenge Problem**
• Now global (important) answers are strongly dependent on very fast/small timescales.
• If you have to worry about very small timescales, it makes the problem very very hard.

• Reconnection is a **multiscale** problem.
Currently, Two Choices

• Macro Simulations:
  – Treat reconnection in a non-physical way.
  – Simulate Large Systems.

• Micro Simulations
  – Treat reconnection physically.
  – Simulate small idealized systems.

• Multiscale Methods?
  – I’m working on these also.
One Simplification: The Fluid Approximation
Fluid Approximation

• Break up plasma into infinitesimal cells.
• Define average properties of each cell (fluid element)
  – density, velocity, temperature, etc.
  – Okay as long as sufficient particles per cell.
The Simplest Plasma Fluid: MHD

- Magnetohydrodynamics (MHD):
  - Describes the slow, large scale behavior of plasmas.
- Now, very straightforward to solve numerically.

\[
m_n \frac{d}{dt} \mathbf{V} = \frac{\mathbf{B} \cdot \nabla \mathbf{B}}{4\pi} - \nabla \left( nT + \frac{\mathbf{B}^2}{8\pi} \right)
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\]
Simulating Fluid Plasmas

- Define Fluid quantities on a grid cell.
- Dynamical equations tell how to step forward fluid quantities.

- **Problem with Numerical MHD:**
  - No reconnection in equations.
  - Reconnection at grid scale.

[Diagram of grid cells with n, V, B known]
MHD Macro Simulations

• Courtesy of the University of Michigan group:
  – Remember that reconnection occurs only at grid scale.
Non-MHD Micro Fluid Simulations

- Include smaller scale physics but still treat the system as a fluid.
Effective Gyration Radius

- Frozen-in constraint broken when scales of variation of $\mathbf{B}$ are the same size as the gyro-radius.

Electron gyroradius $<<$ Ion gyroradius

$\Rightarrow$ Dissipation region develops a 2-scale structure.
Removing this Physics

\[ \frac{m_e}{m_i} = 1/25 \]

Out of Plane Current

Hall Term

No Hall Term

Reconnected Magnetic Flux

\[ \begin{align*}
&\text{Hall Term} \\
&\text{No Hall Term}
\end{align*} \]
Simulating Particles

• Forces due to electric and magnetic fields.
  – Fields exist on grids $\Rightarrow$ Fluid
  – Extrapolate to each particles location.

• Particles can be thought of as a Monte-Carlo simulation.
Simulating Kinetic Reconnection

- Kinetic Particle in Cell
  - E,B fluids
  - Ions and electrons are particles.
  - Stepping fluids: particle quantities averaged to grid.
  - Stepping particles: Fluids interpolated to particle position.
3-D Magnetic Reconnection: with guide field

- Particle simulation with 670 million particles
- $B_z = 5.0 B_x$, $m_i/m_e = 100$, $T_e = T_i = 0.04$, $n_i = n_e = 1.0$
- Development of current layer with high electron parallel drift
  - Buneman instability evolves into electron holes

![Image of 3-D Magnetic Reconnection](movie.jz2d.jz2d)