

Magnetic Reconnection

STFC Introductory Course in Solar & Solar-Terrestrial Physics

25 August 2026, University of Southampton

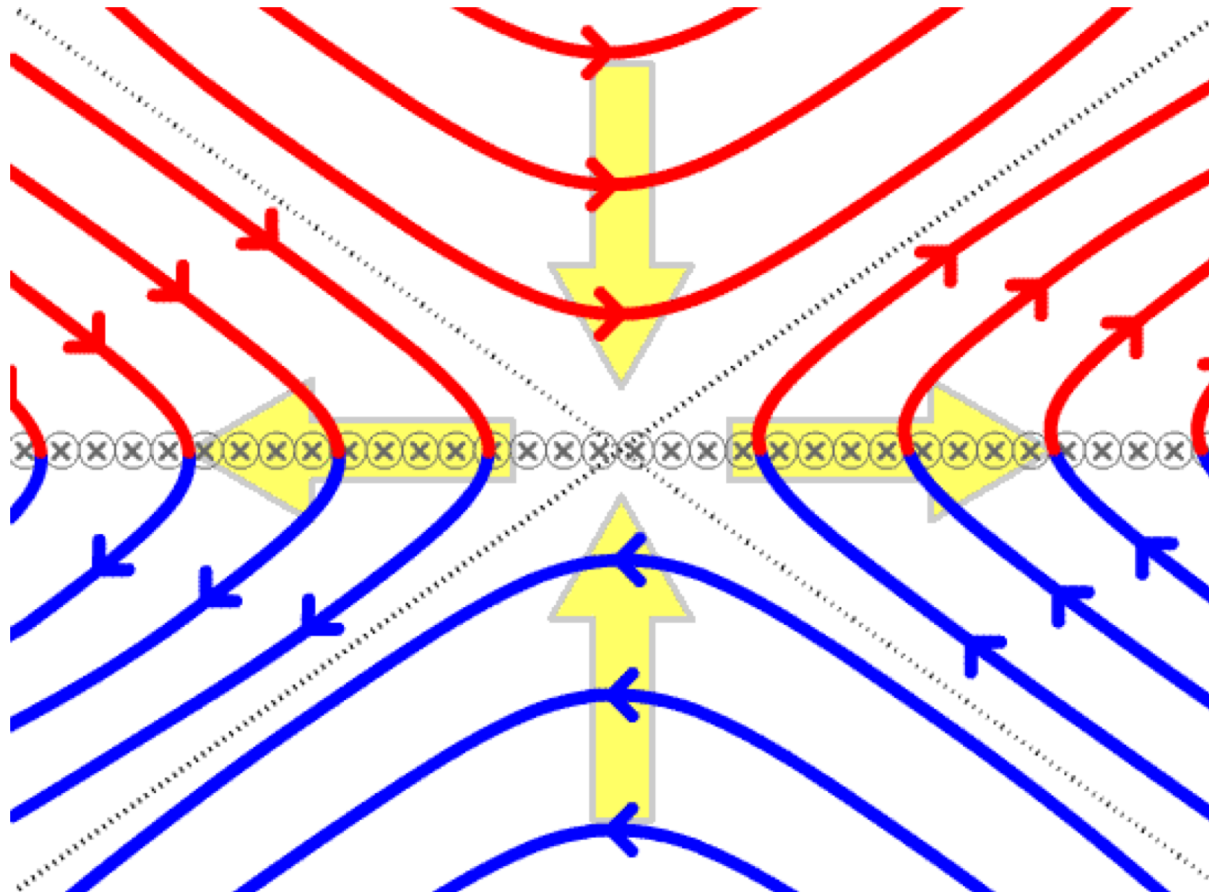
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- **Part 1:** What IS magnetic reconnection?
- **Part 2:** History of magnetic reconnection
- **Part 3:** Reconnection in the Solar System
- **Part 4:** Studying reconnection in space physics
- **Part 5:** Open Questions

Part 1

What IS magnetic reconnection?

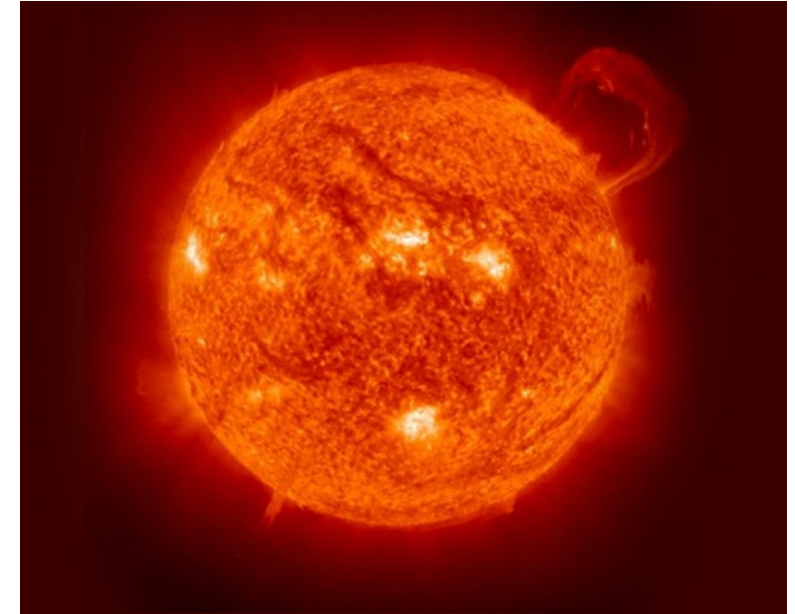


Source: Wikipedia

- A quasi-neutral gas of charged ions and electrons (+ neutrals)
- Exhibit collective behaviour (Chen, 1974)
- Obey electromagnetic forces

We can look at plasma

- As single particles
- As a fluid – magnetohydrodynamics (MHD)
- Statistically – kinetic theory



Plasma Example: The Sun
(Source: NASA)

Reconnection is
here.

- Fluid dynamics – but governed by EM forces

$$\frac{\partial \mathbf{B}}{\partial t} = \underbrace{\nabla \times (\mathbf{V} \times \mathbf{B})}_{\text{Convective Term}} + \underbrace{\frac{\nabla^2 \mathbf{B}}{\mu_0 \sigma}}_{\text{Diffusive Term}}$$

- Magnetic Reynolds number measures balance between the two terms.

$$R_m = \frac{\text{convective term}}{\text{diffusive term}} = \frac{\nabla \times (\mathbf{V} \times \mathbf{B})}{\nabla^2 \mathbf{B} / \mu_0 \sigma} \simeq \mu_0 \sigma V_c L_c$$

Conductivity (red arrow pointing to σ)
Plasma Velocity (blue arrow pointing to V_c)
Domain Length (black arrow pointing to L_c)

Frozen-in Condition

- $R_M \gg 1$: convection term dominates.

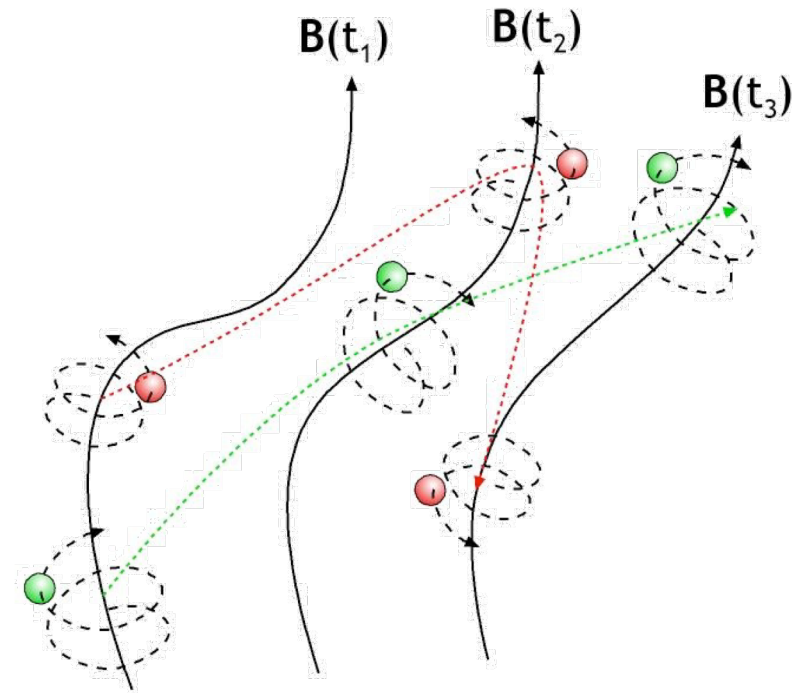
$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{V} \times \mathbf{B}) + \cancel{\frac{\nabla^2 \mathbf{B}}{\mu_0 \sigma}}$$

Solar Wind: $R_M \sim 10^6$ (Wrench et al., 2024)

Earth Core: $R_M \sim 10^3$ (Davies et al., 2015)

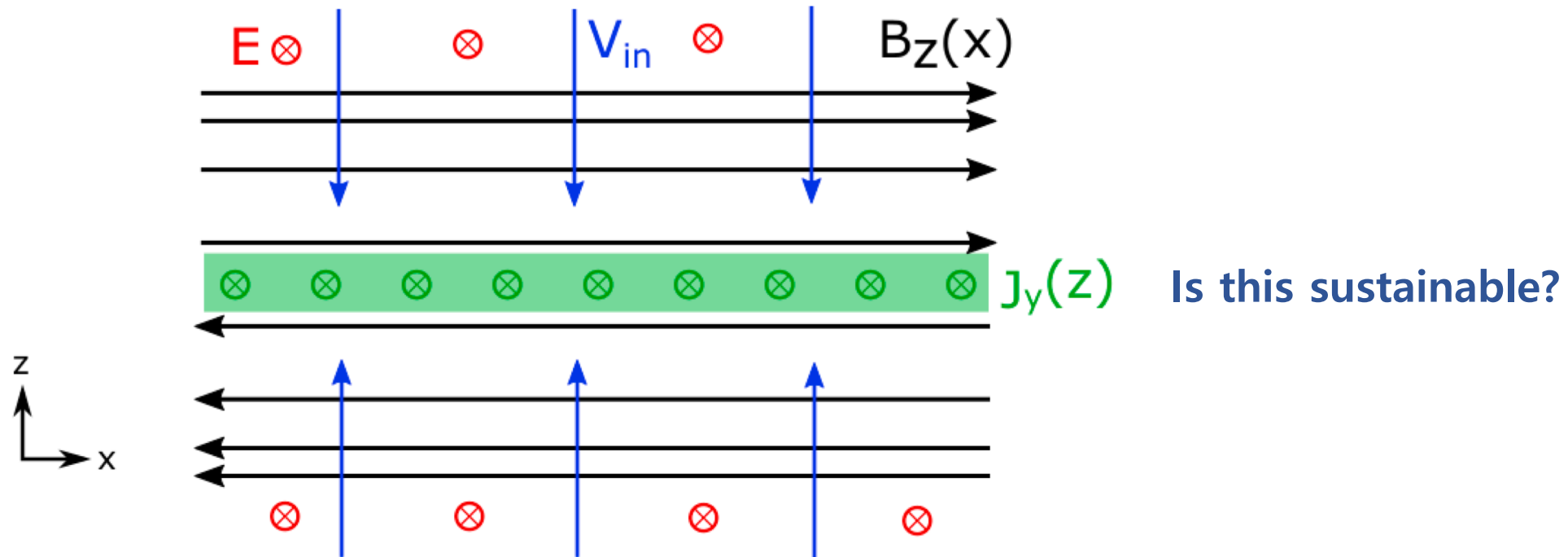
Tokamak: $R_M \ll 1$

- **Plasma travels with magnetic field (and vice versa).**



Source: Robert Fear

Consider a boundary between two magnetic fields.



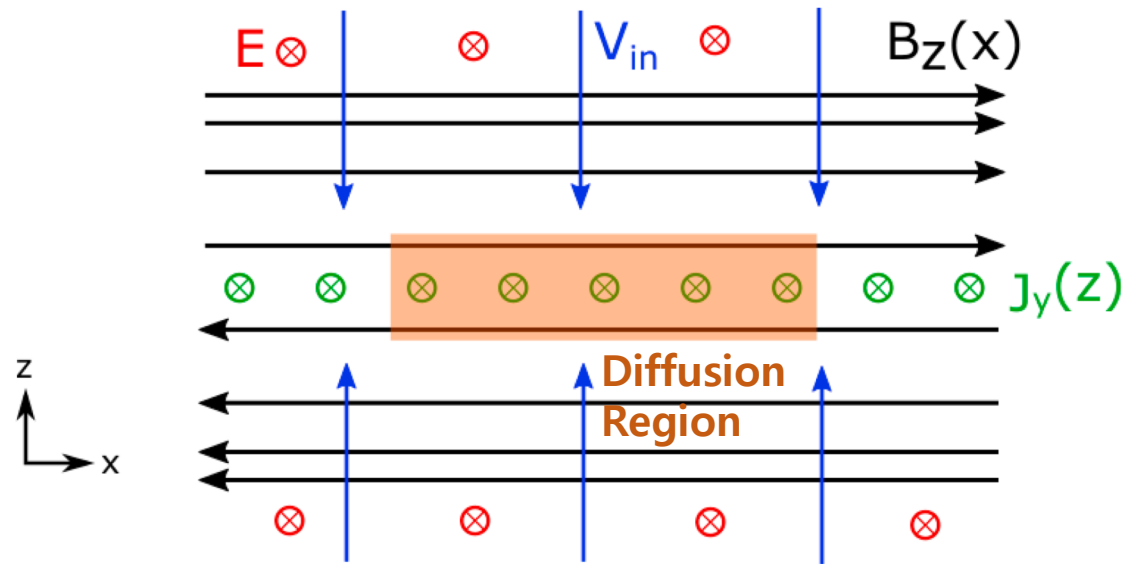
Source: Imogen Gingell

The Diffusion Region

- Strong gradient at current sheet – diffusive term returns!

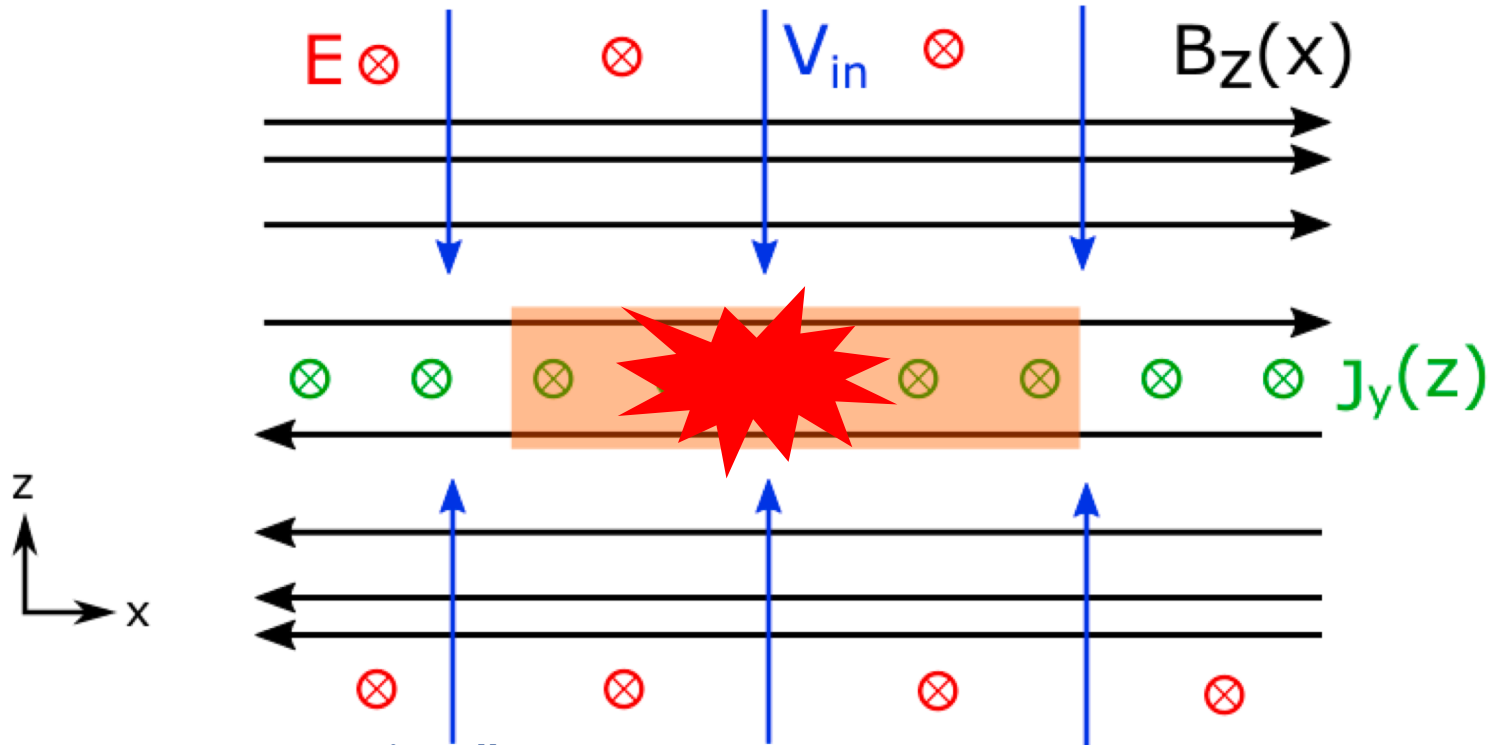
$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{V} \times \mathbf{B}) + \frac{\nabla^2 \mathbf{B}}{\mu_0 \sigma}$$

- **Frozen-in condition broken!**



Here plasmas can mix, but where do they go?

Source: Imogen Gingell



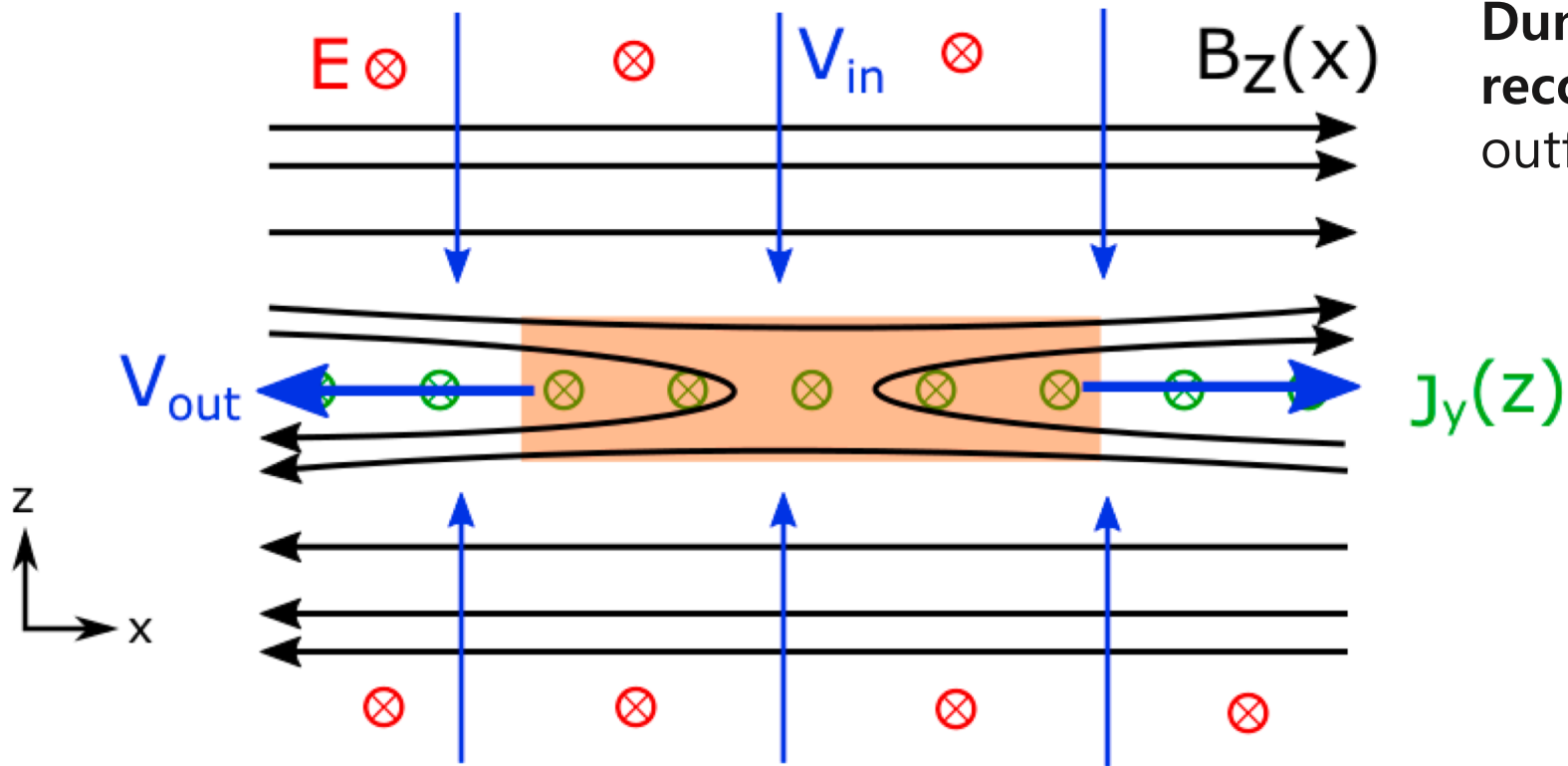
Source: Imogen Gingell

Magnetic Annihilation (1946-53)

- B-field and plasma destroyed, releasing heat and energy.
- "Explains" solar flare (Giovanni, 1946) and aurora (Hoyle, 1949)
- **But** dense, hot, high-pressure plasma at diffusion region soon chokes off inflow.
- Process not sustainable!

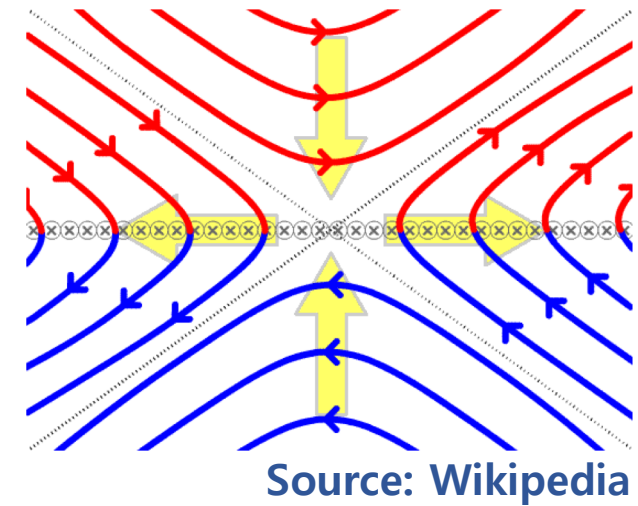
Magnetic Reconnection

- There must be plasma outflow from the diffusion region.



Source: Imogen Gingell

Dungey (1953): B-field lines **reconnect**, carries plasma away as outflow, releasing energy.



Part 2

History of Magnetic Reconnection

1953: Dungey

Reconnection is frequent and can account for phenomena in the Solar System.

"Neutral points are found to be unstable in such a way that a small perturbation will start a discharge in a time of the order of the characteristic time of the system.

Such discharges may account for aurorae, and may also occur in solar flares and the interstellar gas."

LXXVI. *Conditions for the Occurrence of Electrical Discharges in Astrophysical Systems*

By J. W. DUNGEY

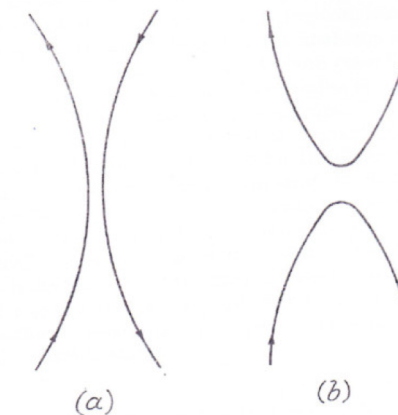
School of Physics, The University of Sydney, Australia*

[Received November 14, 1952, revised March 11, 1953]

SUMMARY

Discharges are shown to be a possible source of high energy particles, if the current density is very large. The growth of the current density is discussed using the fact that the magnetic lines of force are approximately frozen into the ionized gas. It is shown that discharges are unlikely to occur anywhere except at neutral points of the magnetic field. Neutral points are found to be unstable in such a way that a small perturbation will start a discharge in a time of the order of the characteristic time of the system. Such discharges may account for aurorae, and may also occur in solar flares and the interstellar gas.

Fig. 2



Source: Dungey, 1953

1957-58: Sweet-Parker

- **Sweet** (1958) and **Parker** (1957): first quantitative model of reconnection.

Steady-state, infinite,
planar current sheet

$$E_y = V_{in}B_{in} = V_{out}B_{out}$$

Incompressible
plasma flow

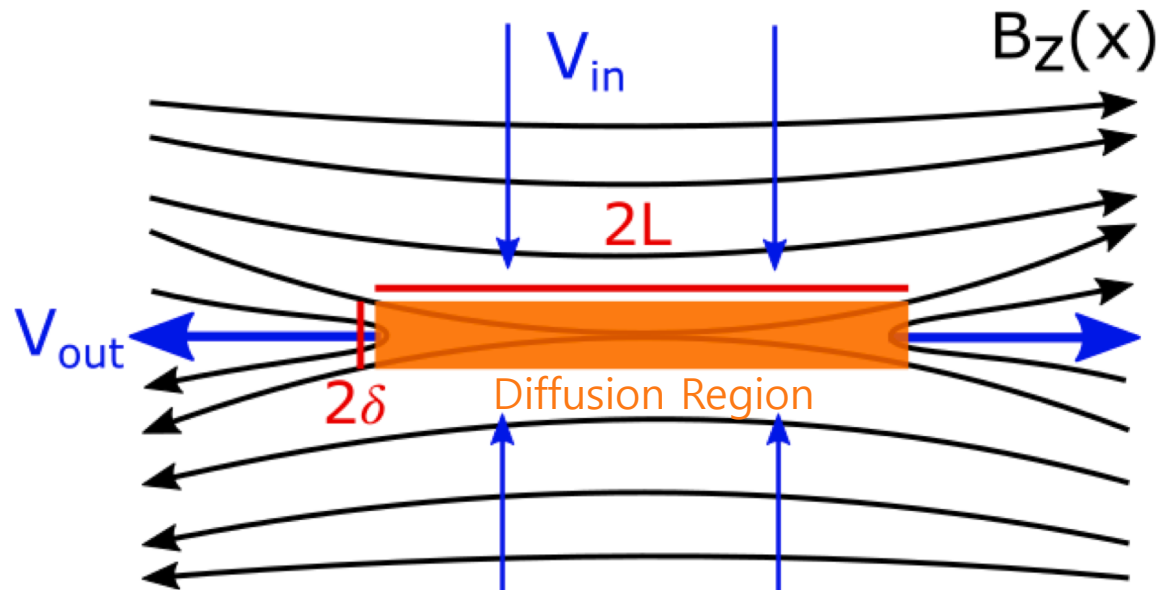
$$V_{in}L = V_{out}\delta \quad \delta \ll L$$

Energy conservation
(Poynting flux =
plasma flow energy
change)

$$\frac{E_y B_{in}}{\mu_0} = \frac{1}{2}(\rho V_{in})(V_{out}^2 - V_{in}^2)$$

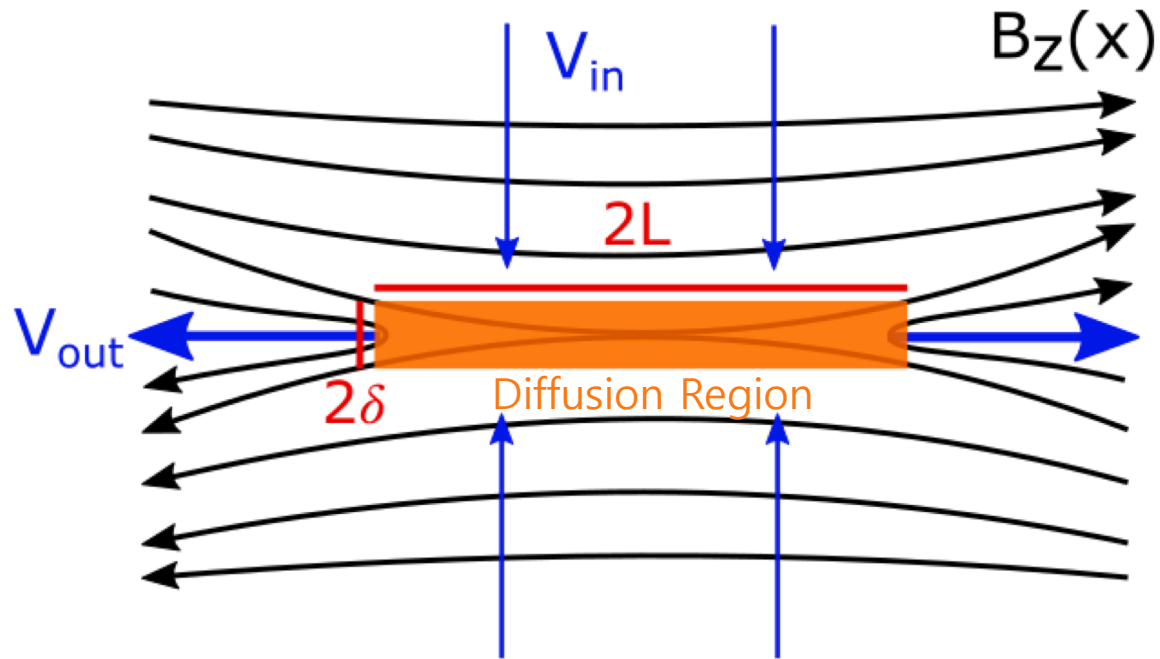
$$V_{out}^2 \sim \frac{B_{in}^2}{\mu_0 \rho_{in}} \sim V_A^2$$

Outflow velocity ~ Alfvén speed



Source: Imogen Gingell (adapted by Nawapat Kaweeyanun)

Problem: Realistic values of L and δ leads to tiny V_{in} , V_{out} .
Reconnection far too slow to explain solar flares & other phenomena.

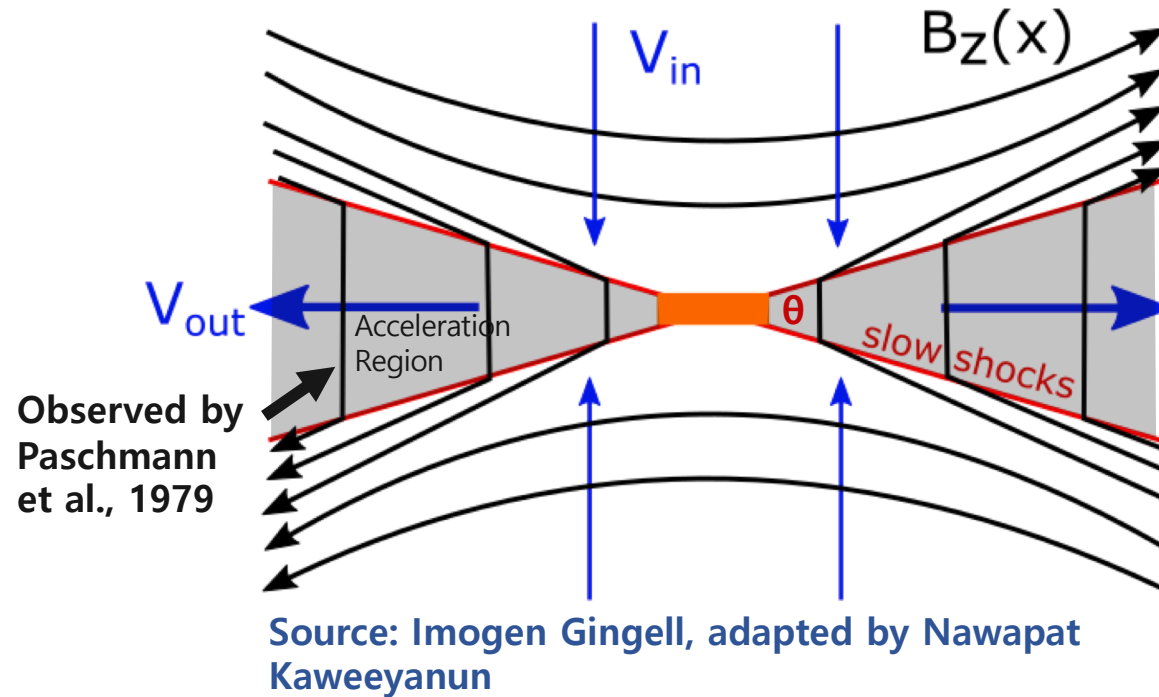


Sweet-Parker: All plasma must pass through diffusion region during reconnection.

Diffusion region is a bottleneck.

But what if they don't have to?

1964: Petschek



- Only tiny diffusion region needed to rearrange B-field.

$$V_{in}L = V_{out}\delta \quad \delta \text{ tiny}$$

- Most plasma remains outside, accelerated by Alfvén or slow mode shock waves.

- Outflow still at Alfvénic velocity, but much larger volume and rate

$$V_{out} \sim V_A \cos \theta \quad \theta = \text{angle between shocks}$$

Hall Reconnection

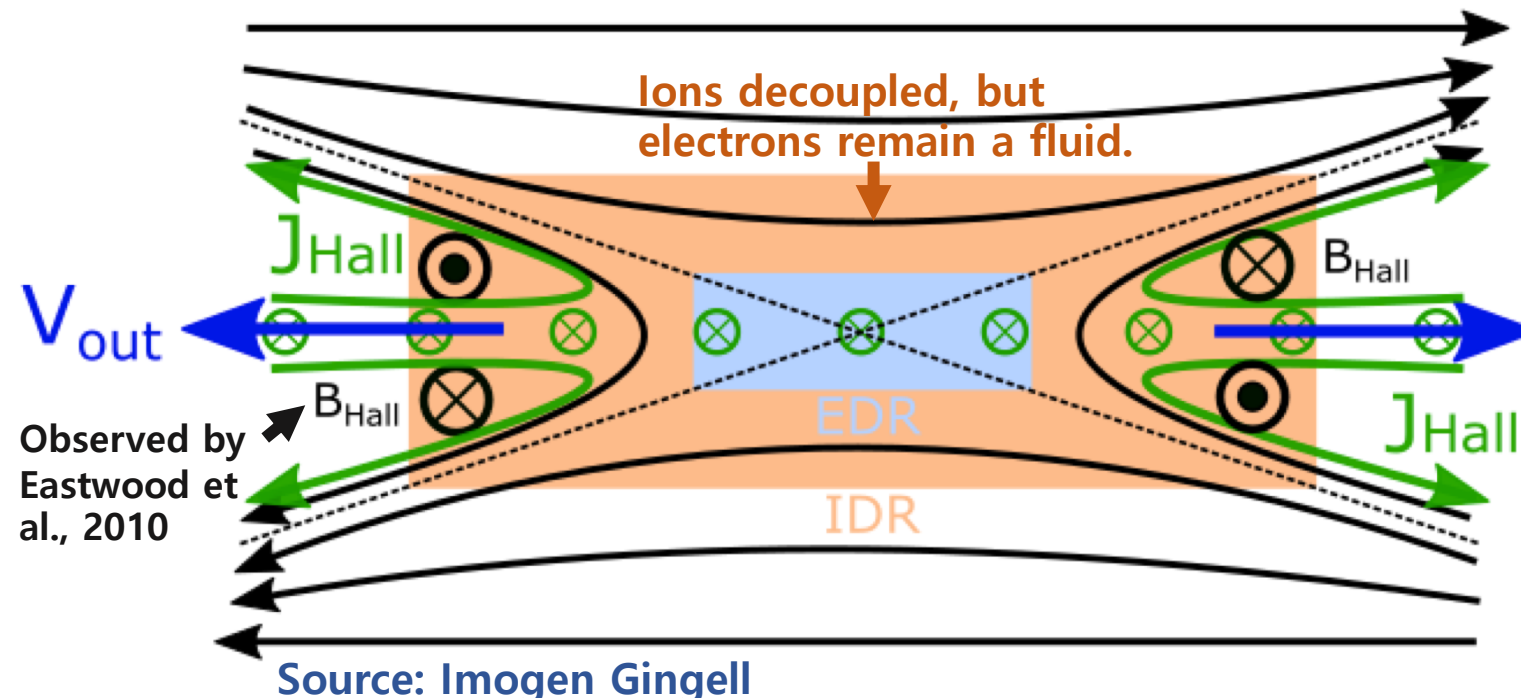
- Plasma is made of ions and electrons, which behave as separate MHD fluids.
- Divergence between ion and electron motions create **Hall effect**.

Hall Effect



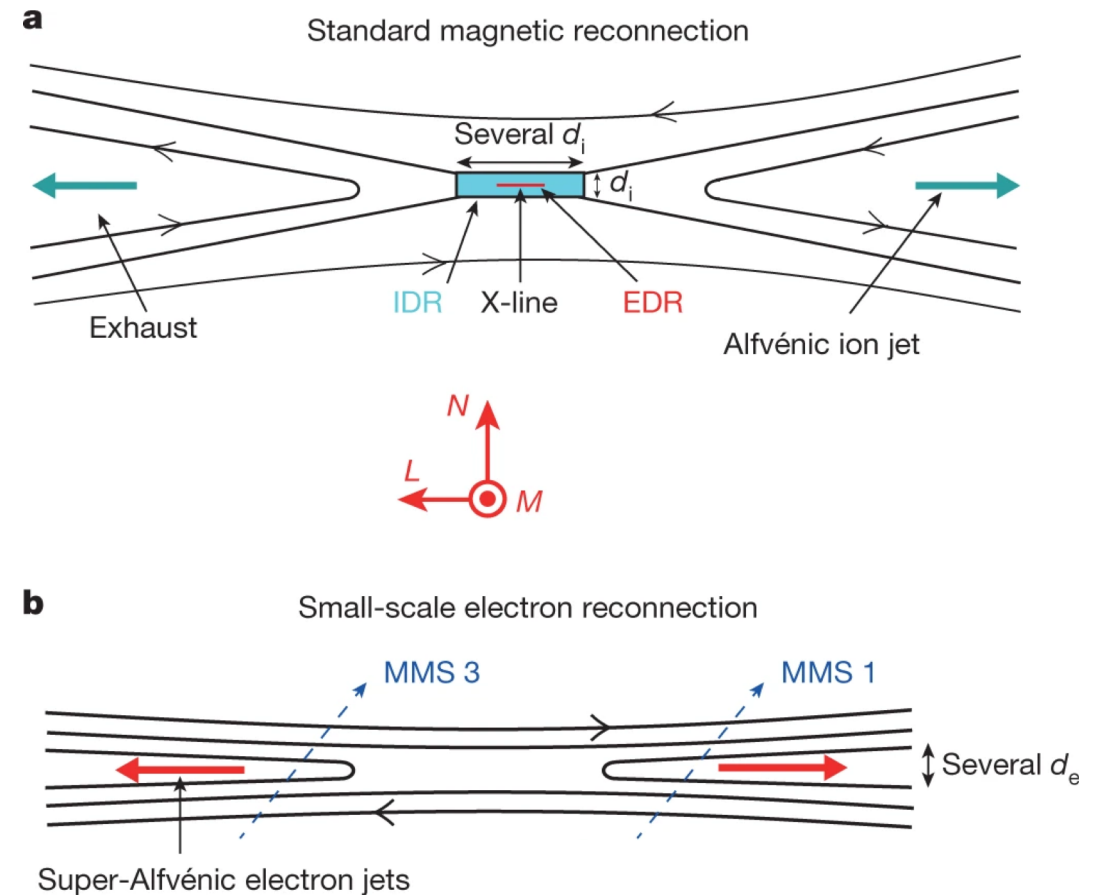
Hall Reconnection (1994) (Mandt et al., 1994)

- Electron diffusion region inside ion diffusion region
- Hall currents (see Gen. Ohm's Law)
- Quadripolar Hall magnetic field (observable by spacecraft)
- Outflow driven by whistler wave



2018: Electron-Only

- At sufficiently small scale (turbulence), electron diffusion region can exist alone.
- Resulting reconnection has only electron outflows (Phan et al., 2018).
- Much faster than standard reconnection.
- Very active area of research!



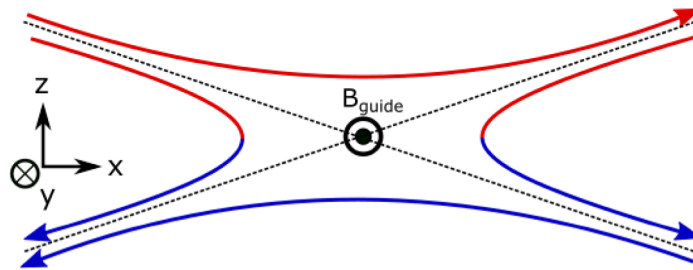
Source: Phan et al., 2018

Guide field Reconnection

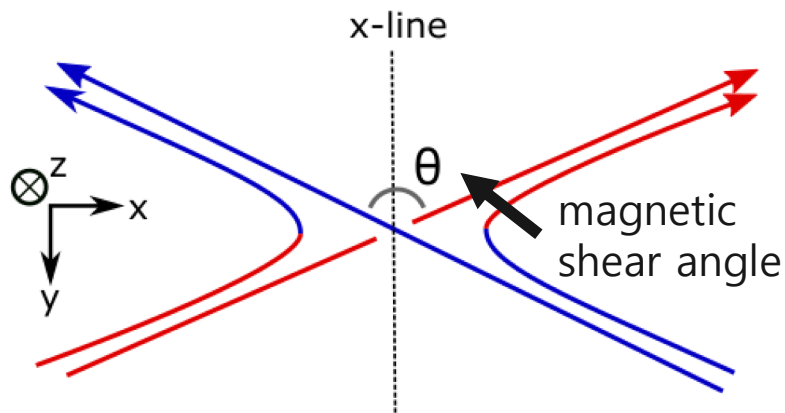
- We looked at reconnection in 2D, but reality is 3D
- Out-of-plane guide field $\mathbf{B}_{\text{Guide}}$ add complexity.

AKA Component Reconnection

Top View



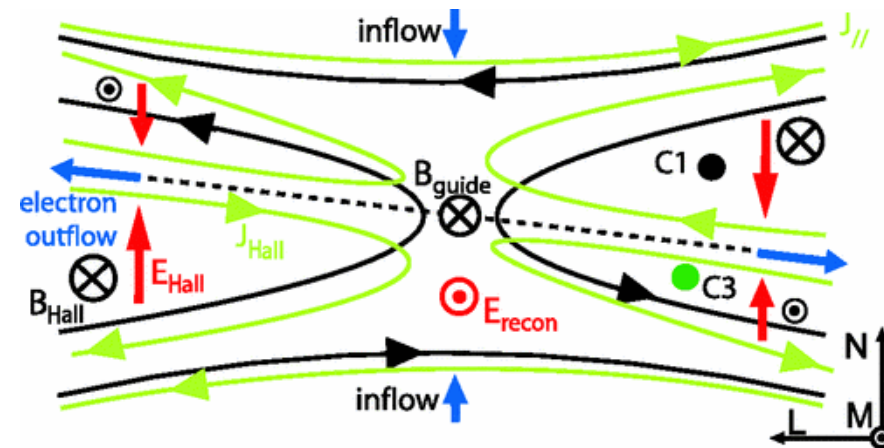
Side View



Source (Both): Imogen Gingell

Reconnection still possible if two fields are antiparallel in at least one direction.

Force term $\mathbf{J}_{\text{Hall}} \times \mathbf{B}_{\text{guide}}$ introduces electron outflow asymmetry (no longer along L axis)

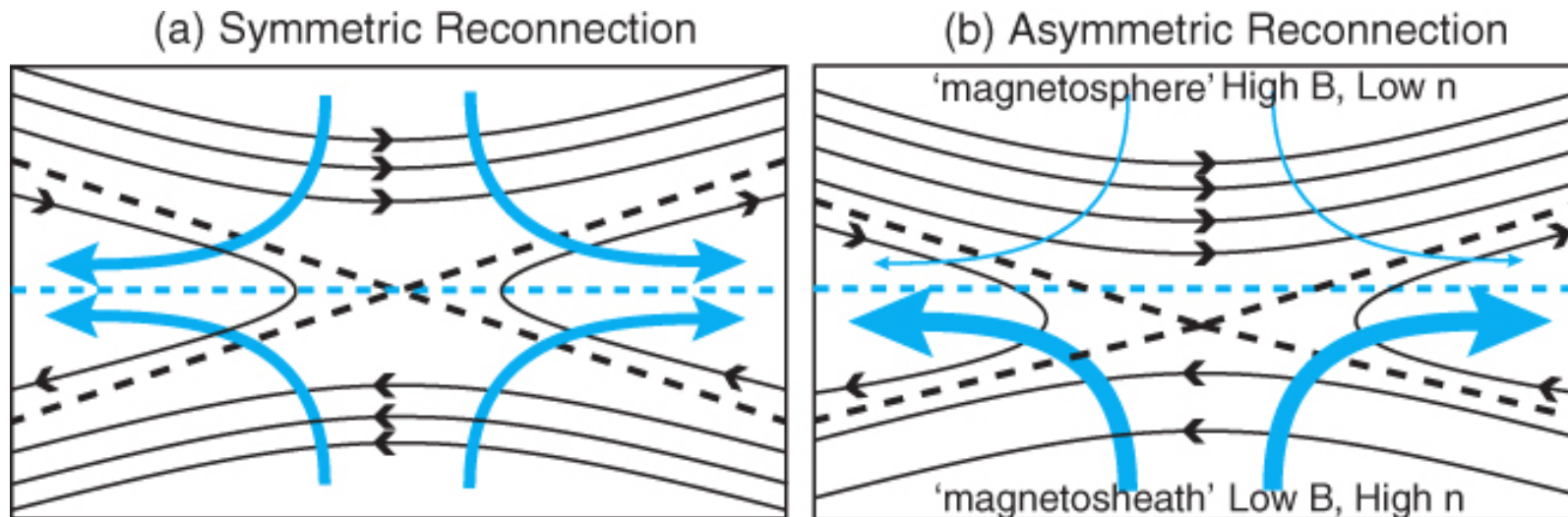


Asymmetric Reconnection

- Often, conditions ($|\mathbf{B}|$, n , T) also asymmetric across the boundary.
 - e.g., magnetosphere
- Outflow displaced toward high field, low density side
 - Plasma into magnetosphere.

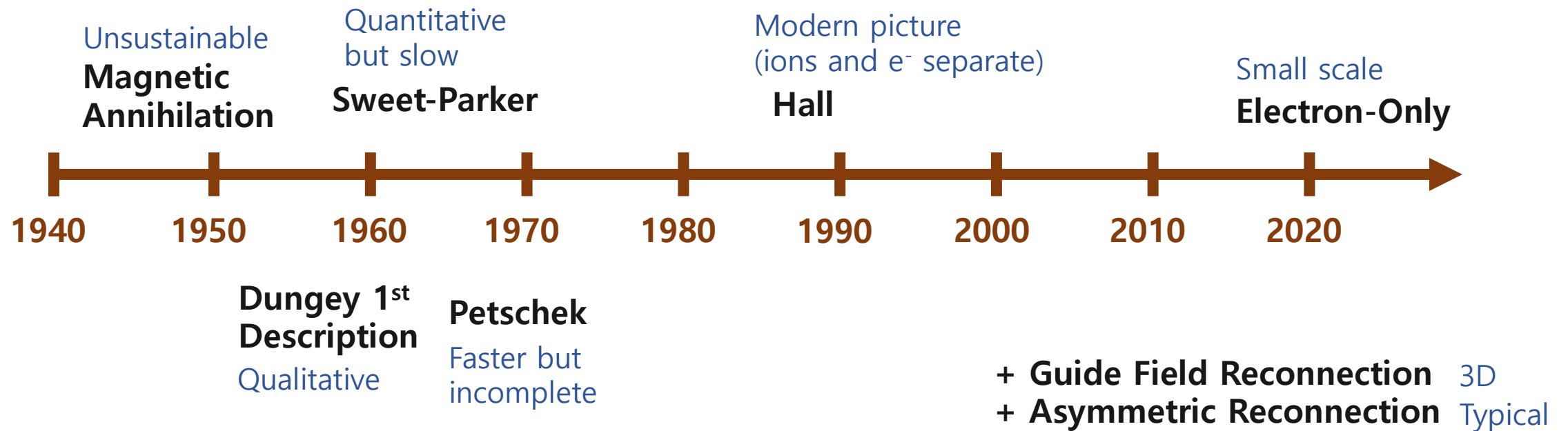
$$V_{out}^2 \sim \frac{B_1 B_2 (B_1 + B_2)}{\mu_0 (\rho_1 B_2 + \rho_2 B_1)}$$

**Modified asymmetric
Sweet-Parker outflow
velocity**



**Source:
Eastwood et al.,
2013**

Timeline of Reconnection



Interlude

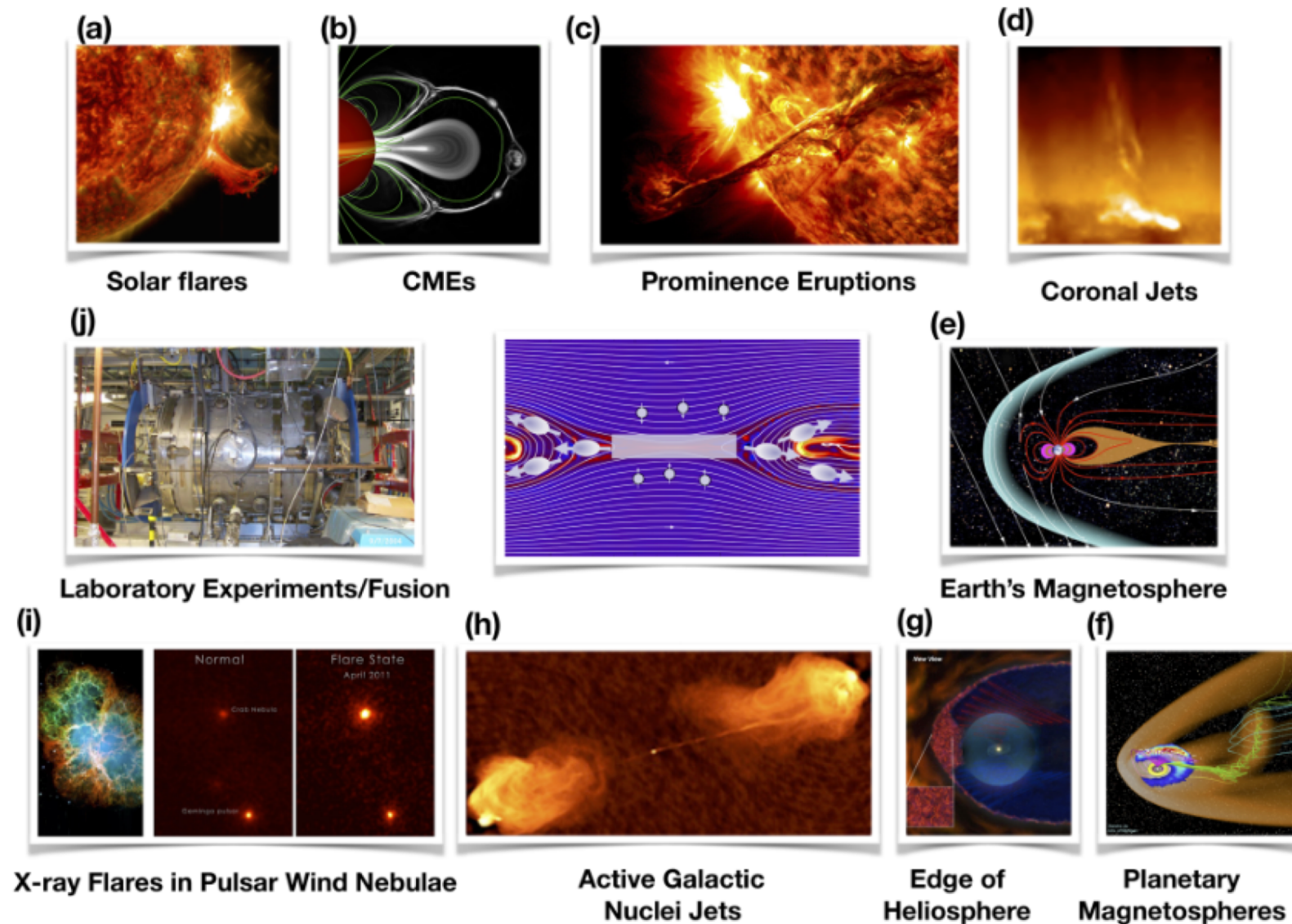
Any questions?

Part 3

Reconnection in the Solar System

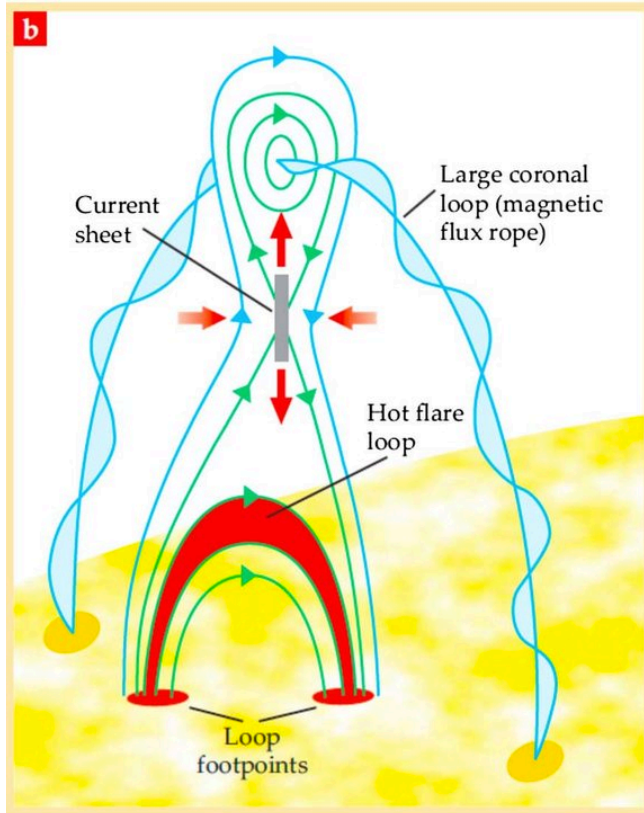
Magnetic reconnection is everywhere in the universe.

Today, we focus on the star system we call home.

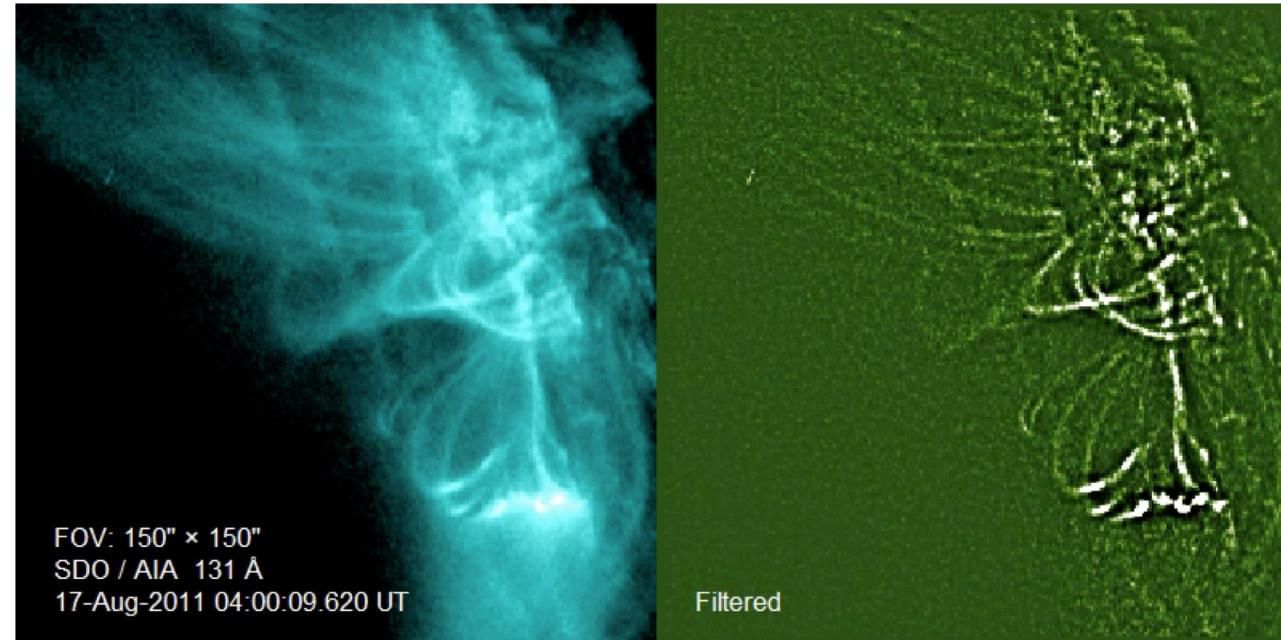


Source:
Hesse & Cassak, 2020

Figure 2. Some settings where magnetic reconnection occurs, with descriptors beneath each panel. Panels (a), (c), (d), (e), (g), (h), and (i) are courtesy of NASA. (b) Credit: J. Karpen; used with permission. (f) Credit: X. Jia; used with permission. (j) Credit: H. Ji, used with permission.



Reconnection at a coronal loop
(Holman et al. 2012)



Direct observation of reconnection at a solar flare, imaged in EUV+X-ray by SDO (Su et al. 2015)

Reconnection in the Sun's upper atmosphere initiates solar create flares and eject* mass.

- May provide acceleration observed beyond Parker's theoretical prediction.

***Not all CMEs are from reconnection**

National Aeronautics and Space Administration

Where Do Switchbacks Come From?

Switchbacks are sudden reversals in the solar wind's magnetic field. They were a surprise discovery as NASA's Parker Solar Probe made its first close flyby of the Sun in November 2018.

How do switchbacks form? Here are the current theories competing to explain them.

(Not to scale)
www.nasa.gov

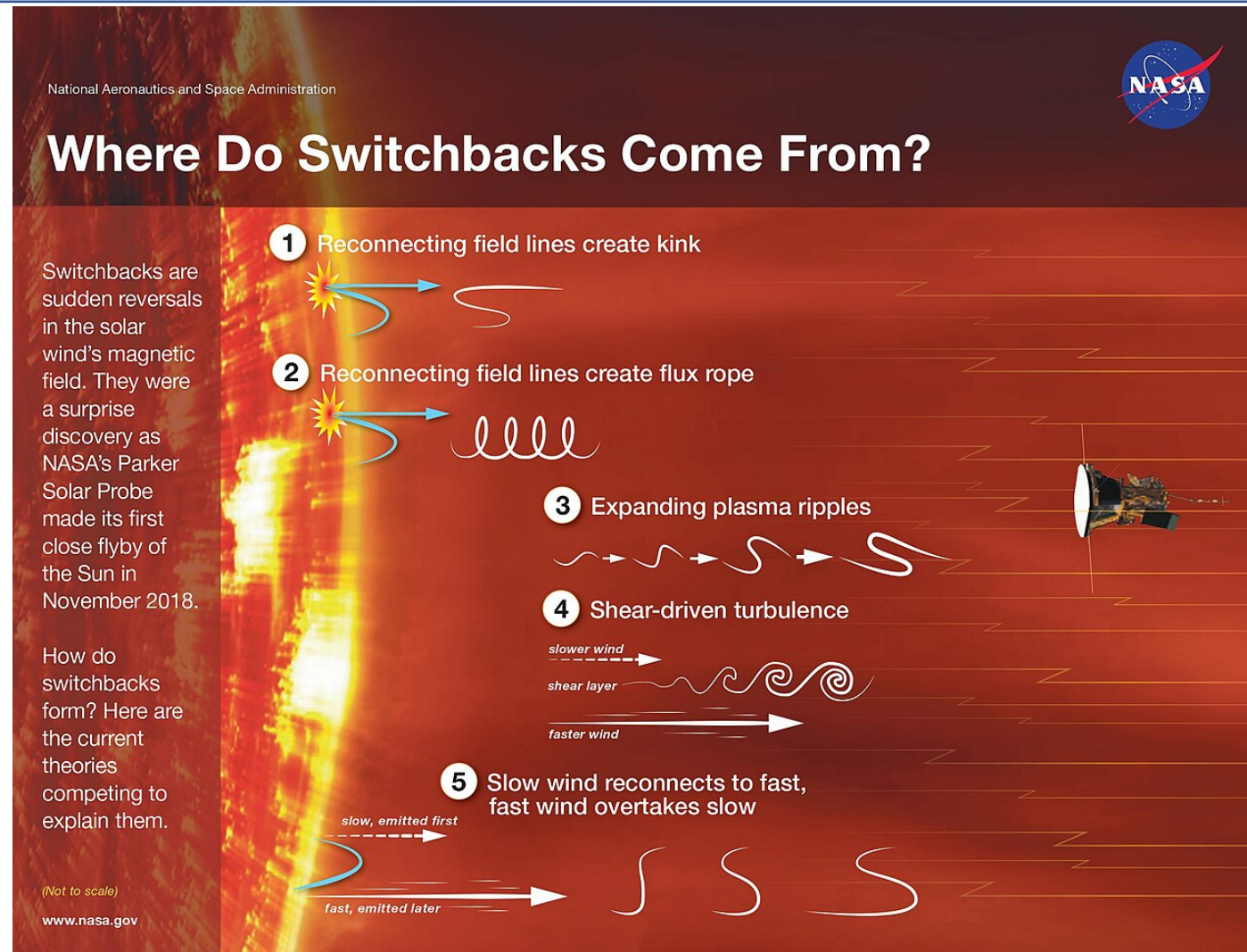
1 Reconnecting field lines create kink

2 Reconnecting field lines create flux rope

3 Expanding plasma ripples

4 Shear-driven turbulence

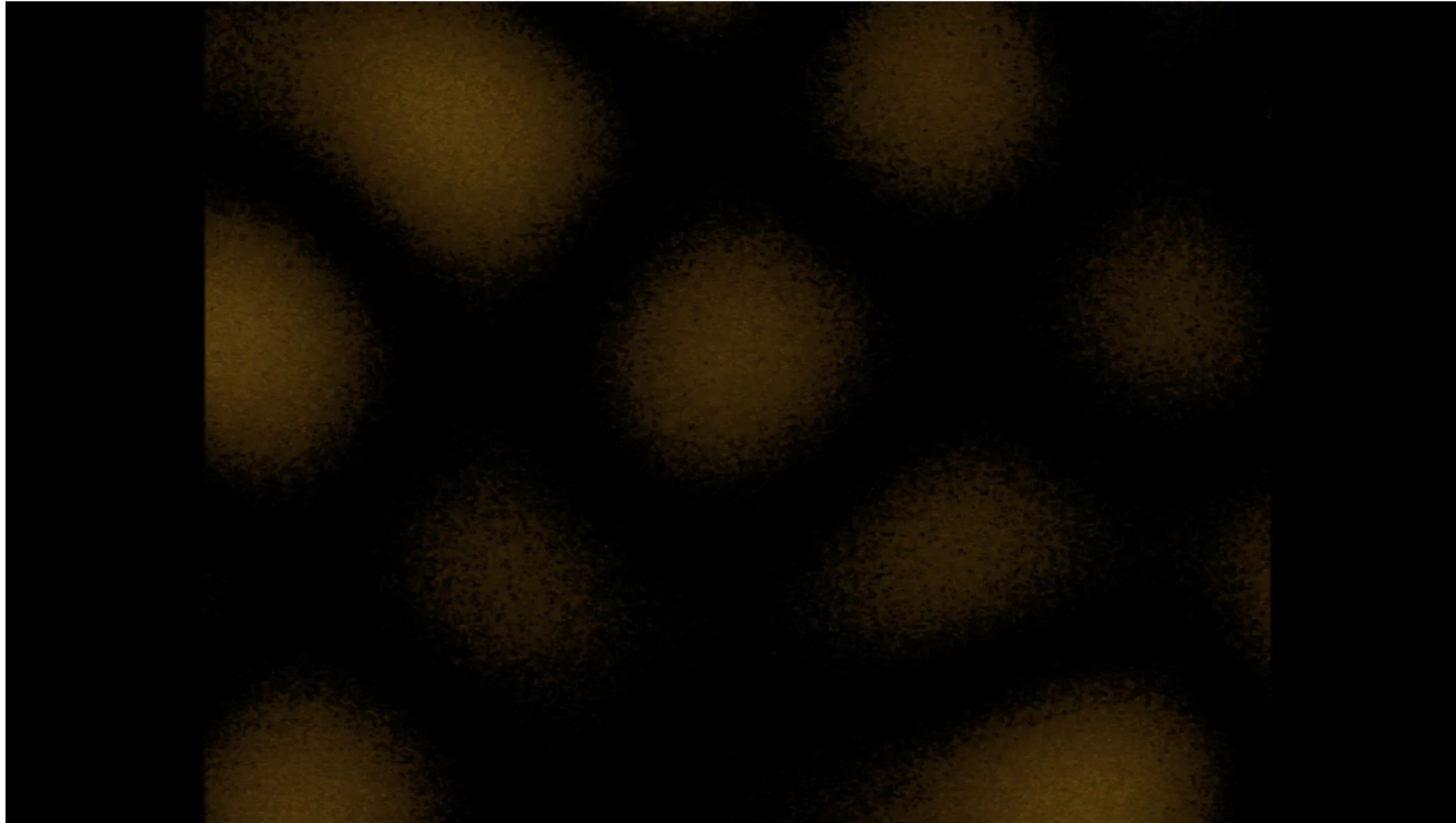
5 Slow wind reconnects to fast, fast wind overtakes slow



Parker Solar Probe

Source: NASA

Solar Wind Turbulence



Small-scale reconnection
laboratory to explore
fundamental theory

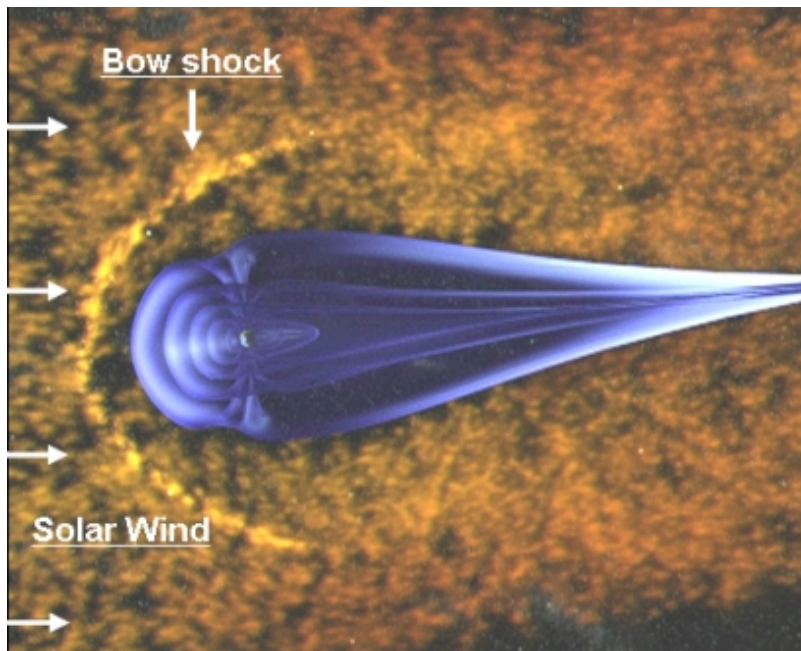
Visualisation of turbulent magnetic reconnection

(Source: Lisa Poje, Colby Haggerty, Tulasi Parashar)

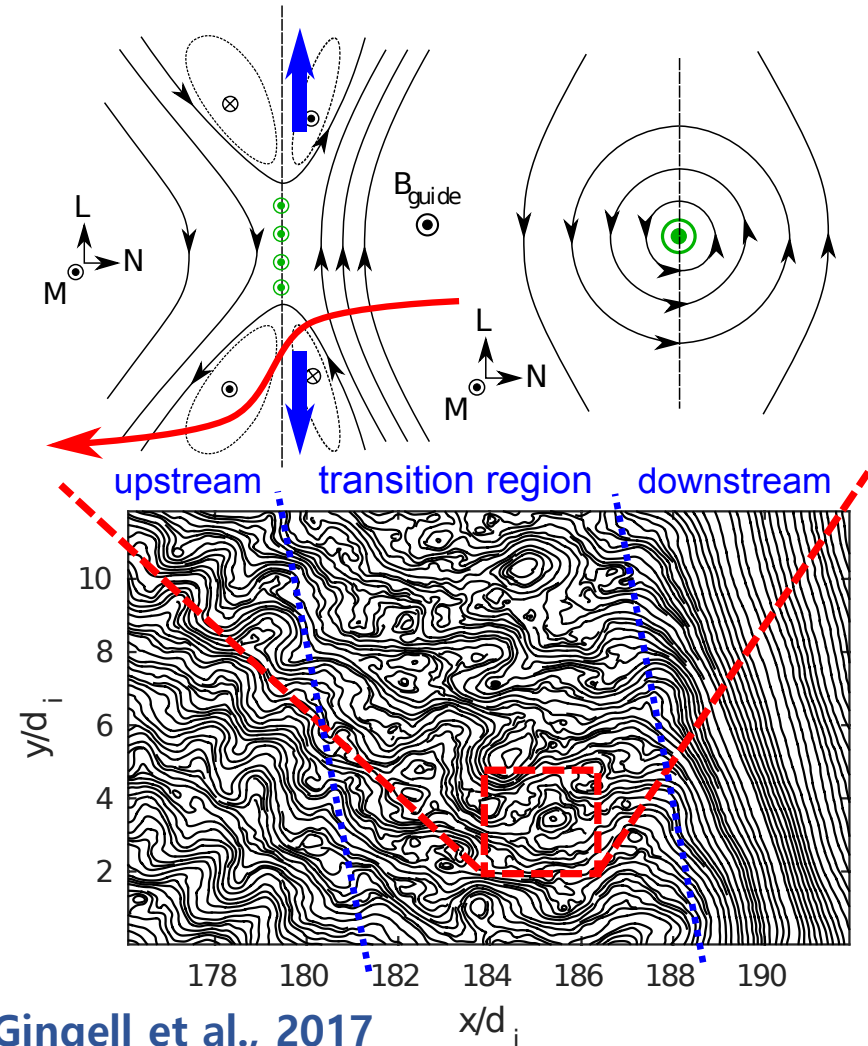
Shock Reconnection

Solar wind decelerates as it approaches Earth's magnetosphere → bow shock.

Plasma reflections at bow shock induces reconnection in the transition region (e.g., Gingell et al., 2017).

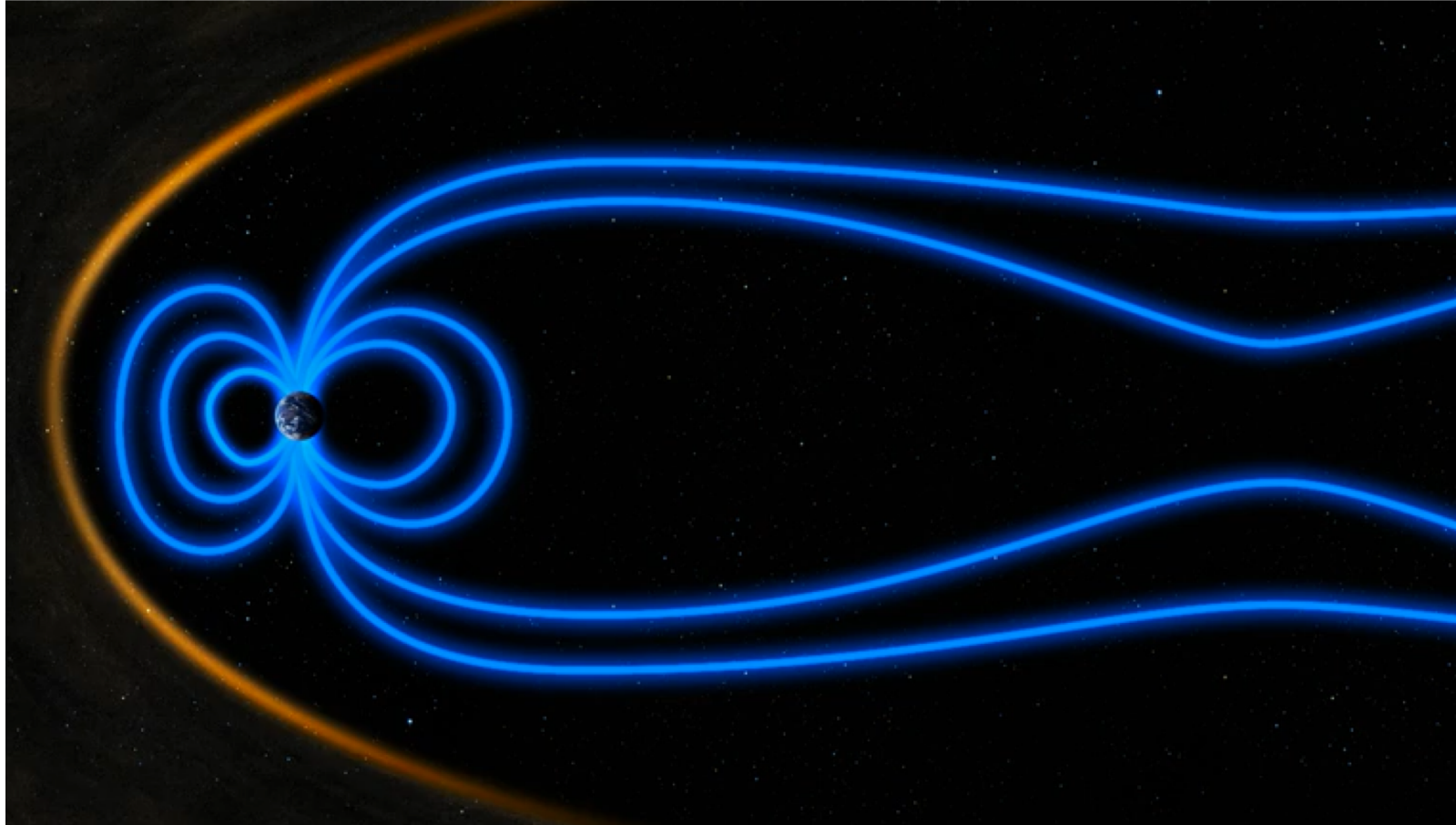


Source: ESA



Source: Gingell et al., 2017

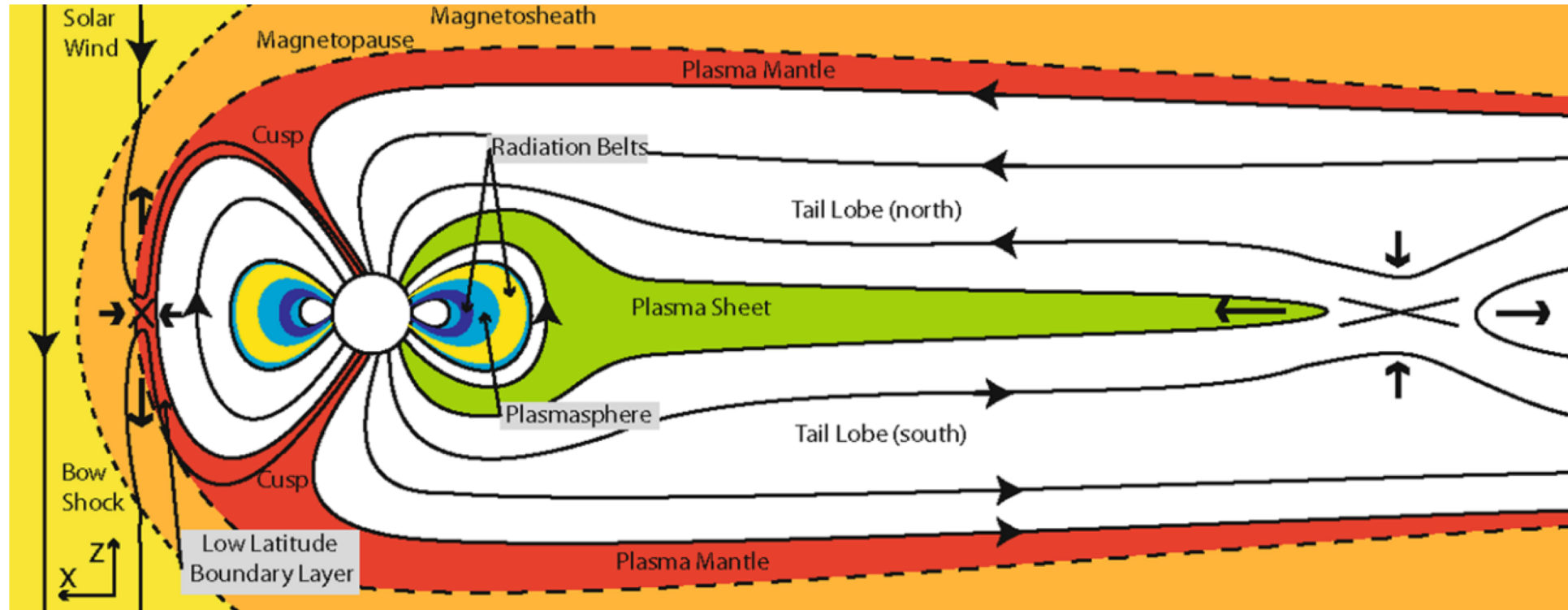
Earth's Magnetosphere



Reconnection drives the
Dungey Cycle (1961)

Dayside reconnection
opens Earth B-lines,
nightside reconnection
close them.

Source: ESA

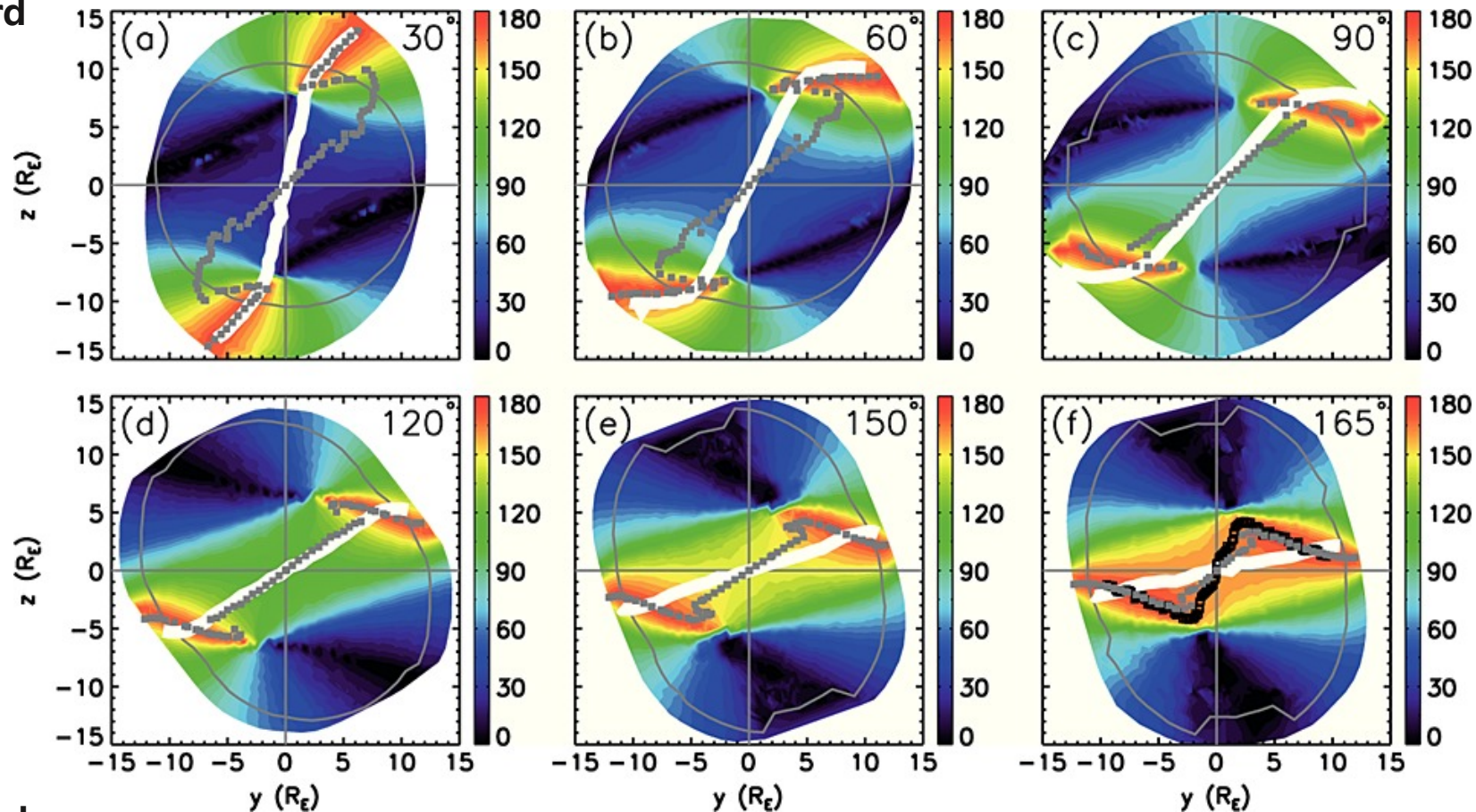


Source: Eastwood et al., 2015

In 3D, reconnection "X" often extends into "**X-line**", which can last hours (quasi-stationary).

X-lines of Reconnection

Northward
IMF



Southward
IMF

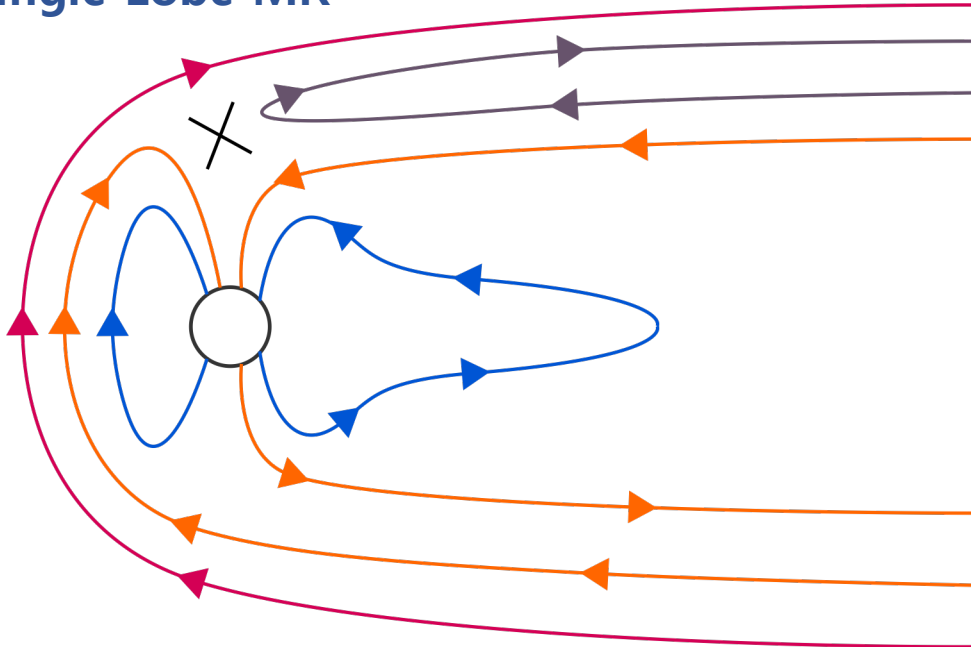
Source: Komar et al., 2015

Northward IMF

Reconnection occurs at high-latitudes, not at equator where fields are parallel.

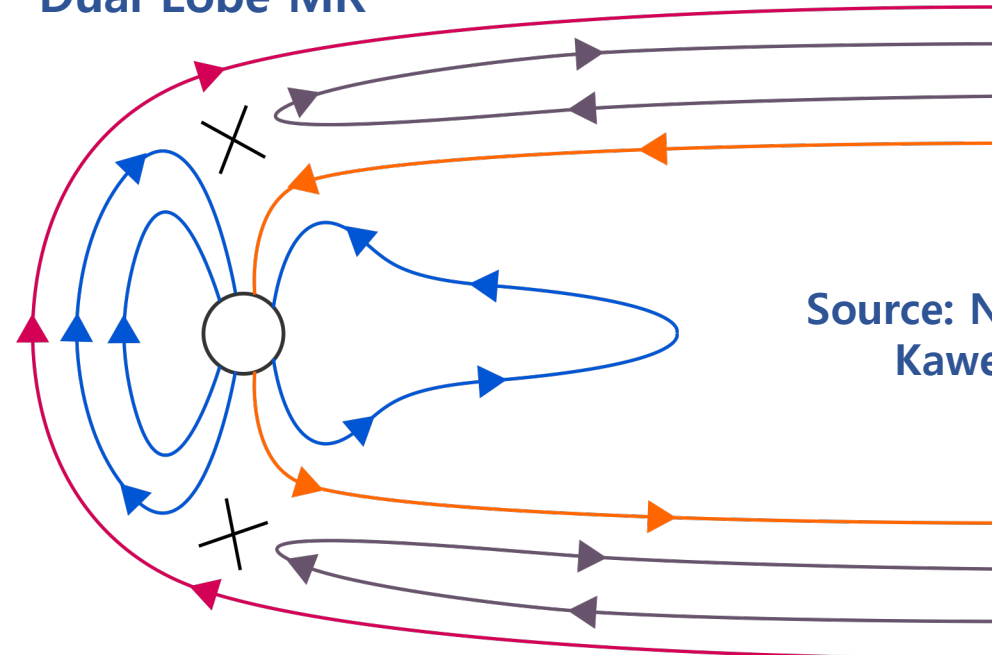
— IMF — Open
— Closed — Disconnected

Single Lobe MR



Open + Open $\rightarrow$ Open + Disconnected
No. Open B-lines unchanged

Dual Lobe MR

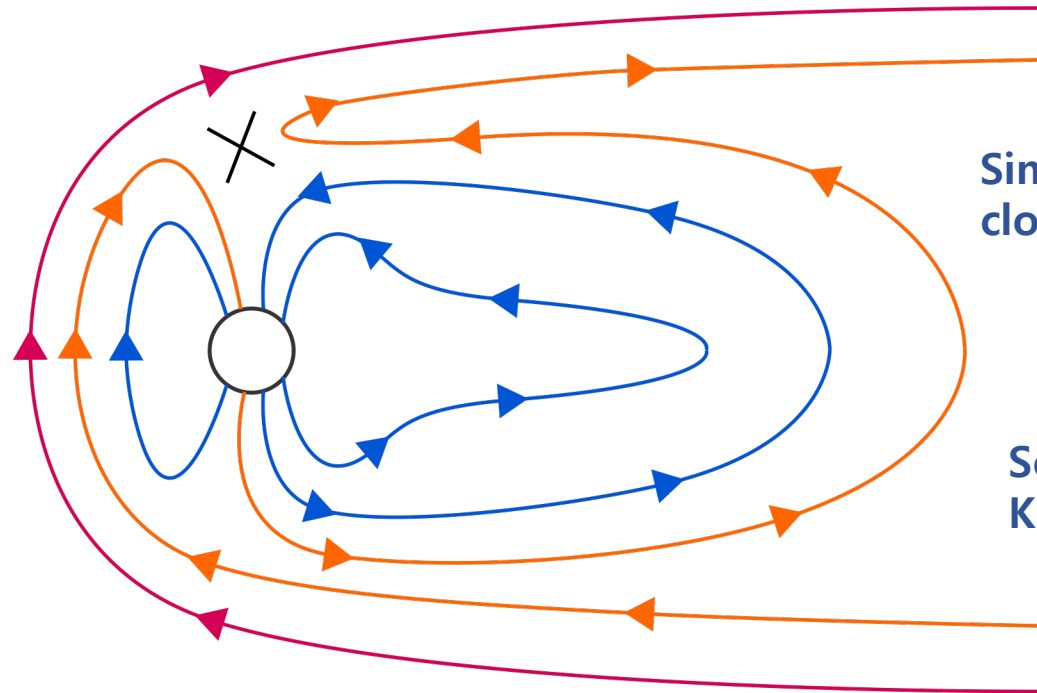
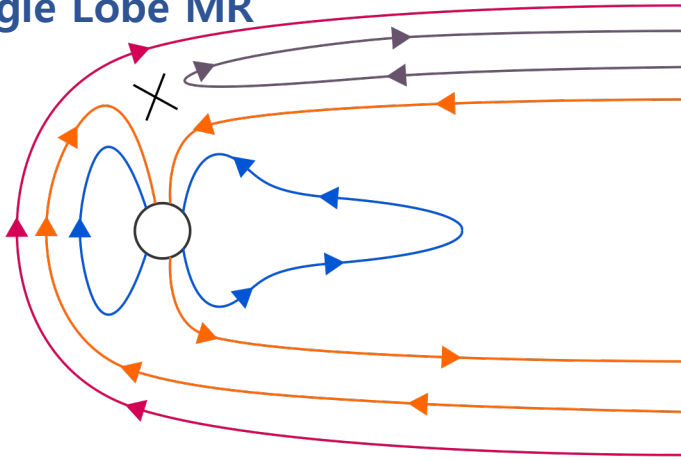


Open + Open $\rightarrow$ Closed + Disconnected
No. open field lines decreases

Source: Nawapat
Kaweeyanun

N-IMF: Partially Closed Cap

Single Lobe MR



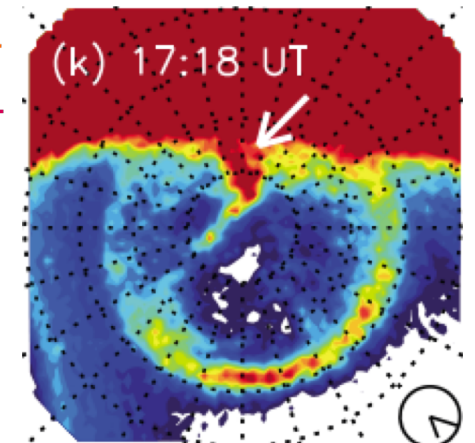
Single Lobe MR (partially
closed polar cap)

Source: Nawapat
Kaweeyanun

Open + Closed $\rightarrow$ Open + Open
No. open field lines increases

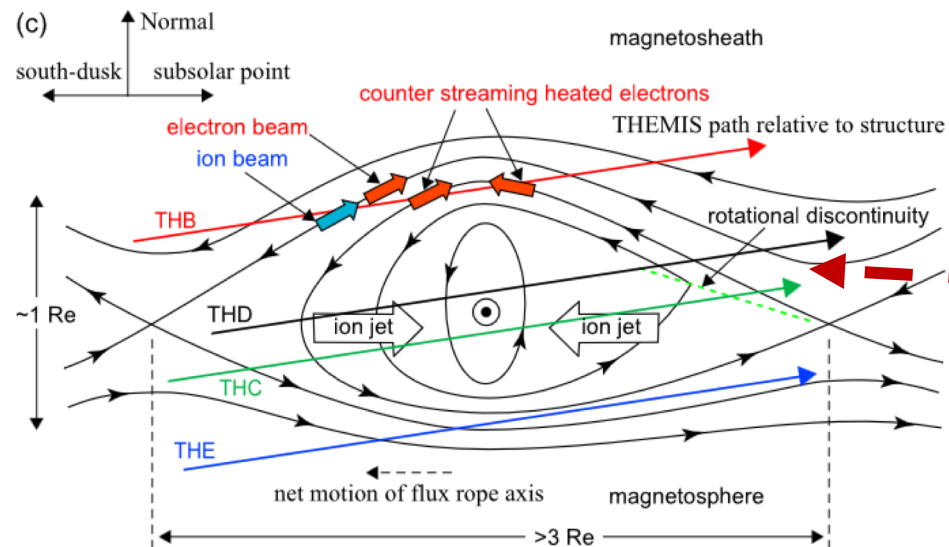
Often, this results in transpolar arc (TPA) signatures (Fear et al., 2015;
Kaweeyanun et al., 2025)

Source: Fear et al., 2015

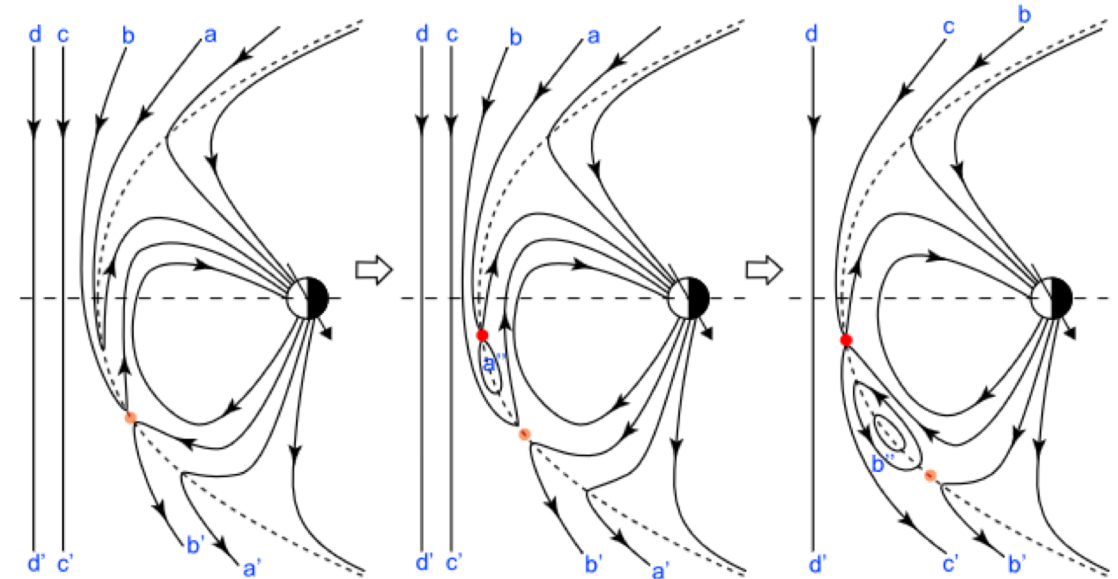


Flux Transfer Events

- Reconnection can also be transient – Flux Transfer Events (FTEs)
- Seconds lifetime yet can transfer significant magnetic flux.
 - ~1% of the Earth's total open flux?



Source: Hasegawa et al., 2010; Paschmann et al., 2013



Source: Paschmann et al., 2013

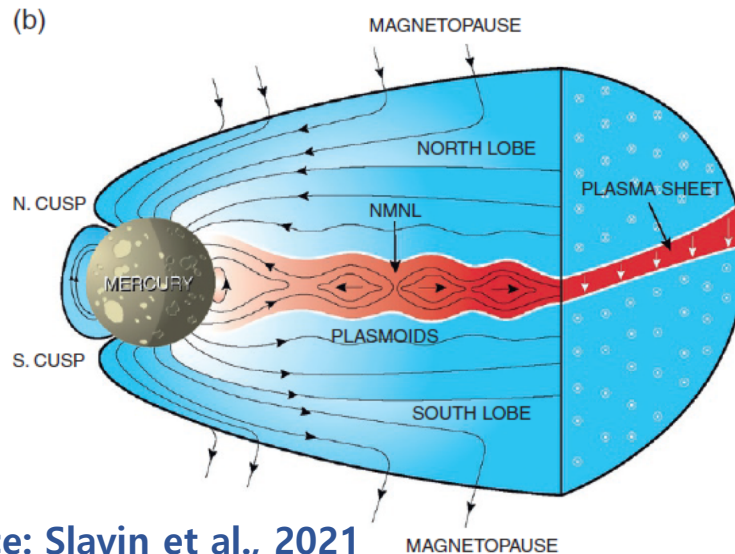
Spacecraft cutting across an FTE observes bipolar normal field component (B_N).

$$\Phi_{\text{FTE}} = B_N \times \text{radius} \times \text{length}$$

Earth-like Systems*

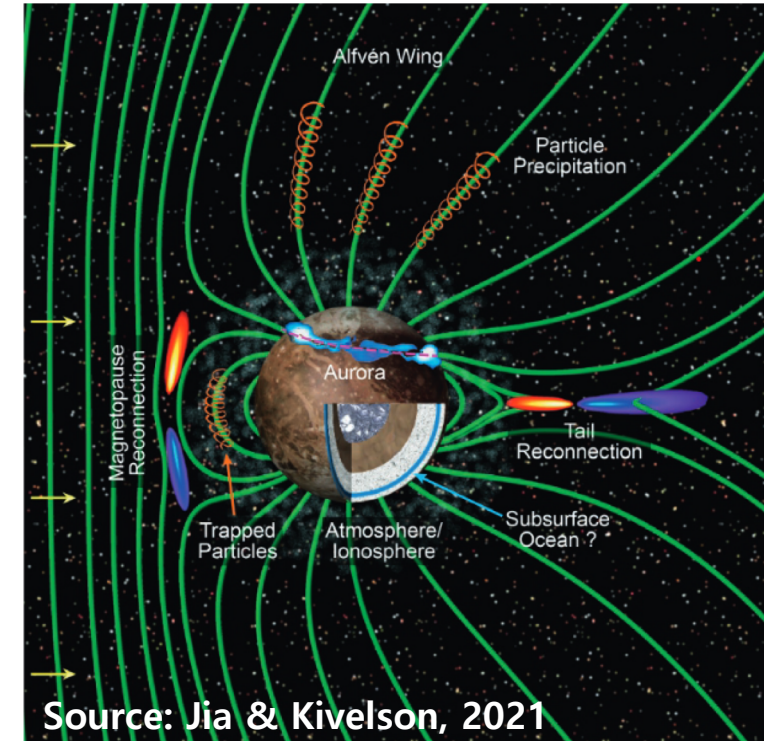
*To a degree

Reconnection are also present in other planets, sometimes with even greater impact.



At Mercury, FTEs can drive up to 5% of total system flux per event (Fear et al., 2019).

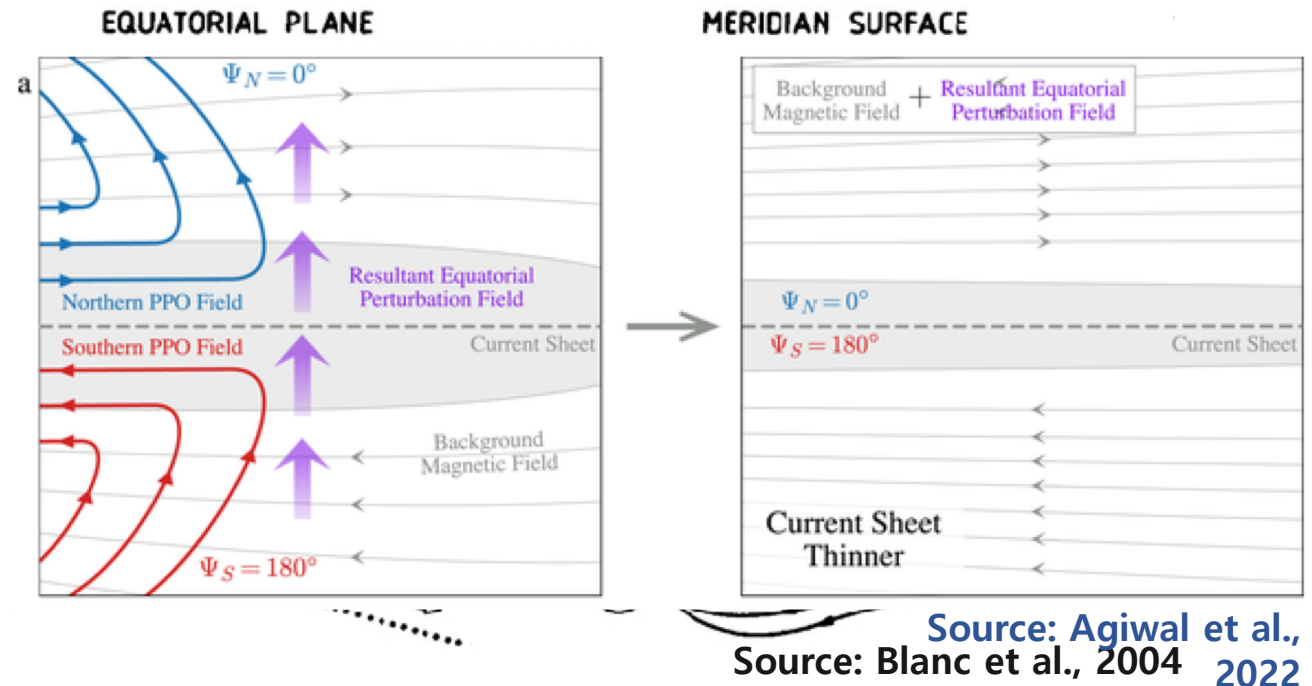
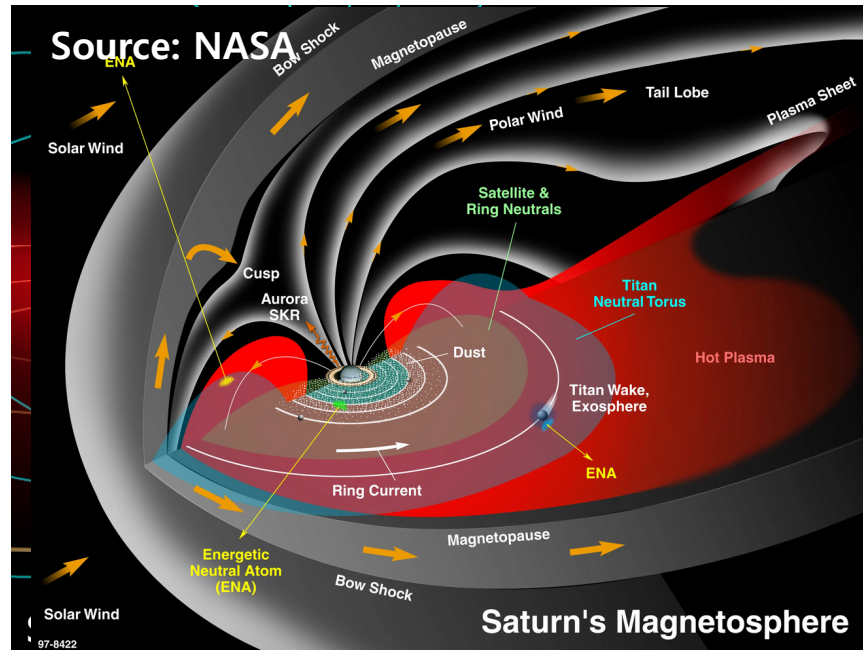
High FTE frequency result in "stressed" magnetosphere with multiple tail reconnection sites (Slavin et al., 2021).



Ganymede has ~10x reconnection rate as Mercury due to perpetual antiparallel Jupiter's field (Kaweeyanun et al., 2020, 2021)

FTEs also drive convection there (Jia et al., 2008).

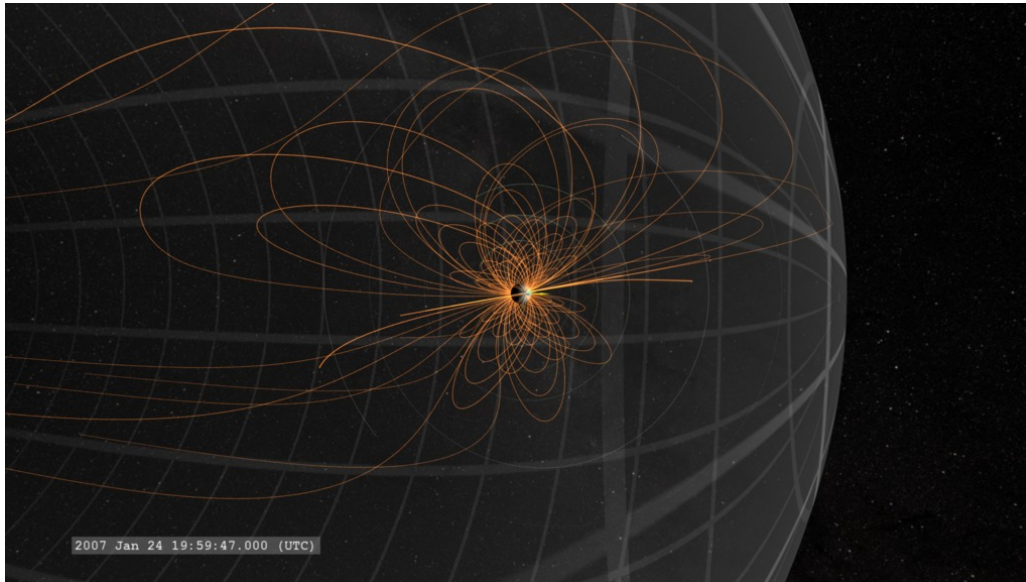
Jupiter and Saturn



Rapidly rotating systems (Jupiter/Saturn) have **Vasyliunas Cycles*** (1983) with some Dungey elements.

Plasma in corotation gradually move outward due to **interchange reconnection** in magnetotail (e.g., Bagenal & Delamere, 2011).

Saturn also has unique **planetary period oscillations** (PPOs) inducing extra reconnection in its current sheet (Agiwal et al., 2022).



Big dipole tilts at Uranus (58.6° , shown) and Neptune (47° , not shown)
(Source: NASA)

Uranus

- Complex reconnection structure (Masters, 2014).
- Highly variable reconnection rate (e.g., Zomerdijk-Russell et al., 2025)
- Not clear if Dungey or Vasyliunas (e.g., DiBraccio et al., 2019; Cao et al., 2026).

Neptune

- Complex reconnection structure (Masters, 2015)
- Not so dependent on IMF orientation? (Jasinski et al., 2022)
- Magnetotail reconnection expected (Selesnick, 1990).

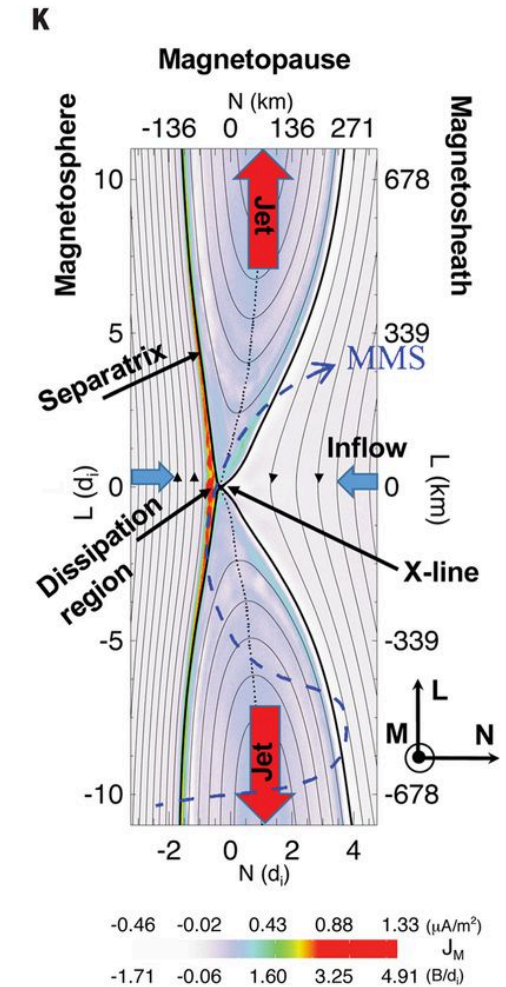
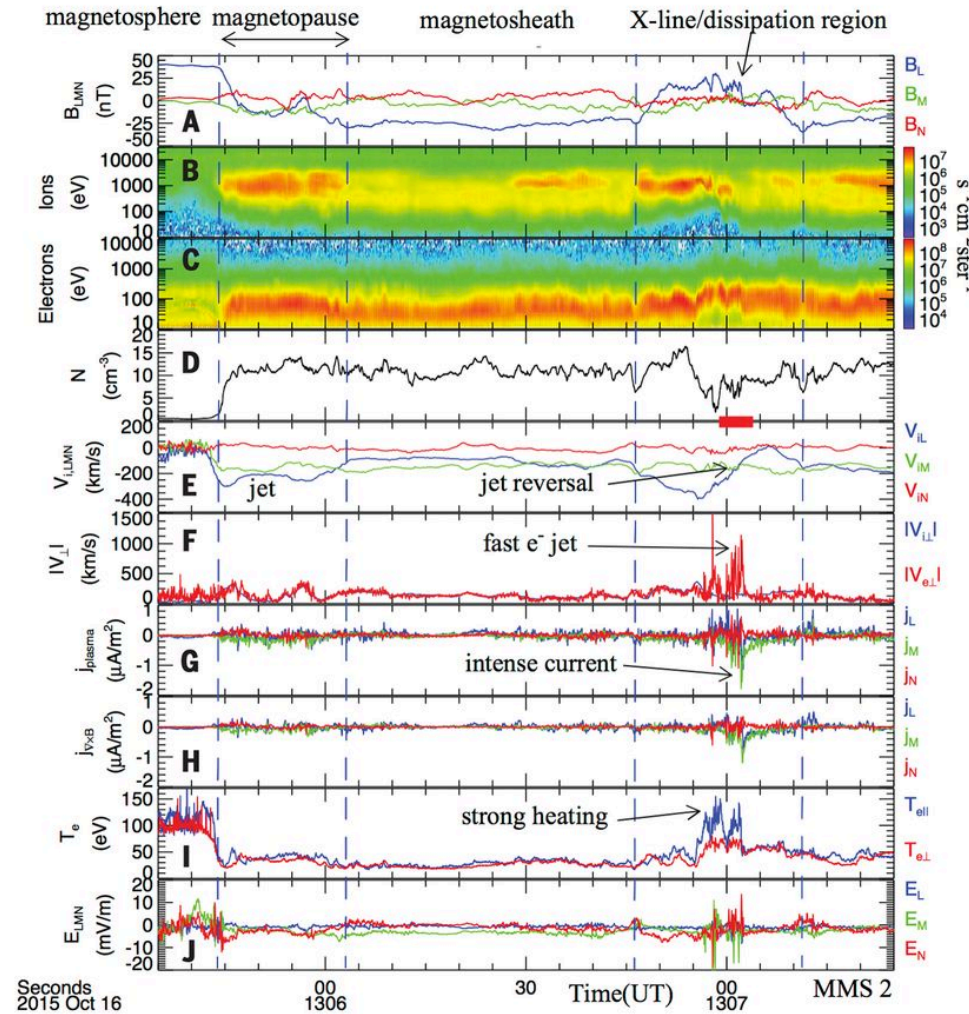
Part 4

Studying Reconnection in Space Physics

In Situ Satellites

- Parker
- MMS
- Cluster
- THEMIS
- BepiColombo (Mercury)
- Galileo (Jupiter)
- Cassini (Saturn)
- Voyager 2 (Uranus/Neptune)
- & many more!

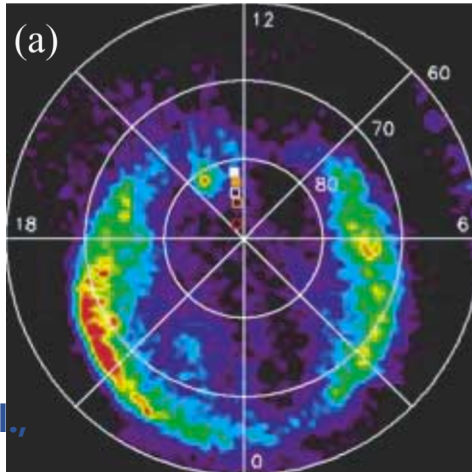
Look at plasma and magnetic field data together



Source: Burch et al., 2016

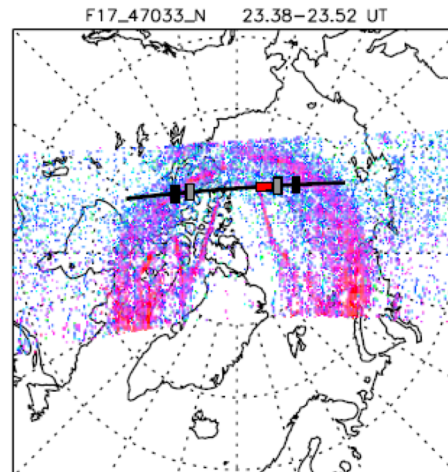
Remote Sensing

Source:
Phan et al.,
2003

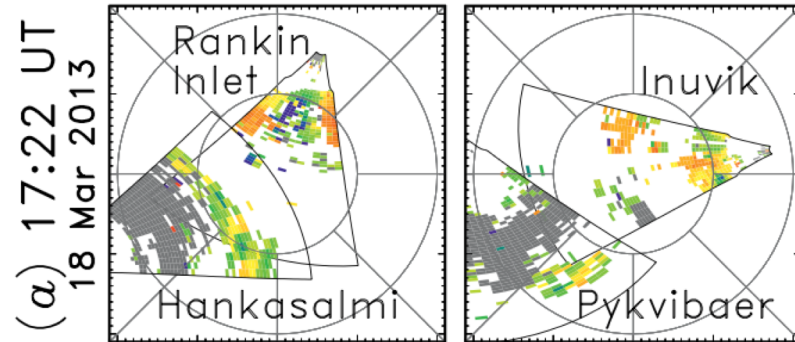


Cusp spot reconnection signature (e.g., Phan et al., 2003)

Source:
Reidy et al., 2018

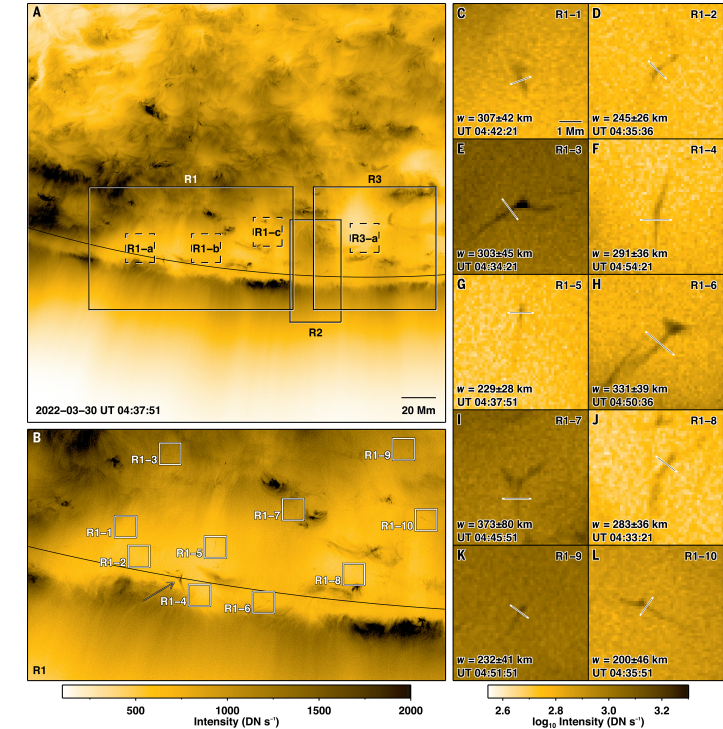


Horse-collar aurora from dual lobe reconnection (e.g., Milan et al., 2020b).



Ground-based radars like SuperDARN can help compute reconnection rate (e.g., Milan et al., 2022)

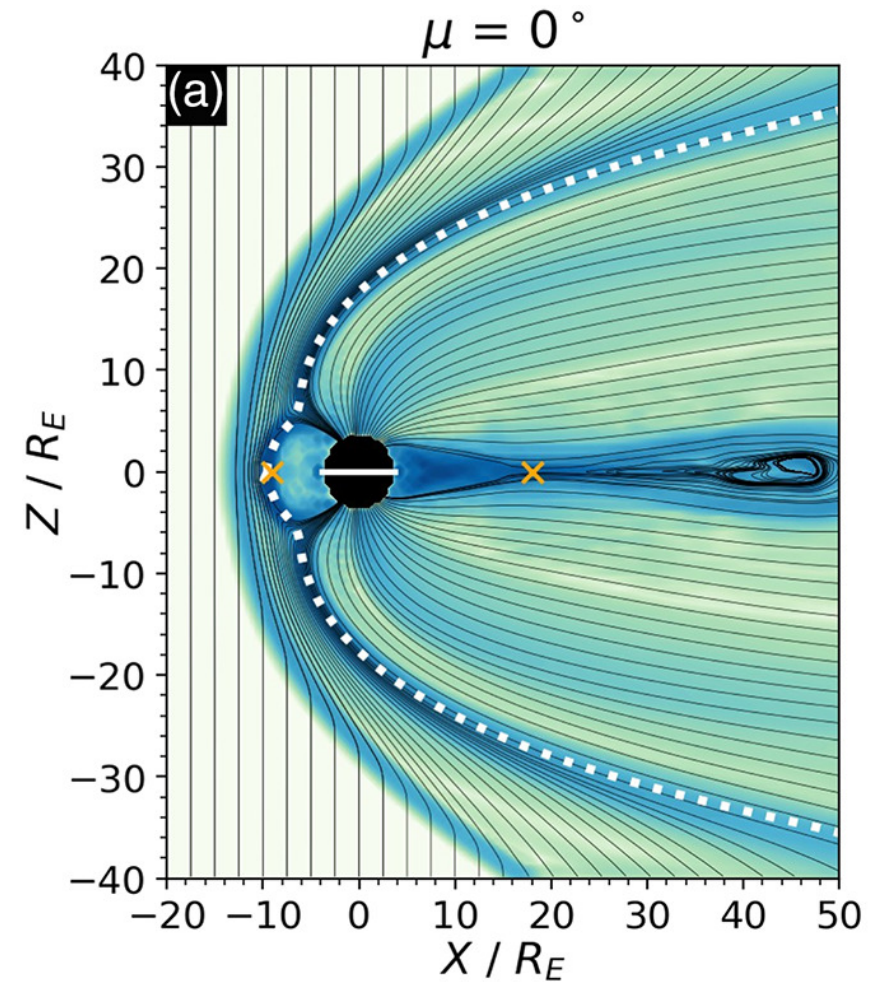
Source: Milan et al., 2022



Source: Chitta
et al. 2023

Picoflare jets from ~100km scale reconnection sites in the solar coronal holes. (from high-resolution EUV imager)

- MHD vs hybrid vs kinetic models
- 3D kinetic models too intensive for Earth but okay Mercury/Ganymede
 - Unless Vlasiator
- Global MHD models cannot capture diffusion region physics
- However, they can locate reconnection sites by “numerical resistivity”.
 - A numerical effect at magnetopause
 - Example: BATS-R-US, Gorgon, OpenGGCM

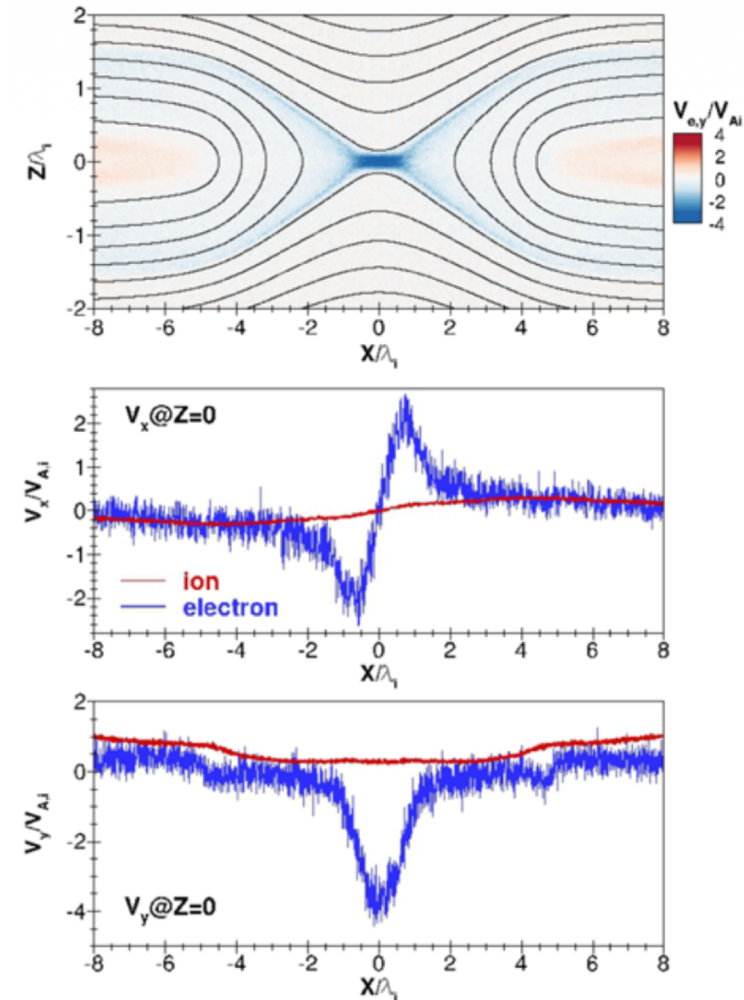


Source: Eggington et al., 2020

Local Simulations

- Useful for smaller-scale reconnections (turbulence, shocks)
- 2D limit can free up computation power
- Kinetic (particle-in-cell) models viable

Source: Zentaini et al., 2012;
Nagai et al., 2011



- Parametrise boundary with simple equations.
- Very efficient, but results only estimates.
- Can assess fundamental reconnection onset (e.g., Kaweeyanun et al., 2020)

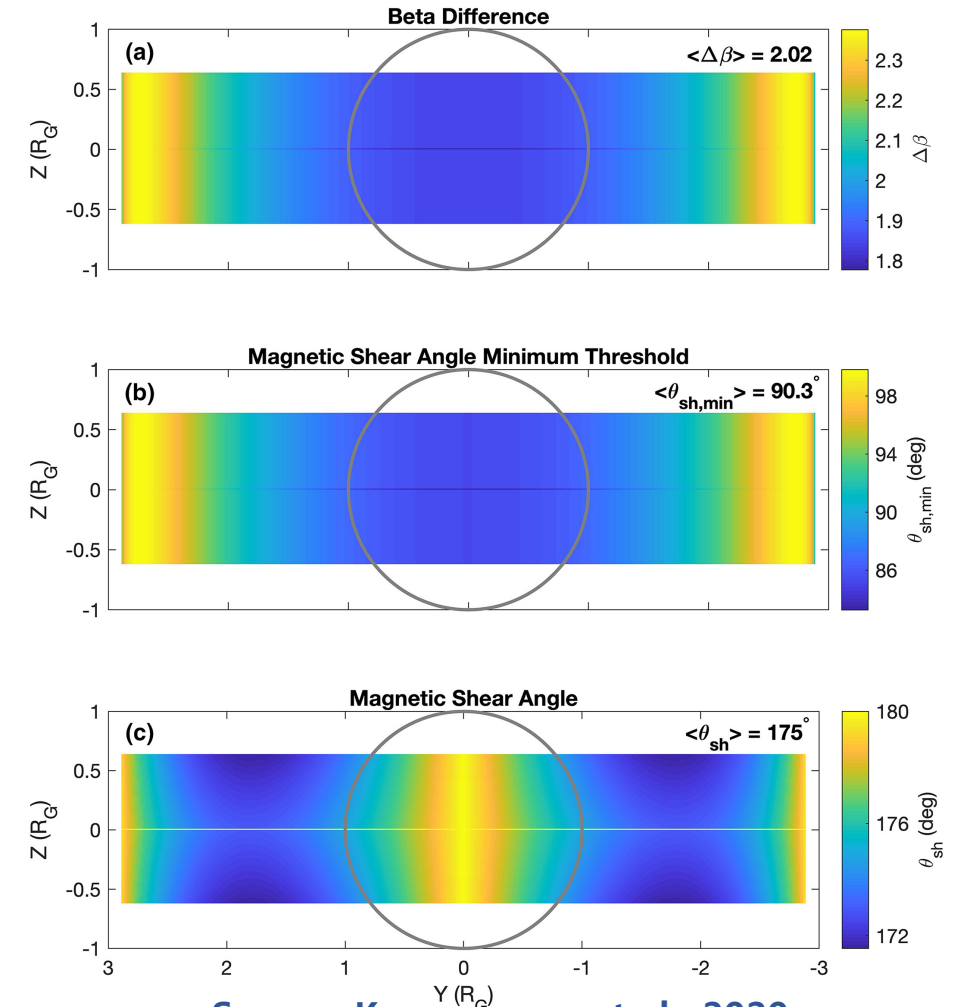
Beta-Shear Condition

$$\theta_{sh} > 2 \tan^{-1} \left(\frac{d_i \Delta \beta}{L} \right) = 2 \tan^{-1} (\Delta \beta)$$

Flow Shear Condition

$$v_{sh} = \frac{|v_1 - v_2|}{2} < v_{out} \left(\frac{\rho_1 B_2 + \rho_2 B_1}{2(\rho_1 B_2 \rho_2 B_1)^{1/2}} \right)$$

If either not satisfied, location too unstable for reconnection.

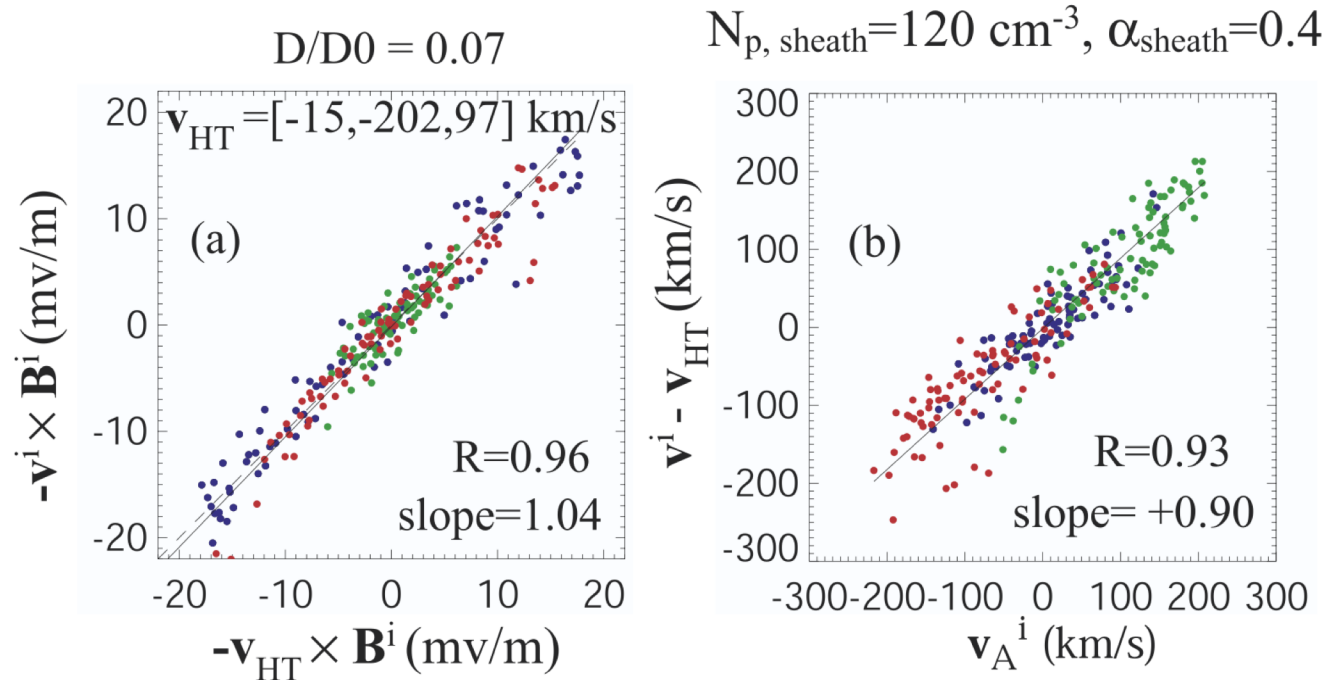


Source: Kaweeyanun et al., 2020

Walén Test

- Detect reconnection from plasma data.

Find the **Hoffmann-Teller (dHT) frame**, or rest frame of reconnection site.
 $\mathbf{E}' = \mathbf{E} + \mathbf{V}_{HT} \times \mathbf{B} = 0$



Magnetic reconnection if dHT frame plasma velocity $\propto$ Alfvén velocity.

Source: Phan
et al., 2003

Part 5

Open Questions

- **Cross-scale Coupling:** How do micro-scale/kinetic-scale physics in the diffusion region couple to the global evolution of the reconnecting system?
- **Onset:** What triggers the rapid onset of reconnection (and fast reconnection rates)? Especially important for solar atmospheric studies, e.g. flares & CMEs
- **Particle Acceleration & Energy Repartition:** What mechanisms acceleration particles in at reconnection sites? How is energy redistributed in the system? (How is the energy thermalized?)

- From the solar corona to Neptune, magnetic reconnection drive plasma interactions in the Solar System.

Solar Flares, Turbulence, Dungey Cycle, Magnetotail Current Sheet

- Reconnection occurs at magnetic boundaries, where magnetohydrodynamics break down.

Diffusion region, outflow acceleration, ion and electron distinction

- Reconnection has been studied for over 70 years and we are still learning, through observations and through models.

Sweet-Parker, Petschek, Hall. In-situ signatures, global/local/analytical simulations. Onset conditions and Walén test.