RECONNECTION

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OUTLINE

▸ Arturo: “Please take a minute of your talk to introduce yourself and the path that took you to where you are now.”

▸ What is Magnetic Reconnection?

▸ Where Reconnection Happens and Why We Care

▸ How Reconnection is Studied

▸ Magnetic Field Lines Can Break?

▸ The Basics

▸ Modern Research
INTRODUCTION

- Research
  - Physical Chemistry (UA)
  - High Energy Physics (UA)
  - Nuclear Theory (UW)
  - Applied Math (UW)
  - Plasma Physics (UMd, UD)
  - Physics Education (UMd)
INTRODUCTION

- West Virginia University (WVU)
- Morgantown, West Virginia

https://www.bestplaces.net/city/west_virginia/morgantown

Courtesy of WVU
INTRODUCTION

- Plasma Faculty/Research at WVU
  - Koepke - Experimental plasma physics, fundamental plasma physics, HEDLP, Low temperature plasma physics, plasma astrophysics, nonlinear dynamics, ...
  - Scime - Experimental plasma physics, fusion, space physics and cubesat technology, industrial plasmas, diagnostics, biophysics, ...
  - Cassak - Reconnection theory/simulation
  - Tu - Radiation belt simulation and data analysis
  - Kobelski (TAP) - Solar observations
  - Goodrich (starting in 2021) - Bow shock, solar wind, planetary observations
  - Fowler (RAP starting in 2021) - Planetary observations
- Other Research at WVU
  - Astronomy and astrophysics (Green Bank nearby, discovery of Fast Radio Bursts, etc.)
  - Condensed matter experiment and theory/simulations, biophysics
  - Physics Education Research
WHAT IS RECONNECTION?

Definition of reconnection: the act or result of restoring a connection: the state of being reconnected. Your best bet is to arrange a utility transfer as far ahead as possible to avoid any disruption in service and the dreaded and totally avoidable reconnection fee. —

Reconnection | Definition of Reconnection by Merriam-Webster
https://www.merriam-webster.com/dictionary/reconnection

The Reconnection
https://www.thereconnection.com

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People also ask
What is Reconnective Healing?
WHAT IS MAGNETIC RECONNECTION?

Burch et al., Science, 2016
MAGNETIC RECONNECTION – UNDER THE HOOD

- Results of reconnection:
  - Plasma jets
  - Heating and particle acceleration

- Ingredients for reconnection:
  - Plasma
  - Magnetic field component changing directions
  - Often between different plasma domains

Hesse and Cassak, JGR, 2020
WHERE RECONNECTION HAPPENS – THE SUN

Courtesy of NASA’s Goddard Space Flight Center

Also see Kathy Reeves’ talk!
WHERE RECONNECTION HAPPENS – THE SUN

- Solar flares (all sizes)
- Coronal mass ejections
- Coronal heating, driving the solar wind
- Chromospheric and coronal jets
- Prominence eruptions
- Ellerman bombs
WHERE RECONNECTION HAPPENS - EARTH’S MAGNETOSPHERE

- Earth’s magnetic domain
- Dayside magnetopause
- Magnetotail
WHERE RECONNECTION HAPPENS - TOKAMAKS

- Minor disruptions (sawtooth crash, below)
- Major disruptions (right), a catastrophic loss of confinement

Yamada et al., Phys. Plasmas, 1994

Courtesy of M. Beidler, ORNL

Also see Michael Brown’s talk!
WHERE RECONNECTION HAPPENS – ELSEWHERE IN THE SOLAR SYSTEM

- Reconnection occurs at other planetary bodies (left) - Mercury - Earth-like; Saturn/Jupiter - rapid rotators, Neptune/Uranus - oriented differently; Magnetized moons - e.g. Ganymede (Jupiter); Unmagnetized objects - Mini-magnetospheres at the moon and Mars; Comet tails

- In the solar wind (top right) - ICMEs, between adjacent structures

- At the heliopause (bottom right, yellow) where the solar system (blue) meets the interstellar medium (red)

Courtesy of Fran Bagenal & Steve Bartlett

Borovsky, JGR, 2008

http://www.issibern.ch/teams/structureofheliopause/
WHERE RECONNECTION HAPPENS – ASTROPHYSICAL SETTINGS

Also see Ellen Zweibel’s talk!

Fast radio bursts
(Courtesy of https://www.quanta.org)

Soft gamma repeater (Courtesy of NASA)

Stellar flare
(Artist’s conception)

Black hole flare (Courtesy of NASA Compton X-ray Lab)

Relativistic Jet (Courtesy of NASA)

Pulsar winds

How Fast Radio Bursts Work

Fast radio bursts are brief, energetic blasts of radio waves that originate far across the universe. At least one repeats, which has added to the challenge of explaining what might be causing them. A new model accounts for past observations and predicts specific features that should be seen going forward.

1. A magnetor releases a flare of electrons and other charged particles.
2. The flare collides with the remnants from an old flare, creating huge magnetic fields.
3. In the ensuing shock, energetic electrons generate energetic radio waves. As the shock slows, the radio signal downshifts to lower frequencies.
WHERE RECONNECTION HAPPENS – AS AN ELEMENT OF OTHER PHYSICAL PROCESSES

- Magnetorotational Instability (MRI) (Balbus and Hawley, 1991)
- Kelvin-Helmholtz Instability (KHI) in magnetized plasmas (Nykyri and Otto, JGR, 1991)
- Plasma turbulence (Phan et al., Nature, 2018, animation courtesy of NASA)
- Dynamo (Moffatt and Proctor, 1985)
WHERE RECONNECTION HAPPENS – EXOTIC SETTINGS I

- Electric field lines effectively “reconnect” for radiation (e.g., Zangwill E&M book)

  https://www.en.didaktik.physik.uni-muenchen.de/multimedia/dipolstrahlung/index.html

- “Vortex reconnection” (reconnection of lines of vorticity) in neutral fluids

  https://www.youtube.com/watch?v=uV06pi.OPZM
WHERE RECONNECTION HAPPENS - EXOTIC SETTINGS II

- “Vortex reconnection” in superfluid helium (left) and optical solitons (right)

  [Video Link](https://www.youtube.com/watch?v=wgqUBqPWU_0)

  [Image of Vortex Reconnection]

- Abrikosov vortex “cutting” in superconductors (left) and string theory (right)

  [Images of Vortex Cutting]

  [Image of String Theory Reconnection]


WHY WE CARE – EFFECTS OF RECONNECTION

- Loss of confinement in tokamaks (bottom right), ionospheric scintillation from flares (left), power outages (center), aurora (top right)

Life Magazine, vol 8, no 15, page 38, April 8, 1940


Courtesy of E. Kepko, NASA GSFC

Courtesy of H. Singer, NOAA

Courtesy of M. Beidler, ORNL
HOW RECONNECTION IS STUDIED – SATELLITE AND GROUND-BASED OBSERVATIONS

- Satellites - Heliospheric System Observatory (right)
  - Magnetosphere - ISEE, Polar, Cluster, THEMIS/ARTEMIS, **MMS**, Parker Solar Probe, …
  - Solar - SOHO, Hinode, STEREO, RHESSI, SDO, IRIS, …

- Ground based -
  - Green Bank Telescope (left), Very Large Array, D-KIST, etc.

https://www.astronomynotes.com/telescop/s4.htm
HOW RECONNECTION IS STUDIED – NASA’S MAGNETOSPHERIC MULTISCALE (MMS)

- Four-satellite mission designed specifically to study magnetic reconnection using Earth’s magnetosphere as a laboratory (Burch et al., Space Sci. Rev., 2016)

- Takes data ~100 x faster than previous missions!
HOW RECONNECTION IS STUDIED – LABORATORY EXPERIMENTS

- Fusion devices - NSTX, DIIID, MST, MAST, ...
- A number of HEDLP labs
- Some devices devoted to reconnection:
  - PPPL - MRX (Yamada), FLARE (Ji)
  - Swarthmore - SSX (Brown)
  - Univ. Wisconsin - TREX (Egedal)
  - West Virginia University - PHASMA (Scime)
- Measure distribution functions!

Also see Michael Brown’s talk!
HOW RECONNECTION IS STUDIED – THEORY AND SIMULATIONS

- **Theory**
  - Fluid - MHD, Hall-MHD/two-fluid, 10 moment-model
  - Kinetic theory - distribution functions
  - Gyrokinetic - gyro-averaged distribution functions

- **Simulations**
  - Local ("reconnection in a box", top left) or global (tokamak/corona/magnetosphere, top right)
  - Fluid, kinetic (particle-in-cell - top left, Vlasov, hybrid), gyrokinetic, mixture (top right)
  - Typically performed on supercomputers (DOE machine "Cori", bottom, 13th fastest in the world)

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Burch et al., Science, 2016
Chen et al., JGR, 2017

https://docs.nersc.gov/systems/cori/
MAGNETIC FIELD LINES CAN BREAK? – WHY MAGNETIC RECONNECTION IS WEIRD

- We are often told that Gauss’ law for electricity and magnetism implies...

\[ \nabla \cdot \mathbf{E} = \frac{\rho}{\varepsilon_0} \quad \nabla \cdot \mathbf{B} = 0 \n\]

Electric fields only end on positive or negative charges

Magnetic field lines have no ends

- Doesn’t magnetic reconnection violate Gauss’ law?!?
The statements on the previous slide are incorrect!
- Electric and magnetic field lines can also end...
  - at infinity
  - where the field is zero!
- This does NOT contradict Maxwell’s equations!
  - Maxwell’s equations actually say...
    - electric fields diverge from positive charges & converge to negative charges
    - magnetic fields never diverge from anywhere \( \nabla \cdot B = 0 \)
MAGNETIC FIELD LINES CAN BREAK? – SOME DETAILS

- Early researchers did not like reconnection (Chapman, Alfvén, ...)
- Issues with magnetic field lines having an identity and a velocity
- Frozen-in theorem (aka Alfvén’s theorem, equivalent to Kelvin circulation theorem)
  - From Faraday’s law $\frac{d\Phi_B}{dt} = -\int \mathbf{E} \cdot d\mathbf{l}$, an (out-of-plane) $\mathbf{E}$ is needed to change magnetic flux
  - In a magnetized plasma, the electric field is often given by Ohm’s law
    
    \[
    \mathbf{E} + \mathbf{v} \times \mathbf{B} = 0 \quad \text{(Ideal-MHD Ohm’s law)}
    \]
    
    \[
    \mathbf{E} + \mathbf{v} \times \mathbf{B} = \mathbf{R} \quad \text{(non-Ideal-MHD Ohm’s law)}
    \]
- Magnetic field lines in **ideal-MHD** cannot reconnect
- Non-ideal effects *can* allow reconnection to occur!
The Basics – Fluid Picture of Reconnection

- Simple steady-state scaling analysis: “Sweet-Parker scaling”
- Mass flux into box equals mass flux out of box:
- Energy flux into box equals energy flux out of box:
  
  2 equations with 2 unknowns; solve for \( v_{out} \):
  
  - The outflow speed scales as the Alfvén speed!

\[
\rho_{in} v_{in} L h \sim \rho_{out} v_{out} \delta h
\]

\[
\left(\frac{B_{in}^2}{2\mu_0}\right) v_{in} L h \sim \left(\frac{1}{2} \rho_{out} v_{out}^2\right) v_{out} \delta h
\]

\[
v_{out} \sim \frac{B_{in}}{\sqrt{\mu_0 \rho_{in}}} = c_{A,in}
\]
Now solve the equations for $v_{in}$:

$$v_{in} \sim \left( \frac{\rho_{out}}{\rho_{in}} c_{A,in} \right) \frac{\delta}{L}$$

- $v_{in}$ gives a proxy for the rate at which reconnection occurs
- Depends strongly on $\frac{\delta}{L}$! This, in turn, depends on RHS of $\mathbf{E} + \mathbf{v} \times \mathbf{B} = \mathbf{R}$!
WITH OHM'S LAW GIVING $E + v \times B = R$

If reconnection is collisional, then $R = \eta J$ and one can show (for resistivity that is not too small)

$$v_{in} = \left(\frac{\eta}{\mu_0 c_{A,in} L}\right)^{1/2} c_{A,in}$$

If reconnection is collisionless, $R = \frac{J \times B}{ne} + \ldots$ and

$$v_{in} \sim 0.1 c_{A,in}$$

Consider a sawtooth crash (at MAST, with $c_{A,in} \sim 13$ km/s); to reconnect the core with radius $r = 0.32$ m, the time it takes is $\tau \sim r/v_{in}$

Collisional reconnection is too slow! Collisionless reconnection is fast enough: $\tau \sim 25 \mu$s
THE BASICS – KINETIC PICTURE OF RECONNECTION

Gyrating positively charged ion (larger gyroradius than electrons!)

Electron diffusion region (electrons decouple from magnetic field, electron thermal and inertial effects important, electrons accelerated and heated)

Gyrating positively charged electron (smaller gyroradius than ions!)

Ion diffusion region (ions decouple from magnetic field, plasma is far from equilibrium, ions and electrons act differently, Hall effect important)

Charged particles \(E \times B\) drift towards where \(B\) reverses (this is the inflow)

Charged particles \(E \times B\) drift away (this is the outflow)

Uses physics discussed by Will Fox and Steffi Diem yesterday

Modified from Kuznetsova et al., 2007
MODERN RESEARCH – STEADY RECONNECTION

- What sets the rate that reconnection proceeds for the simple 2D picture discussed here? (Essentially solved)
- What sets the rate of reconnection in more realistic configurations (the effect of asymmetries, out-of-plane magnetic fields, bulk flows, presence of neutrals, …)?
- What kinetic-scale physics allows collisionless reconnection?
- For given “upstream” conditions, how much energy goes into kinetic/ion-thermal/electron-thermal energy?
- How and where are charged particles accelerated, and which are the dominant mechanisms for various settings?
MODERN RESEARCH - DYNAMICS OF RECONNECTION

- How does reconnection start (i.e., the onset problem)?
- What “prevents” onset before reconnection, allowing energy to accumulate?
- How does reconnection stop?
- Under what conditions is reconnection steady vs. bursty (secondary islands/plasmoids/flux transfer events/dipolarization fronts/…)?
- How does reconnection occur as a secondary process (turbulence, KHI, MRI, dynamo, etc.)?

Shepherd and Cassak, PRL, 2010
MODERN RESEARCH – MATCHING WITH REAL SYSTEMS

- What is the nature of 3D reconnection?
- How does the local process of reconnection couple to the global dynamics? When is reconnection the leading cause of energy release, and when is it the global dynamics?
- How does the global dynamics influence the rate of reconnection, the location it occurs, and when it onsets?
FURTHER RESOURCES

- Textbooks focused on reconnection:

- Review papers on reconnection:

- Landmark papers in reconnection:
  - See references within Hesse and Cassak (2020)

Thanks to Arturo and the PPPL SULI team!

To all - practice Diversity, Equity, and Inclusivity, now and always!

Please contact me!
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