RECONNECTION

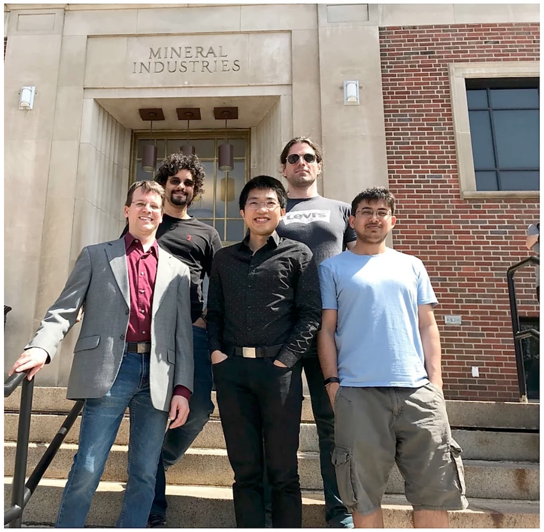
PAUL CASSAK (PAUL.CASSAK@MAIL.WVU.EDU)
WEST VIRGINIA UNIVERSITY

2020 INTRODUCTION TO FUSION ENERGY AND PLASMA PHYSICS COURSE

JUNE 17, 2020

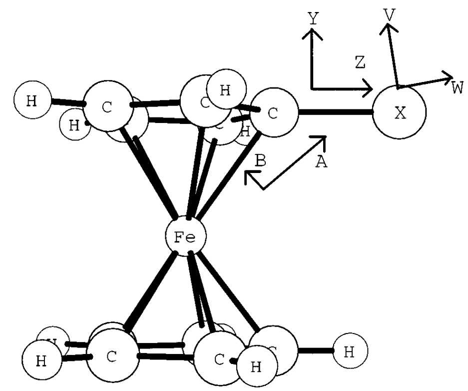
OUTLINE

- 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

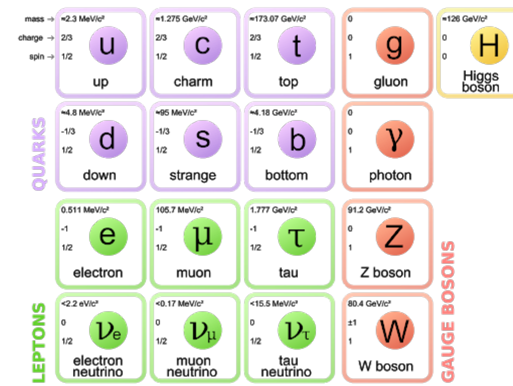


INTRODUCTION

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



Drouin et al., 1997



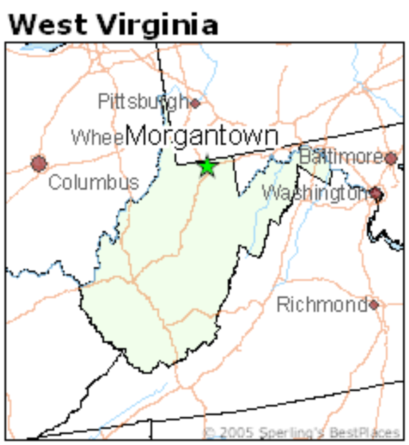
http://quantum.lassp.cornell.edu/lecture/elementary_particle_physics

with Jim Drake, UMd, 2006

with Mike Shay, UD, 2008

INTRODUCTION

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



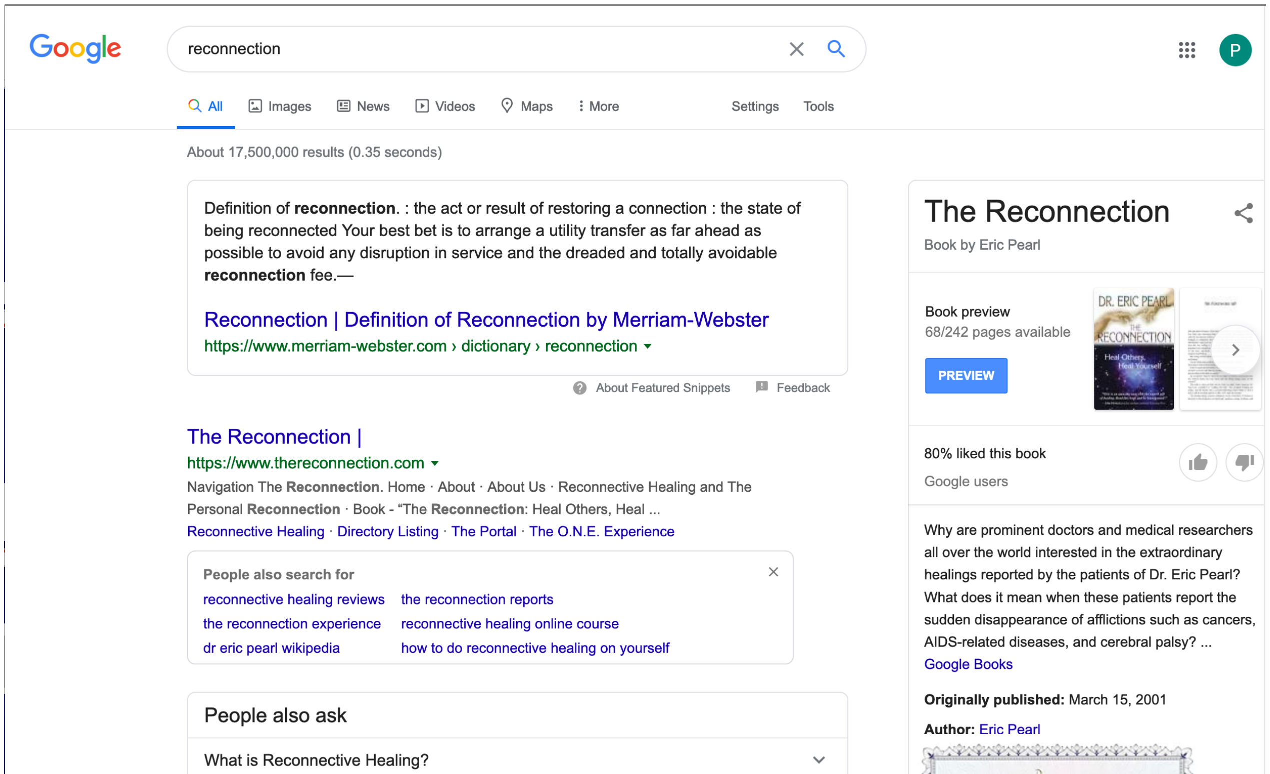
https://www.bestplaces.net/city/west_virginia/morgantown

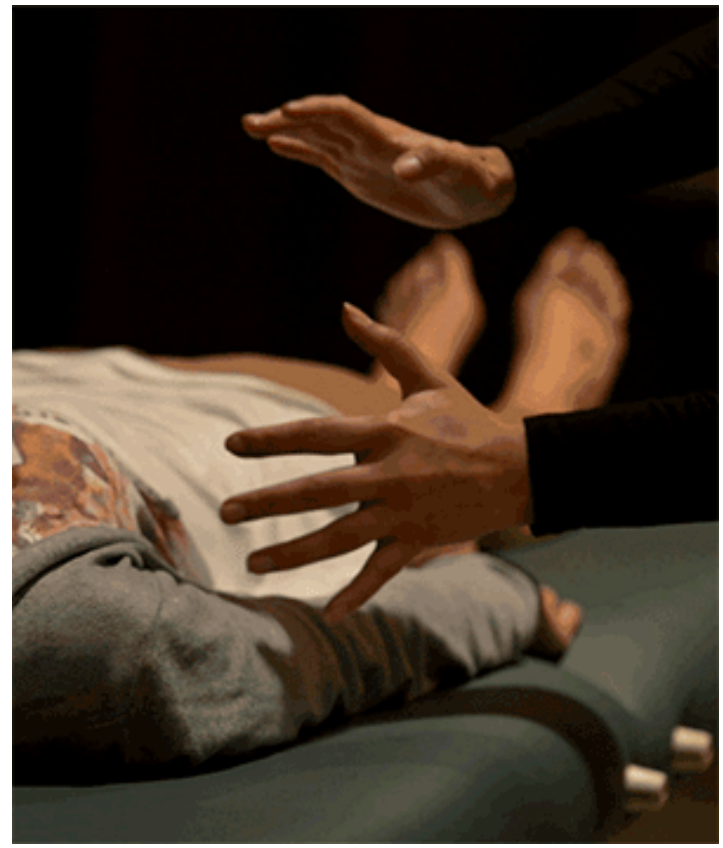
Courtesy of WVU

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

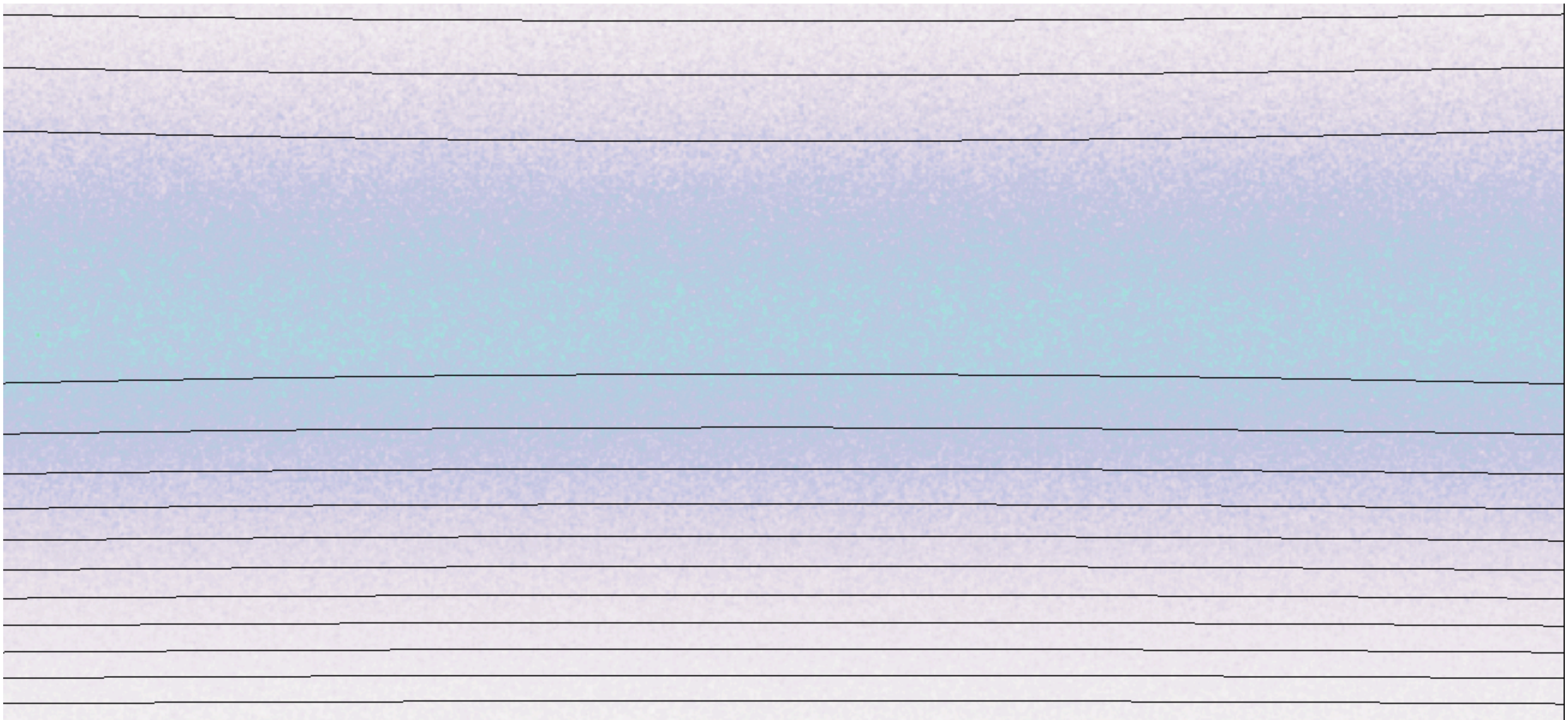
WHAT IS RECONNECTION?





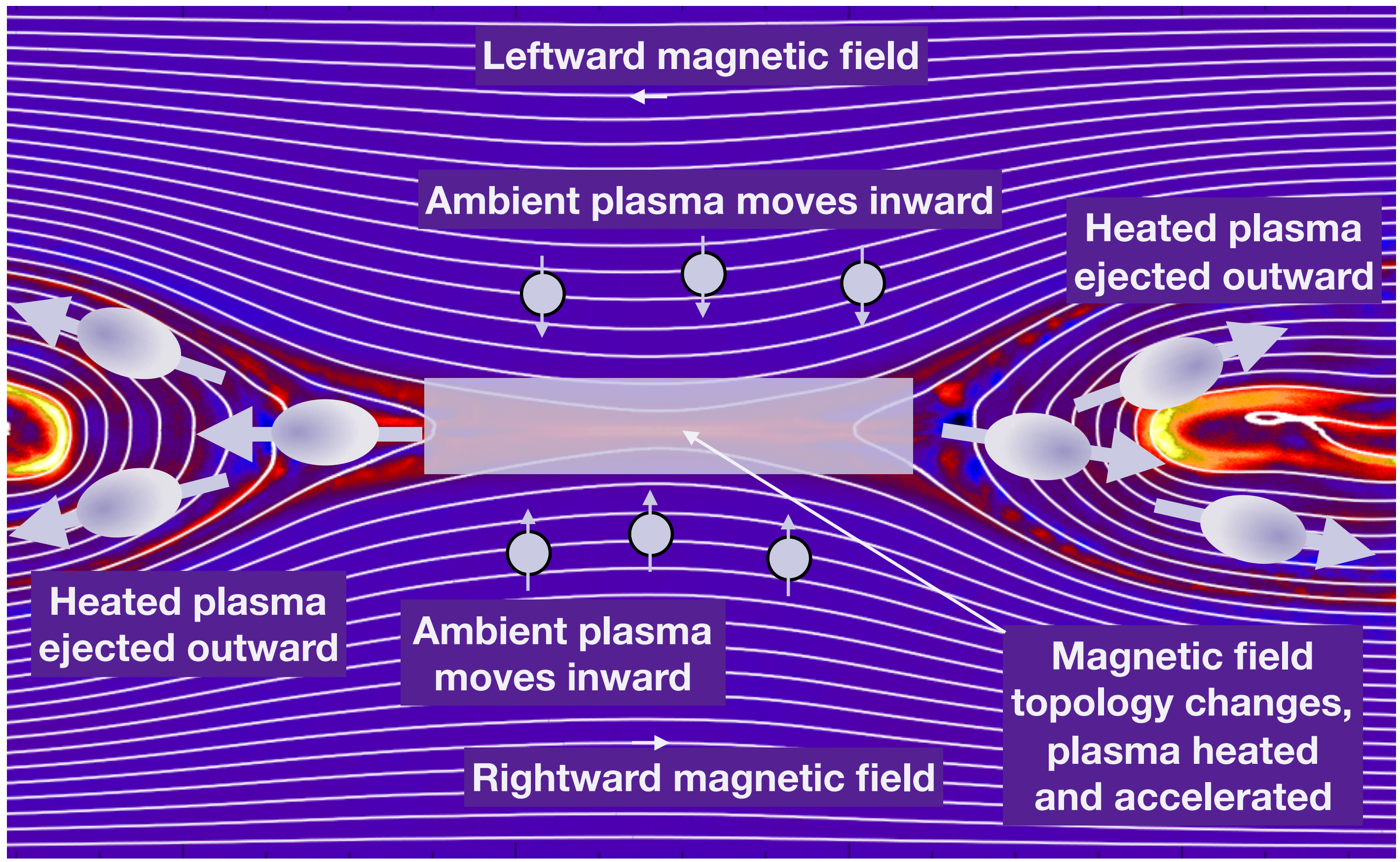
WHAT IS MAGNETIC RECONNECTION?

Burch et al., Science, 2016



MAGNETIC RECONNECTION – UNDER THE HOOD

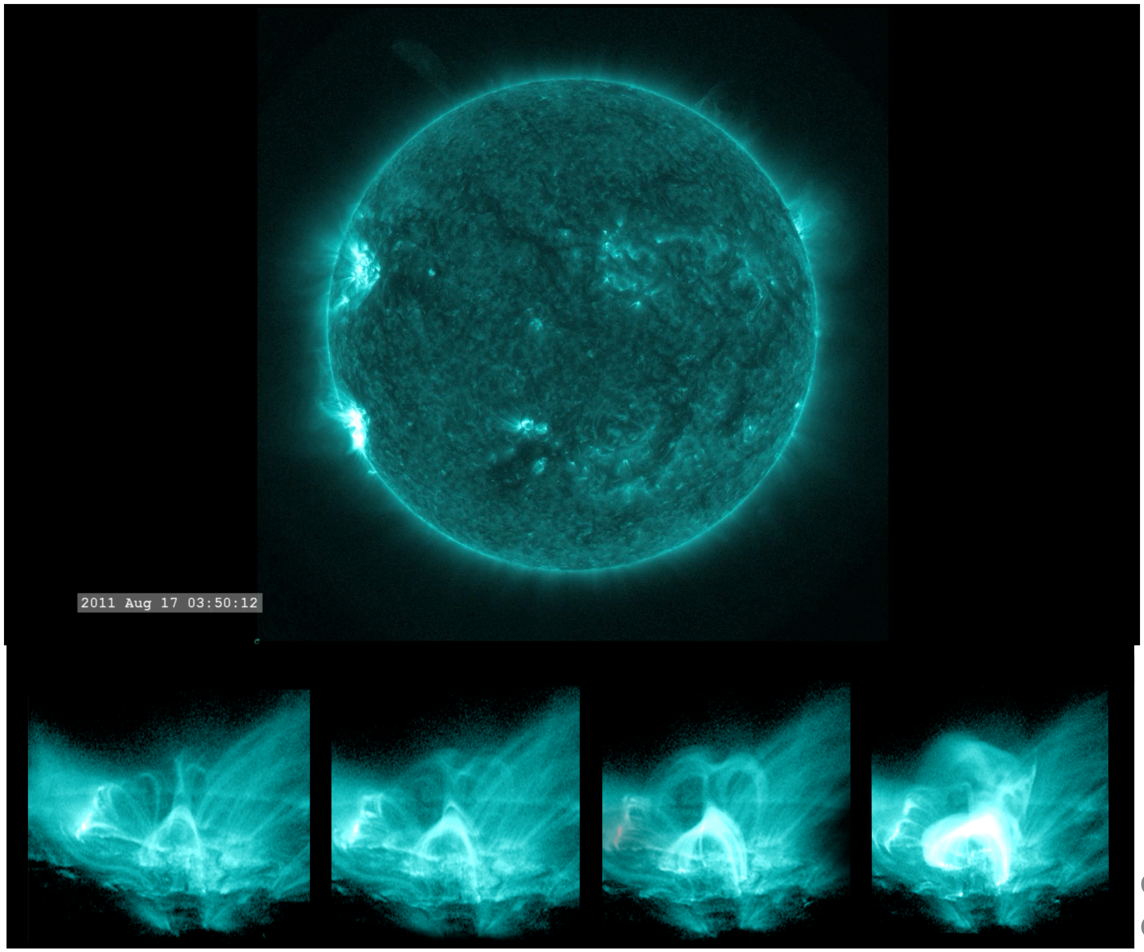
- Results of reconnection:
  - Plasma jets
  - Heating and particle acceleration
- Ingredients for reconnection:
  - Plasma
  - Magnetic field component changing directions
    - Often between different plasma domains



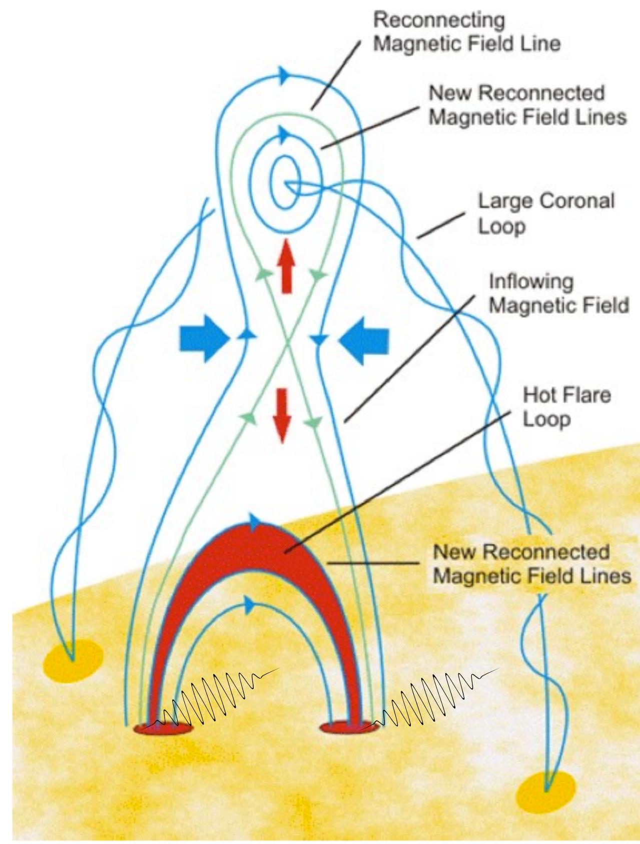
Hesse and Cassak, JGR, 2020

WHERE RECONNECTION HAPPENS – THE SUN

Also see Kathy Reeves' talk!



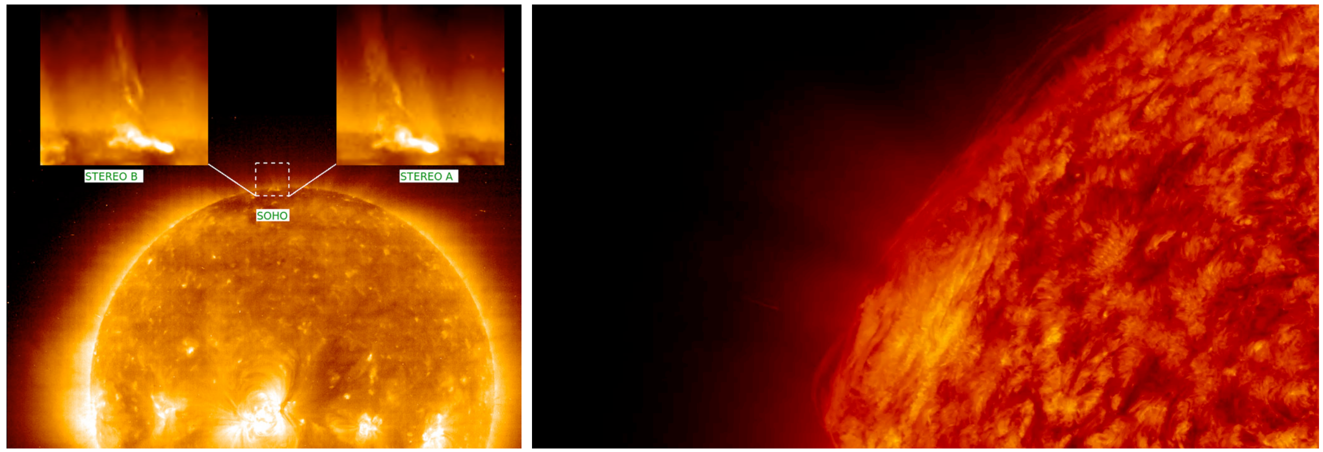
Courtesy of NASA's
Goddard Space Flight Center



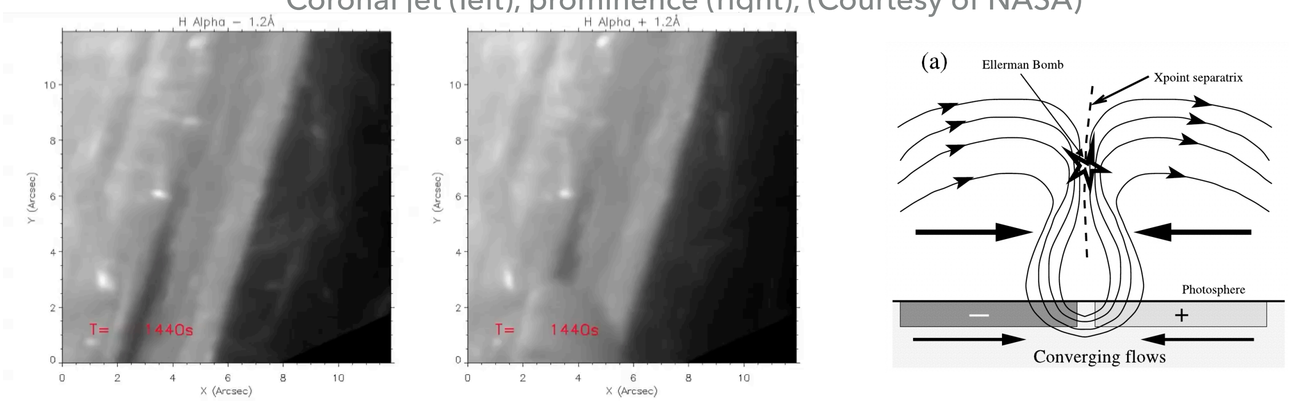
Courtesy of NASA

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



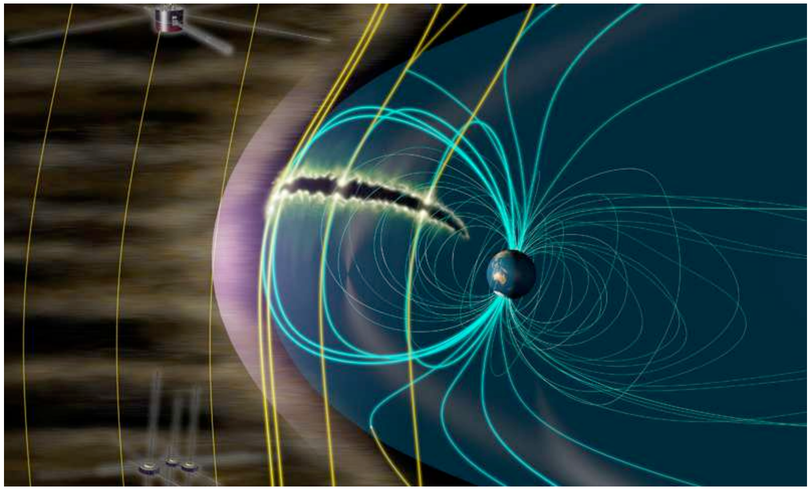
Coronal jet (left), prominence (right), (Courtesy of NASA)

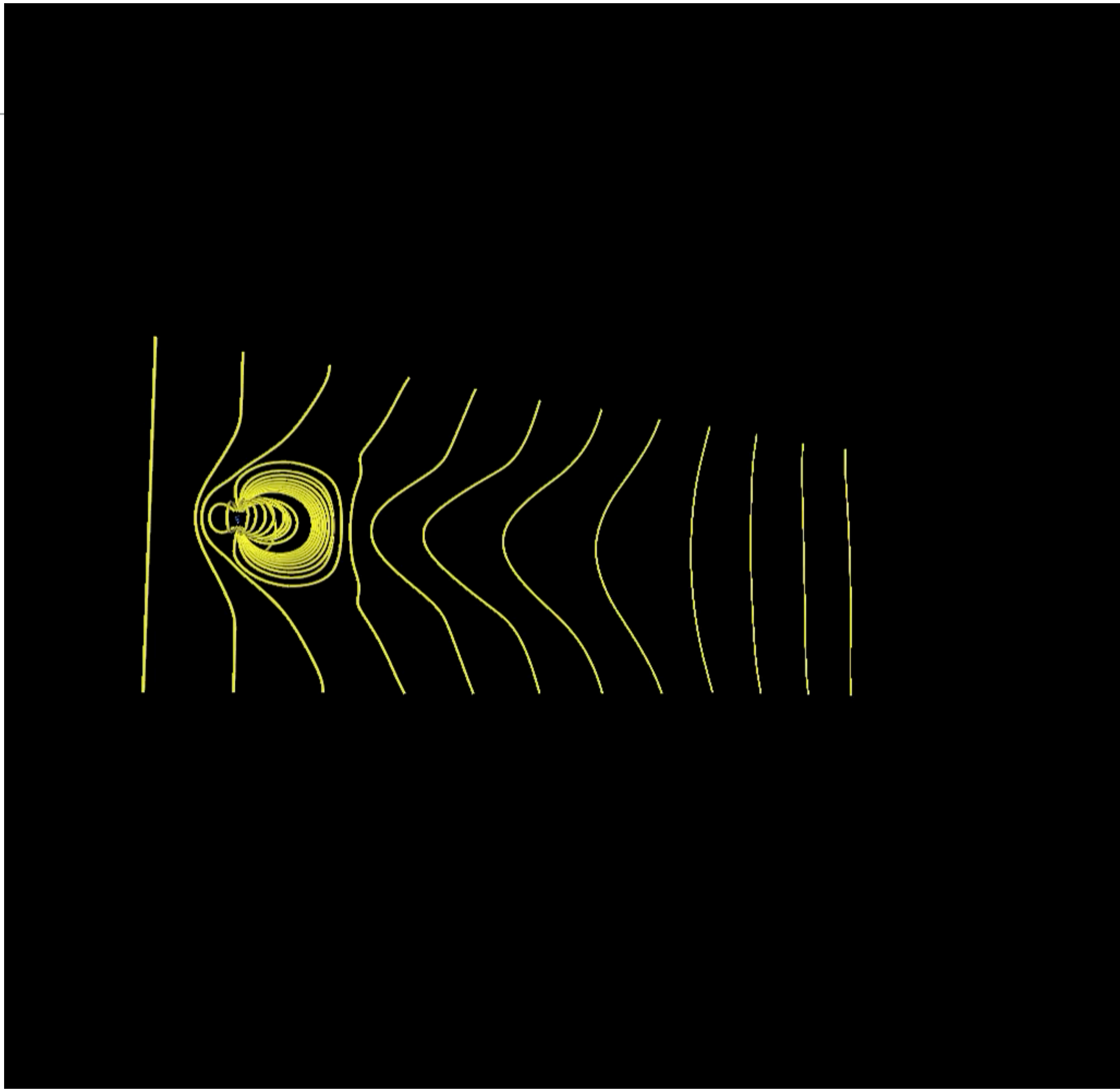


Ellerman bomb (Courtesy of NASA)

WHERE RECONNECTION HAPPENS - EARTH'S MAGNETOSPHERE

- Earth's magnetic domain
  - Dayside magnetopause
  - Magnetotail

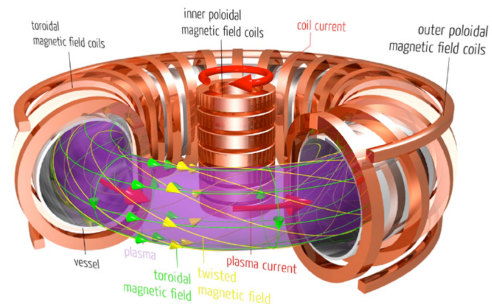


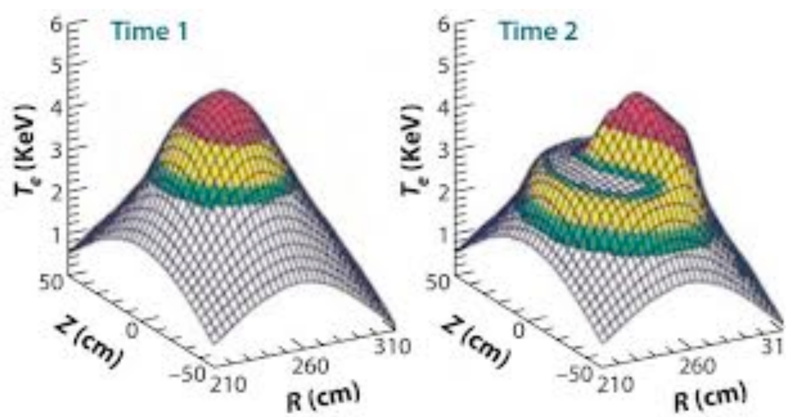


WHERE RECONNECTION HAPPENS – TOKAMAKS

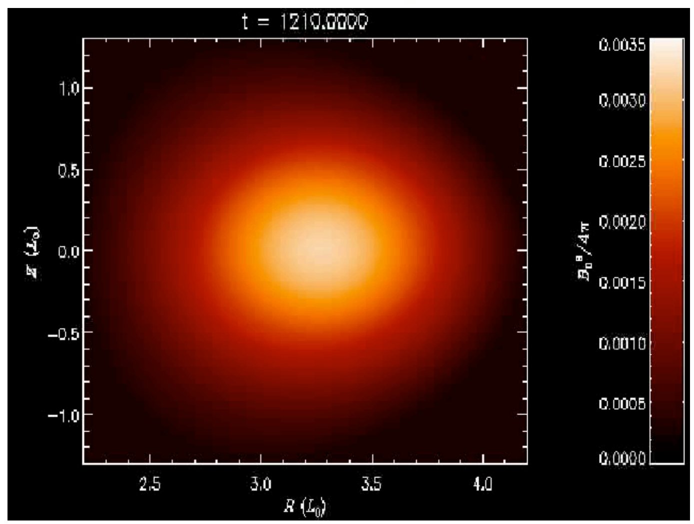
Also see Michael Brown's talk!

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





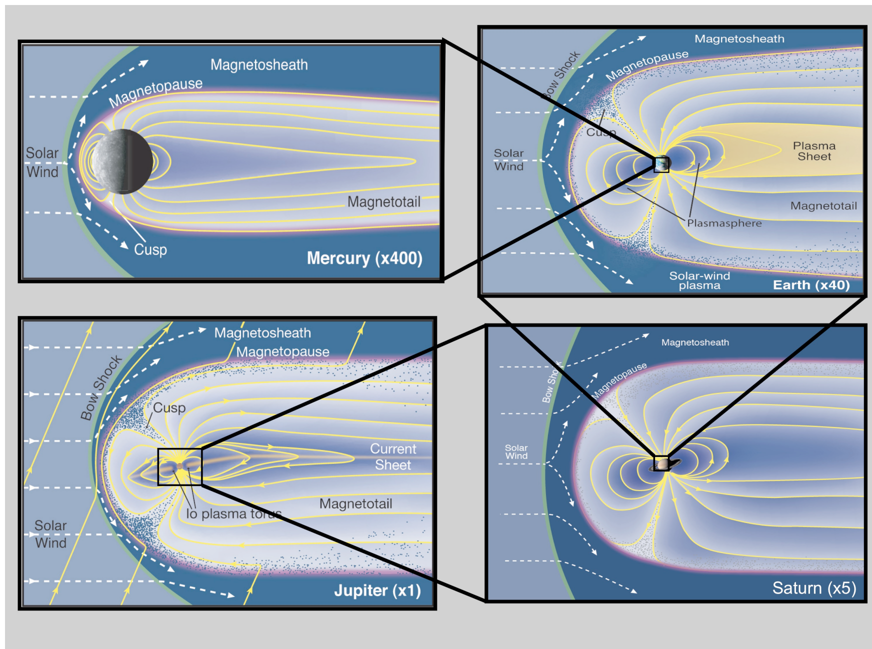
Yamada et al., Phys. Plasmas, 1994



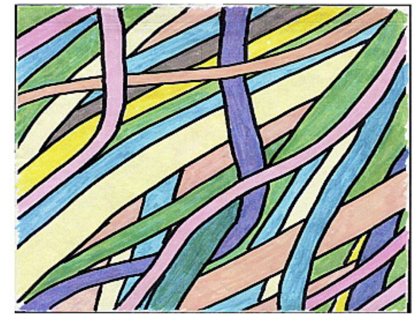
Courtesy of M. Beidler, ORNL

WHERE RECONNECTION HAPPENS - ELSEWHERE IN THE SOLAR SYSTEM

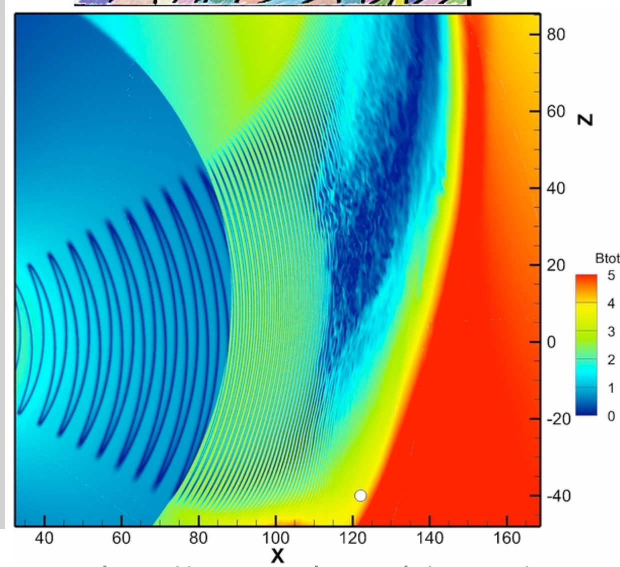
- Reconnection occurs at other **planetary** bodies (left) - **Mercury** - Earth-like; **Saturn/Jupiter** - rapid rotators, **Neptune/Uranus** - oriented differently; **Magnetized moons** - e.g. Ganymede (Jupiter); **Unmagnetized objects** - Mini-magnetospheres at the moon and Mars; **Comet tails**
-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



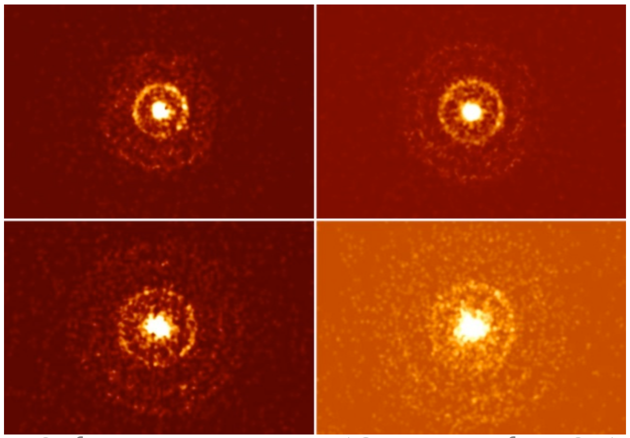
Borovsky, JGR, 2008



http://www.issibern.ch/teams/structureofheliopause/

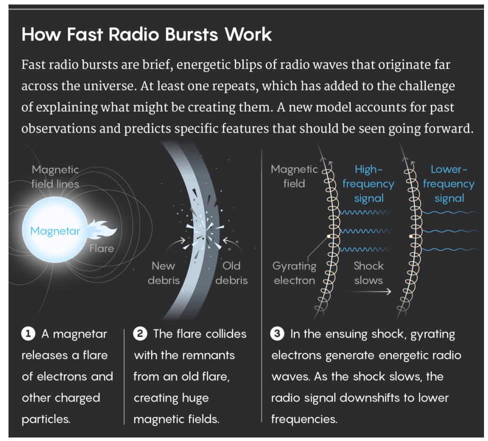
WHERE RECONNECTION HAPPENS – ASTROPHYSICAL SETTINGS

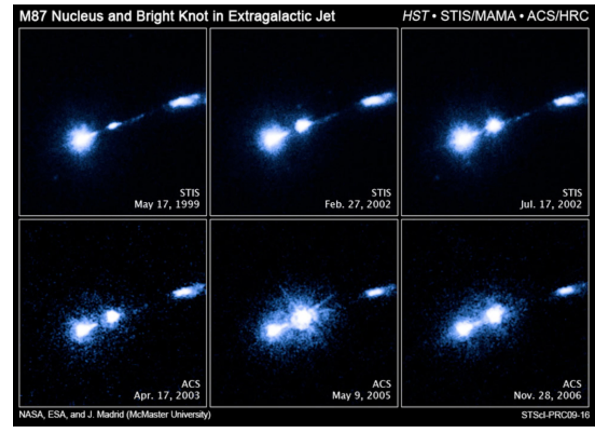
Also see Ellen Zweibel's talk!



Soft gamma repeater (Courtesy of NASA)

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

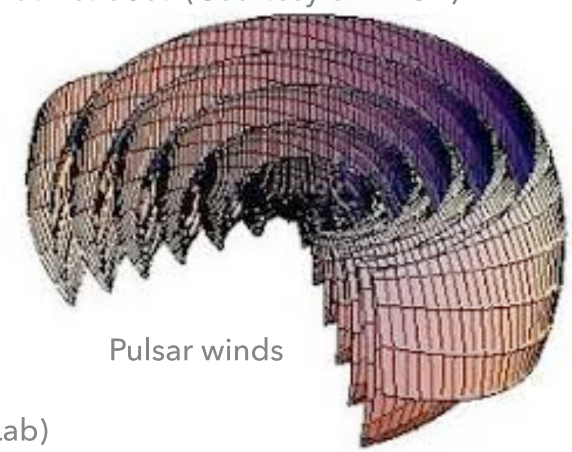




Relativistic Jet (Courtesy of NASA)

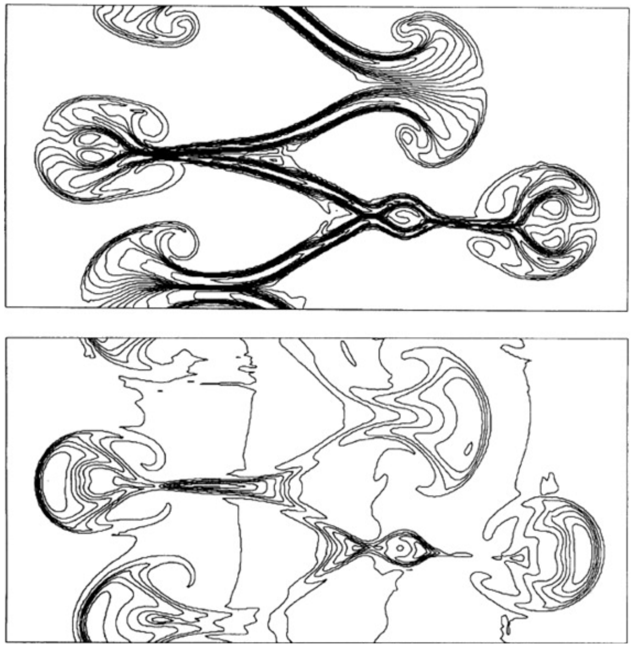
Stellar flare (Artist's conception)

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

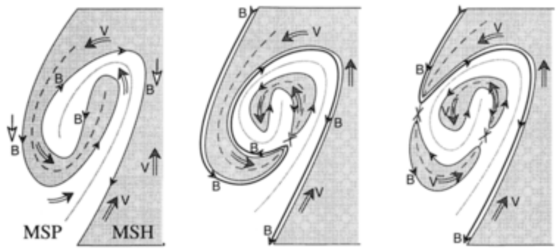


Pulsar winds

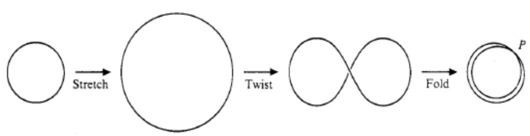
WHERE RECONNECTION HAPPENS – AS AN ELEMENT OF OTHER PHYSICAL PROCESSES



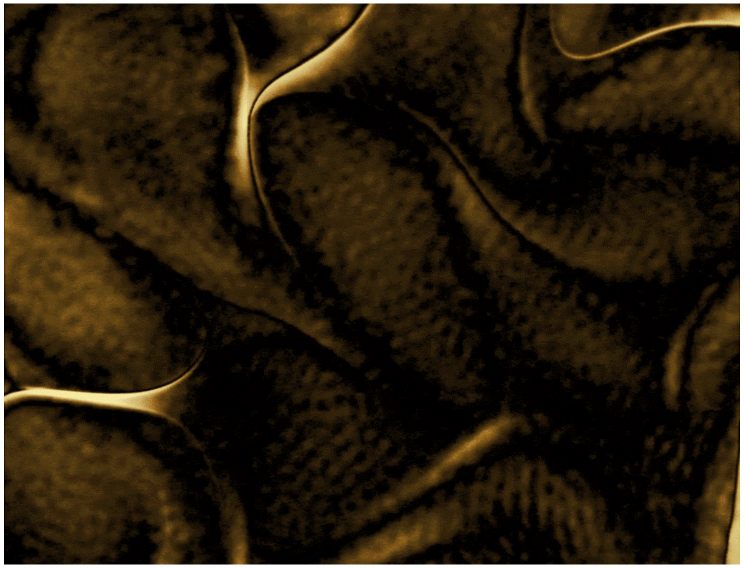
Magnetorotational Instability (MRI) (Balbus and Hawley, 1991)



Kelvin-Helmholtz Instability (KHI) in magnetized plasmas (Nykyri and Otto, JGR, 1991)



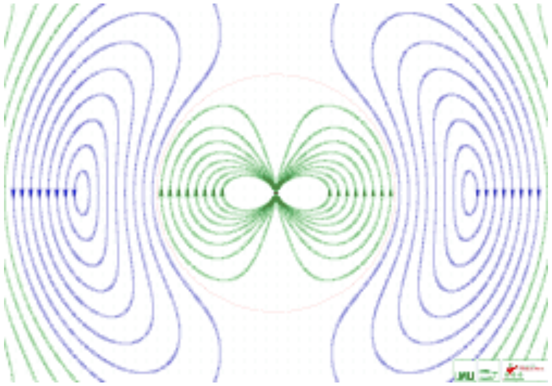
Dynamo (Moffatt and Proctor, 1985)



Plasma turbulence (Phan et al., Nature, 2018, animation courtesy of NASA)

WHERE RECONNECTION HAPPENS – EXOTIC SETTINGS I

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



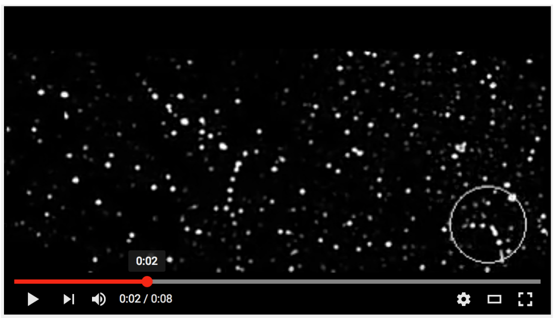
https://www.en.didaktik.physik.uni-muenchen.de/multimedia/dipolstrahlung/index.html

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

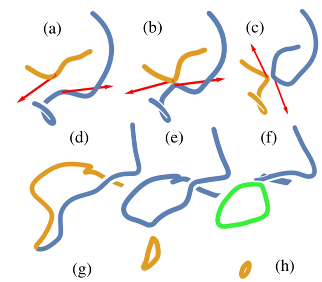
https://www.youtube.com/watch?v=uV06pi_OPZM

WHERE RECONNECTION HAPPENS – EXOTIC SETTINGS II

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

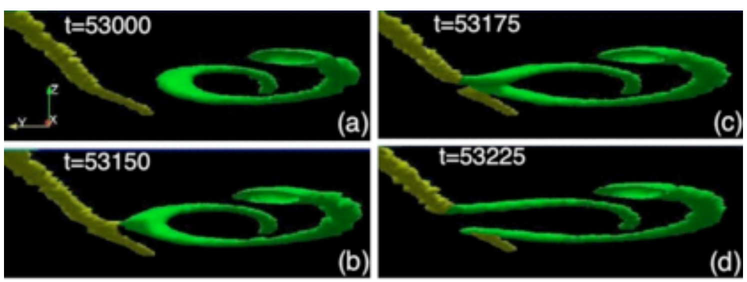


https://www.youtube.com/watch?v=wgqUBqPWU_0

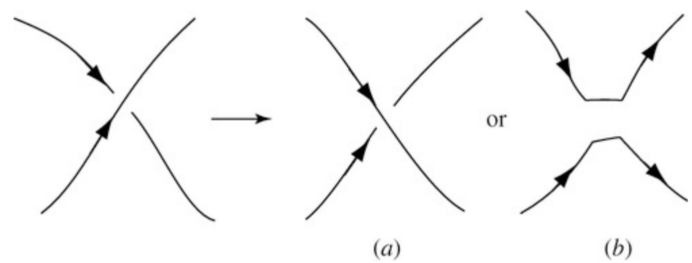


Federov et al., Phys. Rev. Lett., 2019

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



Glatz et al., Phys. Rev. B, 2016

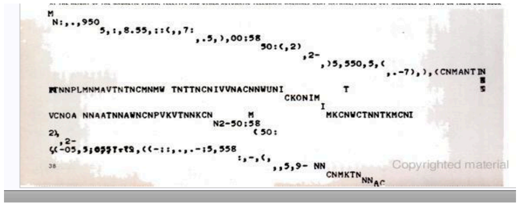


Copeland and Kibble, Proc. Royal Astr. Soc. A, 2010

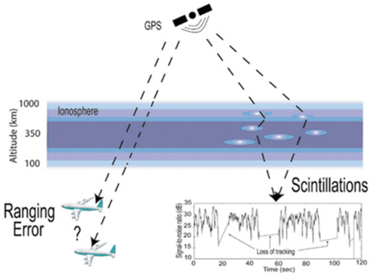
WHY WE CARE – EFFECTS OF RECONNECTION

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

Courtesy of E. Kepko, NASA GSFC

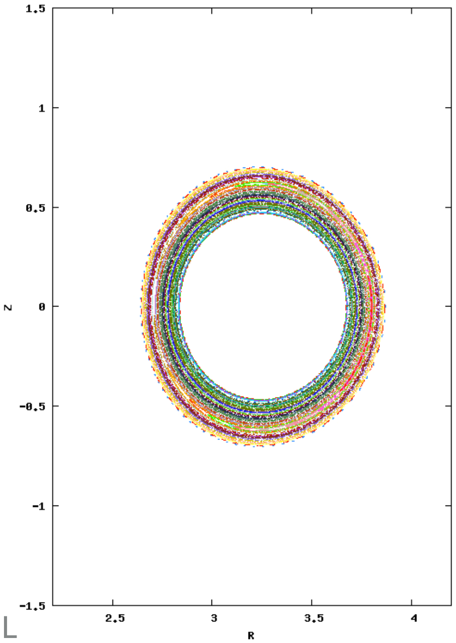


Life Magazine, vol 8, no 15, page 38, April 8, 1940



https://www.doncio.navy.mil/CHIPS/ArticleDetails.aspx?ID=2782

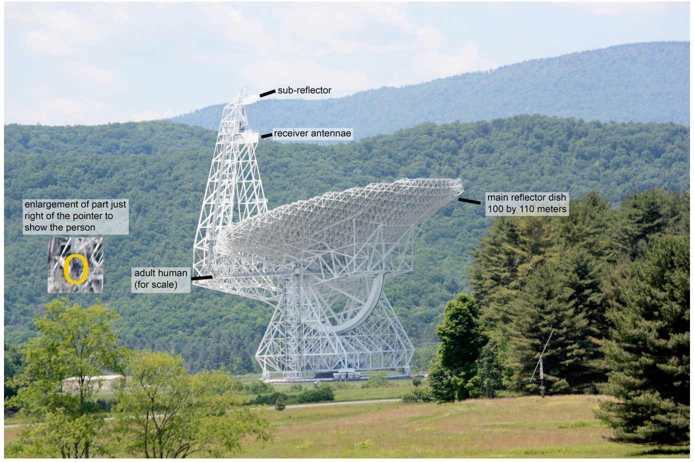
Courtesy of H. Singer, NOAA



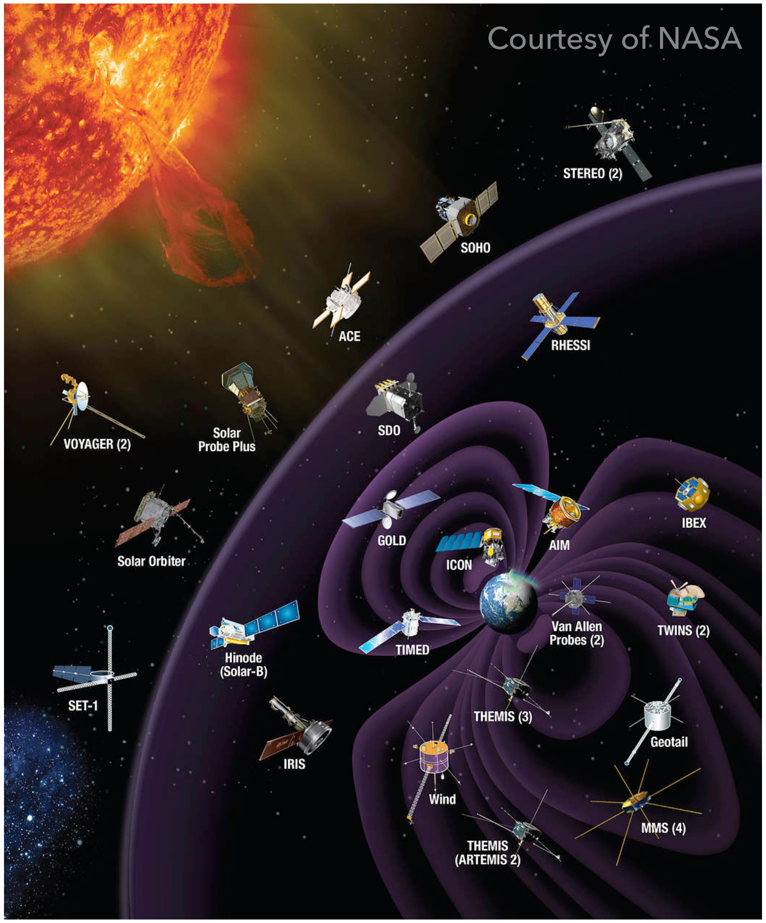
Courtesy of M. Beidler, ORNL

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.



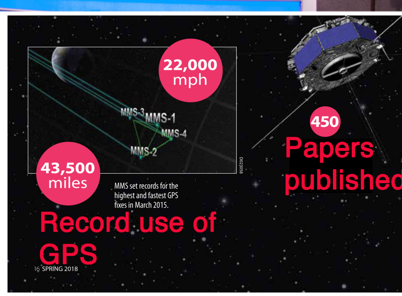
https://www.astronomynotes.com/telescop/s4.htm



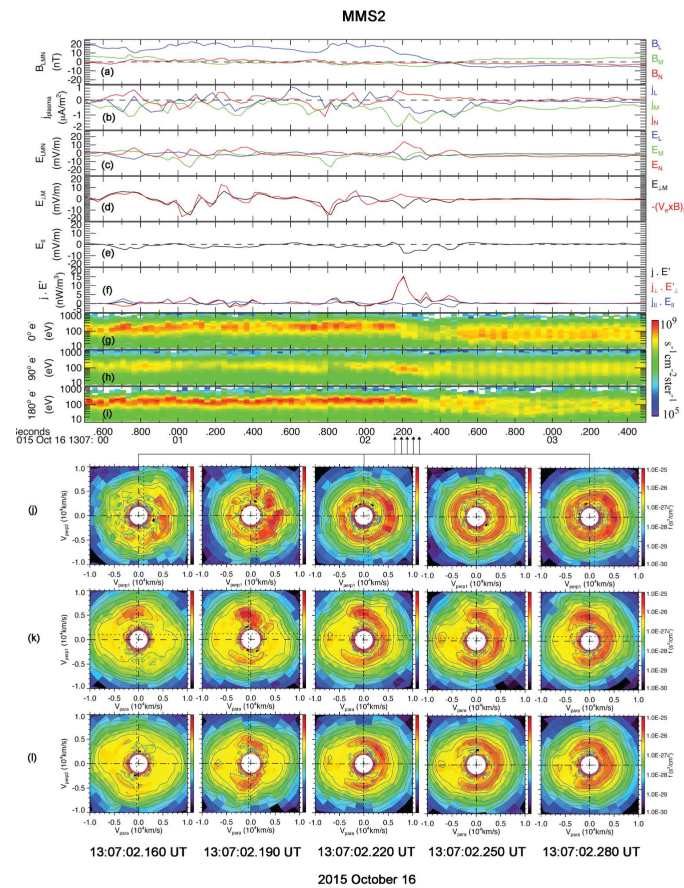
HOW RECONNECTION IS STUDIED – NASA'S MAGNETOSPHERIC MULTISCALE (MMS)

- 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!

Courtesy of
George Diller, NASA




Courtesy of
Jim Burch, SWRI



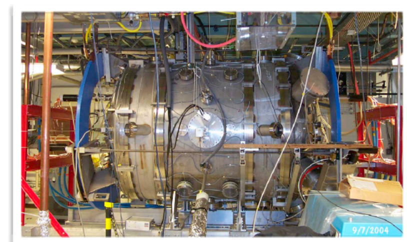
Burch et al., Science, 2016

HOW RECONNECTION IS STUDIED – LABORATORY EXPERIMENTS

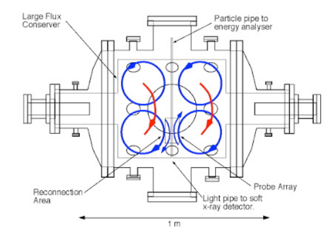
Also see Michael Brown's talk!

- 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!

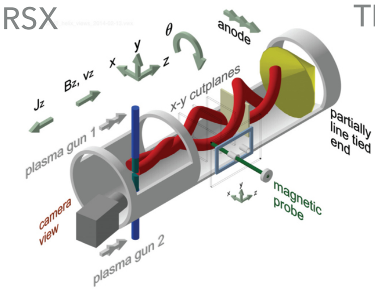
MRX



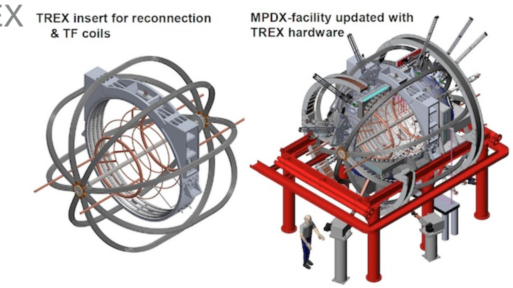
SSX



RSX



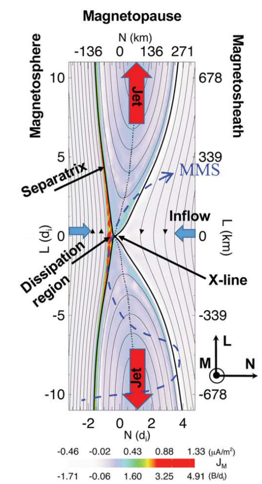
TREX



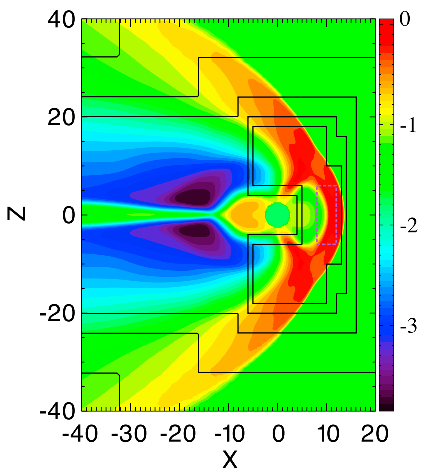
PHASMA

HOW RECONNECTION IS STUDIED – THEORY AND SIMULATIONS

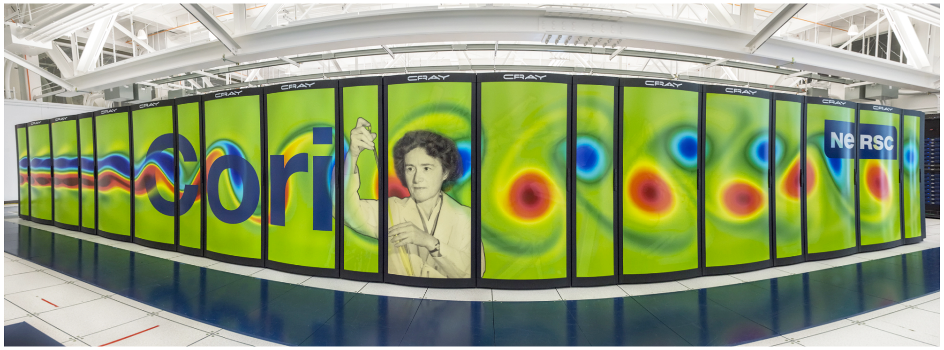
- Theory
  - Fluid - MHD, Hall-MHD/two-fluid, 10 moment-model
  - Kinetic theory - distribution functions
  - Gyrokinetic - gyro-averaged distribution functions
- Simulations
  - Local (“reconnection in a box”, top left) or global (tokamak/corona/magnetosphere, top right)
  - Fluid, kinetic (particle-in-cell - top left, Vlasov, hybrid), gyrokinetic, mixture (top right)
  - Typically performed on supercomputers (DOE machine “Cori”, bottom, 13th fastest in the world)



Burch et al., Science, 2016



Chen et al., JGR, 2017



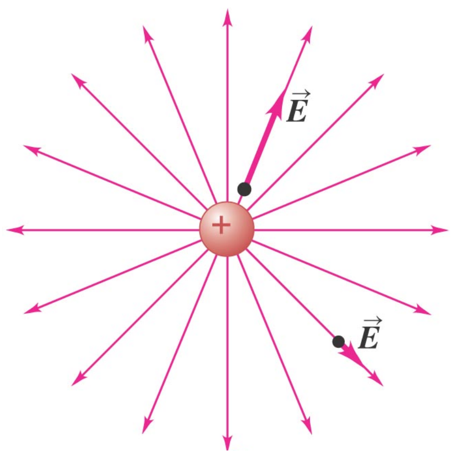
https://docs.nersc.gov/systems/cori/

MAGNETIC FIELD LINES CAN BREAK? – WHY MAGNETIC RECONNECTION IS WEIRD

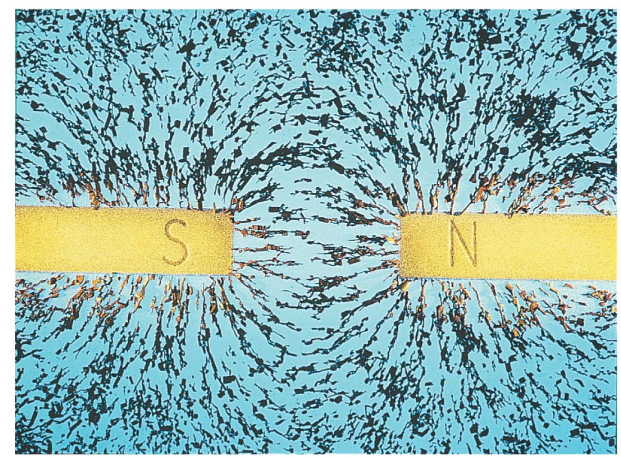
- We are often told that Gauss' law for electricity and magnetism implies…

$$\nabla \cdot \mathbf{E} = \frac{\rho_c}{\epsilon_0} \qquad \nabla \cdot \mathbf{B} = 0$$

Electric fields only end on positive or negative charges



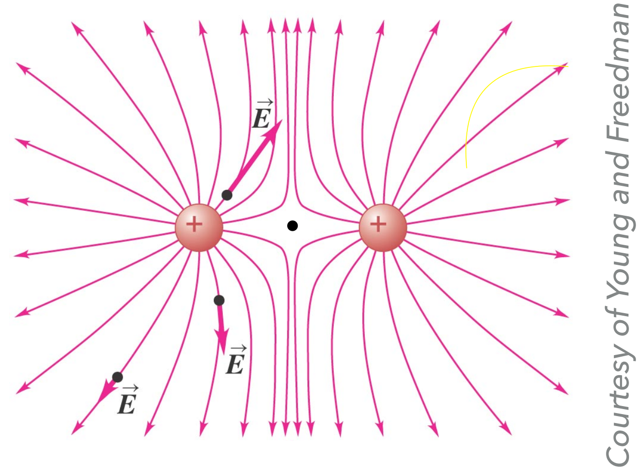
Magnetic field lines have no ends



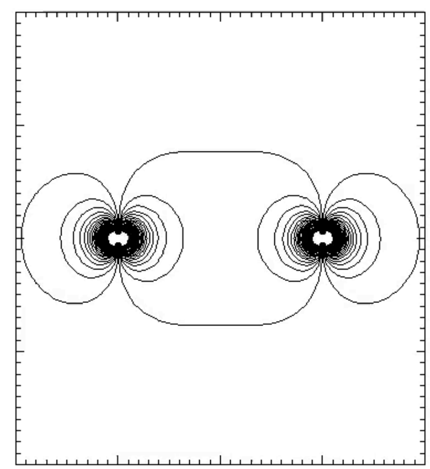
Images courtesy of Young and Freedman

- Doesn't magnetic reconnection violate Gauss' law?!?

MAGNETIC FIELD LINES CAN BREAK? – WHY MAGNETIC RECONNECTION IS NOT WEIRD



- 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 $\nabla \cdot \mathbf{E} = \frac{\rho_c}{\epsilon_0}$
      - magnetic fields never diverge from anywhere $\nabla \cdot \mathbf{B} = 0$



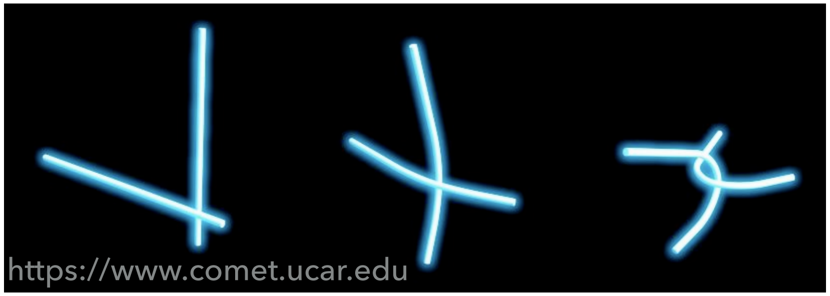
MAGNETIC FIELD LINES CAN BREAK? – SOME DETAILS

- 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 $\frac{d\Phi_B}{dt} = -\oint \mathbf{E} \cdot d\mathbf{l}$, 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

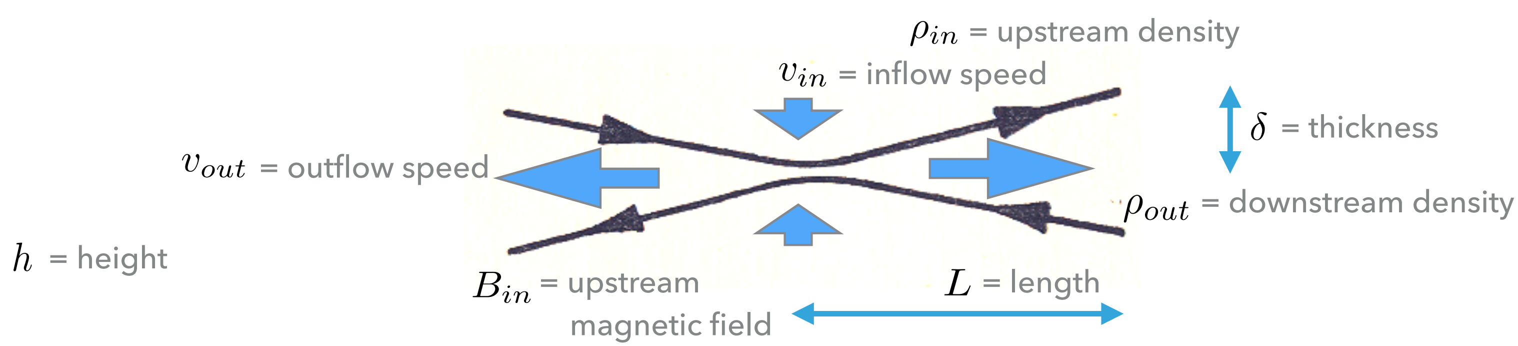
$$\mathbf{E} + \mathbf{v} \times \mathbf{B} = \mathbf{0}$$ Ideal-MHD Ohm's law

$$\mathbf{E} + \mathbf{v} \times \mathbf{B} = \mathbf{R}$$ 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

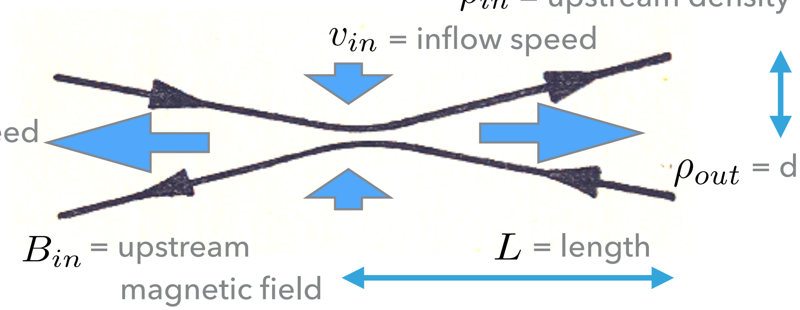


Think of ρ_{in}, B_{in}, and L as known

Modified from Dungey, 1953

- Simple *steady-state* scaling analysis: "Sweet-Parker scaling"
  - Mass flux into box equals mass flux out of box: $$\rho_{in} v_{in} L h \sim \rho_{out} v_{out} \delta h$$
  - Energy flux into box equals energy flux out of box: $$\left(\frac{B_{in}^2}{2\mu_0}\right) v_{in} L h \sim \left(\frac{1}{2}\rho_{out} v_{out}^2\right) v_{out} \delta h$$
    - 2 equations with 2 unknowns; solve for v_{out}: $$\boxed{v_{out} \sim \frac{B_{in}}{\sqrt{\mu_0 \rho_{in}}} = c_{A,in}}$$
      - The outflow speed scales as the Alfvén speed!

THE BASICS – INFLOW SPEED / RECONNECTION RATE



Modified from Dungey, 1953

- 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 $\dfrac{\delta}{L}$! This, in turn, depends on RHS of $\mathbf{E} + \mathbf{v} \times \mathbf{B} = \mathbf{R}$!

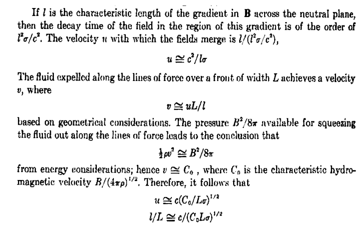
THE BASICS – IMPORTANCE OF SMALL SCALE PHYSICS

- With Ohm's law giving $\mathbf{E} + \mathbf{v} \times \mathbf{B} = \mathbf{R}$
  - If reconnection is collisional, then $\mathbf{R} = \eta \mathbf{J}$ 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, $\mathbf{R} = \dfrac{\mathbf{J} \times \mathbf{B}}{ne} + \ldots$ and

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



If l is the characteristic length of the gradient in $\mathbf{B}$ 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 $l/(l^2\sigma/c^2)$,

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

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

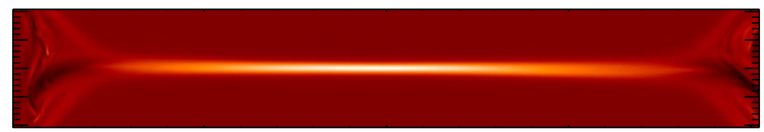
$$\tfrac{1}{2}\rho v^2 \cong B^2/8\pi$$

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

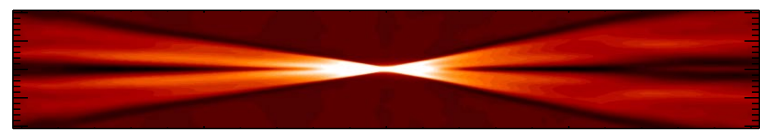
$$u \cong c(C_0/L\sigma)^{1/2}$$

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

Parker, ApJ, 1957



Cassak et al., PRL, 2007



- Consider a sawtooth crash (at MAST, with $c_{A,in}$ ~ 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: $\tau \simeq 25 \; \mu\mathrm{s}$

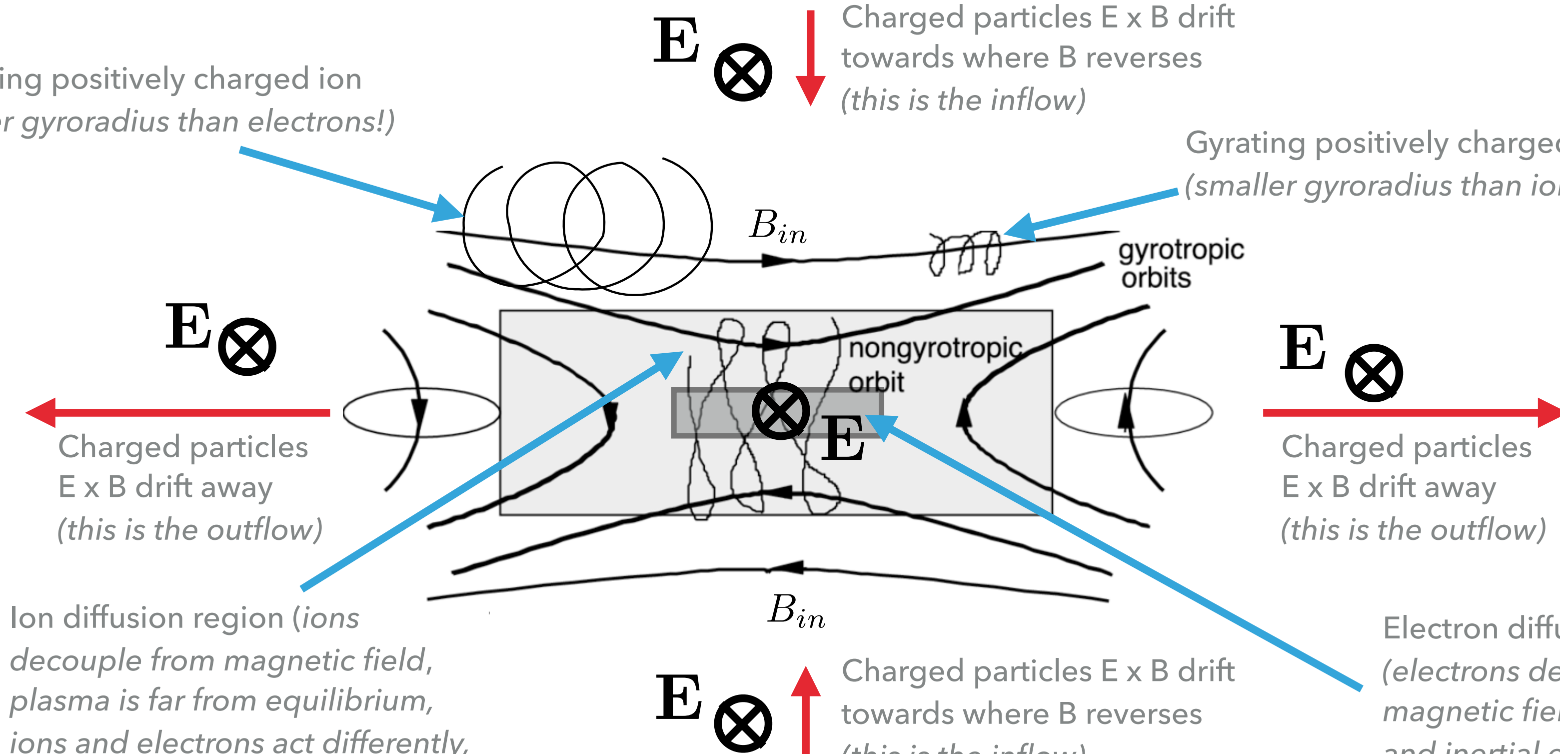
THE BASICS – KINETIC PICTURE OF RECONNECTION

Uses physics discussed by Will Fox and Steffi Diem yesterday

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

Gyrating positively charged ion
(larger gyroradius than electrons!)

Gyrating positively charged electron
(smaller gyroradius than ions!)



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

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

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

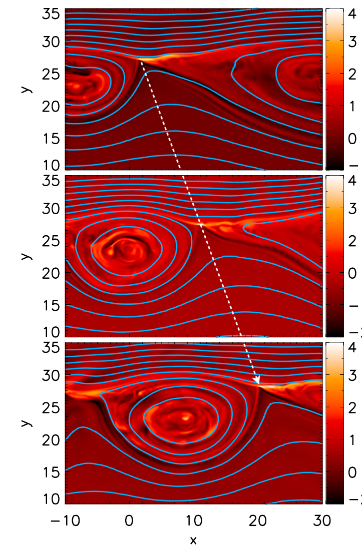
Charged particles E x B drift towards where B reverses
(this is the inflow)

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

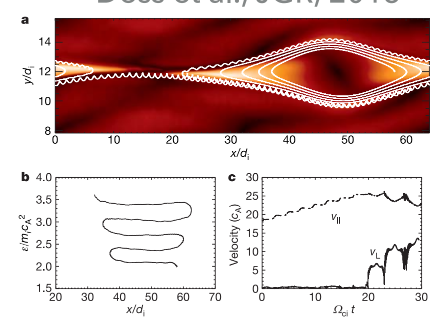
Modified from Kuznetsova et al., 2007

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?



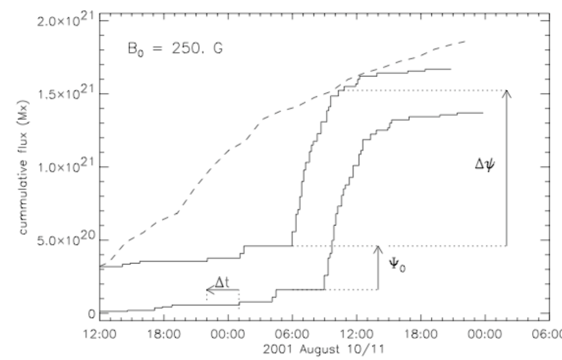
Doss et al., JGR, 2015



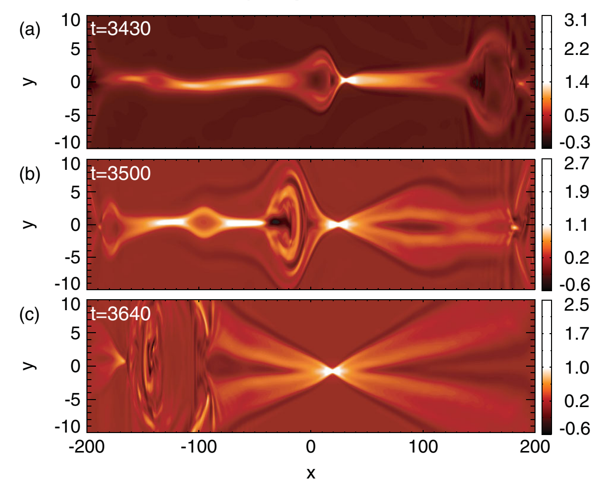
Drake et al., Nature, 2006

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.)?



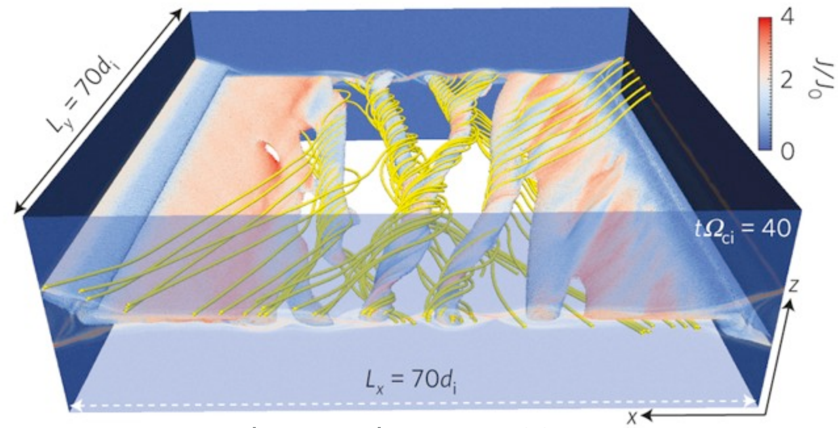
Longcope et al., 2005



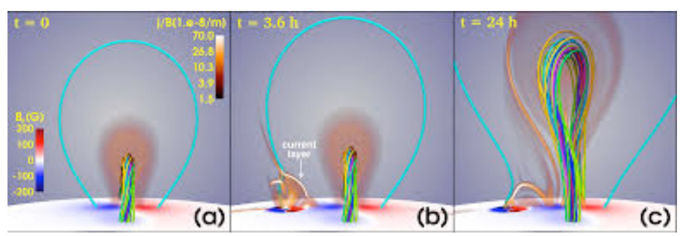
Shepherd and Cassak, PRL, 2010

MODERN RESEARCH – MATCHING WITH REAL SYSTEMS

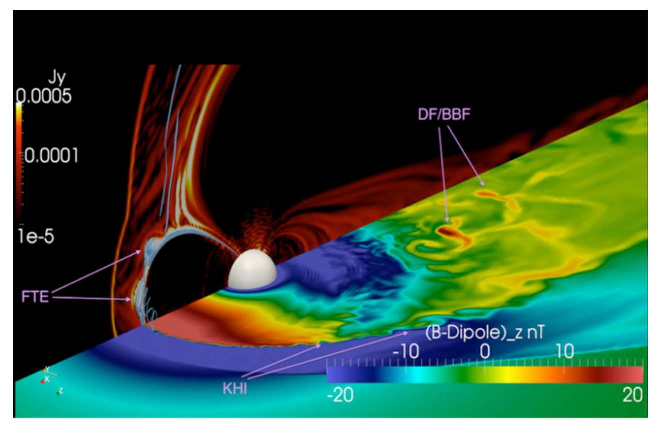
- What is the nature of 3D reconnection?
- How does the local process of reconnection couple to the global dynamics? When is reconnection the leading cause of energy release, and when is it the global dynamics?
- How does the global dynamics influence the rate of reconnection, the location it occurs,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



Daughton et al., Nature, 2011



Dacie et al., ApJ, 2018



Sitnov et al., Eos, 2016

FURTHER RESOURCES

- Textbooks focused on reconnection:
  - Biskamp (2000), Priest and Forbes (2000), Birn and Priest (2006), Gonzalez and Parker (2016)
- Review papers on reconnection:
  - Vasyliunas (1975), Hughes (1995), Zweibel and Yamada (2009), Yamada et al. (2010), Lavraud et al. (2011), Paschmann et al. (2013), Cassak (2016), …
- 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!
Paul.Cassak@mail.wvu.edu