Reconnection Processes

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SHIELD Summer School
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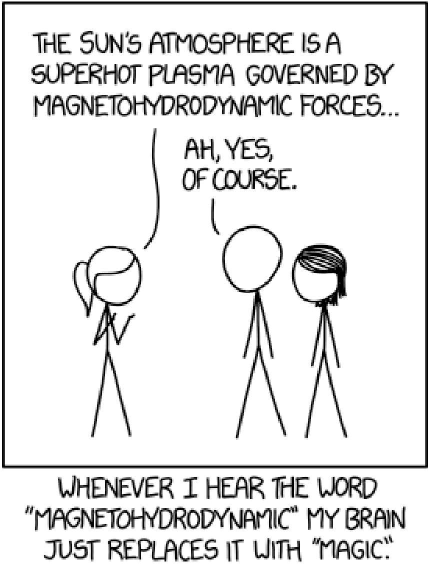
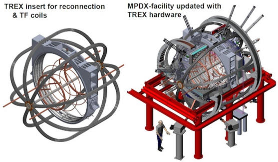
Examples

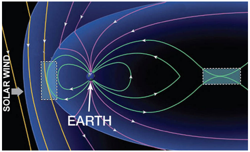


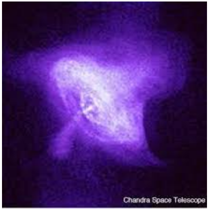
Observations from SDO at 131Å.

10 September 2017

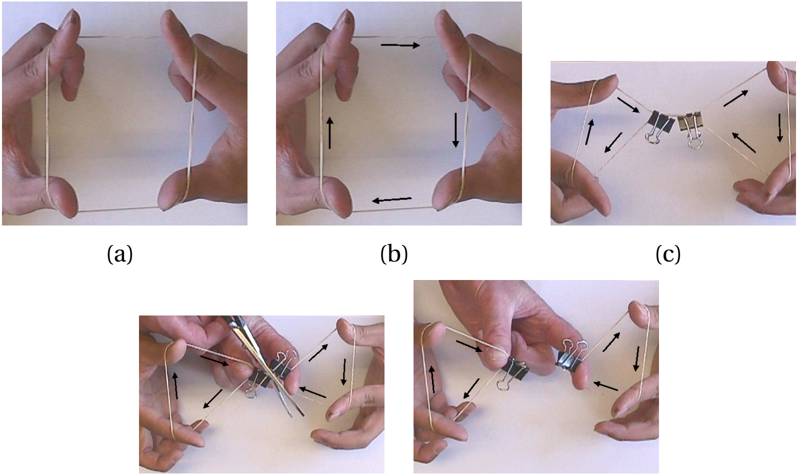
- Lab to the Crab







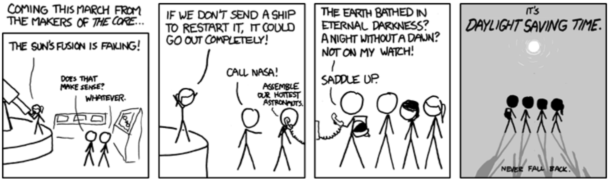
Toy Model



(a) (b) (c)

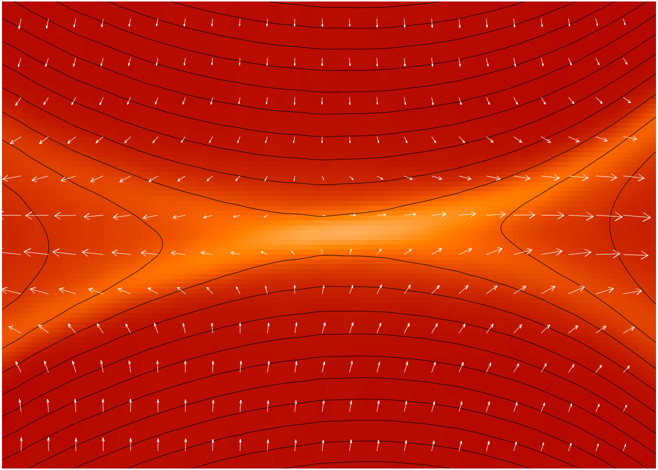
(d) (e)

The Cartoon Guide to Magnetic Reconnection



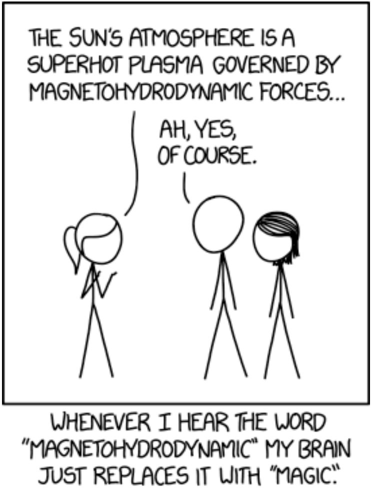
1. Inflow brings in magnetic flux
2. Field lines break & reconnect
3. Reconnected field lines slingshot outwards
4. Pressure drop maintains plasma inflow

A (Slightly) More Realistic Picture



- Backdrop: Out-of-plane current density, $\mathbf{J} = (c/4\pi)\boldsymbol{\nabla} \times \mathbf{B}$
- Bent magnetic field lines have tension: $\mathbf{F}_{\text{tens}} = (\mathbf{B} \cdot \boldsymbol{\nabla})\mathbf{B}/4\pi$
- Longest arrows are Alfvénic: $v_A = B/\sqrt{4\pi\rho}$

https://www.xkcd.com/1851/



Magnetohydrodynamics combines the intuitive nature of Maxwell's equations with the easy solvability of the Navier-Stokes equations. It's so straightforward physicists add "relativistic" or "quantum" just to keep it from getting boring.

Ideal MHD

Density ρ, velocity $\mathbf{v}$, magnetic field $\mathbf{B}$ and no dissipation (e.g., resistivity)

$$\frac{\partial \rho}{\partial t} + \boldsymbol{\nabla} \cdot \rho \mathbf{v} = 0 \qquad \boldsymbol{\nabla} \cdot \mathbf{B} = 0$$

$$\rho \left(\frac{\partial \mathbf{v}}{\partial t} + \mathbf{v} \cdot \boldsymbol{\nabla} \mathbf{v} \right) = -\boldsymbol{\nabla} p + \frac{\mathbf{J} \times \mathbf{B}}{c} \qquad \mathbf{J} = \frac{c}{4\pi} \boldsymbol{\nabla} \times \mathbf{B}$$

And

$$\mathbf{E} = -\frac{\mathbf{v} \times \mathbf{B}}{c} \quad \text{implies} \quad \frac{\partial \mathbf{B}}{\partial t} = \boldsymbol{\nabla} \times (\mathbf{v} \times \mathbf{B})$$

Reconnection CANNOT occur in ideal MHD.

Resistive MHD

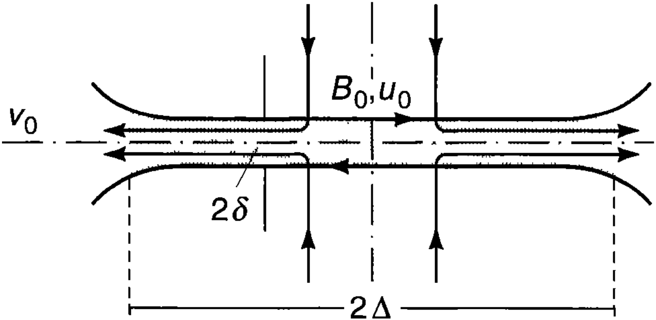
All of the above, but

$$\mathbf{E} = -\frac{\mathbf{v} \times \mathbf{B}}{c} + \eta \mathbf{J}$$

Reconnection in Resistive MHD

Sweet (1958), *Parker* (1957)

$\mathbf{E} \approx -\mathbf{v} \times \mathbf{B}/c$



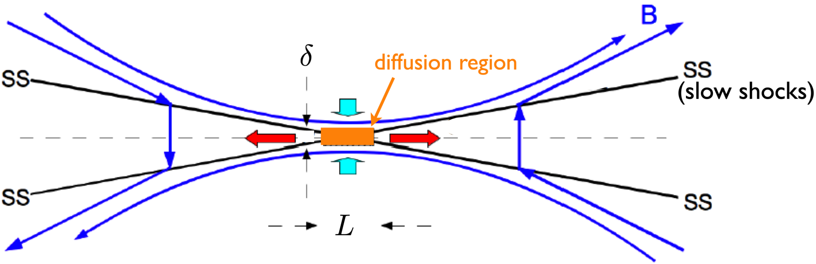
$\leftarrow \mathbf{E} \approx \eta \mathbf{J}$

Biskamp, *Magnetic Reconnection in Plasmas*

- Continuity: $(2\Delta)u_0 = (2\delta)v_0$
- Momentum: $v_0 = B_0/\sqrt{4\pi\rho} \equiv v_A$ (Alfvén speed)
- Reconnection rate: $R \sim (u_0/v_0) = (\delta/\Delta)$

(Petschek) Reconnection in Resistive MHD

Petschek (1964); *Sato & Hayashi* (1979); *Biskamp* (1986)



- Increase in $R \sim (\delta / L)$
- Not self-consistent

Generalized Ohm's Law

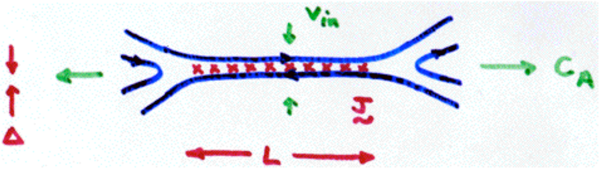
$$\mathbf{E} = -\frac{\mathbf{v}\times\mathbf{B}}{c} + \eta\mathbf{J} + \frac{\mathbf{J}\times\mathbf{B}}{nec} - \frac{\boldsymbol{\nabla}\cdot\mathsf{P}_e}{ne} + \frac{m_e}{ne^2}\left[\frac{\partial\mathbf{J}}{\partial t} + \boldsymbol{\nabla}\cdot\left(\mathbf{J}\mathbf{v} + \mathbf{v}\mathbf{J} - \frac{\mathbf{J}\mathbf{J}}{ne}\right)\right]$$

Each term associated with different length scale

- Resistive scale: $\eta c^2/4\pi c_A$
- Hall term: $d_i \equiv c/\omega_{pi}$
- Pressure gradient: $\sqrt{\beta_e}\, d_i$
- Electron terms: $d_e \equiv c/\omega_{pe}$

- $v_A^2 = B^2/4\pi\rho$
- $\omega_{pi}^2 = 4\pi ne^2/m_i$
- $\beta_e = nk_BT_e/(B^2/8\pi)$

Sweet-Parker (Resistive MHD) Reconnection



$$\frac{\partial \mathbf{B}}{\partial t} = -c\boldsymbol{\nabla} \times \left(\eta \mathbf{J} - \frac{\mathbf{v} \times \mathbf{B}}{c} \right)$$

Alfvén time: $\tau_A = L/c_A$ Resistive time: $\tau_R = \dfrac{4\pi L^2}{\eta c^2}$

Sweet-Parker time: $\tau_{SP} = \sqrt{\tau_R \, \tau_A}$

Generalized Ohm's Law

$$\mathbf{E} = -\frac{\mathbf{v}\times\mathbf{B}}{c} + \eta\mathbf{J} + \frac{\mathbf{J}\times\mathbf{B}}{nec} - \frac{\nabla\cdot\mathsf{P}_e}{ne} + \frac{m_e}{ne^2}\left[\frac{\partial\mathbf{J}}{\partial t} + \nabla\cdot\left(\mathbf{Jv} + \mathbf{vJ} - \frac{\mathbf{JJ}}{ne}\right)\right]$$

Each term associated with different length scale

- Resistive scale: $\eta c^2/4\pi c_A$
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- Electron terms: $d_e \equiv c/\omega_{pe}$

- $v_A^2 = B^2/4\pi\rho$
- $\omega_{pi}^2 = 4\pi ne^2/m_i$
- $\beta_e = nk_B T_e/(B^2/8\pi)$

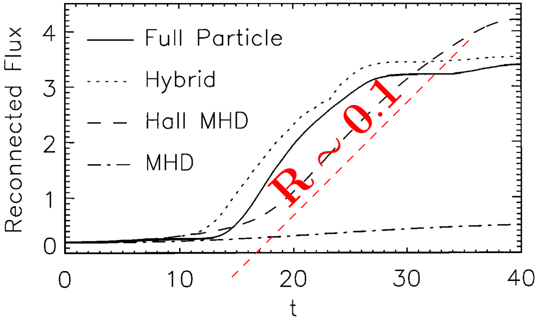
One more term in Ohm's law

$$\frac{\partial \mathbf{B}}{\partial t} = -c\boldsymbol{\nabla} \times \left(\eta \mathbf{J} - \frac{\mathbf{v} \times \mathbf{B}}{c} + \frac{\mathbf{J} \times \mathbf{B}}{nec} \right)$$

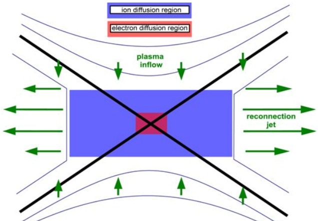
Hall time: $\tau_H \approx 0.1\tau_A$

GEM Challenge

Birn et al. (2001)



- Ion diffusion region: $\approx d_i = c/\omega_{pi} = v_A/\omega_{ci}$ away from the X-line.
- Electron frozen-in condition broken at $\approx d_e$.
- No macroscopic nozzle



Why Doing Plasma Physics via Computer Simulations Using Particles Makes Good Physical Sense

Inspired by Birdsall & Langdon, *Plasma Physics via Computer Simulation*

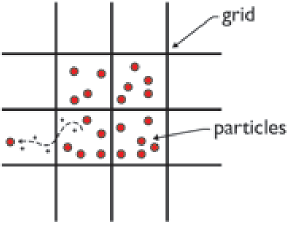
- Debye length $\lambda_D = v_{th}/\omega_{pe} \ll L$; we care about $\lambda \gtrsim \lambda_D$.
- For a meaningful plasma $N_D = n\lambda_D^3 \ggg 1$
- But that means

$$\frac{\text{KE (thermal kinetic energy)}}{\text{PE (electrostatic potential energy)}} = N_D^{2/3} \gg 1$$

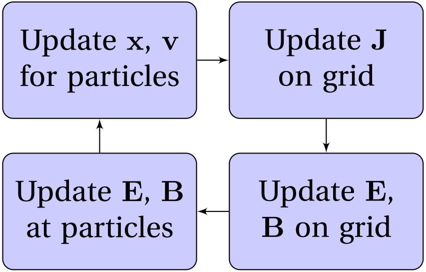
(KE $\sim T$, PE $\sim e^2/r \sim e^2 n^{1/3}$)

Particles interact collectively, not discretely.

PIC Simulations



Spatial Domain



- **Field advancement**:

$$\frac{\partial \mathbf{B}}{\partial t} = -c\boldsymbol{\nabla}\times\mathbf{E} \qquad \frac{\partial \mathbf{E}}{\partial t} = c\boldsymbol{\nabla}\times\mathbf{B}-4\pi\mathbf{J}$$

- **Particle advancement**:

$$\frac{d\mathbf{x}}{dt} = \mathbf{v} \qquad \frac{d(\gamma\mathbf{v})}{dt} = \frac{q}{m}\left(\mathbf{E}+\frac{\mathbf{v}}{c}\times\mathbf{B}\right)$$

GEM Challenge in PIC

Plotted: Out-of-plane current density

GEM Challenge in PIC

Plotted: Out-of-plane magnetic field

A Larger Particle-in-Cell (PIC) Simulation

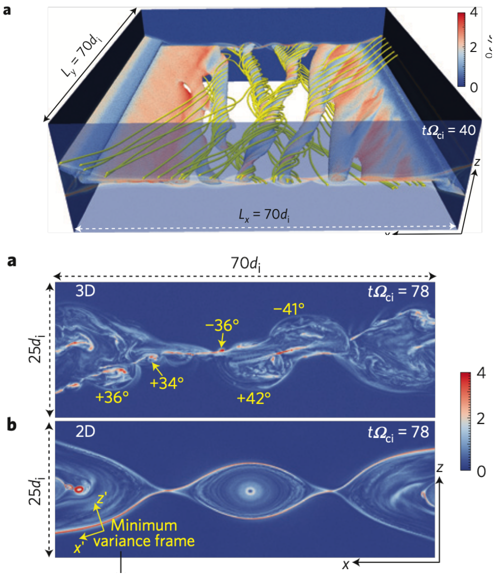
Plotted: $|\mathbf{B}|$

PIC simulation

- Small islands triggered by tearing grow and merge.

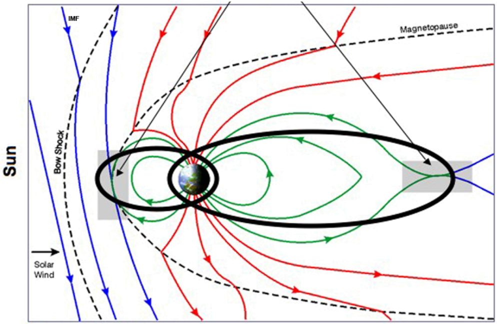
2D vs. 3D PIC

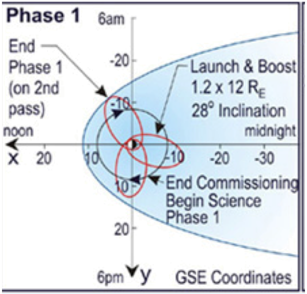
Daughton et al., 2011

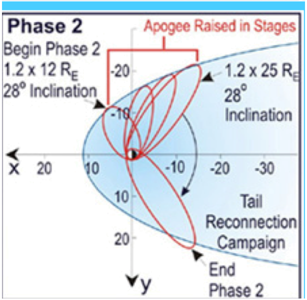


Interplay of Simulations and Observations

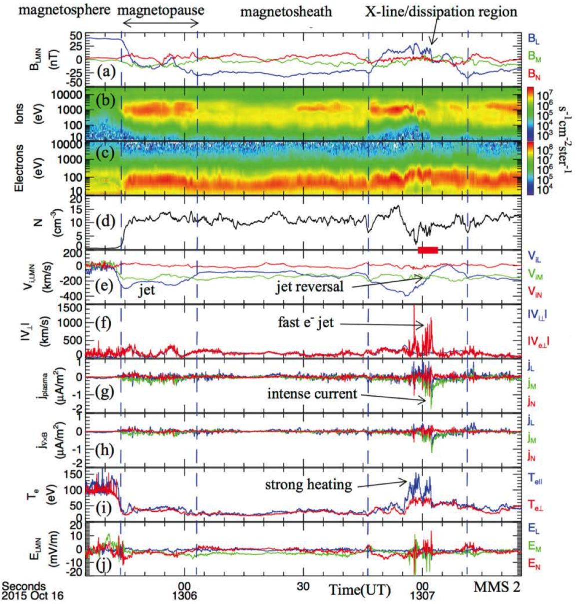
Magnetospheric Multiscale (MMS) Mission

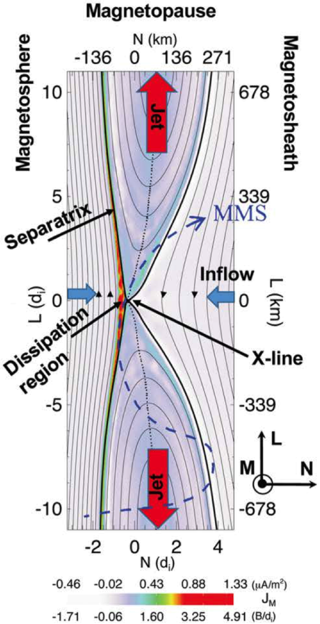






Diffusion Region Crossing: 2 minutes





Summary

- What Is It?
  - Reconnection is the rearrangment of magnetic topology.
- What Does It Do?
  - Triggers large-scale energy exchanges such as auroras, solar flares, astrophysical jets.
- Why Should You Care?
  - Reconnection is the primary sink of magnetic energy in much of the universe.

Extra Slides

Massively Parallel Computing

National Energy Research Scientific Computing Center

- $\approx$ 4K nodes and $\approx$ 900K cores
- #14 on the current Top500 list

Kinetic Scales

How painful?

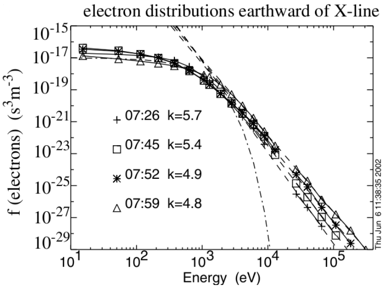
- Solar corona: $B = 50$ G, $n = 10^9$ cm^{-3}, $L \approx 10^9$ m, $\tau \approx 10^3$ s
  - $d_p \approx 10$ m
  - $\Omega_{pc}^{-1} \approx 2 \times 10^{-6}$ s
  - $\omega_{pi}^{-1} \approx 2 \times 10^{-8}$ s
- Magnetosphere: $B = 2 \times 10^{-4}$ G, $n = 20$ cm^{-3}, $L \approx 10^4$ km, $\tau \approx 10^3$ s
  - $d_p \approx 50$ km
  - $\Omega_{pc}^{-1} \approx 0.5$ s
  - $\omega_{pi}^{-1} \approx 2 \times 10^{-4}$ s
- Tokamak: $B = 3 \times 10^4$ G, $n = 2 \times 10^{13}$ cm^{-3}, $L \approx 10^2$ cm, $\tau \approx 10^{-2}$ s
  - $d_p \approx 5$ cm
  - $\Omega_{pc}^{-1} \approx 3 \times 10^{-9}$ s
  - $\omega_{pi}^{-1} \approx 2 \times 10^{-10}$ s

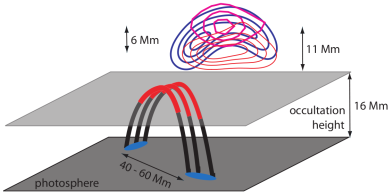
Back

One Use for Simulations: Non-Thermal Electrons

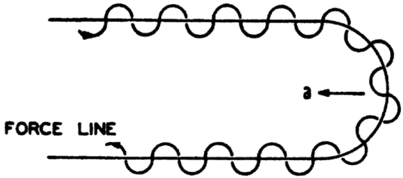
- Reconnection energizes electrons
  - Solar flares
  - Magnetospheres
  - Pulsar flares, ...

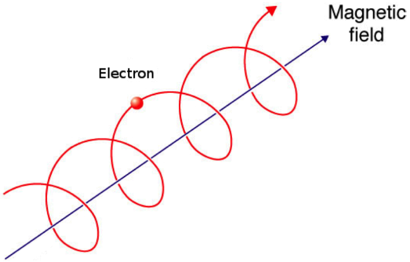
- **What processes drive electron energization?**
- **How efficient are these processes?**





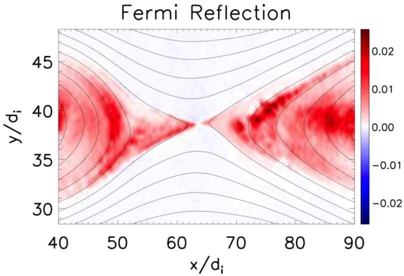
Energization Mechanisms: Fermi, $E_\parallel$, Betatron

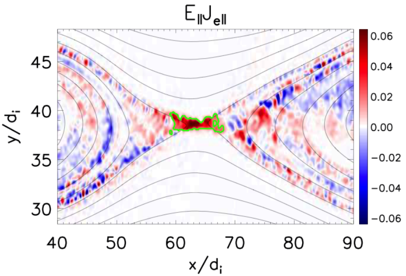




- Fermi: Reflection from field line moving at v_A gains energy, $v_\parallel \to v_\parallel + 2v_A$
- $E_\parallel$: Changes $v_\parallel$. Difficult to sustain over long distances.
- Betatron (conservation of $\mu \propto v_\perp^2/B$): Changes $v_\perp$. Tends to lower $v_\perp$ during reconnection.

Isolate Mechanisms in Simulations





- **Fermi acceleration**
- Reflection from reconnection outflows: volume-filling acceleration
- Strong energy scaling: $d\epsilon/dt \propto \epsilon$

- **Parallel electric fields**
- Primarily ’linear accelerator’ at X-line localized to diffusion region ($>$ 50% of $E_{\parallel}$ energy conversion).
- Weak energy scaling: $d\epsilon/dt \propto \epsilon^{1/2}$

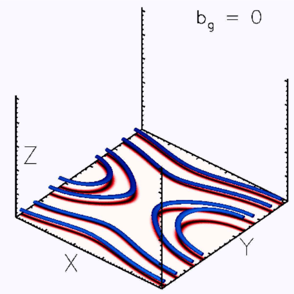
Fermi acceleration during reconnection

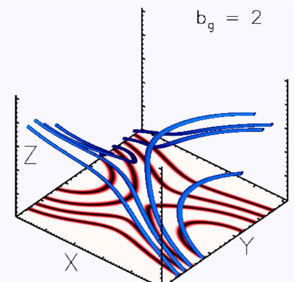
PIC simulation

- Red: heating; blue: cooling
- Island mergers trigger rounds of energization

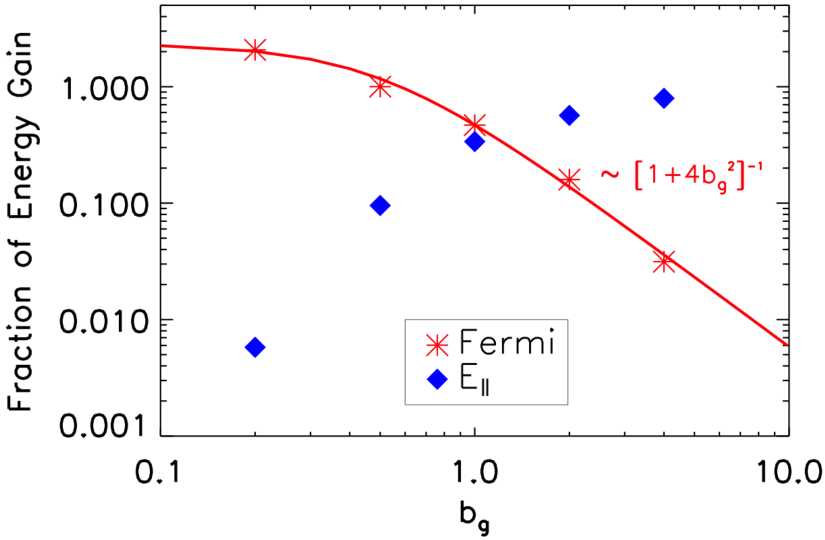
The guide field determines the dominant mechanism

- **A strong guide field throttles Fermi acceleration**
  - $b_g \sim 0$: head-on reflection (strong kick)
  - $b_g \gg 1$: glancing reflection (weak kick)
- $E_{\|}$: Guide field directs particles along reconnection E_z (only in diffusion region).



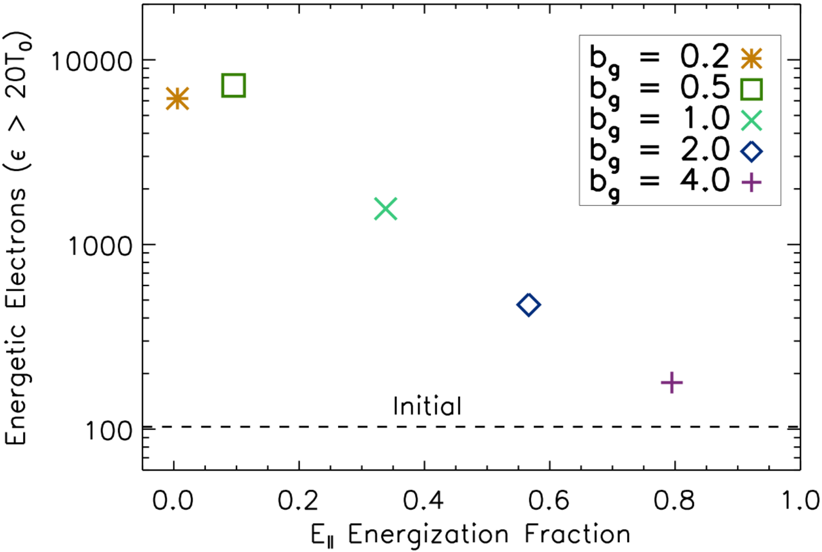


The guide field controls the dominant mechanism



- $b_g \ll 1$: Fermi reflection dominates.
- $b_g \gg 1$: $E_\parallel$ dominates.

BUT: $E_\parallel$ is an inefficient electron accelerator



- $b_g \gg 1$: $E_\parallel$ dominates
- Generates few energetic electrons

BUT

- PIC simulations do not (easily) produce power laws*
- *However, energization is primarily Fermi and does not care about kinetic scales.*

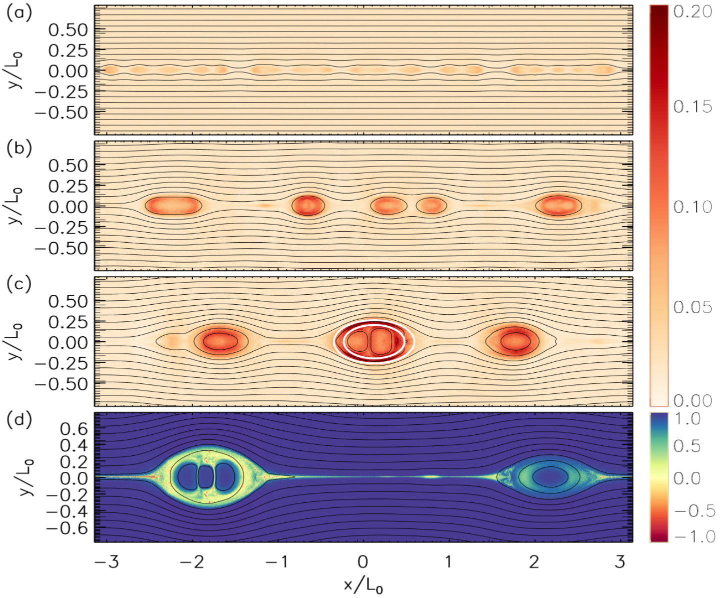
New model: *kglobal*

- MHD backbone with guiding center electrons
- Three species: ion fluid, electron macro-particles, electron fluid (for charge neutrailty)
- Conserves total energy. Passed multiple tests: Alfvén waves, firehose instability, Landau damping.

***kglobal* produces power laws extending over nearly three decades of energy**

kglobal Results

Particle electron T; Firehose parameter



kglobal Equations (Sorry!)

Drake et al. (2019), Arnold et al. (2019)

MHD Backbone

$$\frac{\partial n_i}{\partial t} = -\boldsymbol{\nabla}\cdot n_i \boldsymbol{v_i}$$

Particle Feedback

$$\rho_i \frac{d\boldsymbol{v_i}}{dt} = \frac{1}{c}\boldsymbol{J}\times\boldsymbol{B} - \boldsymbol{\nabla}(P_i + \boxed{P_{ef}) - \boldsymbol{\nabla}\cdot\boldsymbol{P_{ep}} - m_e n_{ef} v_{||ef}^2 \boldsymbol{\kappa}}$$

$$\frac{d}{dt}\left(\frac{P_i}{n_i^\gamma}\right) = 0$$

$$\boldsymbol{E}_\perp = -\frac{1}{c}\boldsymbol{v_i}\times\boldsymbol{B}$$

$$\frac{\partial \boldsymbol{B}}{\partial t} = -c\boldsymbol{\nabla}\times\boldsymbol{E}_\perp$$

Conservation of Magnetic Moment

$$\boxed{\mu_{ep} = \frac{p_{ep\perp}^2}{2B} = const.}$$

Fermi reflection | Betatron | Large Scale $E_{||}$

$$\frac{d}{dt}p_{e||} = \boxed{p_{e||}\boldsymbol{v_E}\cdot\boldsymbol{\kappa}} - \boxed{\frac{\mu_e}{\gamma_e}\boldsymbol{b}\cdot\boldsymbol{\nabla}B} - \boxed{eE_{||}}$$

Charge Neutrality

$$\boxed{n_{ef} = n_i - n_{ep}}$$

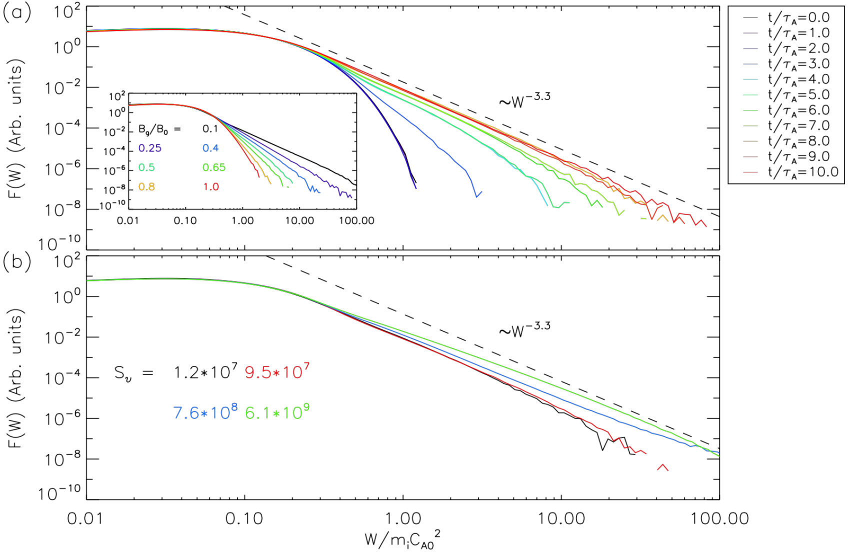
$$\boxed{n_{ef}v_{||ef} = n_i v_{||i} - n_{ep}v_{||ep}}$$

No 0th Order Parallel Flow Current

$$\frac{\partial}{\partial t}\left(\frac{P_{ef}}{n_{ef}^\gamma}\right) = 0$$

$$E_{||} = \frac{-1}{n_i e}\left(\boldsymbol{B}\cdot\boldsymbol{\nabla}\left(\frac{m_e n_c v_{||c}^2}{B}\right) + \boldsymbol{b}\cdot\boldsymbol{\nabla}P_c + \boldsymbol{b}\cdot\boldsymbol{\nabla}\cdot\boldsymbol{T}_h\right)$$

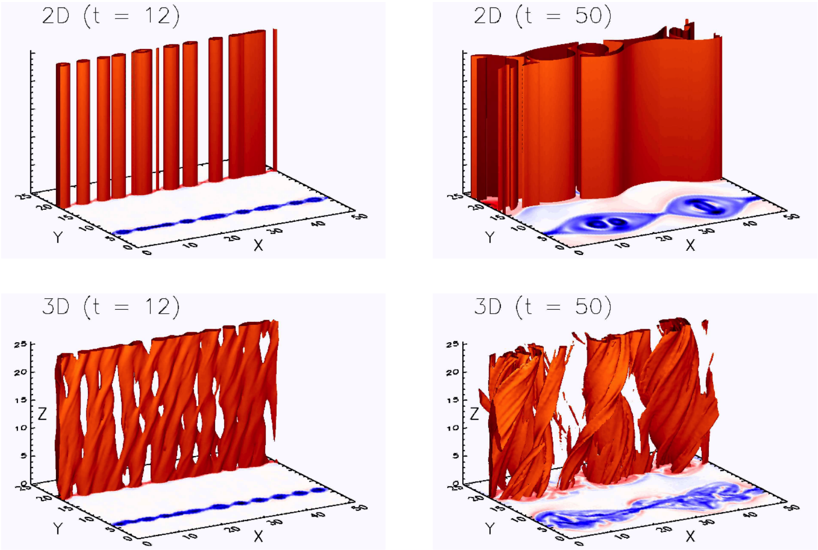
Electron Power Laws



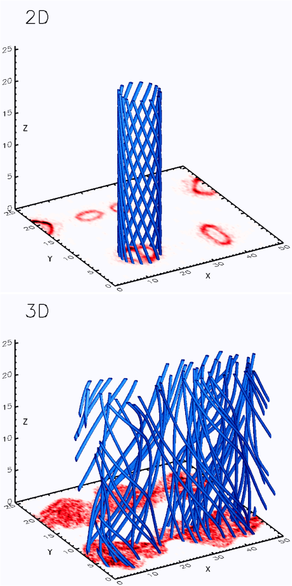
Conclusions

- Reconnection produces non-thermal power laws
- Non-thermal particles from reconnection requires Fermi acceleration
  - Dahlin et al., *Phys. Plasmas*, (2014, 2015, 2016, 2017)
  - Li et al., *Astrophys. J.* (2015, 2018, 2019)
- *kglobal*: **First self-consistent simulations of non-thermal electron energization during reconnection in a macroscale system**
  - Drake et al., *Phys. Plasmas* (2019)
  - Arnold et al., *Phys. Plasmas* (2019)
- More coming soon
  - Imminent posting of paper to arXiv
  - Harry Arnold talk at DPP: 11 November, Abstract PM10.00003, 2:55-3:20
  - Harry Arnold talk at AGU: 15 December, SH045-06, 12:12-12:16

Reconnection Produces Flux Ropes

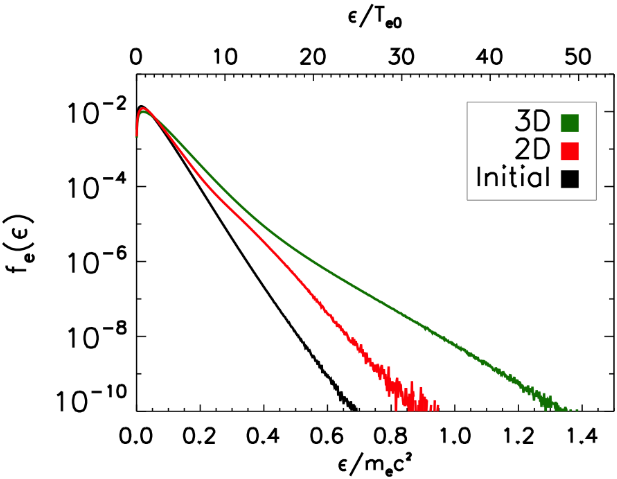


3D transport (chaotic field lines) is key



- Particles follow field lines
- 2D: Single acceleration period then ejection into closed island. Limited energy gain.
- 3D: Stochastic fields allows particles to escape islands and continuously accelerate.

Acceleration is enhanced in 3D systems



- Comparable magnetic energy release in 2D, 3D
- Factor of ≈ 10 increase in high-energy electrons in 3D.
- **Why does a larger energy fraction go into energetic electrons in 3D?**

The Annoyances of Reality

And How to Get Around Them

Explicit PIC must resolve kinetic scales: λ_D, d_e, ρ_e

Real systems $\gg$ kinetic scales. Unfortunately, Nature insists on making the situation worse.

- $m_p/m_e \approx 1836$
- $c/v_A \gg 1$ (v_A is the Alfvén speed)

This produces computational challenges. Artificial values help.

- $m_p/m_e = 400,\ 100,\ 25$
- $c/v_A = 20 - 50$

Unfortunately $\cdots$

Continuity is not, in general, satisfied

Corrections fall into two broad categories

- "Fix" $\mathbf{E}$
- "Fix" $\mathbf{J}$

An approach of the first type: Suppose a Φ exists such that

$$\mathbf{E}' = \mathbf{E} - \boldsymbol{\nabla}\Phi \qquad \text{where} \qquad \boldsymbol{\nabla} \cdot \mathbf{E}' = 4\pi\rho$$

Find Φ by solving

$$\nabla^2\Phi = \boldsymbol{\nabla} \cdot \mathbf{E} - 4\pi\rho \equiv b$$

This ($\nabla^2\Phi = b$) is Poisson's equation and can be solved many different ways: FFTs, matrix methods, multigrid methods, $\cdots$

Back

Does PIC Satisfy $\boldsymbol{\nabla} \cdot \mathbf{B} = 0$ and $\boldsymbol{\nabla} \cdot \mathbf{E} = 4\pi\rho$?

Numerically, $\boldsymbol{\nabla} \cdot (\boldsymbol{\nabla} \times) = 0$

$$\frac{\partial}{\partial t}(\boldsymbol{\nabla} \cdot \mathbf{B}) = -c\,\boldsymbol{\nabla} \cdot \boldsymbol{\nabla} \times \mathbf{E} = 0$$

If $\boldsymbol{\nabla} \cdot \mathbf{B} = 0$ at $t = 0$, it remains so (ignoring round-off)

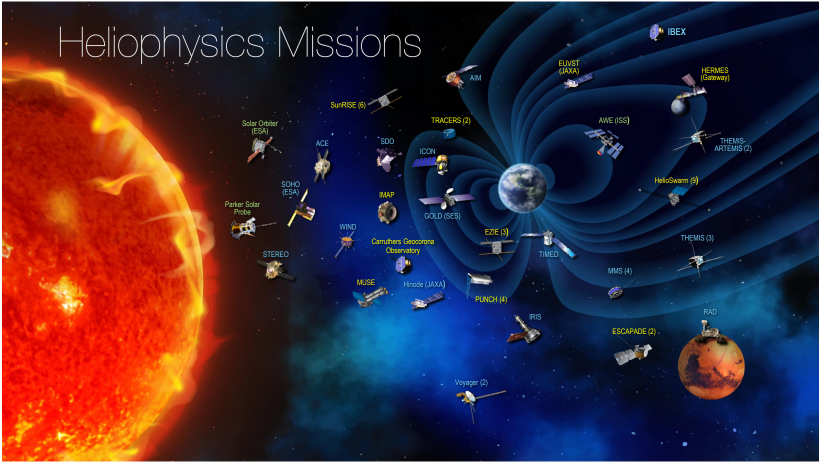
In contrast,

$$\frac{\partial}{\partial t}(\boldsymbol{\nabla} \cdot \mathbf{E}) = c\,\boldsymbol{\nabla} \cdot \boldsymbol{\nabla} \times \mathbf{B} - 4\pi \boldsymbol{\nabla} \cdot \mathbf{J} = -4\pi \boldsymbol{\nabla} \cdot \mathbf{J}$$

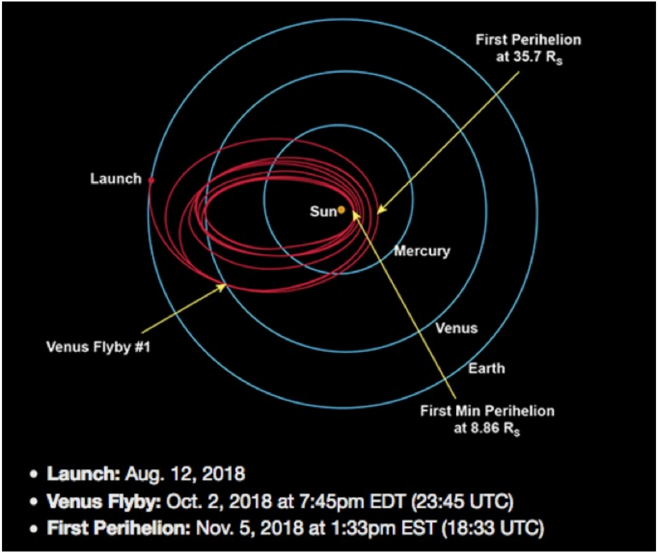
To satisfy Gauss's Law requires

$$\frac{\partial \rho}{\partial t} + \boldsymbol{\nabla} \cdot \mathbf{J} = 0$$

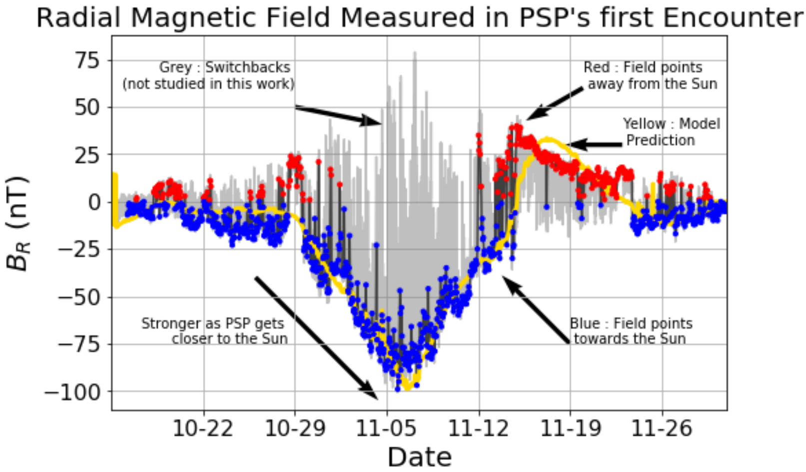
NASA Heliospheric Fleet



Parker Solar Probe: Orbits



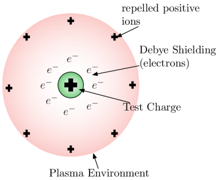
Parker Solar Probe: Switchbacks



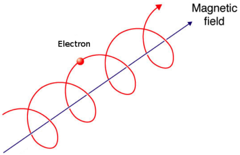
Key Plasma Concepts

Plasmas: ionized gas exhibiting collective behavior

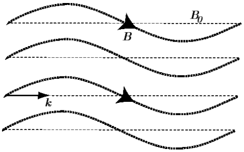
- Debye shielding



- Larmor orbit



- Alfvén speed



Magnetic Reconnection in the Heliosphere