Magnetic Reconnection: explosions in space and astrophysical plasma

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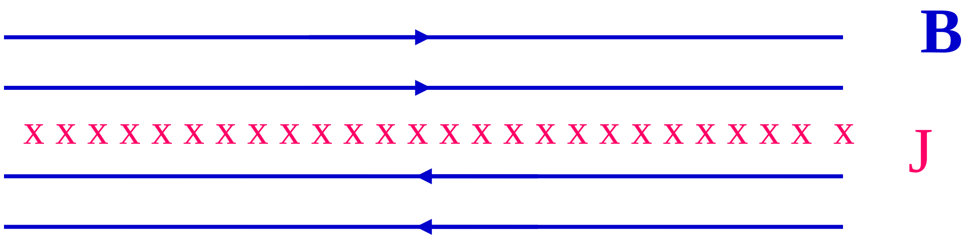
Magnetic Energy Dissipation in the Universe

- The conversion of magnetic energy to heat and high speed flows underlies many important phenomena in nature
    - solar and stellar flares
    - Neutron star “quakes”
    - magnetospheric substorms
    - disruptions in laboratory fusion experiments
- More generally understanding how magnetic energy is dissipated is essential to model the generation and dissipation of magnetic field energy in astrophysical systems
    - accretion disks
    - stellar dynamos
    - supernova shocks
- Known systems are characterized by a slow buildup of magnetic energy and fast release $\Rightarrow$ magnetic explosion
    - mechanism for fast release?
    - Why does the energy release occur as an explosion?

Magnetic Free Energy

- A reversed magnetic field is a source of free energy



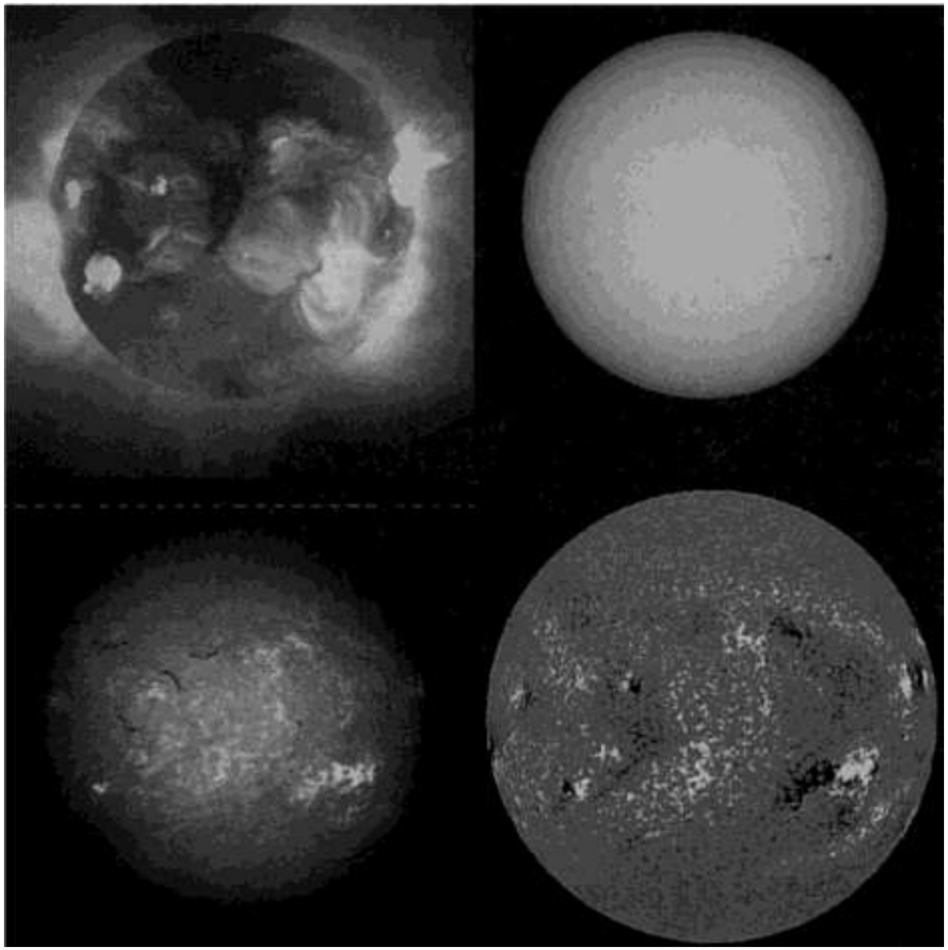
•Can imagine **B** simply self-annihilating
•What happens in a plasma?

Images of the Sun

- Tsuneda ‘96
- Yohkoh

Soft x-rays

TRACE



Normal B at photosphere

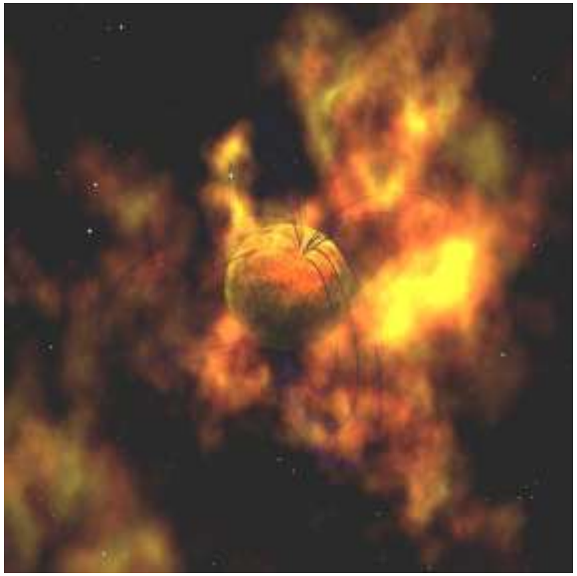
•Soft X-ray emission peaks in solar active regions which are where B is large

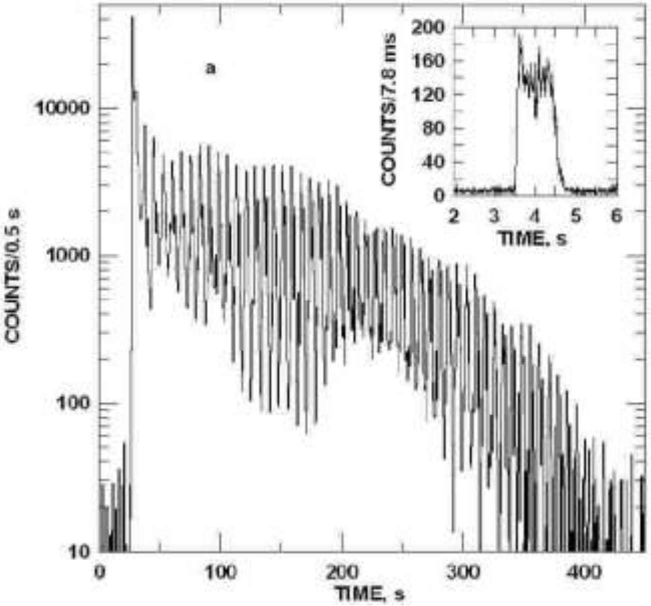
Magnetar flares

- 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: 4×10^{43} ergs/sec.

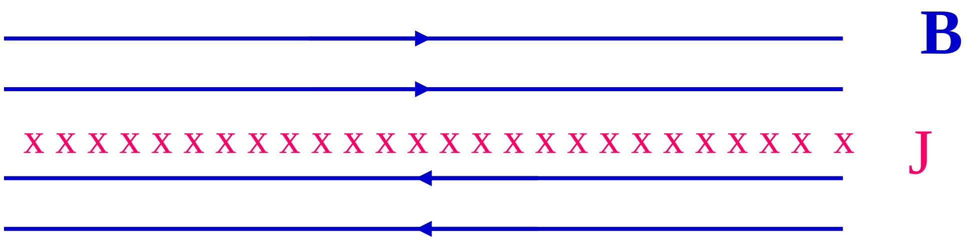
    - Cause: Global crust failure and magnetic reconnection.
    - Could be a source of short duration gamma ray bursts.

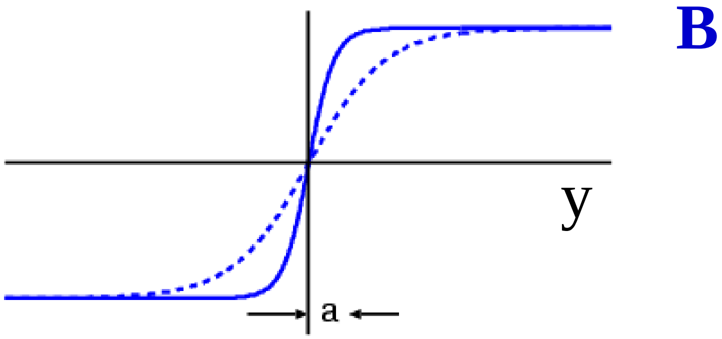




Rhessi data: Hurley et al., 2005

Resistive Diffusion





- Diffusion of magnetic flux

$$\frac{\partial B}{\partial t} = \frac{\eta c^2}{4\pi}\frac{\partial^2 B}{\partial y^2}$$

$\tau_r = 4\pi a^2 / \eta c^2 =$ resistive time

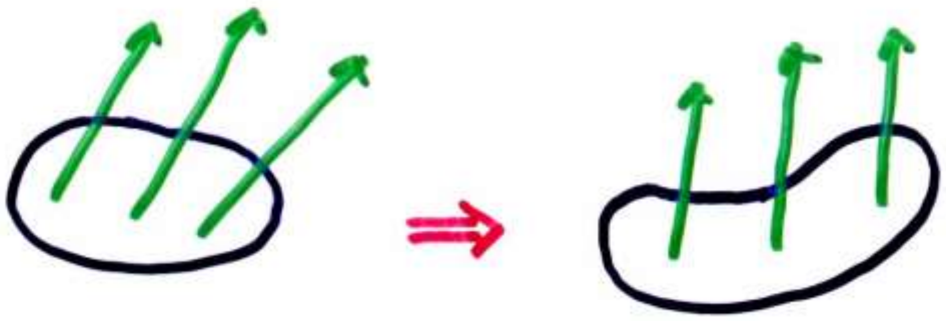
Characteristic Diffusion Times

	Resistive Time	Observed Energy Release Time
Laboratory Tokamaks	1 - 10 sec	50 μsec
Solar Flares	~ 10^4 years	~ 20 min
Magnetospheric Substorms	~ ¥	30 min

Resistive dissipation does not explain the observations

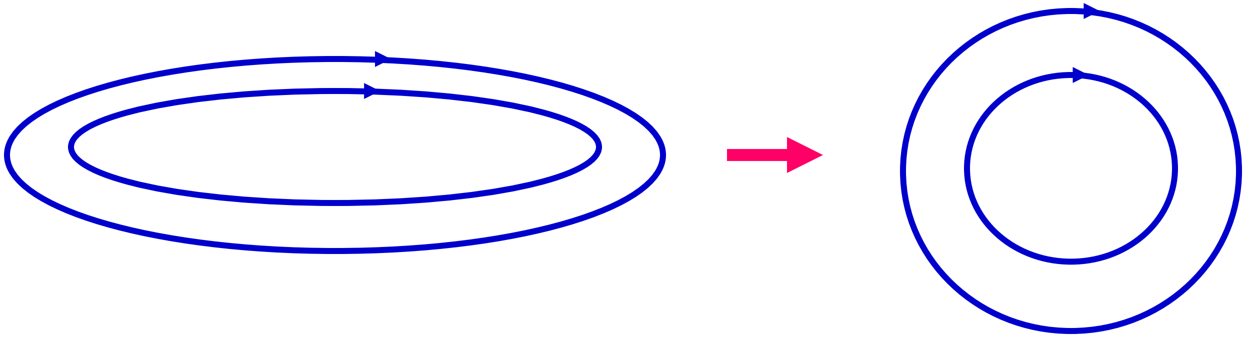
Frozen-in Condition

- In an ideal plasma (η=0), the fluid moves so that the magnetic flux through any fluid element is preserved.



Therefore in the absence of dissipation the plasma and magnetic field move together

Energy Release from Squashed Bubble

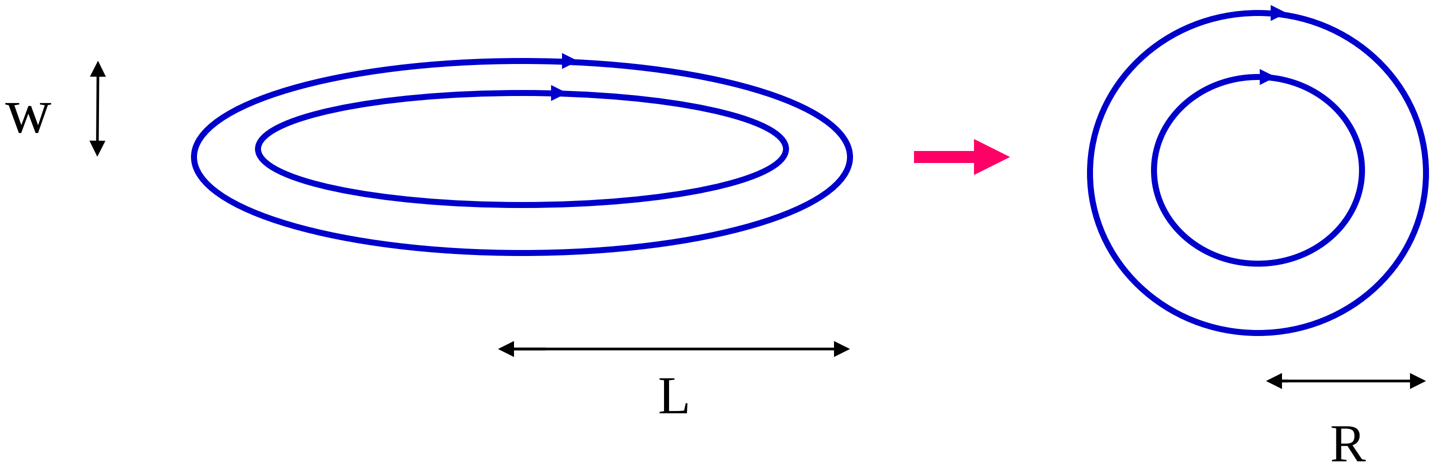


$$\vec{F} = -\vec{\nabla}\left(p + \frac{B^2}{8\pi}\right) + \frac{1}{4\pi}\vec{B} \bullet \vec{\nabla}\vec{B}$$

magnetic tension

- Magnetic field lines want to become round

Energy Release (cont.)



- Evaluate initial and final magnetic energies
  - use conservation law for ideal motion
    - magnetic flux conserved
    - area for nearly incompressible motion

$$W_f \sim (w/L)\, W_i \ll W_i$$

•Most of the magnetic energy is released

Flow Generation

- Released magnetic energy is converted into plasma flow

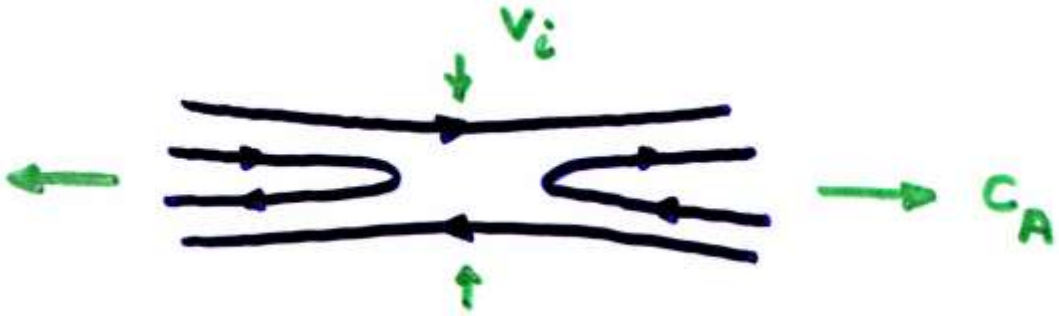
$$\frac{1}{2}\rho v^2 = \frac{B^2}{8\pi}$$

$$v \approx v_A \equiv \left(\frac{B^2}{4\pi\rho}\right)^{1/2} \qquad \tau_A = L / v_A$$

•Alfven time τ_A is much shorter than observed energy release time

•The energy release time is bracketed by τ_A and τ_R .

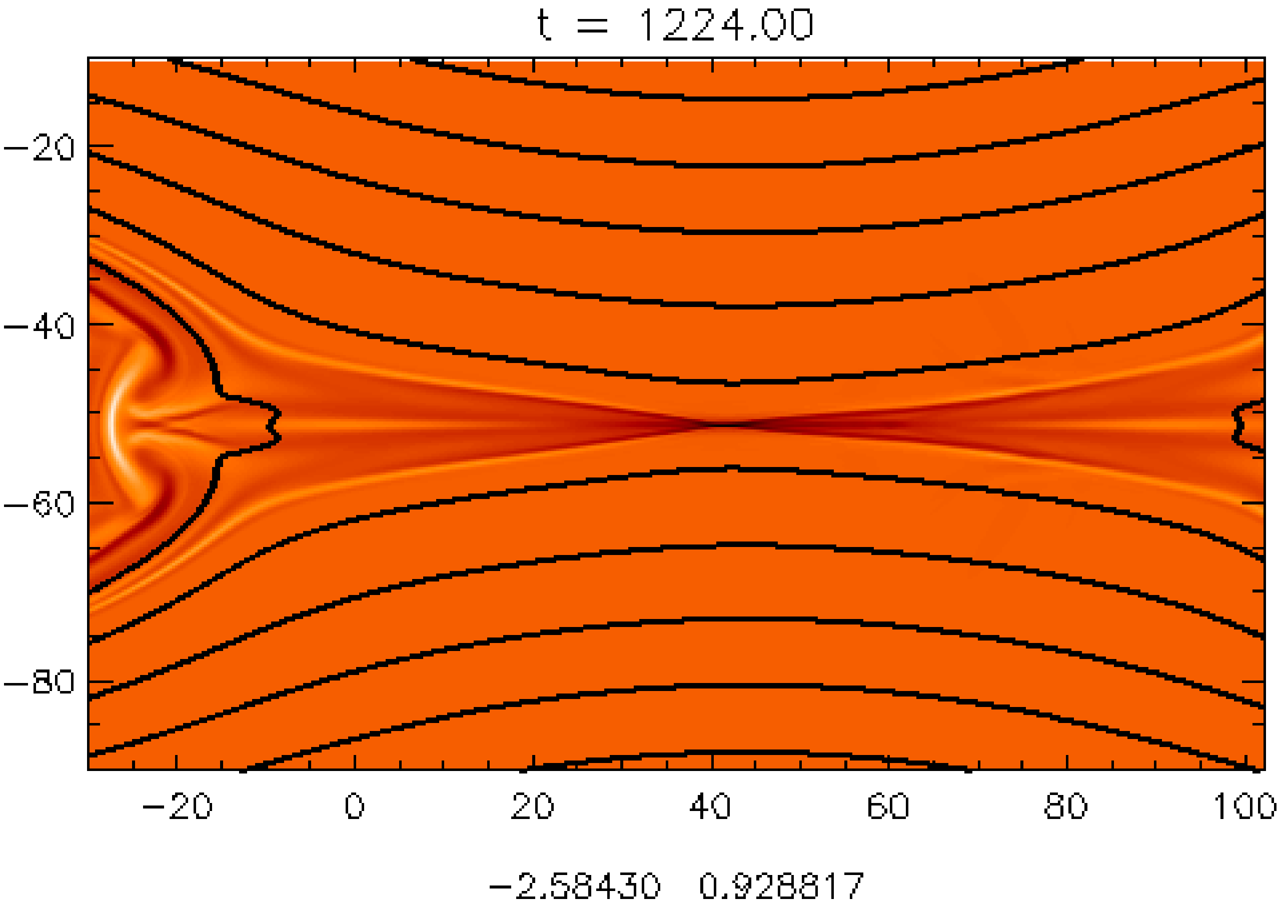
Magnetic Reconnection

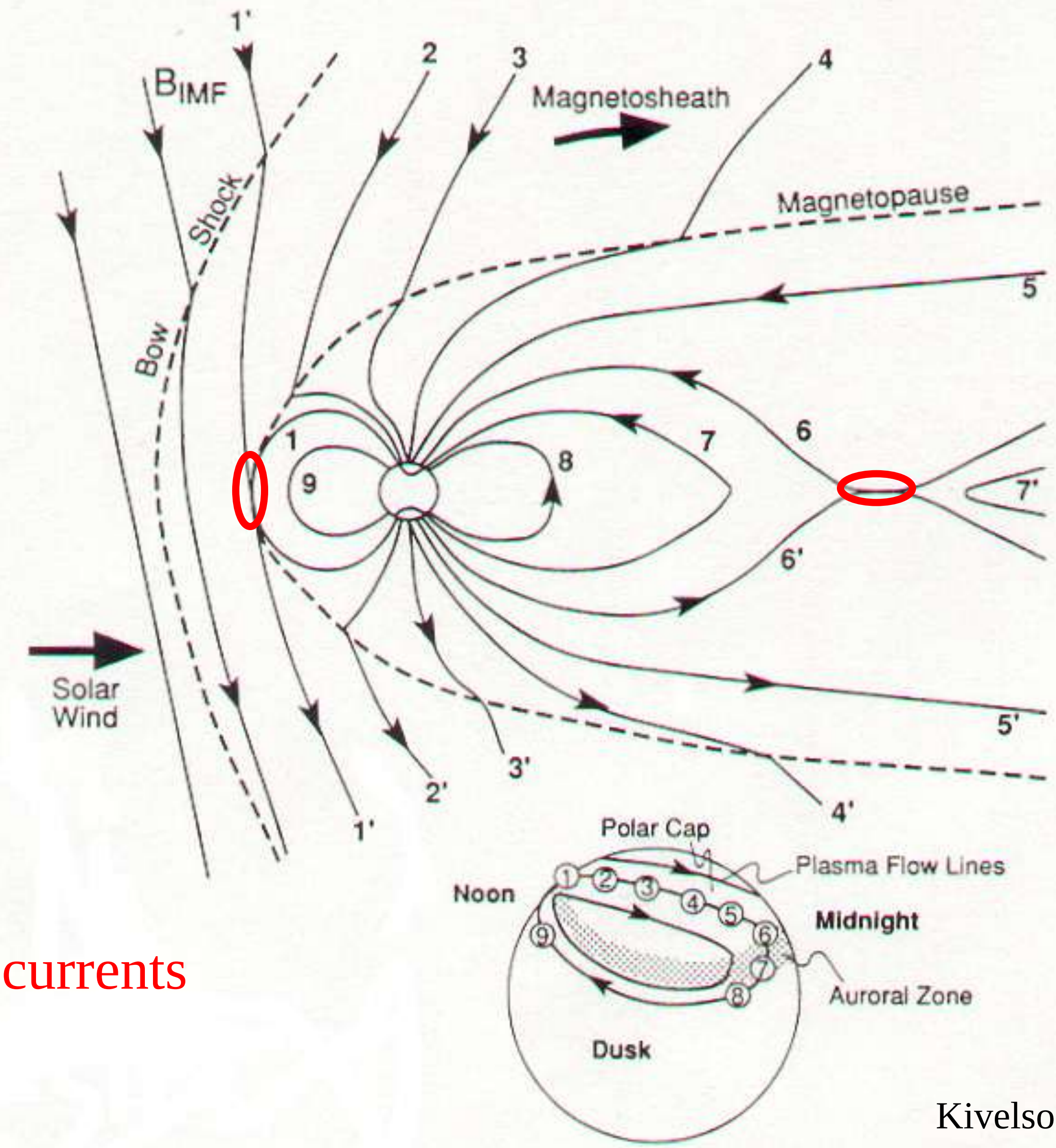


- Strong observational support for this general picture
- Reconnection is driven by the release of magnetic tension of newly reconnected magnetic field lines

Magnetic Reconnection Simulation

- Hall MHD simulation



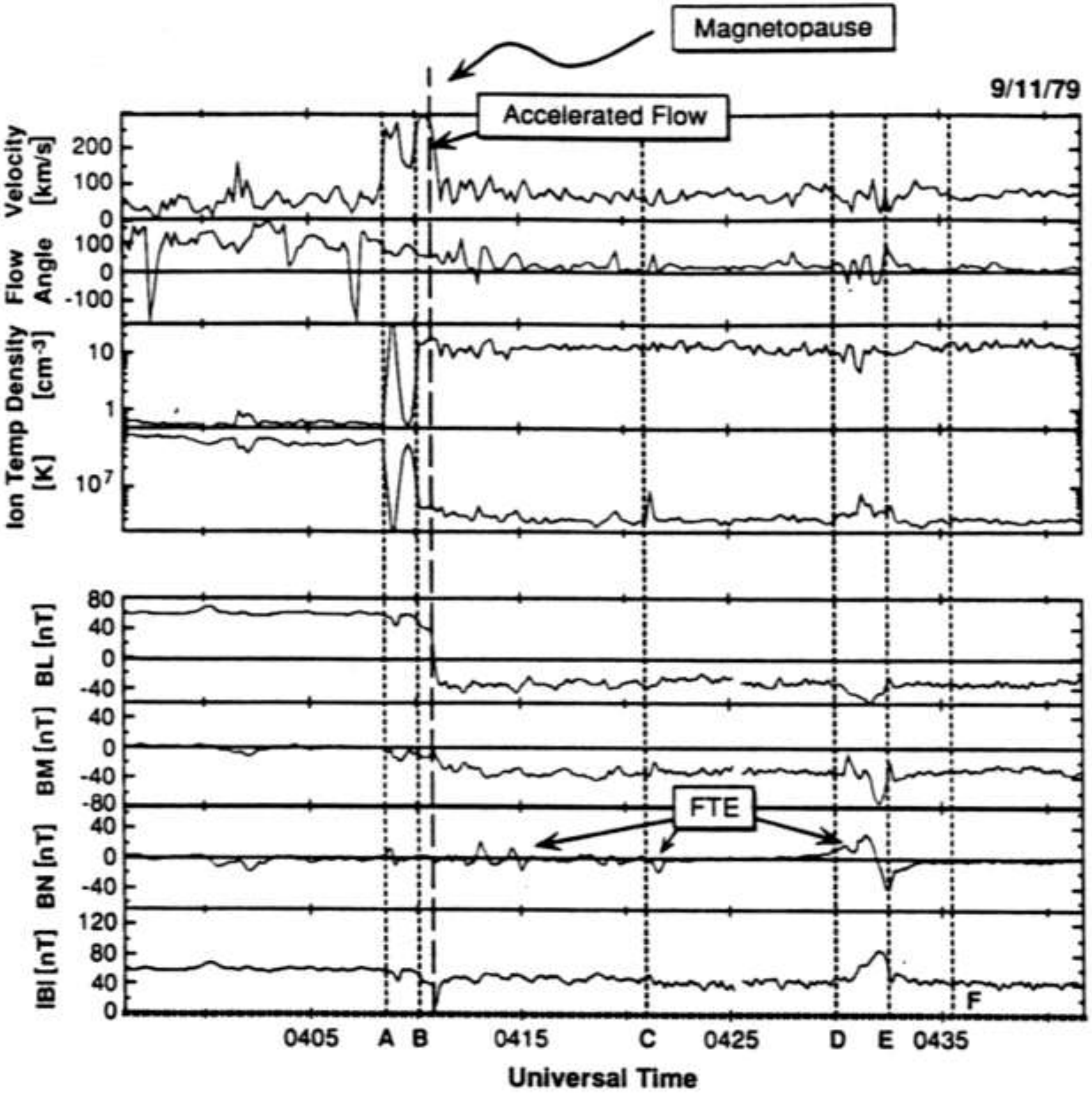


0 Intense currents

Kivelson et al., 1995

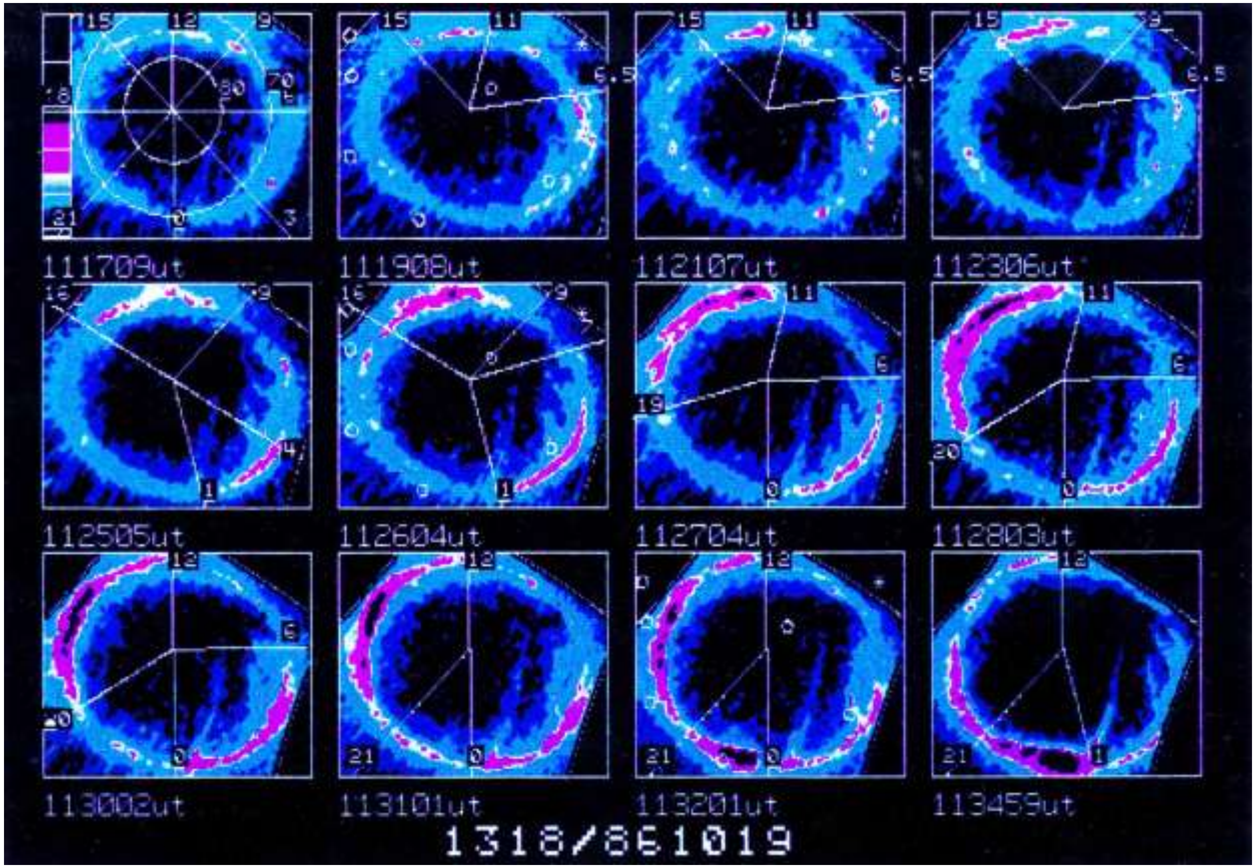
Fast Flows at the Magnetopause

Scurry et al. ‘94



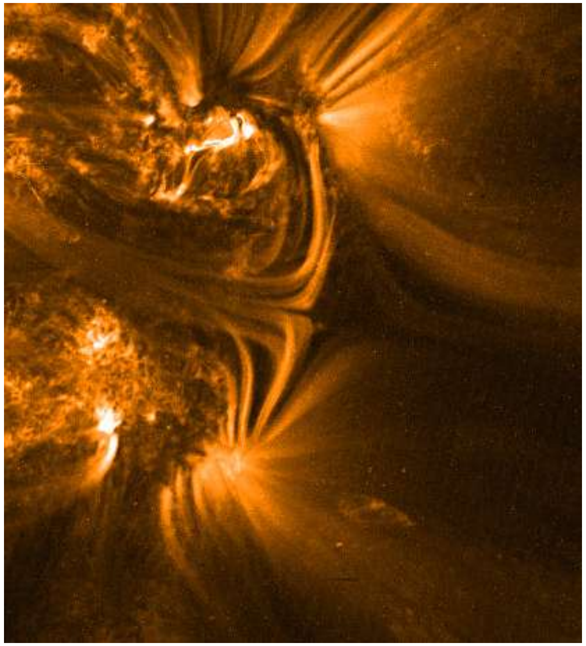
Viking images of polar aurora

- Elphinstone et al. ‘91



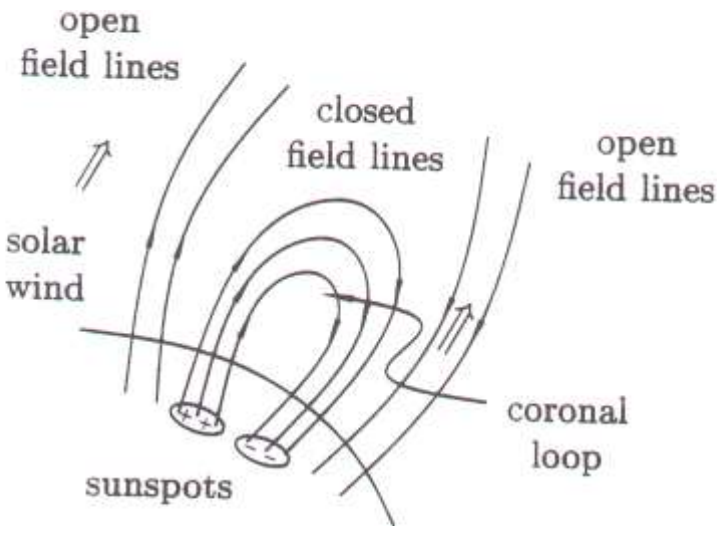
- The aurora are produced by energetic electrons from magnetic reconnection

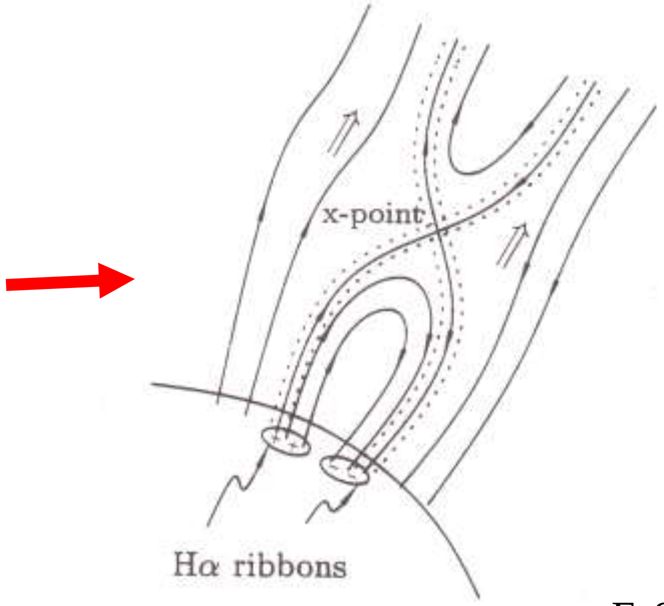
Reconnection in Solar Flares



- 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!

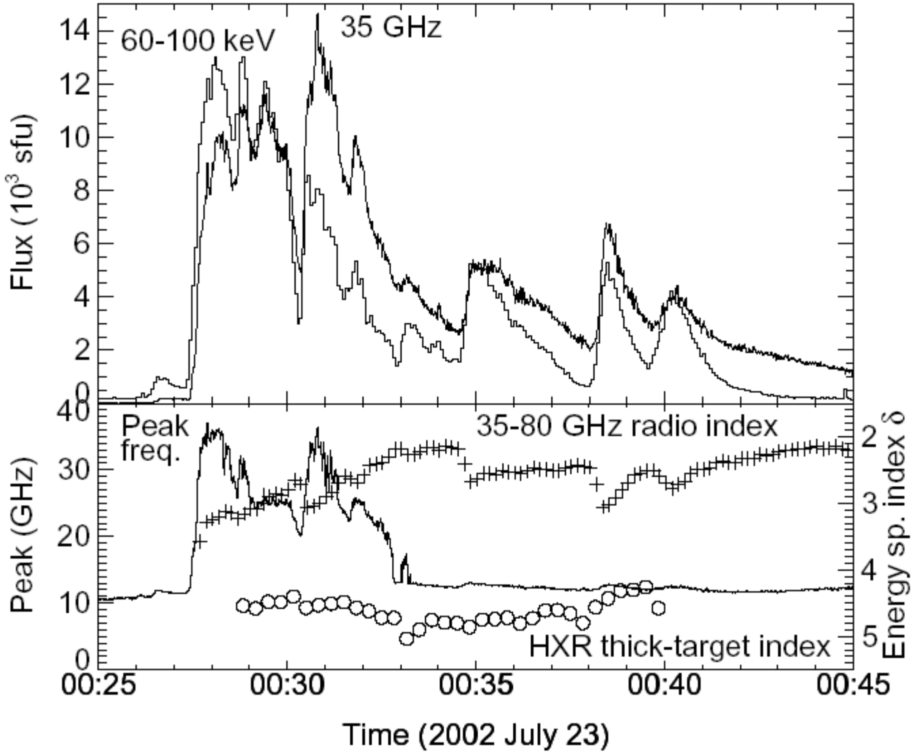




F. Shu, 1992

Impulsive flare timescales

- Hard x-ray and radio fluxes
  - 2002 July 23 X-class flare
  - Onset of 10's of seconds
  - Duration of 100's of seconds.

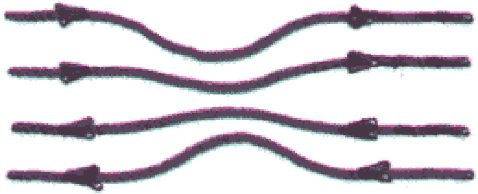


RHESSI and NoRH Data

(White et al., 2003)

Role of Resistivity

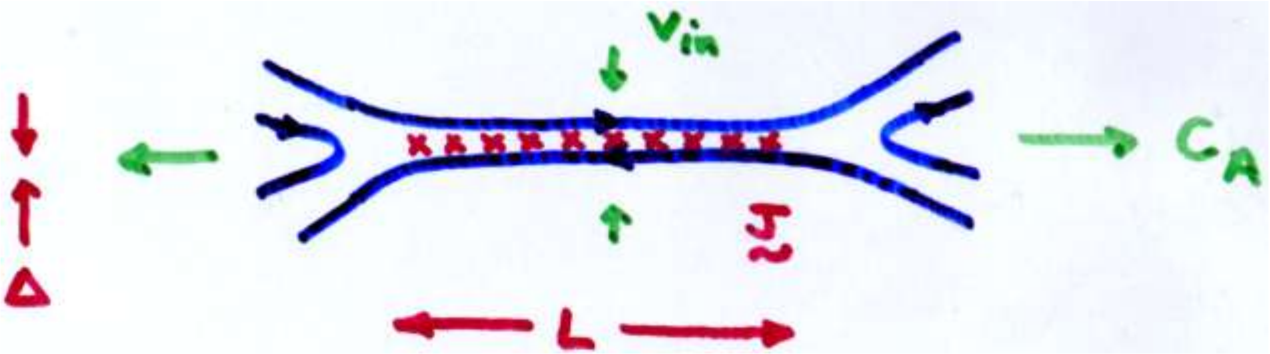
- The frozen-in condition implies that in an ideal plasma ($\eta=0$) no topological change in the magnetic field is possible
  - tubes of magnetic flux are preserved



  - magnetic reconnection requires resistivity some other dissipation mechanism
- A measure of resistivity is the Lundquist number

$$S = \frac{t_r}{t_A}$$

Magnetic Nozzle in the Magnetohydrodynamic (MHD) model

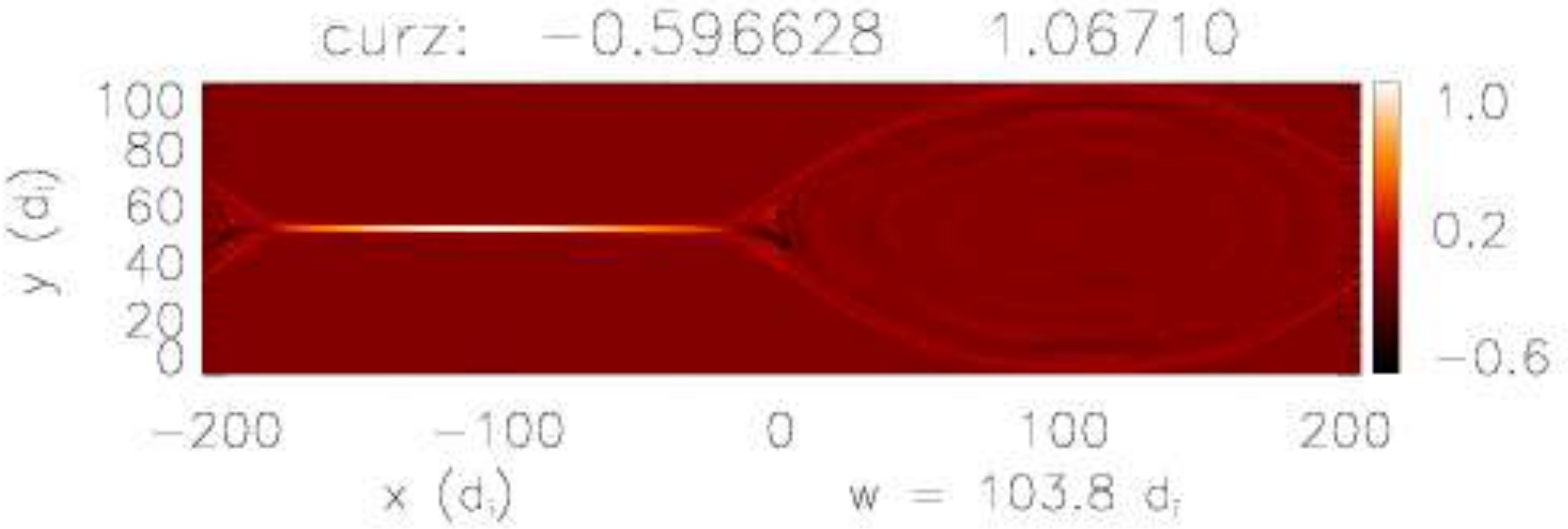


- Formation of macroscopic Sweet-Parker layer

$$\mathbf{V \sim (\Delta / L)\, C_A \sim (\tau_A/\tau_r)^{1/2}\, C_A \ll C_A}$$

- Slow reconnection
- sensitive to resistivity
- macroscopic nozzle

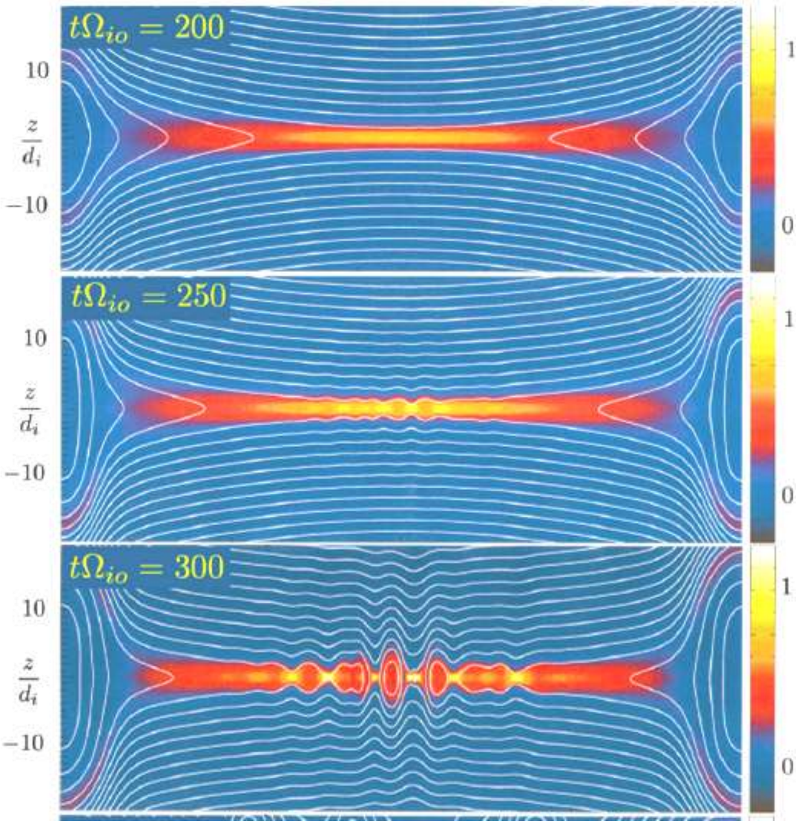
Resistive MHD Solution



- Slow reconnection due to nozzle produced by Sweet-Parker current layer
  - Biskamp, 1986

Transition from MHD to Hall reconnection with plasmoids

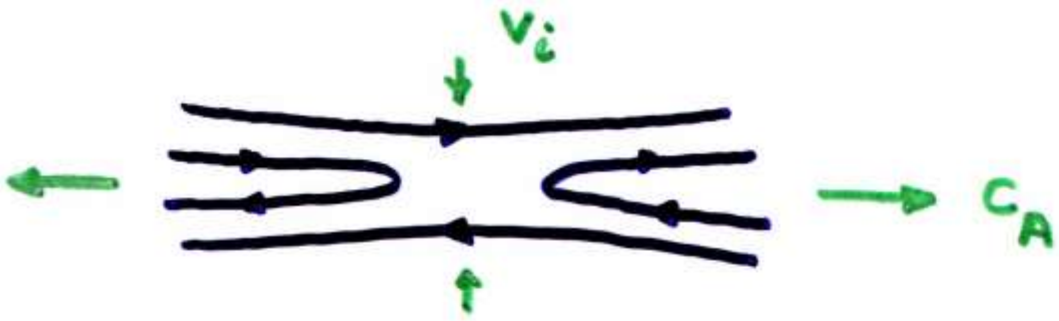
- Sweet-Parker layers break up to form plasmoids (Biskamp ’86, Laureiero et al ‘05)
  - For S > 10^4
  - Faster reconnection because of shorter Sweet-Parker layer
- Can plasmoids produce fast MHD reconnection in the corona?



Daughton et al ‘09

Bhattacharjee et al. (2009)
Cassak et al. (2009)
Uzdensky et al. (2010)
Shepherd and Cassak (2010)
Huang et al (2011)

Resistive MHD reconnection



- Flux diffusion across the Sweet-Parker layer

$$\frac{\partial \psi}{\partial t} + V_{in}\frac{\partial \psi}{\partial x} = \frac{\eta c^2}{4\pi}\frac{\partial^2 \psi}{\partial x^2}$$

- Balancing flux convection and diffusion

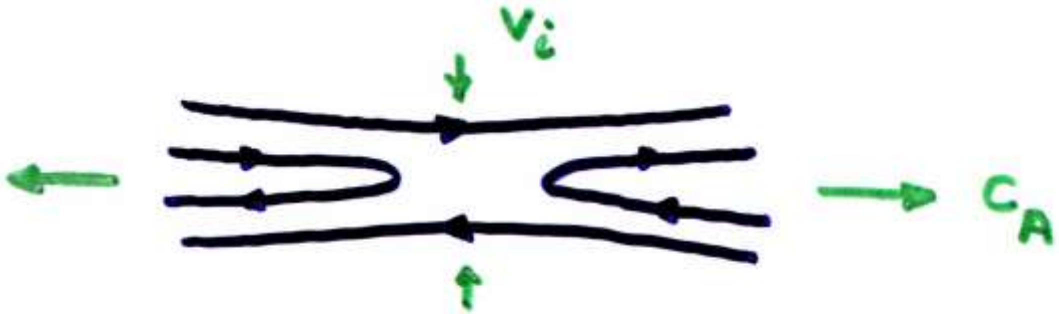
$$V_{in} \sim \frac{\eta c^2}{4\pi\Delta_{sp}} \sim \frac{\eta c^2}{4\pi d_i} \sim 10^{-6} c_A$$

Slow reconnection even with plasmoids!

Failure of the MHD Model

- Reconnection rates too slow to explain observations
  - solar flares
  - sawtooth crash in tokamak plasmas
  - magnetospheric substorms
- Some form of anomalous resistivity is often invoked to explain discrepancies
  - strong electron-ion streaming near x-line drives turbulence and associated enhanced electron-ion drag
- Non-MHD physics at the small spatial scales where the frozen-in condition is broken produces fast reconnection consistent with observations
  - Coupling to dispersive waves is critical

Magnetic Reconnection beyond the MHD model



- What happens when the “slingshot” occurs at very small spatial scales?
  - The MHD model is no longer valid ⇒ no Alfven wave
  - What drives the slingshot?
    - A class of “dispersive” waves dominate
    - Whistler and kinetic Alfven waves

Role of Dispersive Waves

- Coupling to dispersive waves at small scale is the key to understanding magnetic reconnection
  - rate of reconnection independent of the dissipation
  - no macroscopic nozzle

Generalized Ohm's Law

- Electron equation of motion

$$\frac{4\pi}{\omega_{pe}^2}\frac{d\vec{J}}{dt} = \vec{E} + \frac{1}{c}\vec{v}_i \times \vec{B} - \frac{1}{nec}\vec{J} \times \vec{B} - \eta\vec{J}$$

c/ω_{pe}

c/ω_{pi}

scales

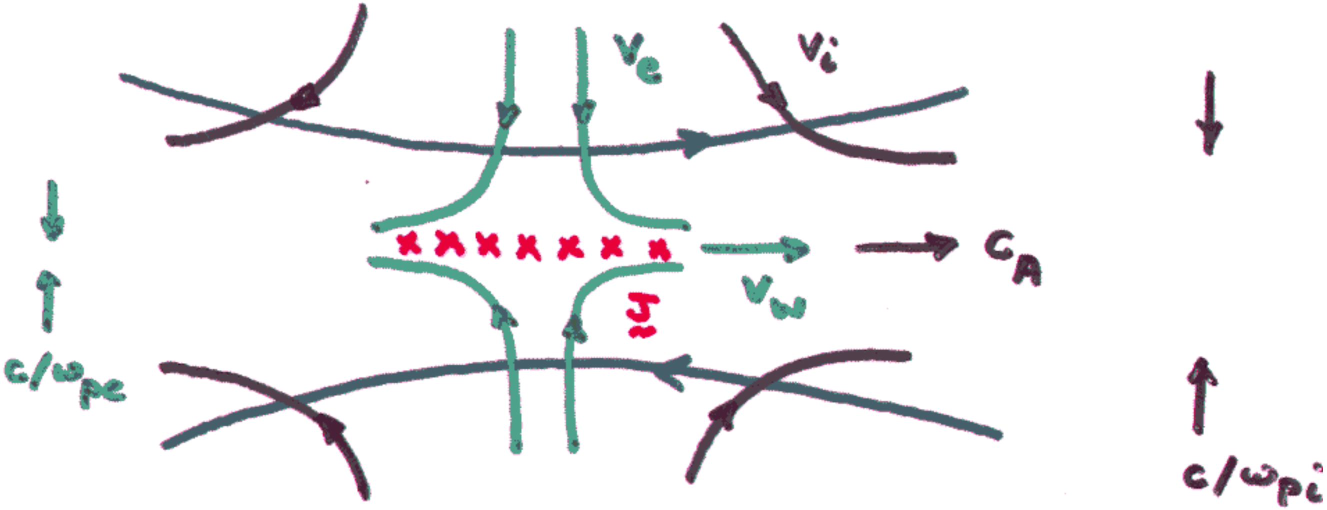
Electron inertia

Alfven waves

whistler waves

- MHD valid at large scales
  - Electrons, ions and magnetic field move together
  - MHD has no intrinsic scale
- Below c/ω_{pi} electron and ion motion decouple
  - electrons move with the magnetic field (frozen-in electrons)
- Electron frozen-in condition broken below c/ω_{pe}

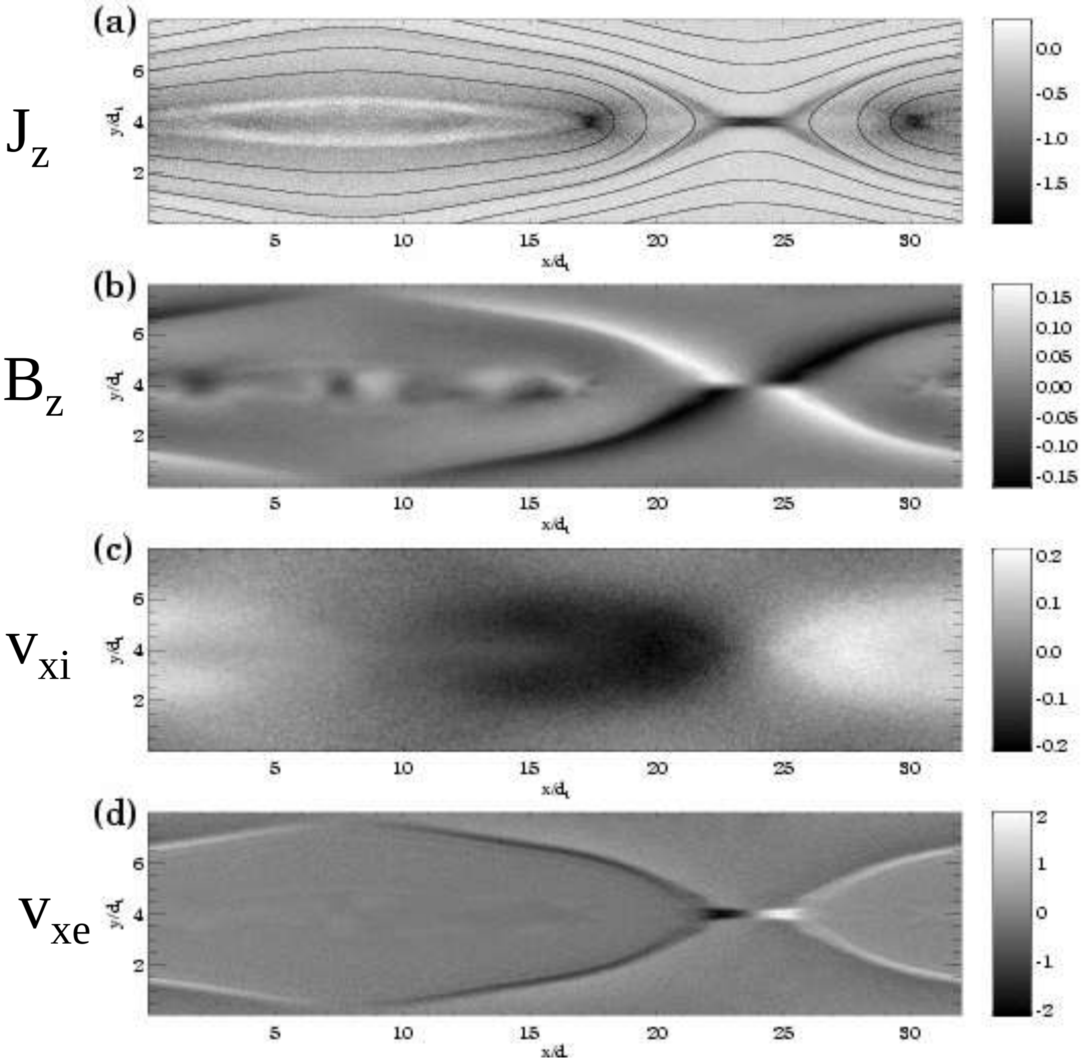
Hall Reconnection



- Ion motion decouples from that of the electrons at a distance c/ω_{pi} from the x-line
  - ion outflow width c/ω_{pi}
- electron current layer broken at c/ω_{pe} from the x-line
  - Electron outflow width c/ω_{pe}
  - The whistler drives the outflow from the x-line
- no macrosopic nozzle

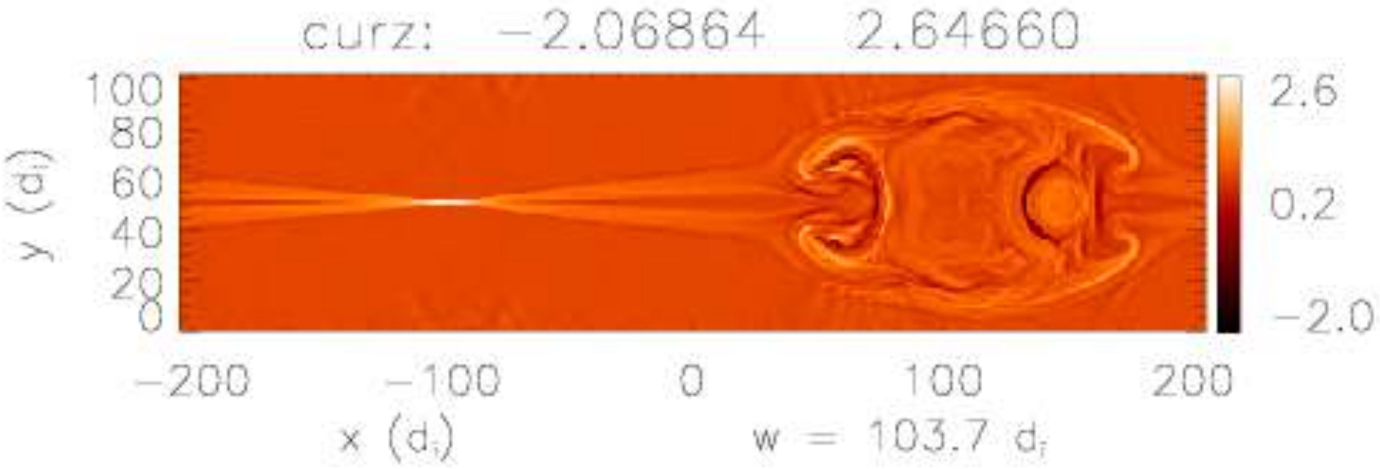
Hall Reconnection

- particle simulation
- Decoupling of the motion of electrons and ions

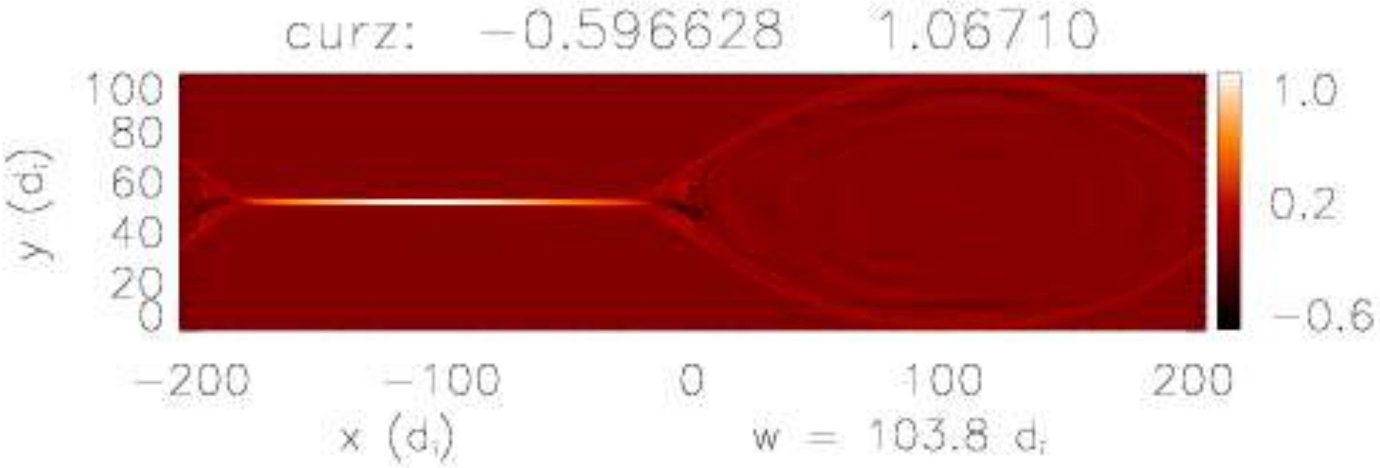


Hall versus MHD reconnection

Hall



MHD



Cassak, et al, 2005

GEM Reconnection Challenge

- National collaboration to explore reconnection with a variety of codes
  - MHD, two-fluid, hybrid, full-particle
- nonlinear tearing mode in a 1-D Harris current sheet

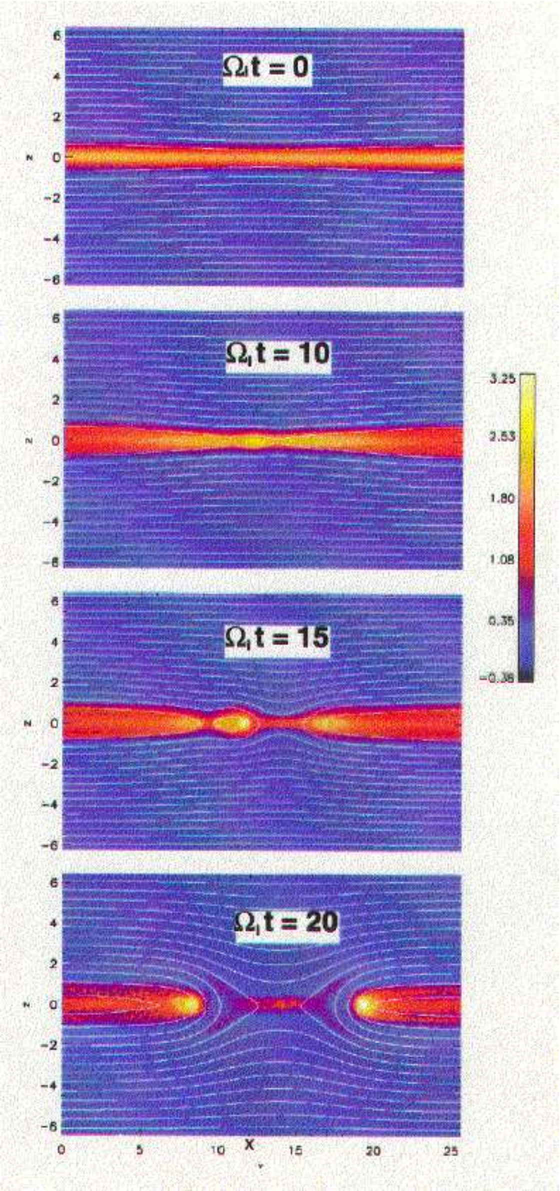
$$B_x = B_0 \tanh(z/w)$$

$$w = 0.5\ c/\omega_{pi}$$

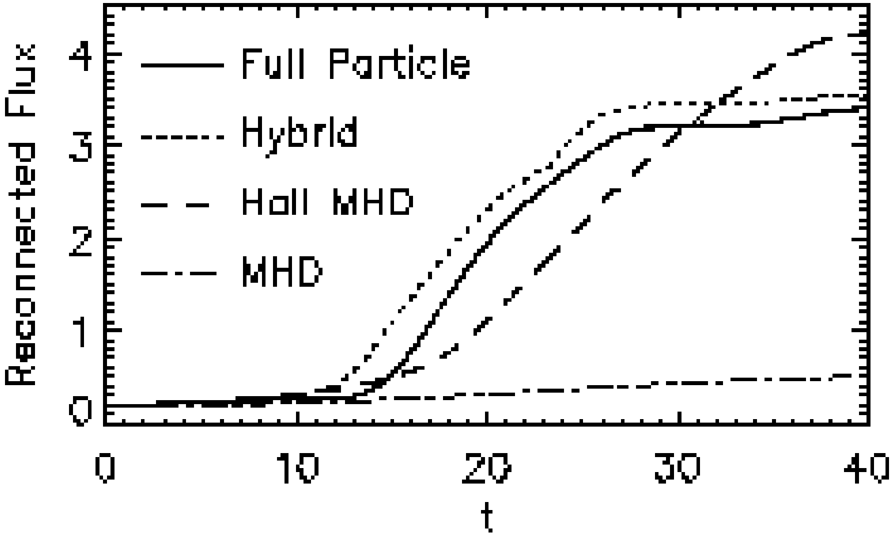
- Birn, et al., 2001

GEM tearing mode evolution

- Full particle simulation (Hesse,GSFC)



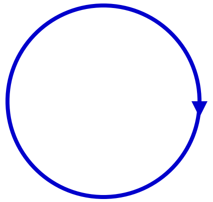
Rates of Magnetic Reconnection



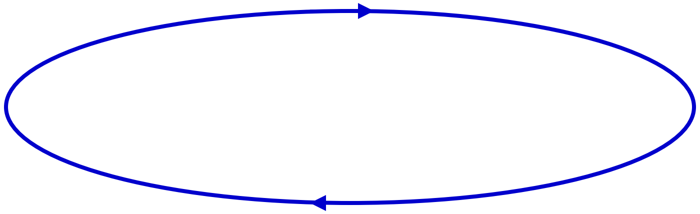
- Rate of reconnection is the slope of the Ψ versus t curve
- all models which include the Hall term in Ohm’s law yield essentially identical rates of reconnection
  - Even though dissipation models differ greatly
  - Why?
- MHD reconnection is too slow by orders of magnitude

Whistler Physics ($\Delta < c/\omega_{pi}$)

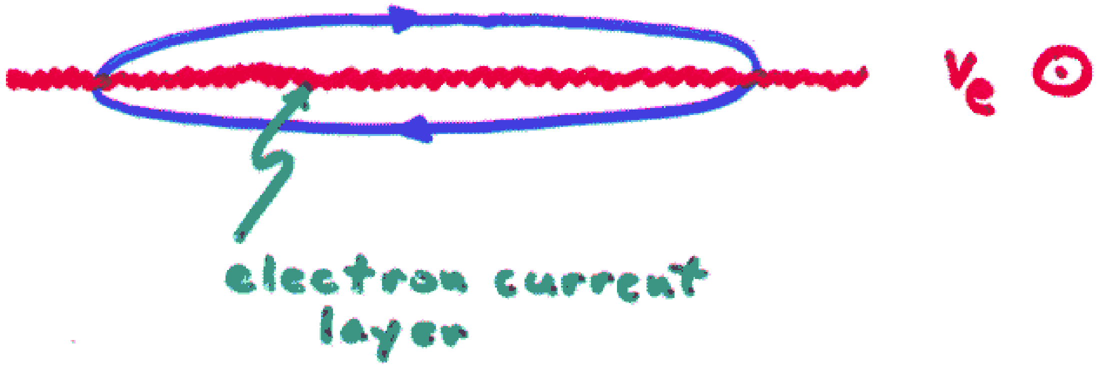
- Ions essentially motionless
- Electrons frozen-in to B
- Cylindrical equilibrium
  - non-trivial unlike as in MHD theory
  - concentric rings of field move with velocities which depend on radius



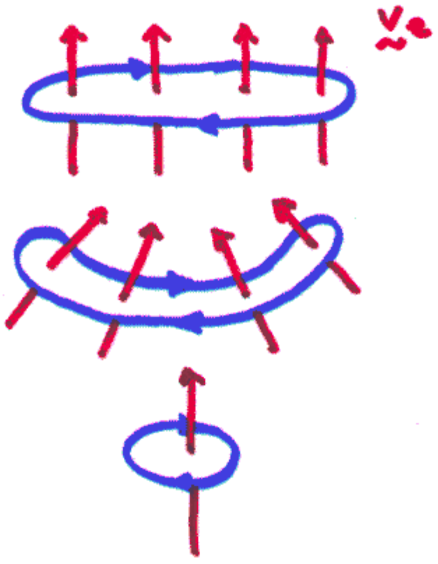
- What happens to squashed rings?



Whistler Physics

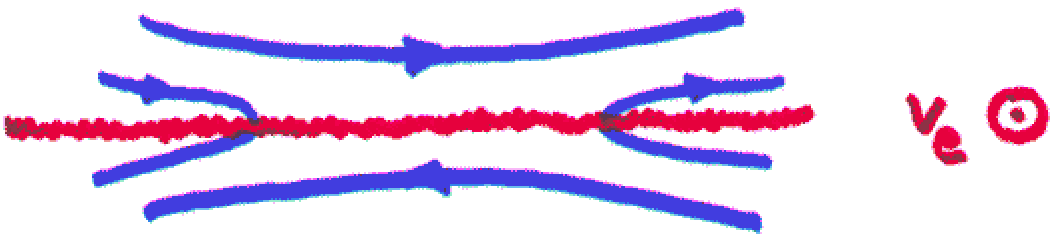


- The ends of the magnetic loop bend upward out of the plane, carried by the electrons



Whistler Driven Reconnection

- At spatial scales below c/ω_{pi} whistler waves rather than Alfven waves drive reconnection. How?

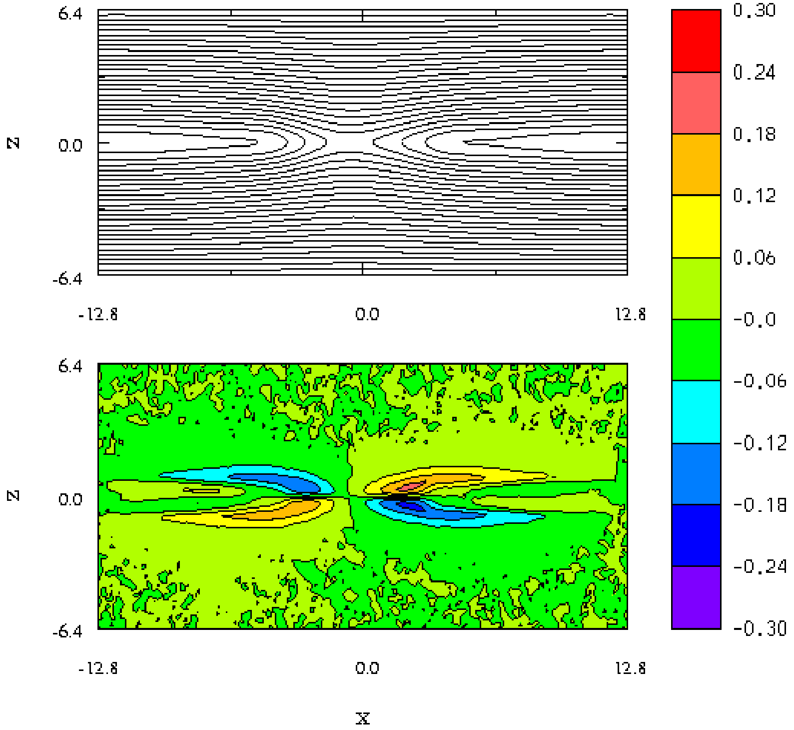


•Side view

•Whistler signature is out-of-plane magnetic field

Whistler signature

- Magnetic field from particle simulation (Pritchett, UCLA)



•Self generated out-of-plane field is whistler signature

Whistler Dispersion

- Quadratic dispersion character

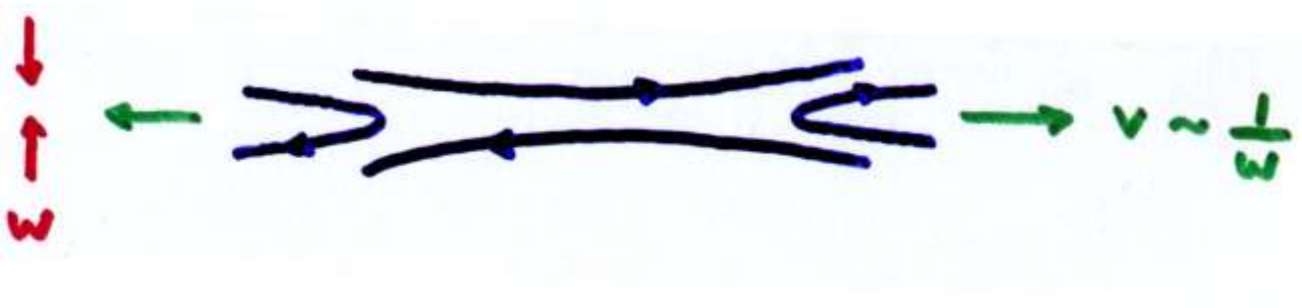
$$\omega \sim k^2$$

$$v_p \sim k$$

  - smaller scales have higher velocities

Sensitivity of reconnection to dissipation mechanism

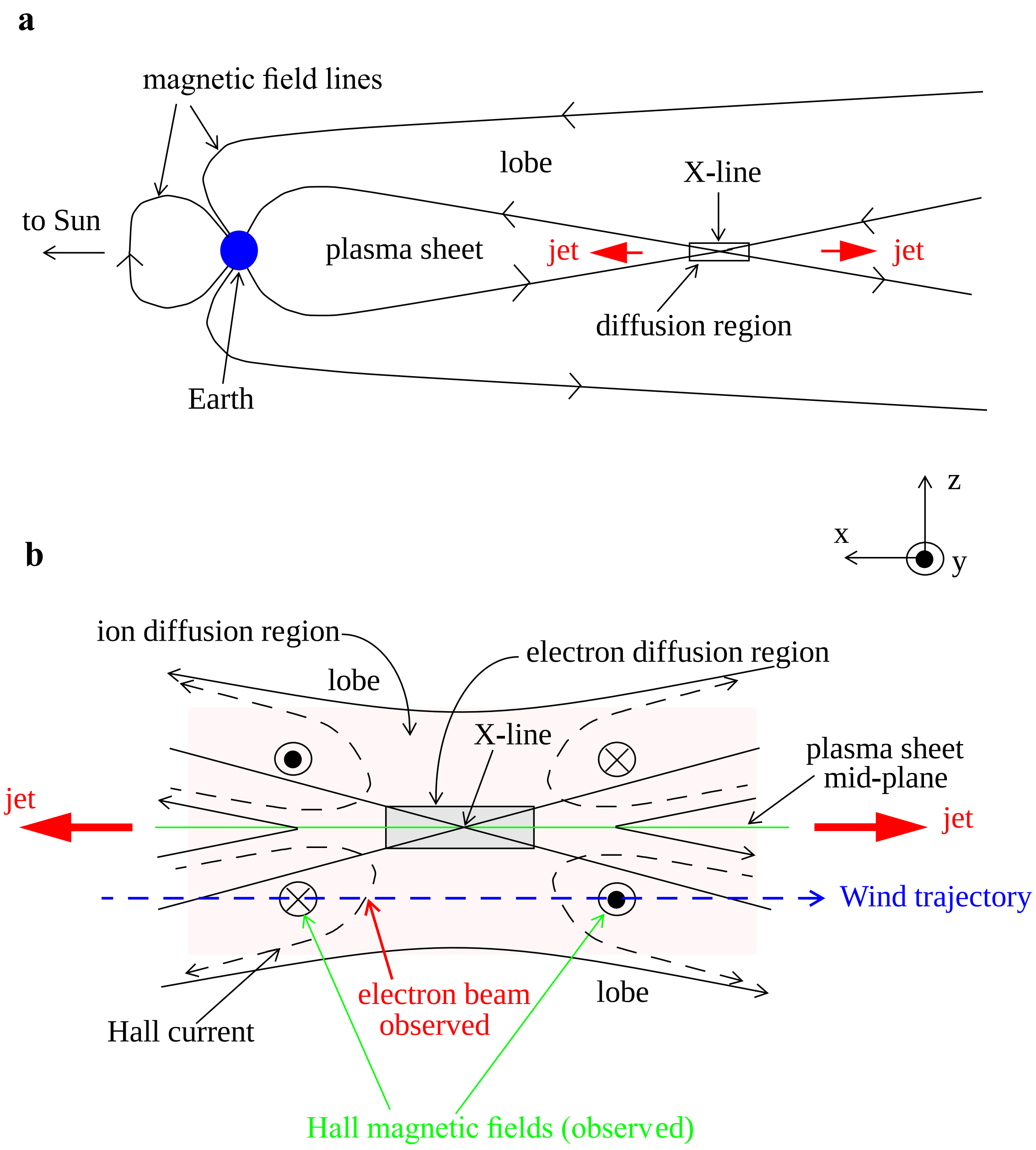
- Assume frozen-in condition broken at scale w



- plasma flux from x-line $\sim vw$
  - independent of scale w
  - plasma flux independent of mechanism which breaks frozen-in condition

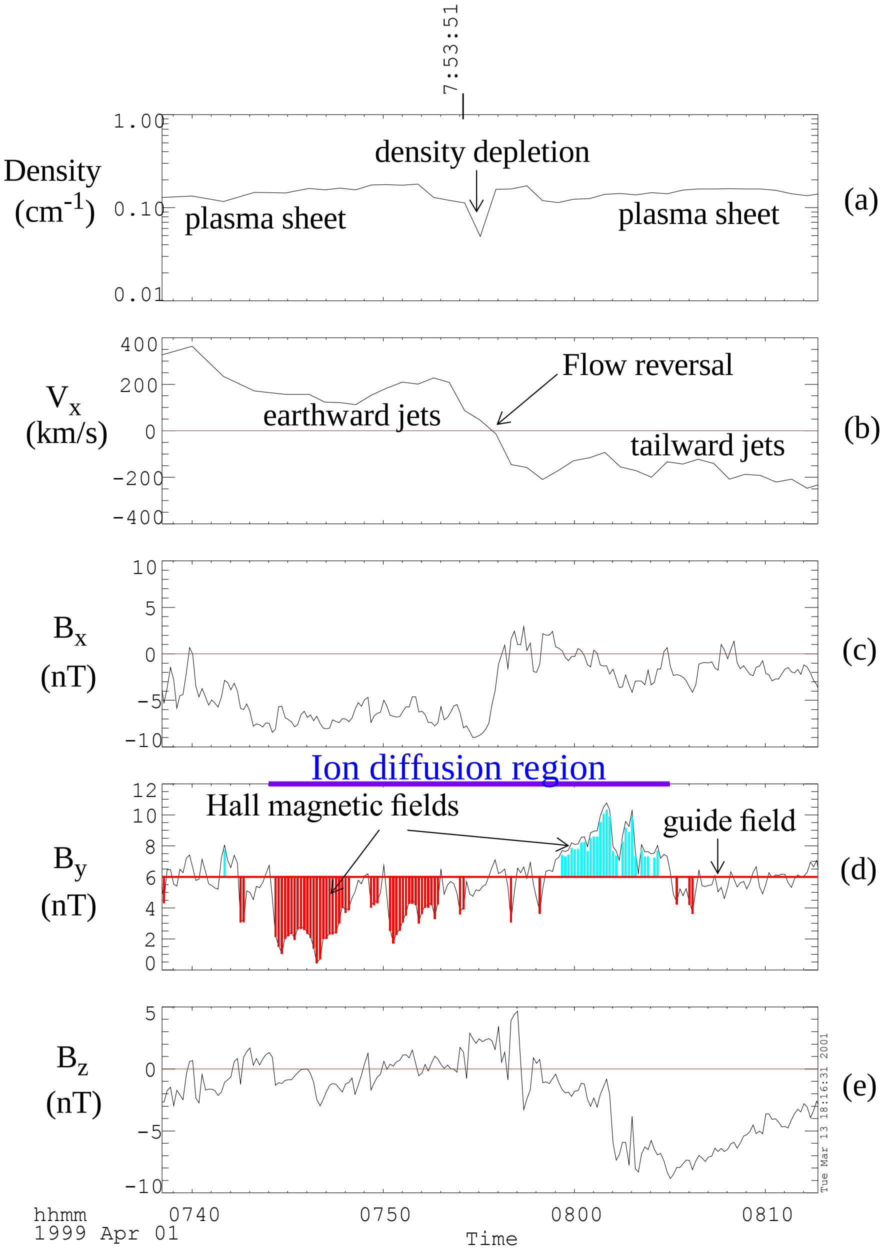
Wind Spacecraft Observations

(Oeierset, et al., 2001)



Magnetic Field Data from Wind

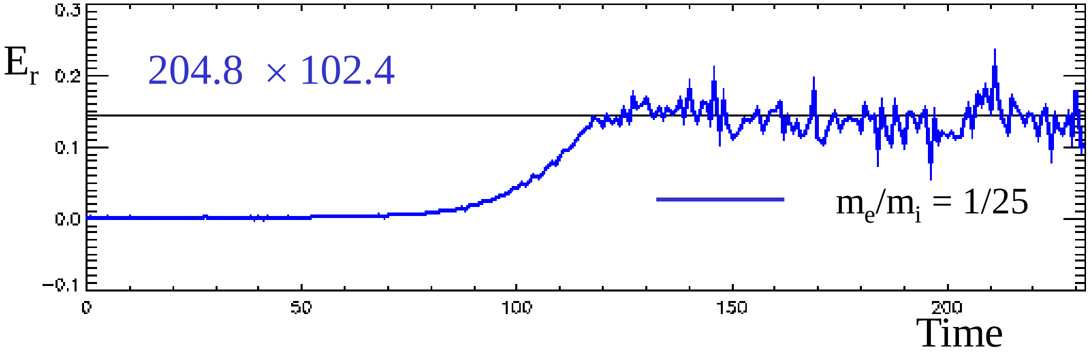
- Out-of-plane magnetic fields seen as expected from standing whistler

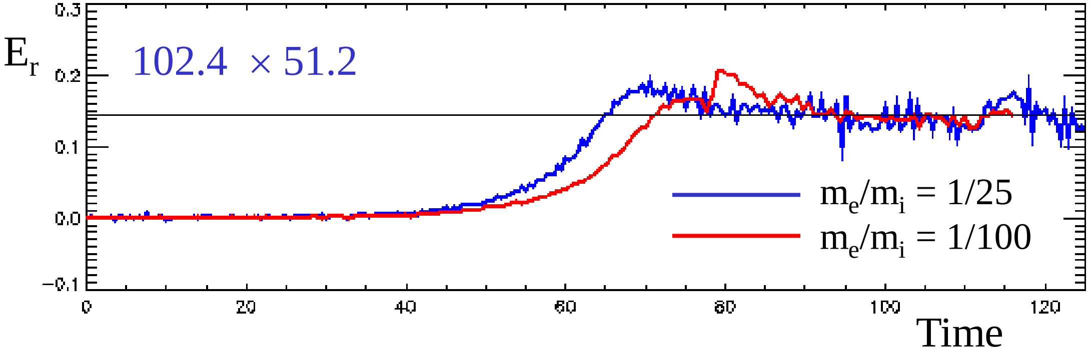


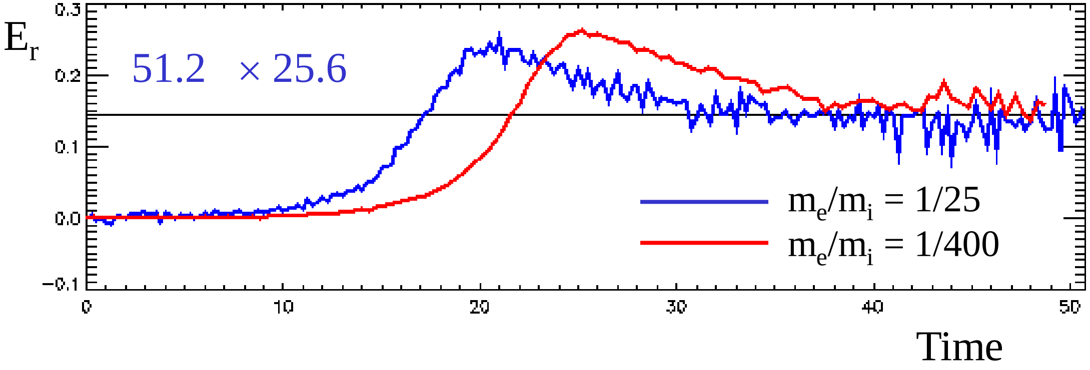
Collisionless Reconnection in large systems

- Collisionless reconnection scaling
  - Insensitive to the electron mass and therefore dissipation
  - Independent of the domain size
  - Slow shocks drive the reconnection outflow (Liu et al ‘12)

Shay et al 2007





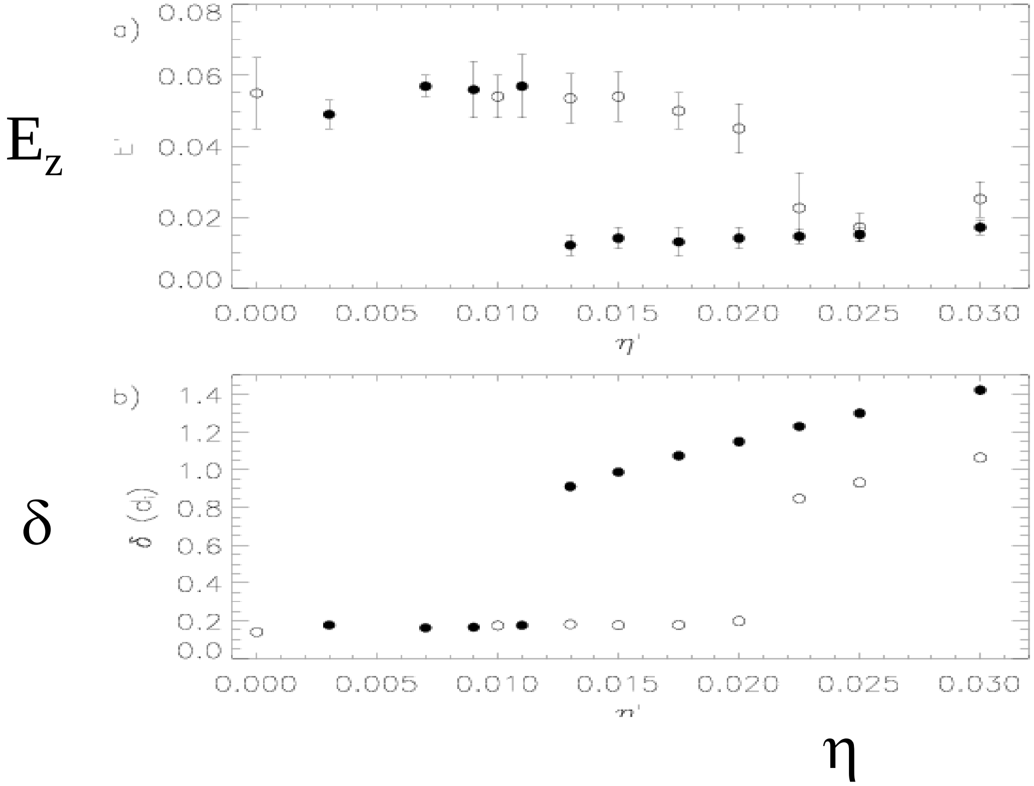


Magnetic Explosions

- Why is the magnetic energy during magnetic reconnection released as an explosion?
  - Since reconnection can be fast why isn't the magnetic energy released as fast as external drivers can supply it?
  - Need to explain why magnetic reconnection is not always fast.

Reconnection onset is a catastrophe

- Slow Sweet-Parker reconnection and fast Hall reconnection are valid solutions for the same parameters



Cassak et al 2005

- Sweet-Parker solution does not exist below a critical resistivity

⇒ For the solar corona the critical temperature is around 100 eV and the reconnection rate will jump a factor of 10^5

Conclusions

- Magnetic reconnection causes an explosive release of energy in plasma systems
  - similar to other types of explosions
    - sonic flows
  - a difference is that the explosion is non-isotropic
- Fast reconnection depends critically on the coupling to dispersive waves at small scales
  - rate independent of the dissipation
  - rate consistent with observations
- Reconnection occurs as an explosion because the onset occurs as a catastrophe
- Satellite observations and laboratory reconnection experiments have verified key predictions of theoretical models