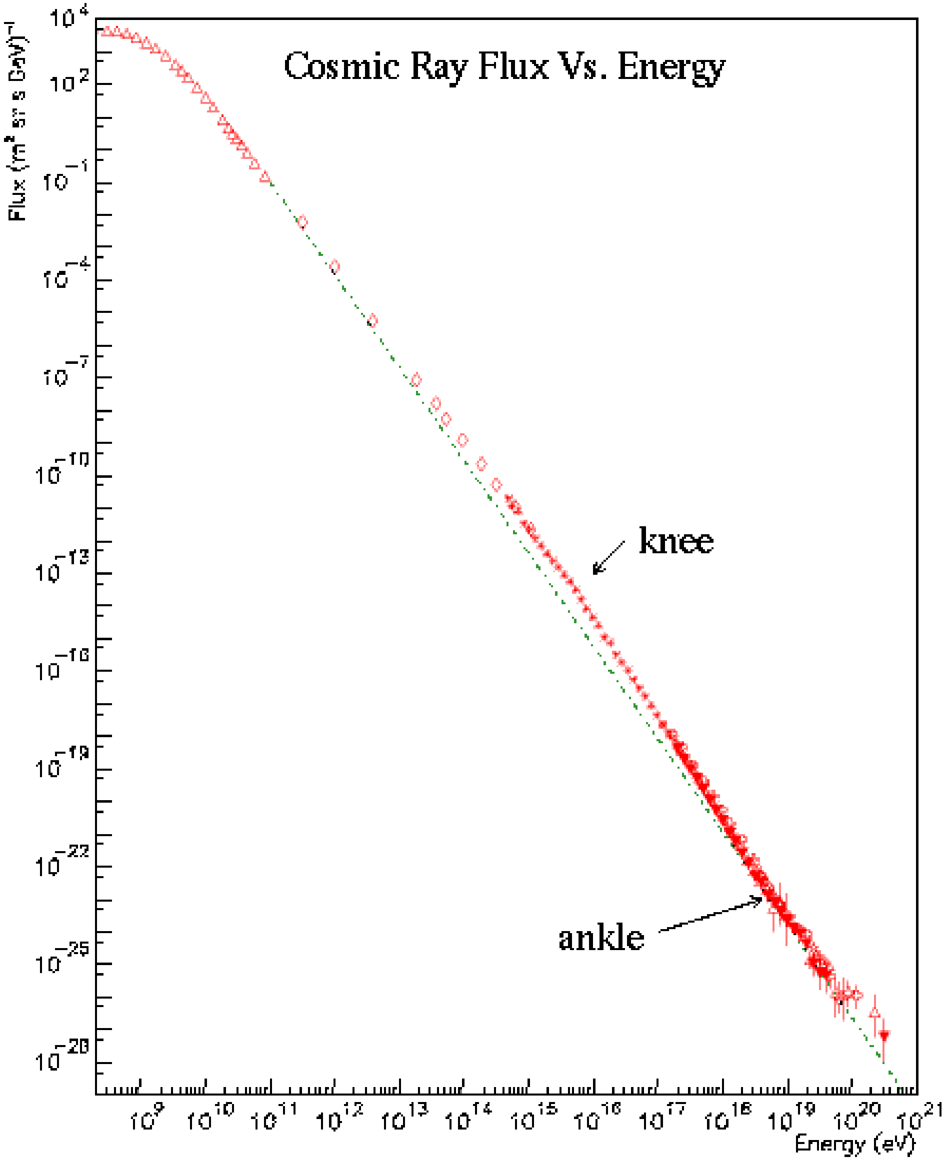
Particle acceleration during collisionless magnetic reconnection

J. F. Drake

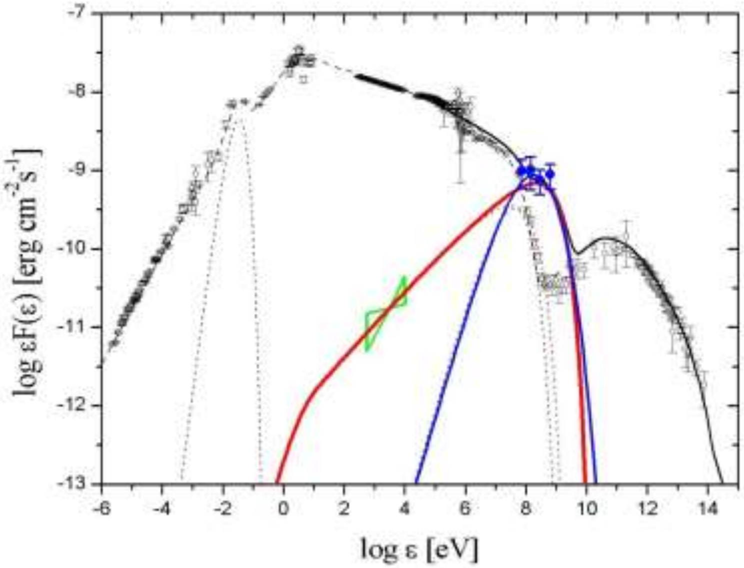
University of Maryland

Cosmic Ray Energy Spectrum

- Total energy density ~1eV/cm^3
  - Comparable to magnetic and thermal energy density of interstellar gas
    - Dynamical importance in the galaxy
- Supernova shocks remain the favored mechanism for producing cosmic rays
  - Fermi reflection across the shock front
    - Converging flow at shock
  - Energies up to ~ 10^{15}eV
    - Too small to contain higher energy particles
  - Powerlaw spectra close to observations
    - ~ E$^{-2.7}$
- Jets from active Galactic nuclei and associated radio lobes are large enough to produce particles above 10^{15}eV
  - A role for magnetic reconnection?



Gamma-Ray Flares in the Crab Nebula

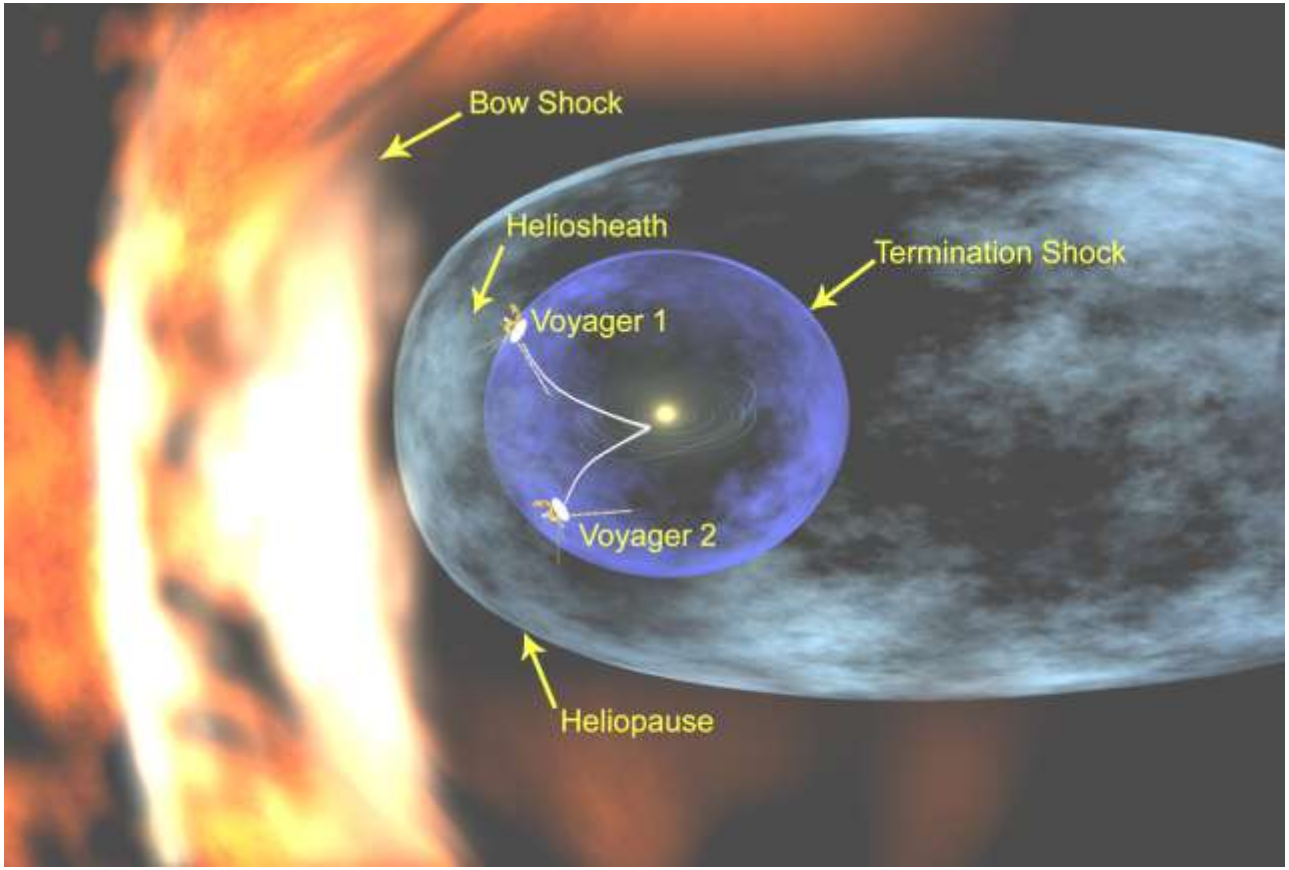


September 2010 AGILE/FERMI γ-flare

Observational constraints:

- Flare duration: $\tau = 1$ day --> $l \sim 3$ x 10^{15} cm
- Photon energy: > 100 MeV --> from PeV electrons
- Isotropic flare energy: $E \sim 4$ x 10^{40} erg
- Reconnection mechanism?

The heliosphere



Energetic particle observations in the heliosphere

- Flare and coronal observations
  - In solar flares energetic electrons up to MeVs and ions up to GeVs have been measured
    - A significant fraction of the released magnetic energy appears in the form of energetic electrons and ions (Lin and Hudson '76, Emslie et al '05, Krucker et al '10)
    - A large number of electrons undergo acceleration – the "numbers problem"
    - Correlation between > 300keV energetic electrons and > 30 MeV ions (Shih et al 2008) ⇒ common acceleration mechanism
  - In impulsive flares see enhancements of high M/Q ions (Mason '07)
  - In the extended corona $T_\perp > T_\parallel$ (Kohl et al '97)
    - Minority ion temperature more than mass proportional

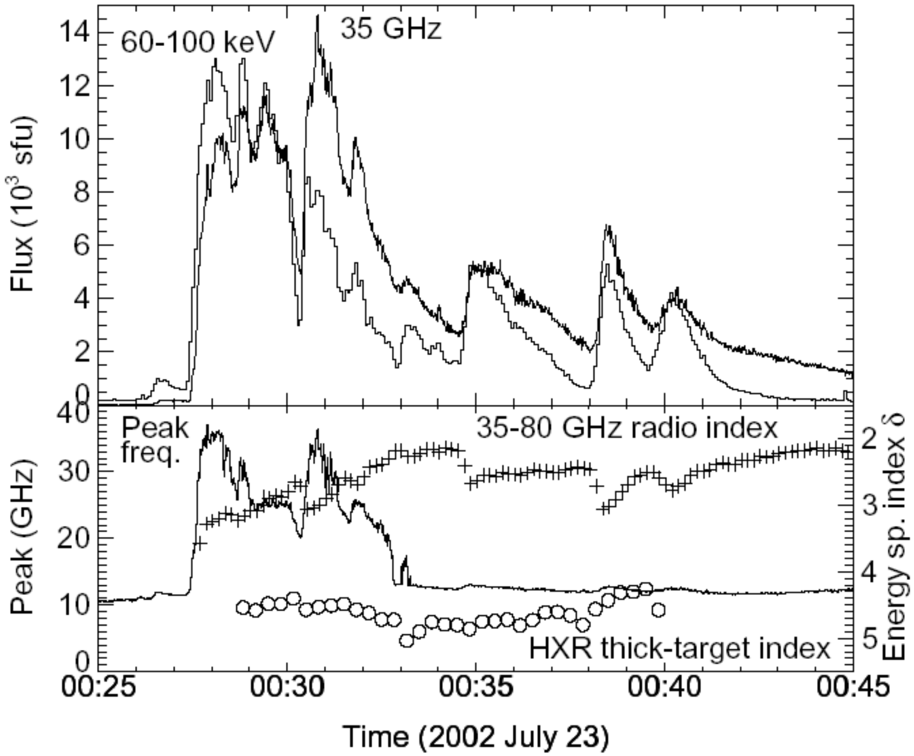
$$T_i / T_p \geq m_i / m_p$$

Energetic particle observations (cont.)

- Solar wind observations
  - Ion heating in solar wind reconnection exhausts but no energetic particles (Gosling et al 2005, Phan et al 2006)
  - Near universal super-Alfvenic ion tails in the slow solar wind $f \sim v^{-5}$ (Fisk and Gloeckler 2006)
- Magnetosphere observations
  - Electrons up to 300keV peaked around a reconnection event deep in the magnetotail (Oieroset et al 2002)
  - Energetic electrons peak within magnetic islands (Chen et al ’09)
- Outer heliosphere observations
  - Anomalous Cosmic Rays (ACRs) are 10-100Mev/nucleon ions that are accelerated from interstellar medium pickup particles (Cummings & Stone 1996)
    - Source is not the termination shock near the Voyager spacecraft

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.
- X-ray emission due to Bremsstrahlung as energetic electrons from reconnection in the corona impact the high density chromosphere



RHESSI and NoRH Data

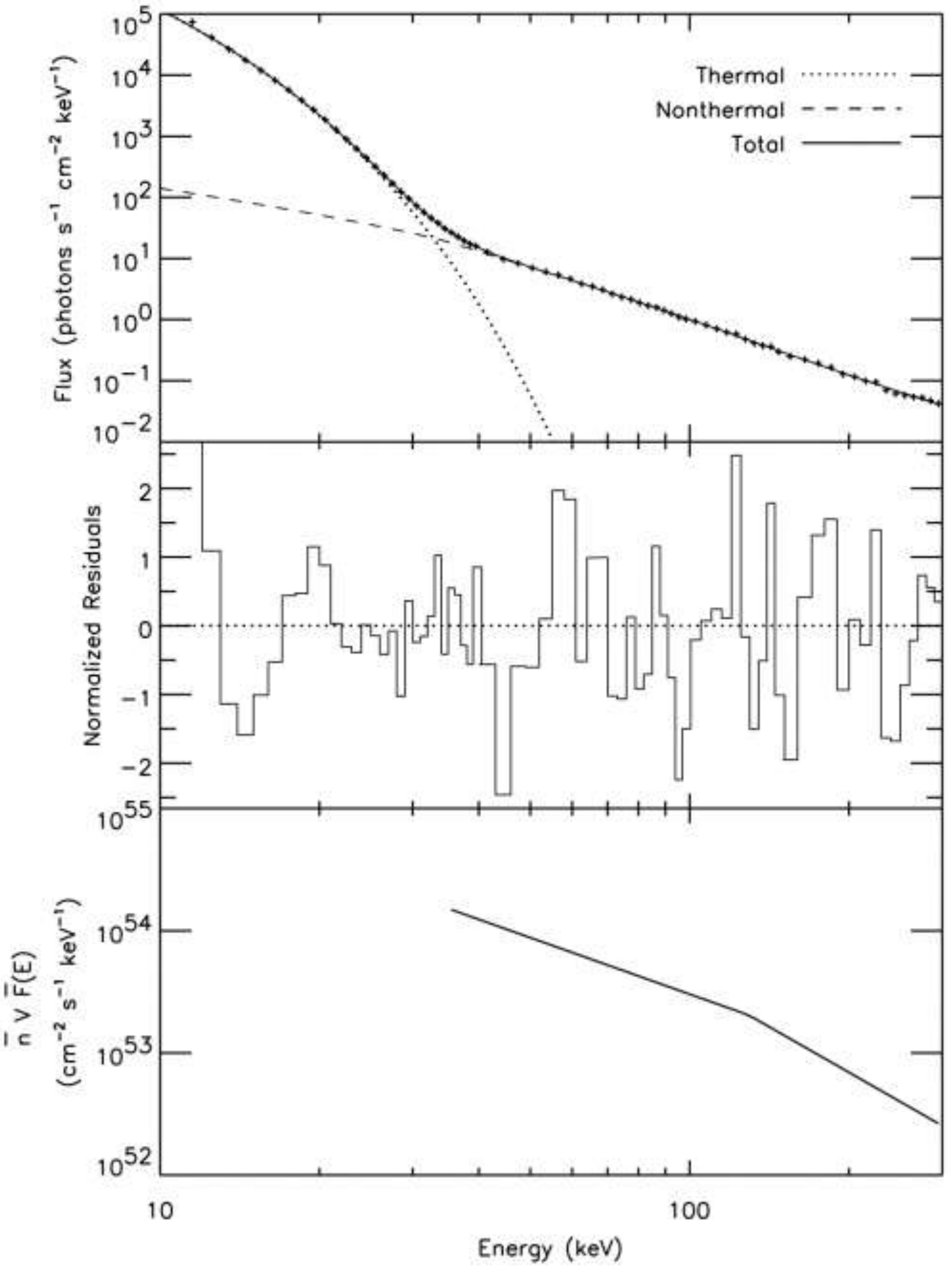
(White et al., 2003)

RHESSI observations

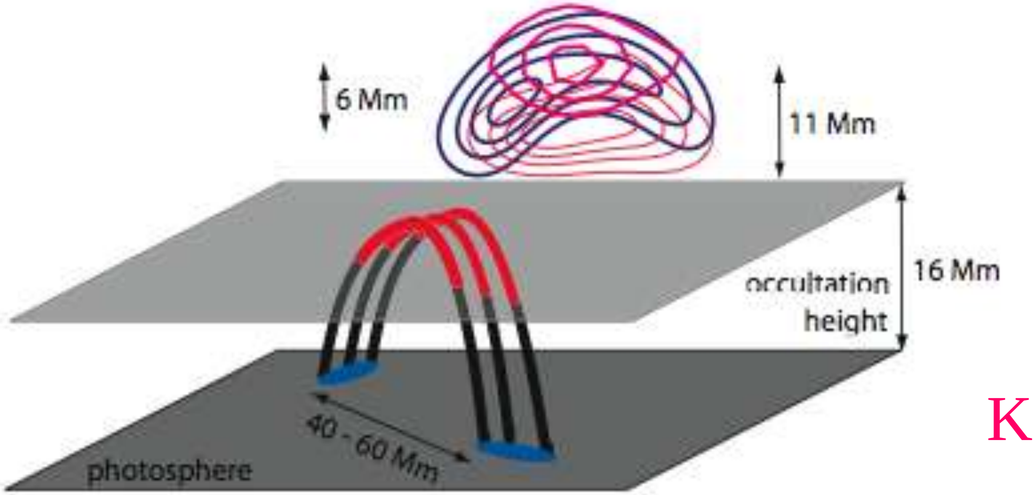
- July 23 γ-ray flare (Holman, *et al.*, 2003)
- Double power-law fit with spectral indices:

  1.5 (34-126 keV)

  2.5 (126-300 keV)



RHESSI occulted flare observations



30-50keV

17GHz

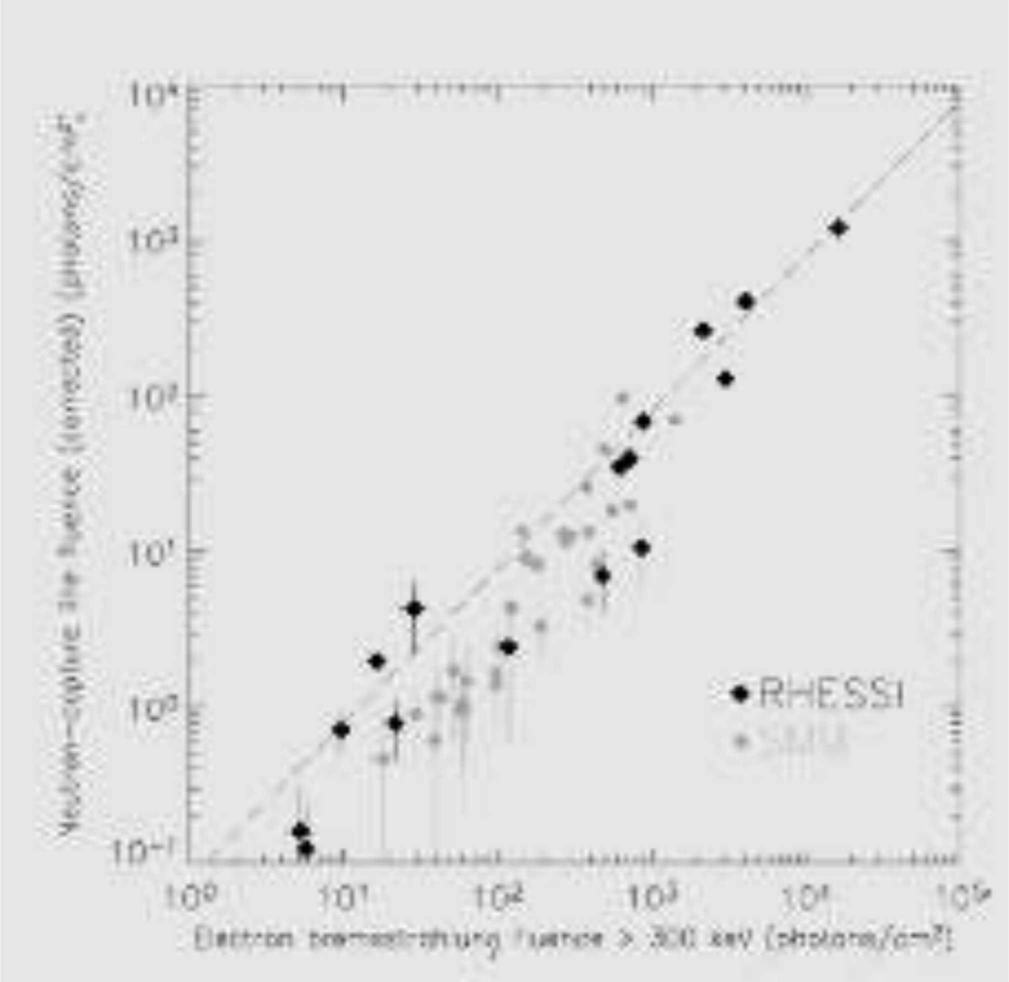
Krucker et al 2010

- Observations of a December 31, 2007, occulted flare
  - All electrons in the flaring region are part of the energetic component (10keV to several MeV)
  - The pressure of the energetic electrons approaches that of the magnetic field
  - Remarkable!

Energetic electron and ion correlation

- > 300keV x-ray fluence (electrons) correlated with 2.23 MeV neutron capture line (> 30 MeV protons)
- Acceleration mechanisms of electrons and protons linked?

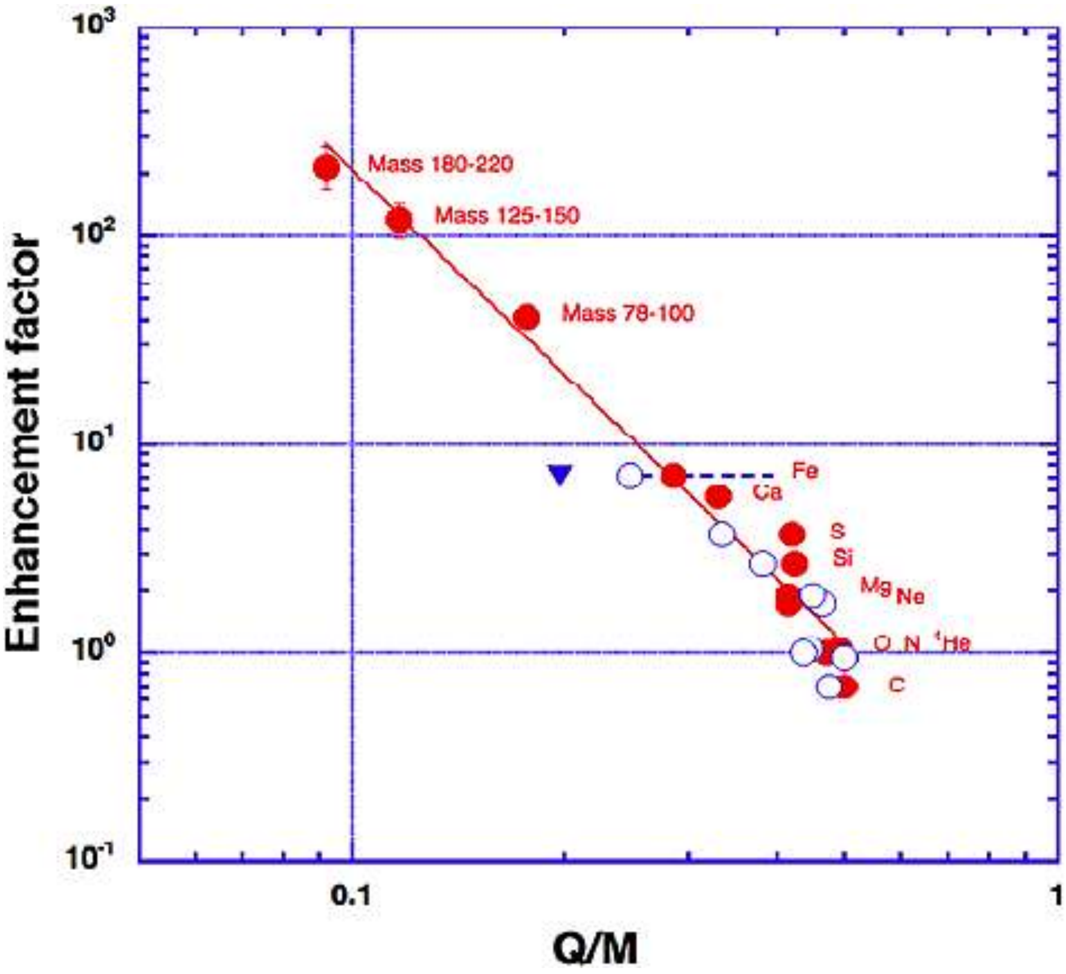
Shih et al 2008



Impulsive flare energetic ion abundance enhancement

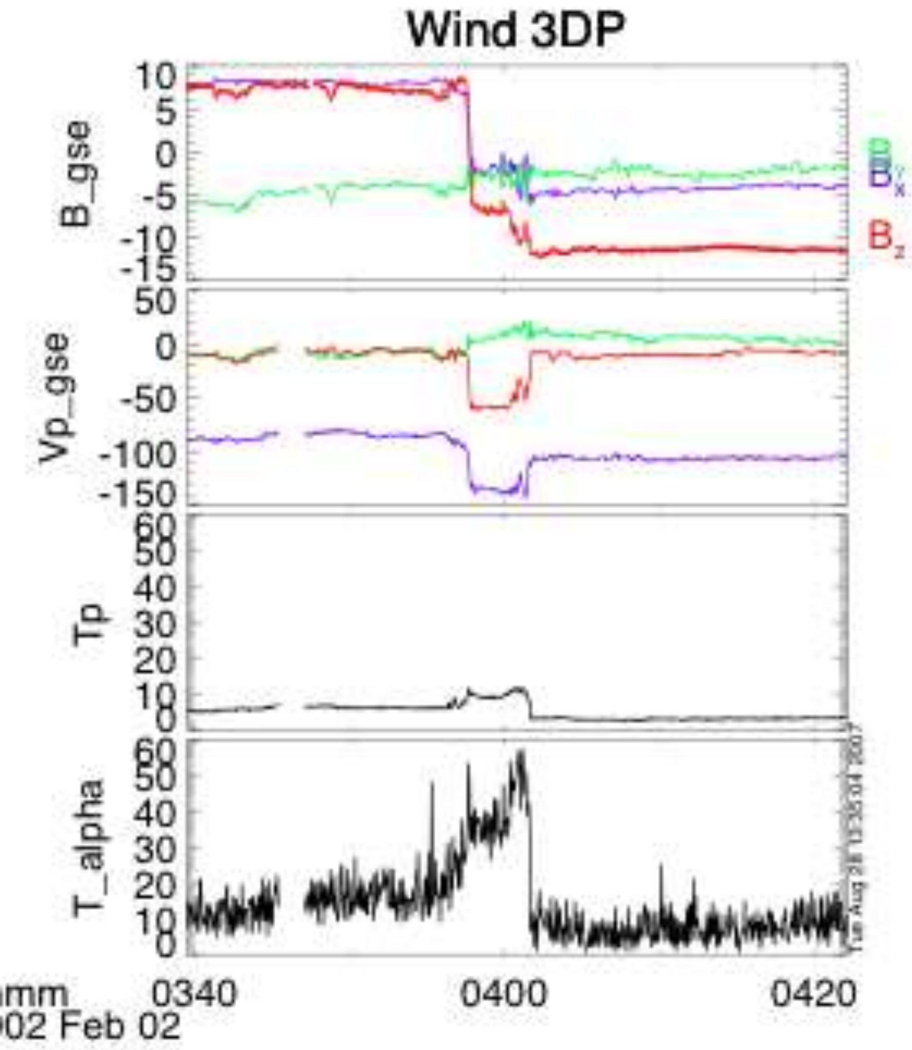
- During impulsive flares see heavy ion abundances enhanced over coronal values
- Enhancement linked to Q/M

$$\propto \left(\frac{Q}{M}\right)^{-3.26}$$



Mason, 2007

Wind observations of solar wind exhaust



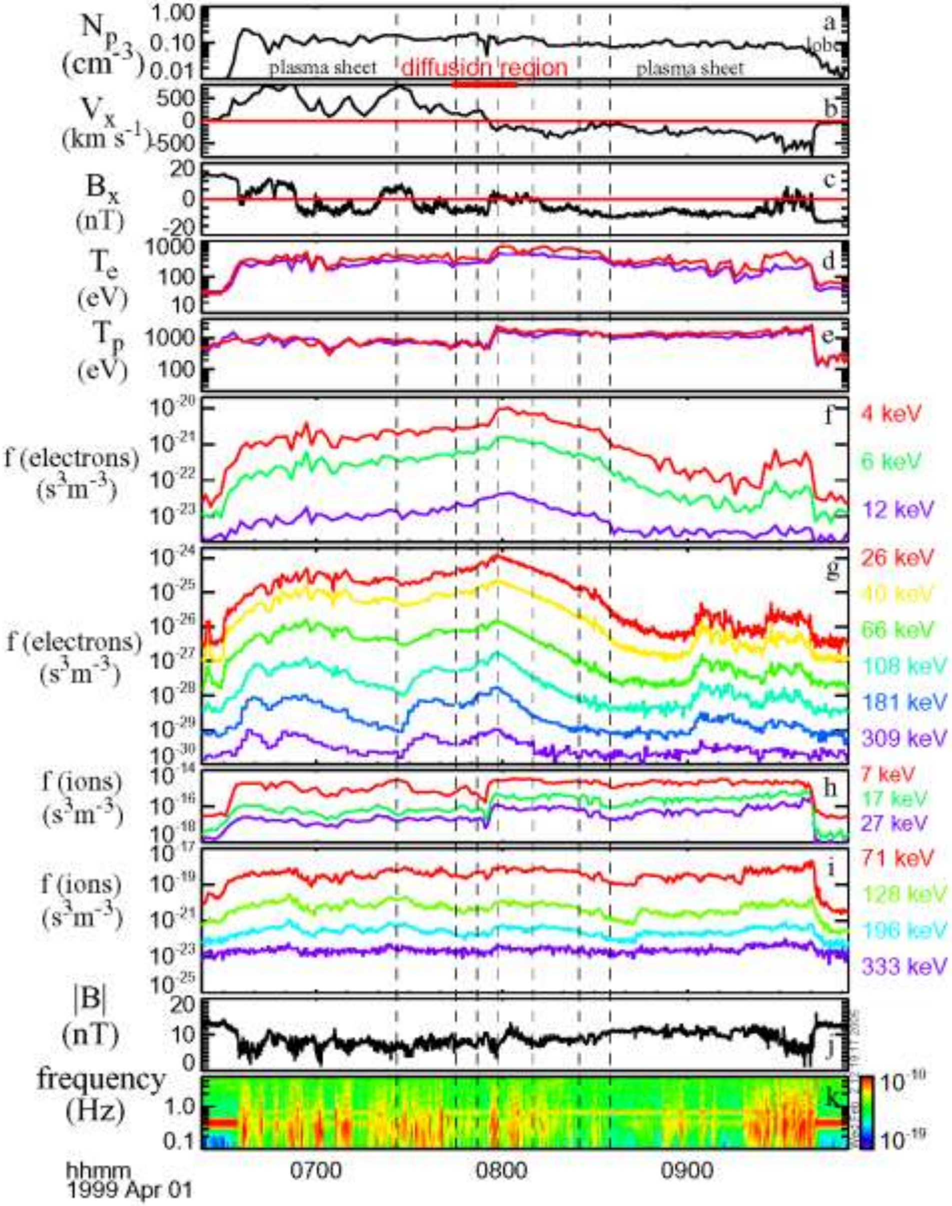
- Very large reconnection event ~300R_E (Phan et al., 2006)
- Exhaust velocity ~ 70km/s
- ΔT_p ~ 7eV
- ΔT_α ~ 30eV

$$\frac{\Delta T_\alpha}{\Delta T_p} = \frac{m_\alpha}{m_p}$$

- Same for higher mass ions

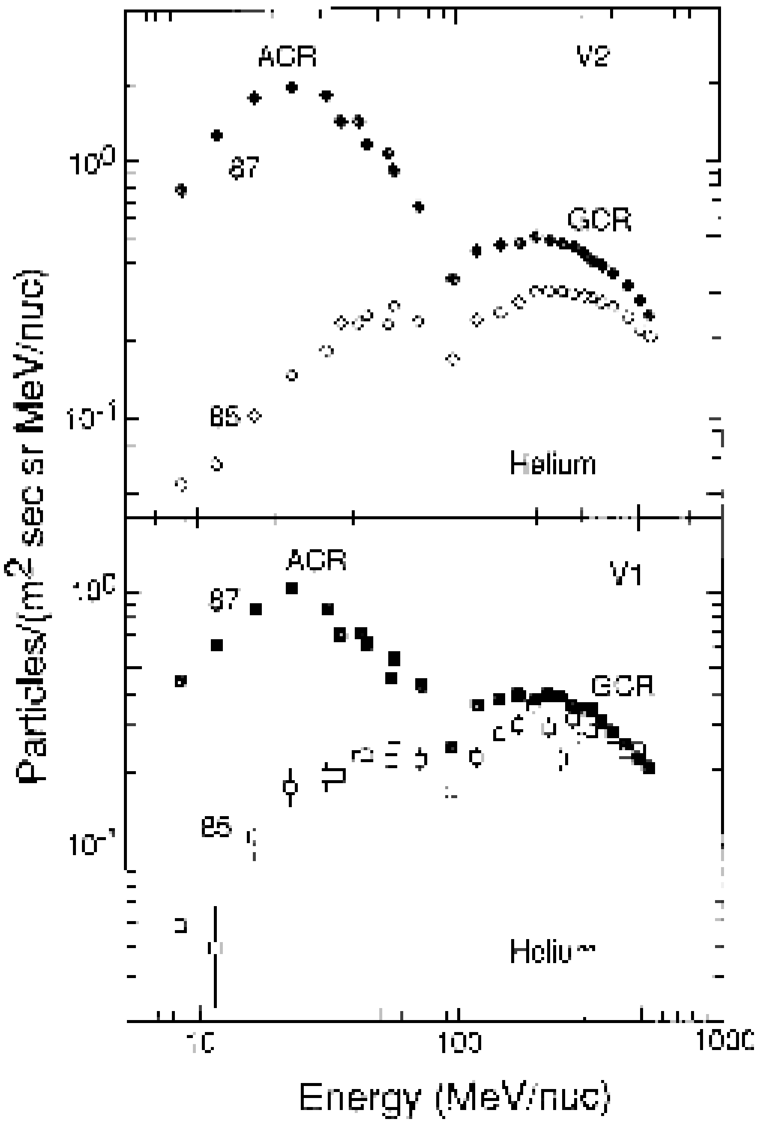
Wind magnetotail observations

- Wind spacecraft observations revealed that energetic electrons peak in the diffusion region (Oieroset, et al., 2002)
  - Energies measured up to 300kev
  - Power law distributions of energetic electrons

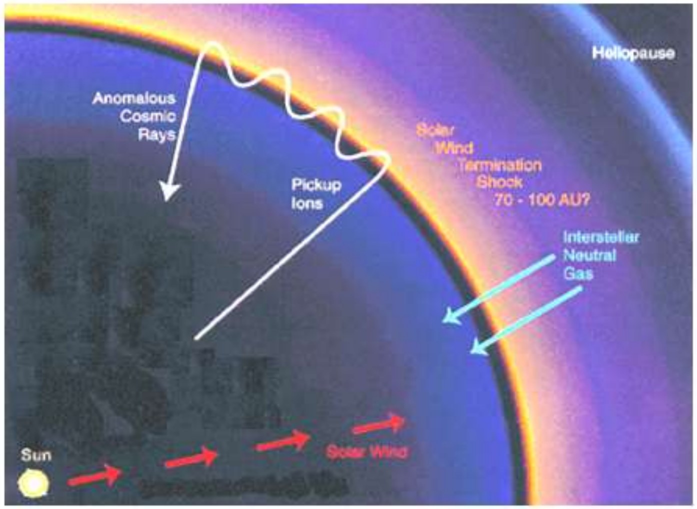


Anomalous Cosmic Rays (ACRs)

- 10-100MeV/nucleon particles
  - Energies just below those of galactic cosmic rays
- Voyager observations of He seen in 1985 and 1987 (Christian et al 1988)
  - Higher fluxes of ACRs with increasing distance from the sun
- The abundances of the various ion species reflect that of the Local Interstellar Medium (LISM)



The classical model: acceleration of ACRs at the termination shock



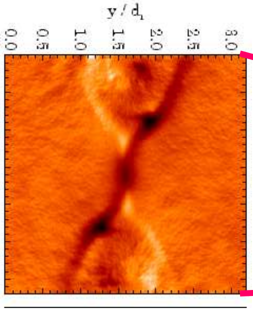
- The LISM neutrals are ionized and picked up deep within the heliosphere

$$T_i \sim m_i V_{sw}^2$$

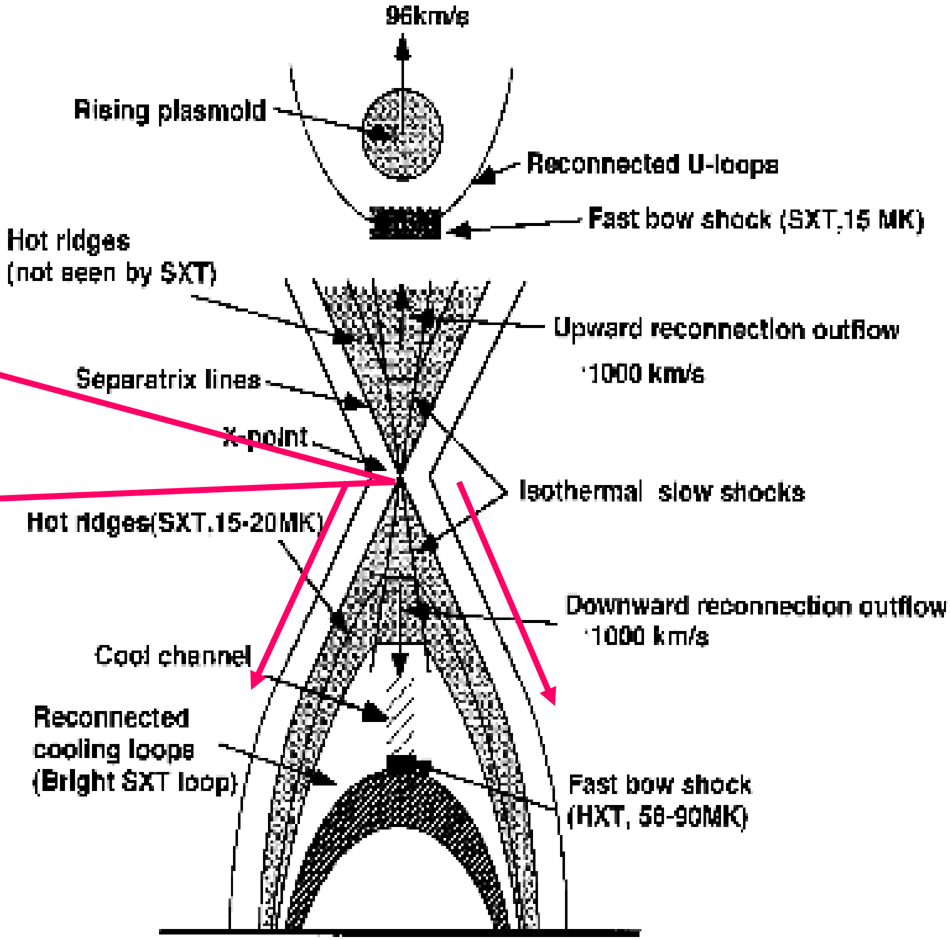
  - LISM pickup ions dominate the pressure in the outer heliosphere
- Carried by the solar wind out to the termination shock (TS) where they undergo diffusive shock acceleration (Fisk et al ‘74; Pesses et al ‘81)
  - LISM particles dominate the ACRs because they start with much higher energy than the solar wind ions
- Voyager observations revealed that the ACRs don’t peak at the termination shock – what is the acceleration mechanism?

Parallel electric fields and the single x-line model:

- Can parallel electric fields in a single x-line produce the large number of electrons seen in flares?
  - Around 10^{37}electrons/s
  - Downflow currents in a single x-line would be enormous
    - Producing 10^9G fields for L ~ 10^4km
  - Parallel electric fields are shorted out except near the x-line



- Magnetic energy is not released at the x-line but downstream as the reconnected fields relax their stress
  - The x-line is not where energy is released
  - The x-line region has negligible volume
- Can’t explain the large number of energetic electrons



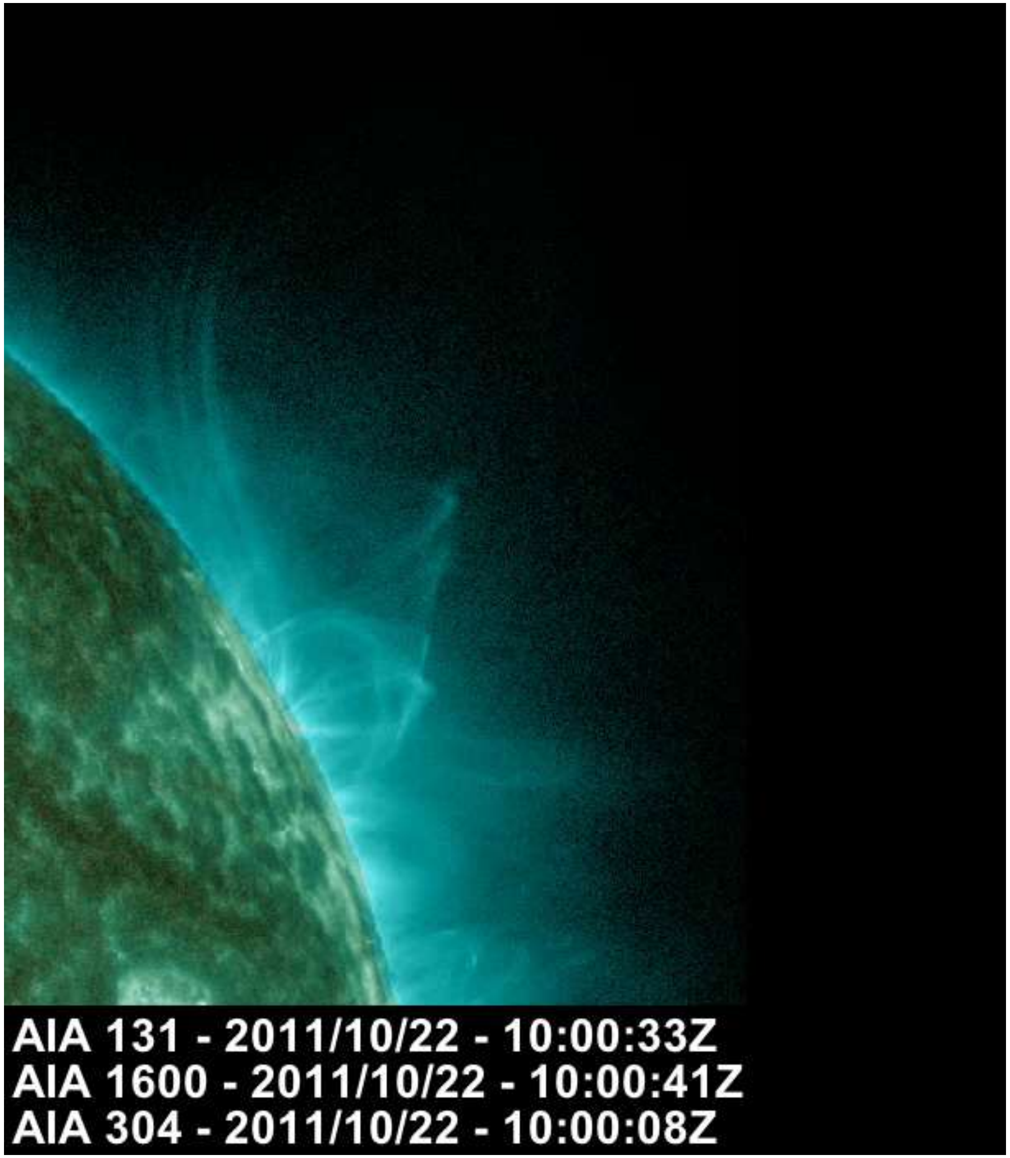
Tsuneda 1997

The parallel electric field model must be discarded!

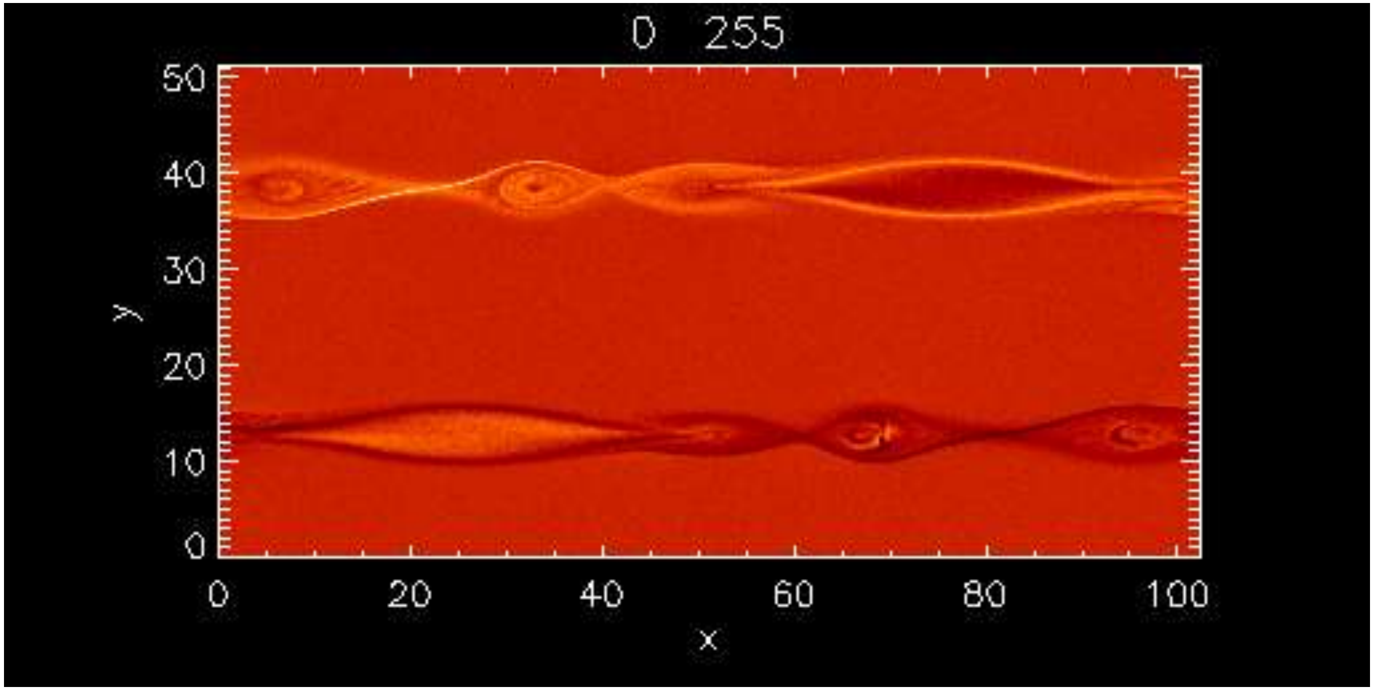
SDO/AIA flare observations

- Super Arcade Downflows (SADs) are interpreted as magnetic islands from an overlying reconnection site (Sheeley et al 2004)
- Such SAD events are now considered typical and not anomalies.
- Must abandon the classical single x-line picture!!

Savage et al 2012

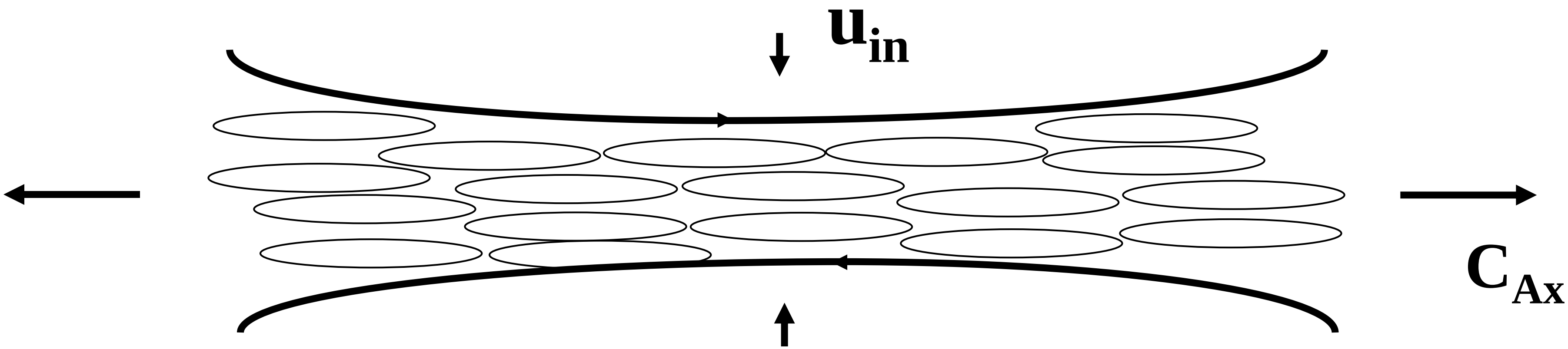


Magnetic reconnection with a guide field



- Reconnection in the corona typically has a non-zero guide field
- Narrow current layers spawn multiple magnetic islands in reconnection with a guide field (Drake et al 2006; Daughton et al 2011; Fermo et al 2012)

A multi-island acceleration model



- Hypothesize that the dissipation of magnetic energy involves the growth and interaction of many magnetic islands
  - Consistent with simulation models and observations of SADs in flares and flux ropes measured in the Earth’s magnetopause and magnetotail
- How are particles accelerated in a multi-island environment?

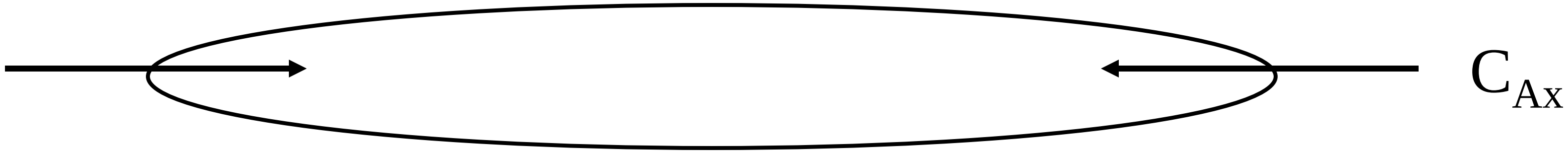
Particle acceleration in multi-island reconnection

- How are electrons and ions accelerated in a multi-island environment?
  - Fermi reflection in contracting magnetic islands (Kliem 94, Drake et al 2006, 2010)

$$\frac{d\epsilon}{dt} \sim 2\epsilon \frac{c_A}{L_x}$$

  - Rate of energy gain independent of particle mass

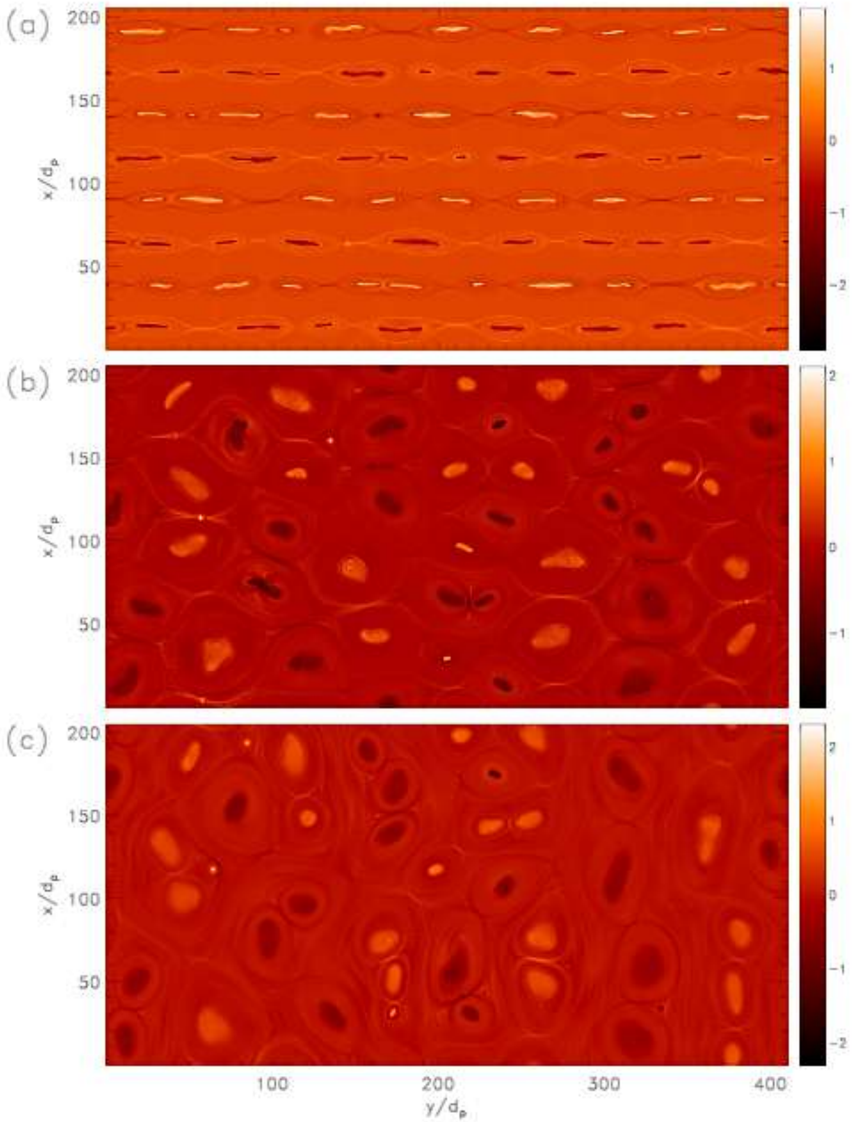
⇒ same for electrons and protons



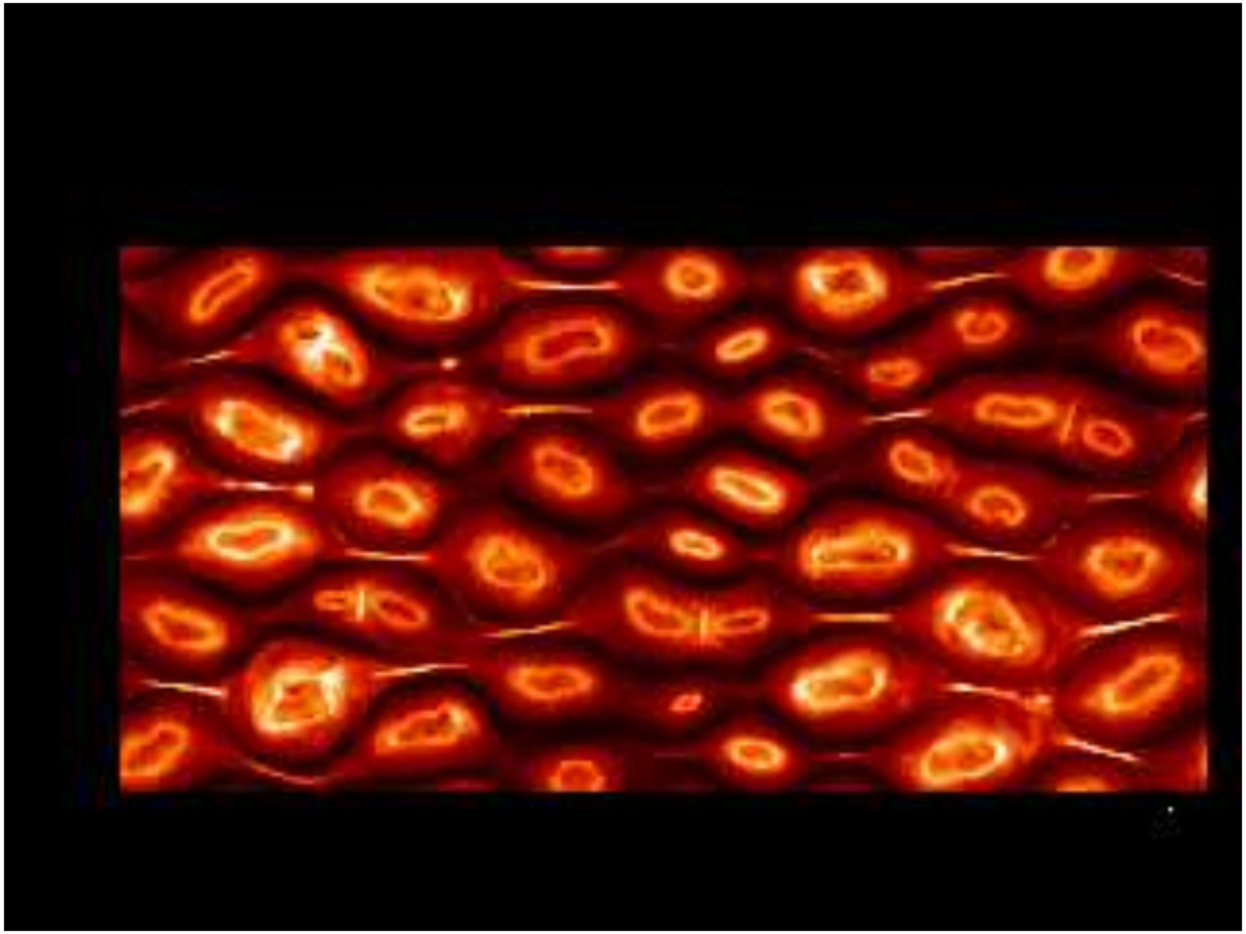
Simulation of multi-island particle acceleration

- Simulations of reconnection and particle acceleration in 3-D while maintaining adequate separation of scales is a computational challenge
  - Carry out 2-D simulations in a multi-current layer system
  - Can study particle acceleration in a multi-island system

J_{ez}



Reconnection dynamics



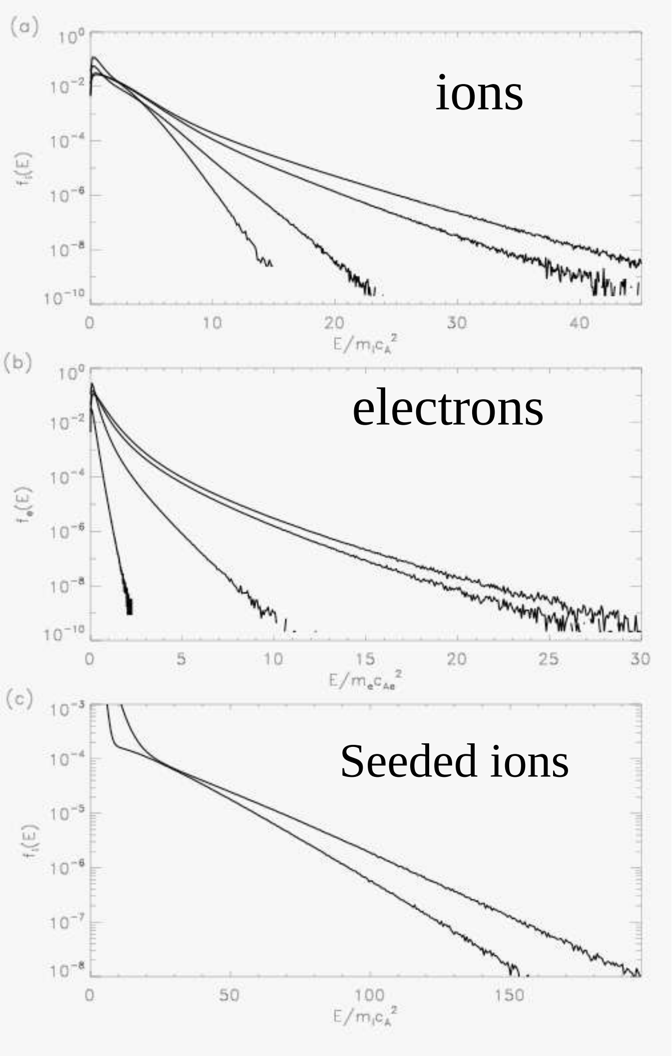
- First have magnetic island growth on individual current layers
- Then merging of islands on adjacent layers

Electron and ion energy spectra

- Both ions and electrons gain energy
- Include 5% population hotter seed particles
- A key feature is that the rate of energy gain of particles increases with energy

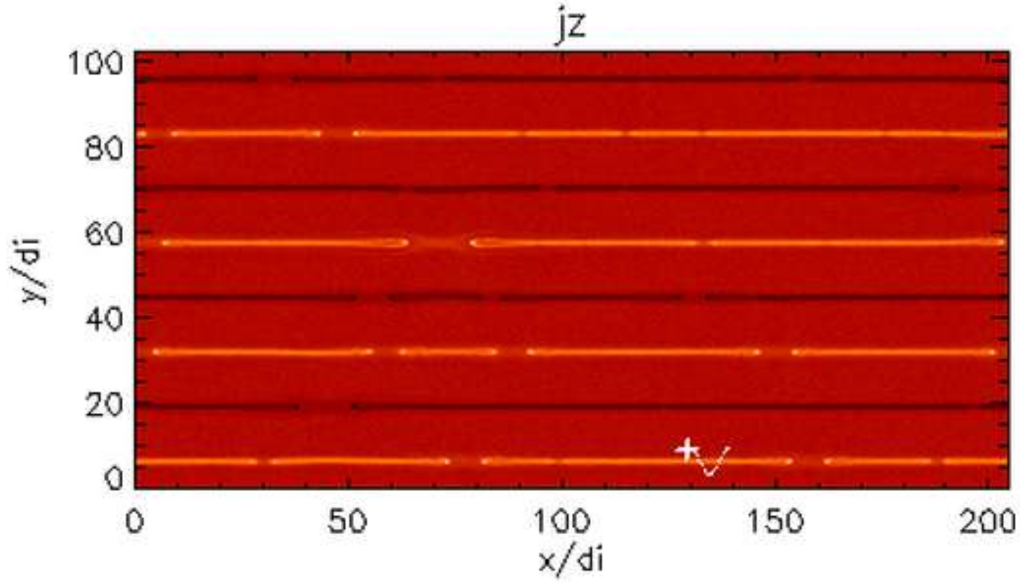
$$\frac{de}{dt} \mu \epsilon$$

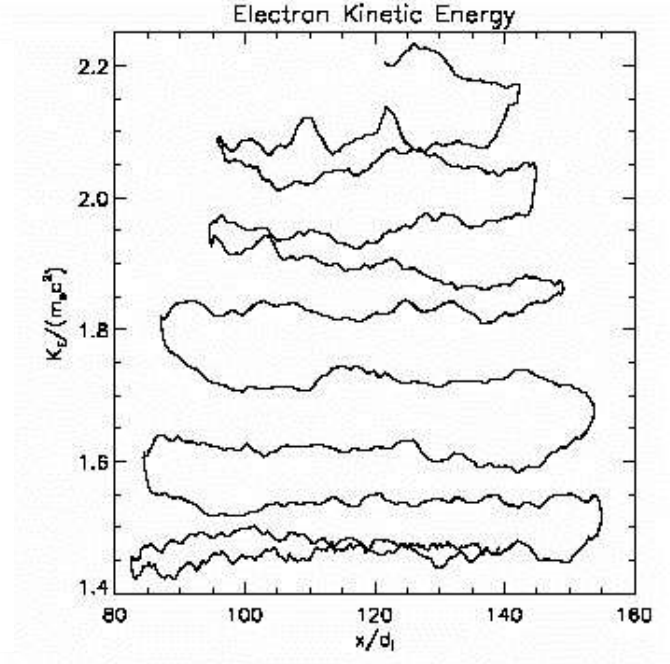
⇒ consistent with first order Fermi

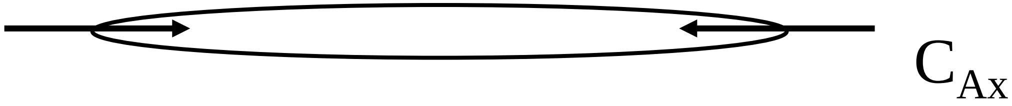


Fermi acceleration

- How do the most energetic particles gain energy?
  - Reflection from the ends of contracting islands
  - Increase of parallel energy and pressure $p_{\parallel}$







$$\frac{d\varepsilon_{\parallel}}{dt} \sim 2\varepsilon_{\parallel}\frac{c_A}{L_x}$$

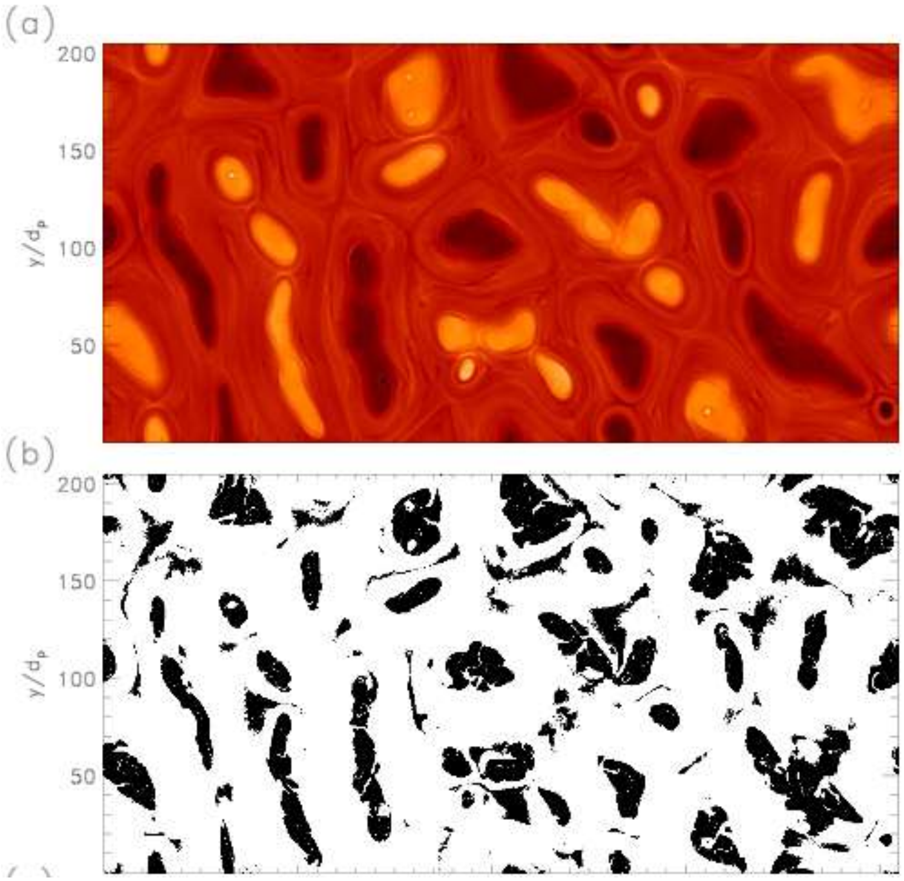
Schoeffler et al 2011

Firehose condition

- In a plasma with a pressure anisotropy the wave dispersion relation is

$$\omega^2 = k_\parallel^2 c_A^2 \left(1 - \frac{1}{2}\beta_\parallel + \frac{1}{2}\beta_\perp\right)$$

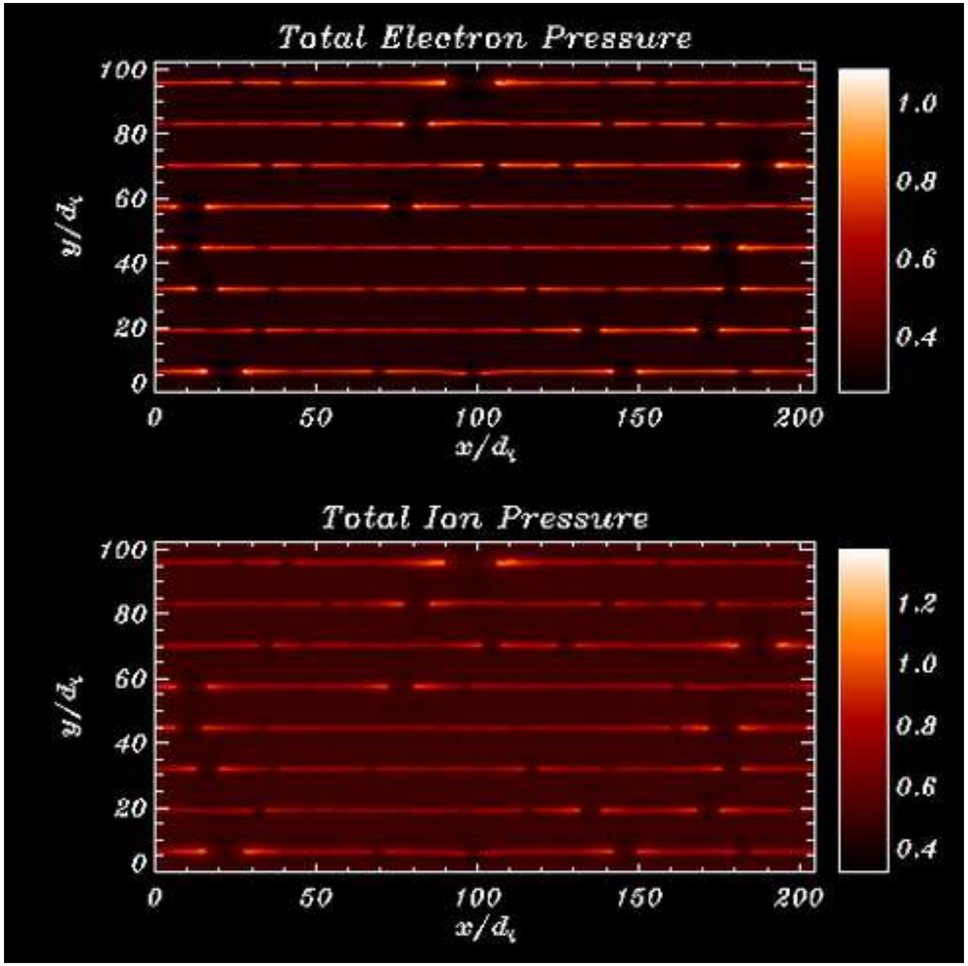
  - Firehose instability for large enough anisotropy
- The firehose condition is violated within islands
  - No tension in magnetic fields when the firehose condition is violated
  - Driving force for reconnection is eliminated
  - Controls particle spectra
- Self-consistency is crucial in exploring particle acceleration



firehose

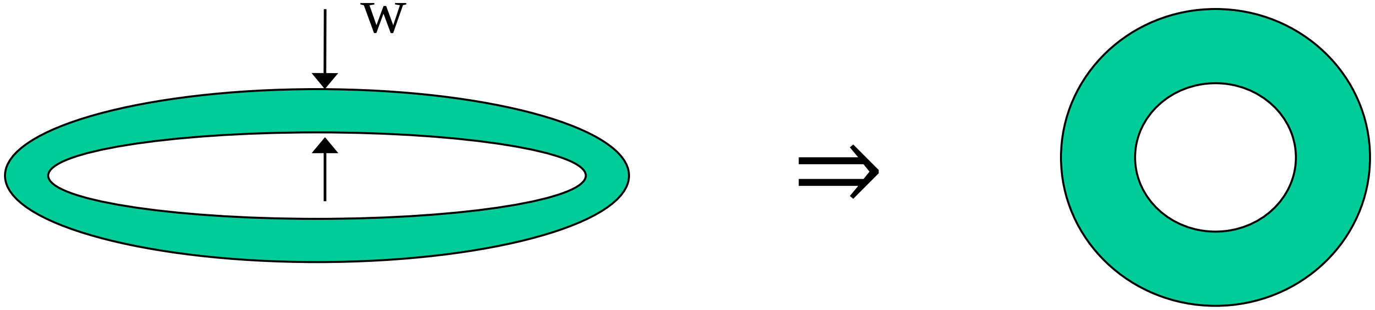
Firehose instability during island contraction

- Fermi reflection within islands increases $p_{\|}$ and leads to firehose



Schoeffler et al 2011

Fermi acceleration in contracting islands



- Area of the island Lw is preserved

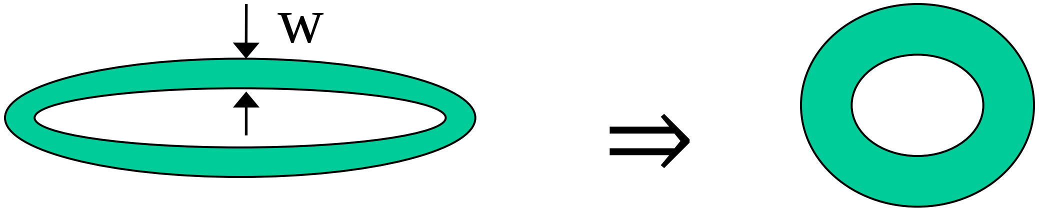
  ⇒ incompressible dynamics

- Magnetic field line length L decreases
- Parker's transport equation

$$\frac{\partial F}{\partial t} + \nabla \bullet uF - \nabla \bullet \kappa \bullet \nabla F - \frac{1}{3}(\nabla \bullet u)\frac{\partial}{\partial v} vF = 0$$

  - Only compression drives energy gain. Why?
  - Parker equation assumes strong scattering ⇒ isotropic plasma

Fermi acceleration in contracting islands



- Area of the island Lw is preserved
- Magnetic flux Bw is preserved
- Particle conservation laws
  - Magnetic moment $\mu = mv_{\perp}^{2}/B$ net energy loss
  - Parallel action $V_{\|}L$ net energy gain
- Energy change for initially isotropic plasma

$$W = \frac{1}{2} m v_0^2 \left(\frac{2L}{3L_0} + \frac{L_0^2}{3L^2} \right)$$

  - No energy gain for infinitesimal change in L ⇒ consistent with Parker
  - Significant energy gain for finite contraction
    - Parker equation is missing some important physical processes

General kinetic description particle acceleration in a multi-island current layer

- The merging of two islands causes field lines to shorten and the magnetic field strength to decrease
- Calculate particle energy gain during the merging of a bath of magnetic islands
  - Energy gain in $v_\parallel$ due to Fermi reflection
  - Energy loss in $v_\perp$ due to magnetic moment conservation
- Kinetic equation for $f(v_\parallel, v_\perp)$ with $\zeta = v_\parallel/v$

$$\frac{\partial f}{\partial t} + \Gamma\left(\frac{\partial}{\partial v_\parallel} v_\parallel - \frac{1}{2v_\perp}\frac{\partial}{\partial v_\perp} v_\perp^2\right) f - \gamma\frac{\partial}{\partial \zeta}\left(1-\zeta^2\right)\frac{\partial}{\partial \zeta} f + \frac{c_A}{L} f = \dot{A} f_0$$

merging drive

pitch-angle scattering

  - Equidimensional equation – no intrinsic scale
  - Powerlaw solutions

Energetic particle distributions

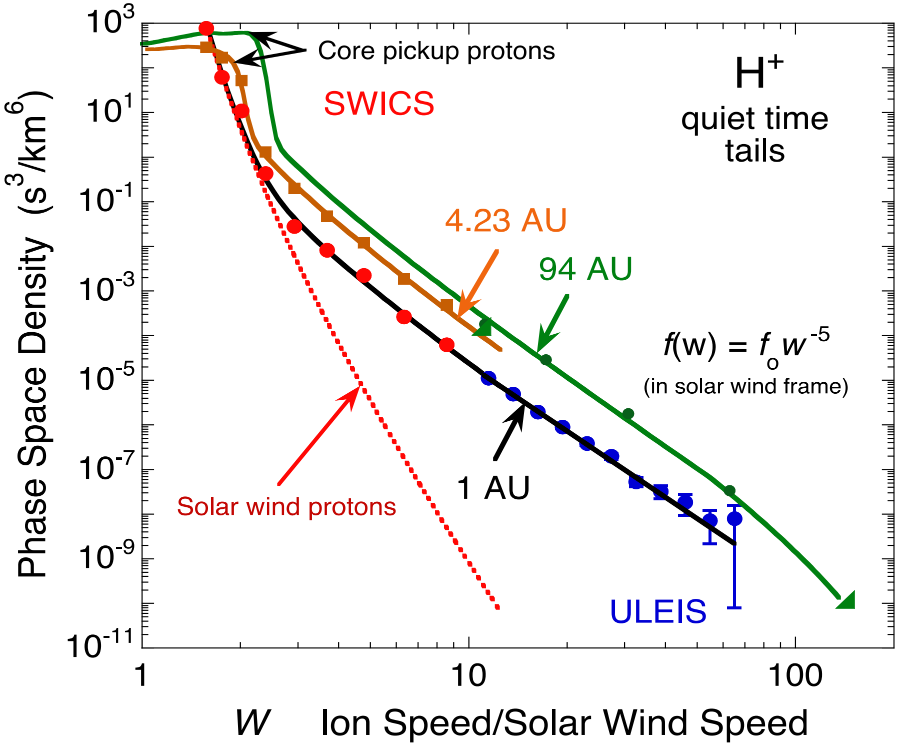
- Solutions in the strong scattering limit with feedback from the high pressure (firehose) and convective loss
  - Powerlaw solutions for the omnidirectional distribution function

$$f(v) \sim v^{-g}$$

  - Universal spectral index given by

$$g = 5$$

Universal super-Alfvenic ion spectrum in the quiet solar wind

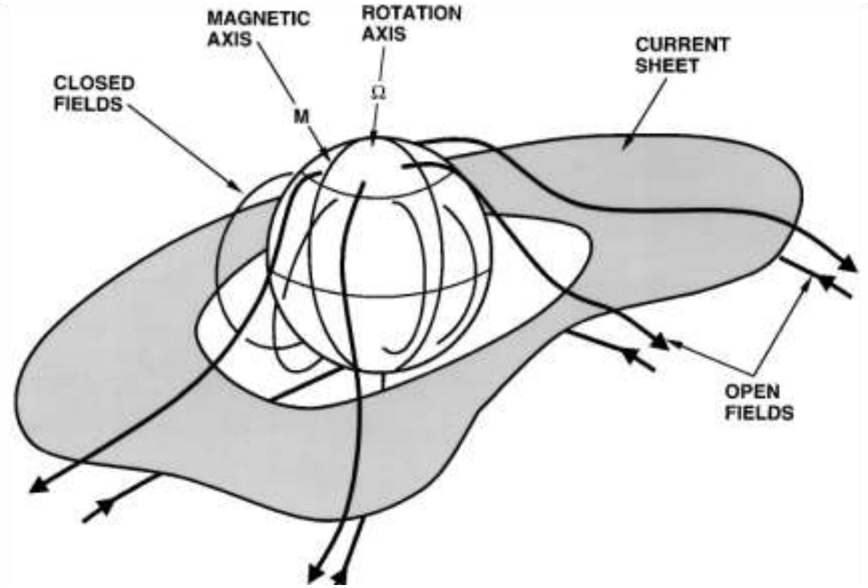


Fisk and Gloeckler, 2006

- Proton spectra of the form f α v^{-5} are observed throughout the heliosphere

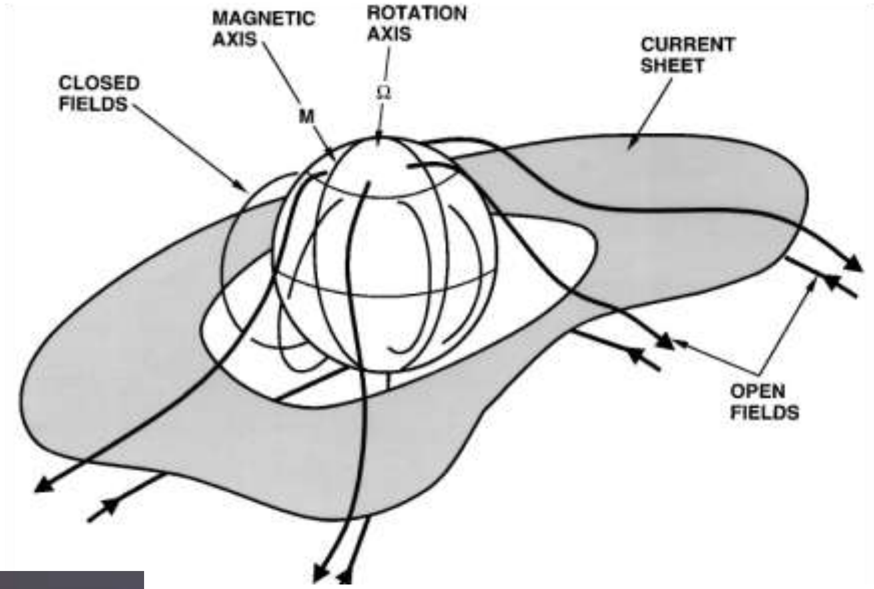
The Parker spiral magnetic field

- The sun’s rotation twists the solar dipole magnetic field into the Parker spiral
  - Dominantly azimuthal magnetic field B_ϕ
  - Dominantly radial current sheet
  - The sign of B_ϕ flips across the current sheet



Sector structure of the heliospheric field

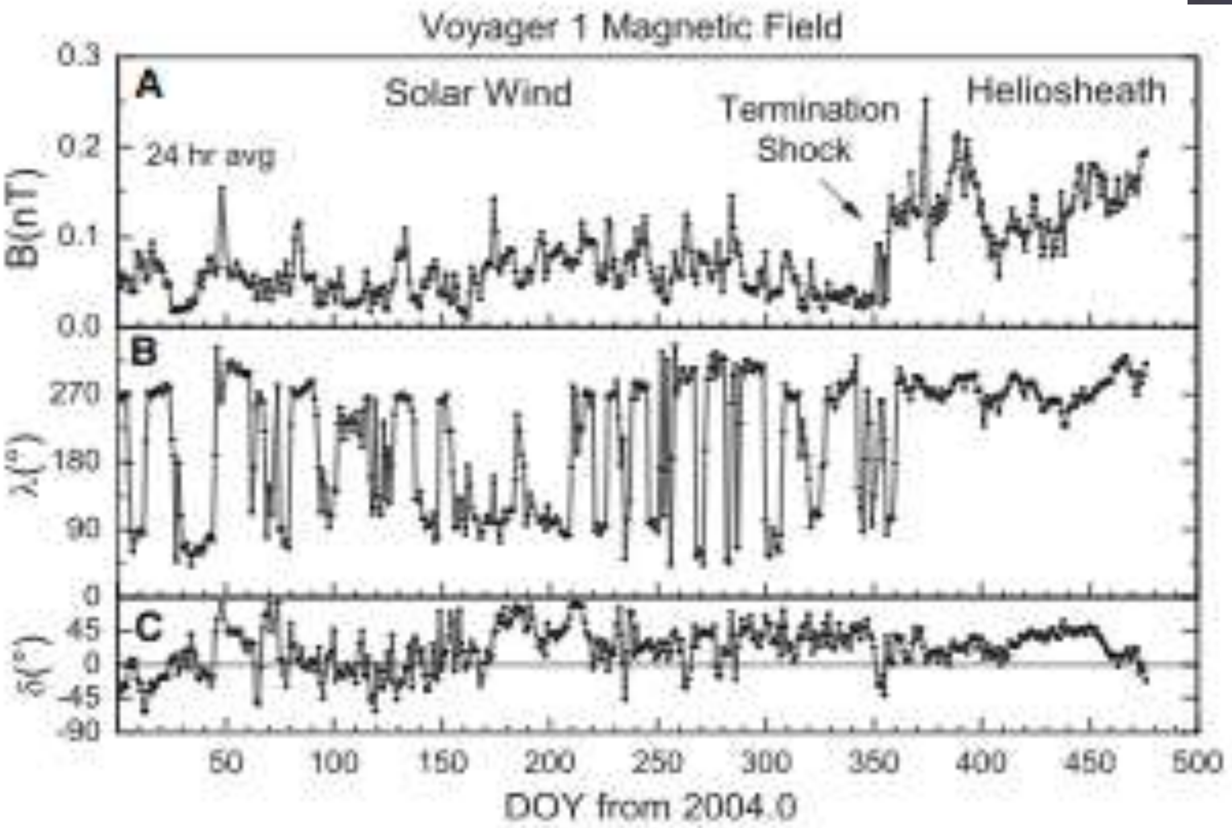
- Misalignment of the magnetic and rotation axes causes the heliospheric current sheet to flap
- Periodic reversal of B_ϕ with increasing radius R

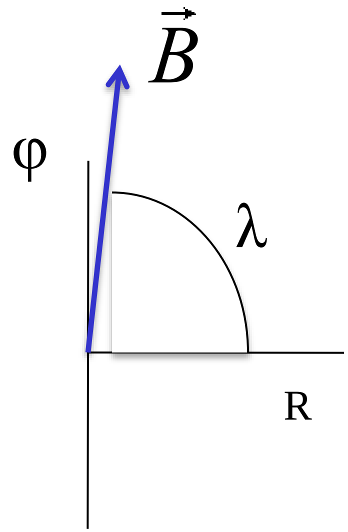


Heliospheric current sheet

Voyager measurements of the sectored magnetic field

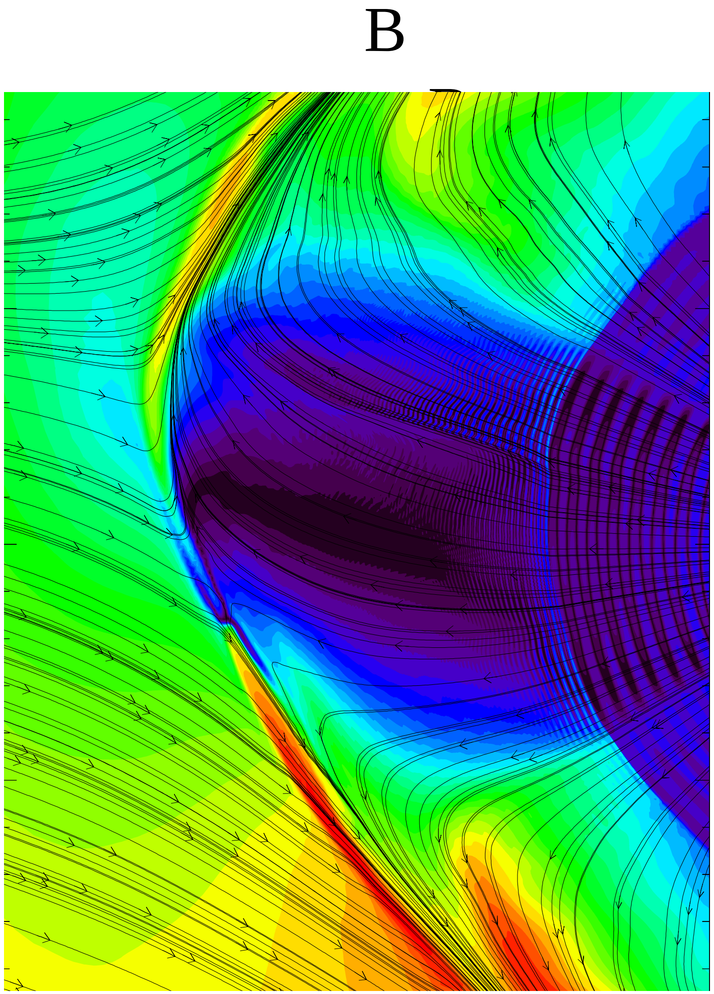
- Periodic reversal of B_ϕ





MHD model of the heliosphere

- 3-D MHD model
- The tilt of the solar magnetic field with respect to the rotation axis generates a sectored magnetic field
  - Latitudinal extent ~ 30 degrees
  - Sectors are compressed across the TS and as the flow slows as it approaches the heliopause
  - The sectors spread to high latitudes on their approach to the heliopause
- Magnetic reconnection of the sectored field is inevitable

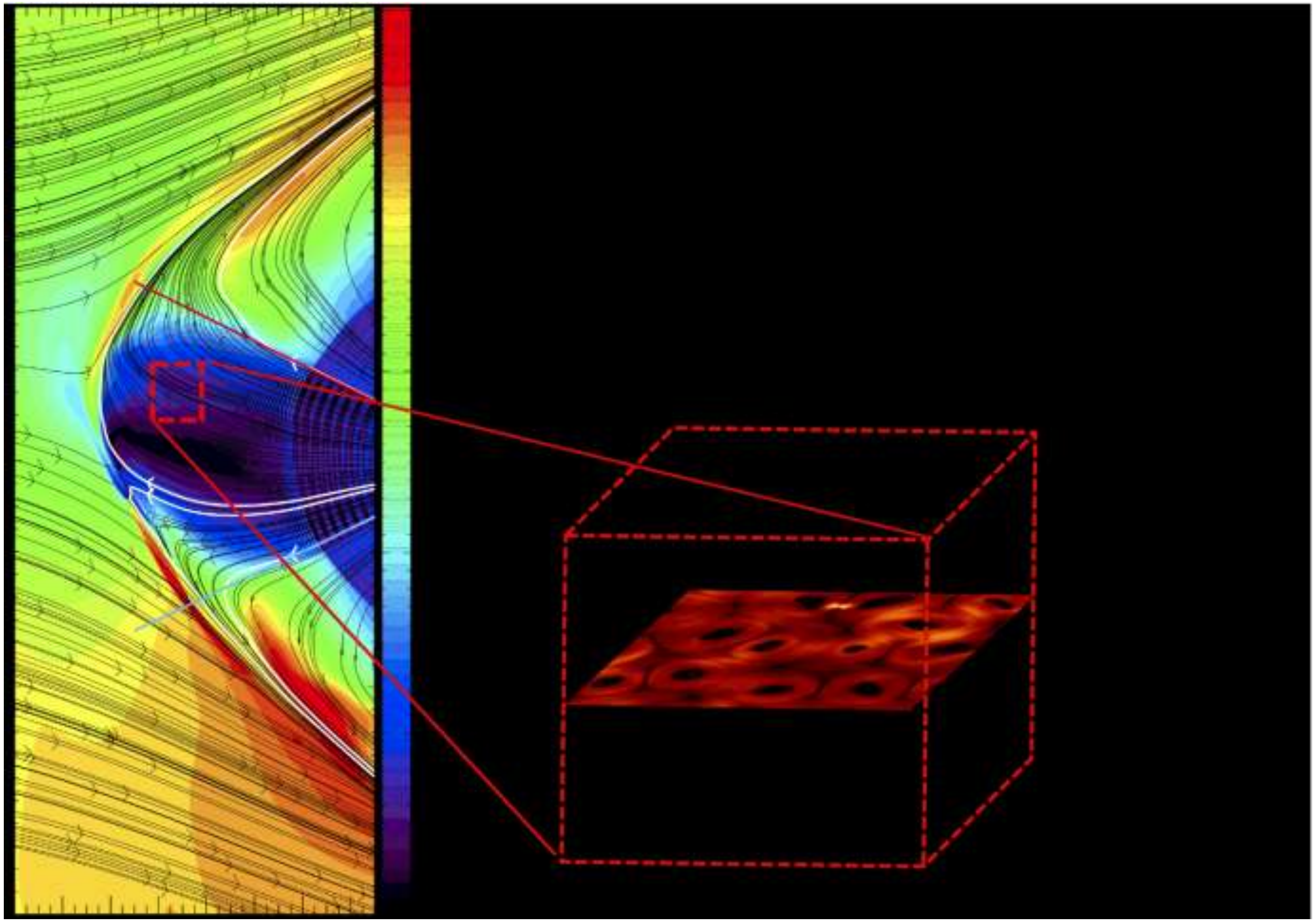


Opher et al 2011

Is the magnetic field of the outer heliosphere laminar or broken up into magnetic islands?

Opher et al 2011

- The Voyager spacecraft are providing evidence that the sectored fields reconnect in the heliosheath
  - An enormous region of reconnecting magnetic fields
  - The islands spread to high latitudes upstream of the heliopause

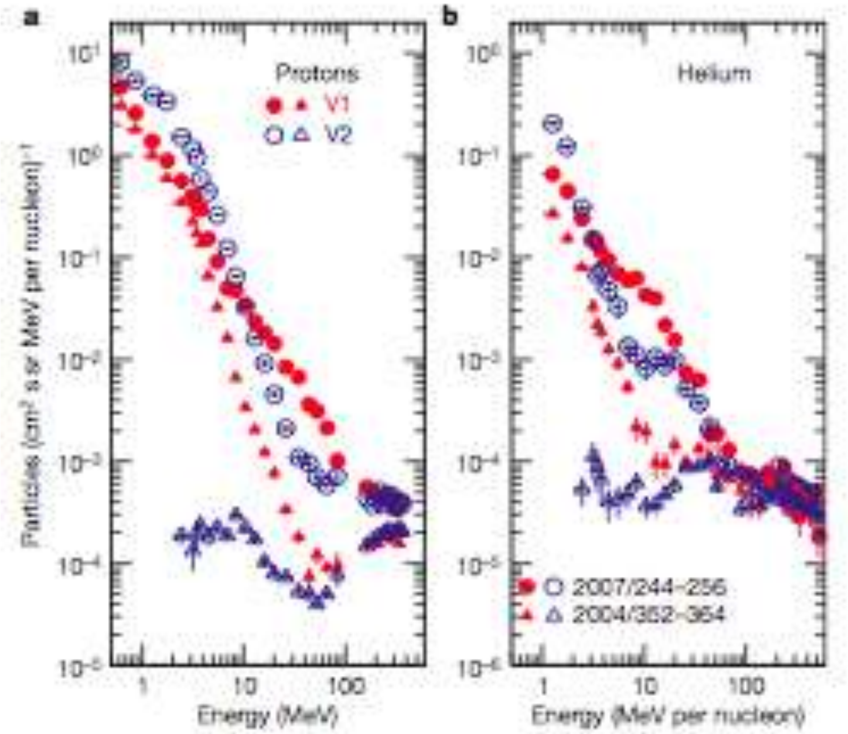


Reconnection model for ACRs

- The Voyagers may be the first spacecraft to enter a region of multi-island reconnection and particle acceleration
- For ACRs the prediction is for powerlaws

$$F \sim v^2 f \sim v^{-3} \sim E^{-1.5}$$

  - This is consistent with measured Voyager spectra



What about particle acceleration in flares?

- Electrons are directly accelerated through the contracting island mechanism even in the low β corona
  - Predicted spectra are consistent with those inferred from the most energetic events
- In low β coronal conditions ions are too slow to bounce
  - Need a seed ion heating mechanism
- Ions are heated as they enter the reconnection exhaust and gain an effective thermal velocity comparable to the exhaust velocity

$$\Rightarrow v_t^2/c_A^2 \sim 1$$

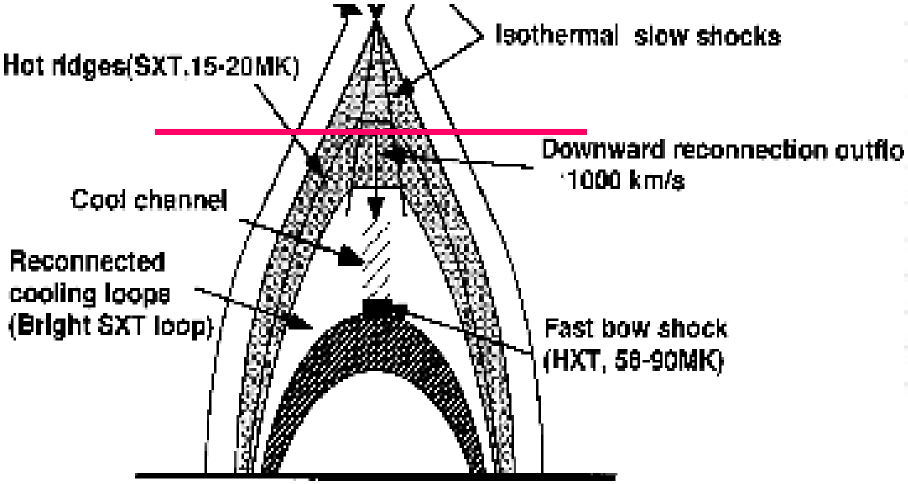
- Once the ion thermal velocity is comparable to the Alfven speed the ions can gain further energy through the reflection in contracting and merging magnetic islands

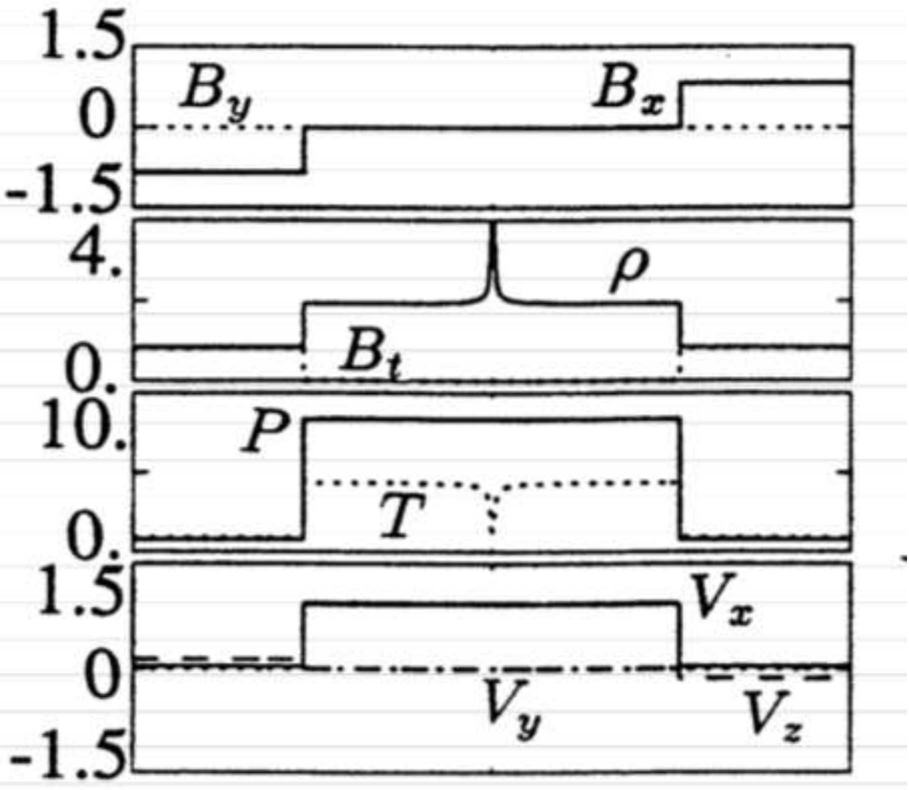
Seeding super-Alfvenic ions through pickup in reconnection exhausts

- Ion heating is dominated by large-scale reconnection exhausts rather than the localized region around the x-line
- Ions moving from upstream cross a narrow boundary layer into the Alfvenic reconnection exhaust
- The ion can then act like a classic “pick-up” particle, where it gains an effective thermal velocity equal to the Alfvenic outflow $T_i \sim m_i c_{Ax}^2$
  - during guide field reconnection there is a threshold for pickup behavior

The MHD description of slow shock heating: anti-parallel magnetic fields

- In the MHD model the reconnection exhaust boundary consists of a pair of switch-off slow shocks (Petschek '64)



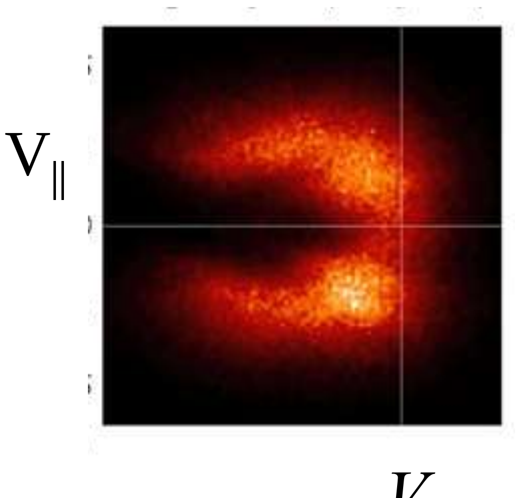


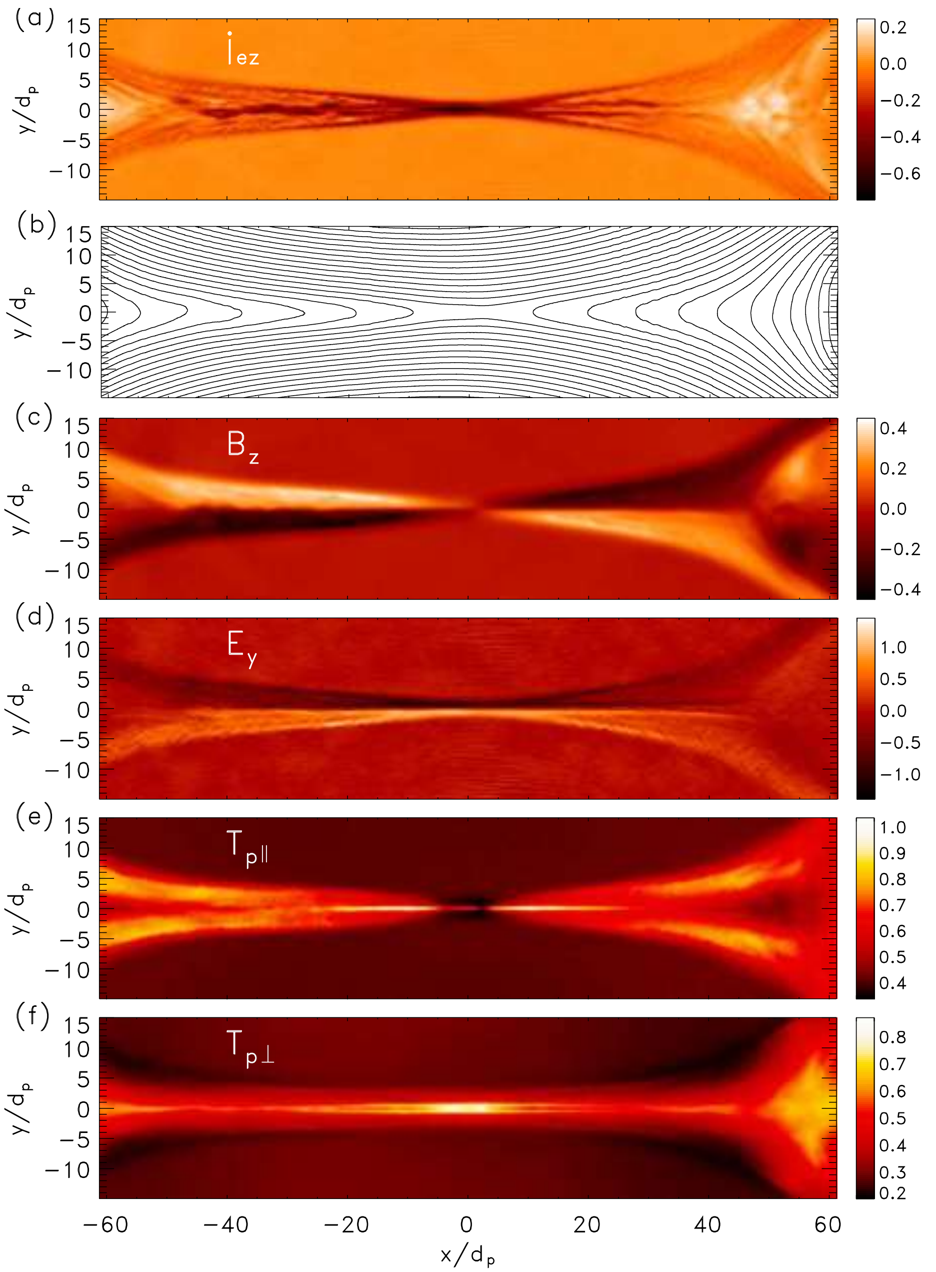
- MHD description fails because mean-free-path is longer than the shock scale
- Strong pressure anisotropy eliminates the switch-off slow shock (Liu et al '02)

Ion acceleration during reconnection

- PIC simulation
- Focus on ion heating well downstream of the x-line?
- Sharp increase of T_i in the exhaust
  - Counterstreaming ions

$$T_{\|} > T_{\wedge}$$

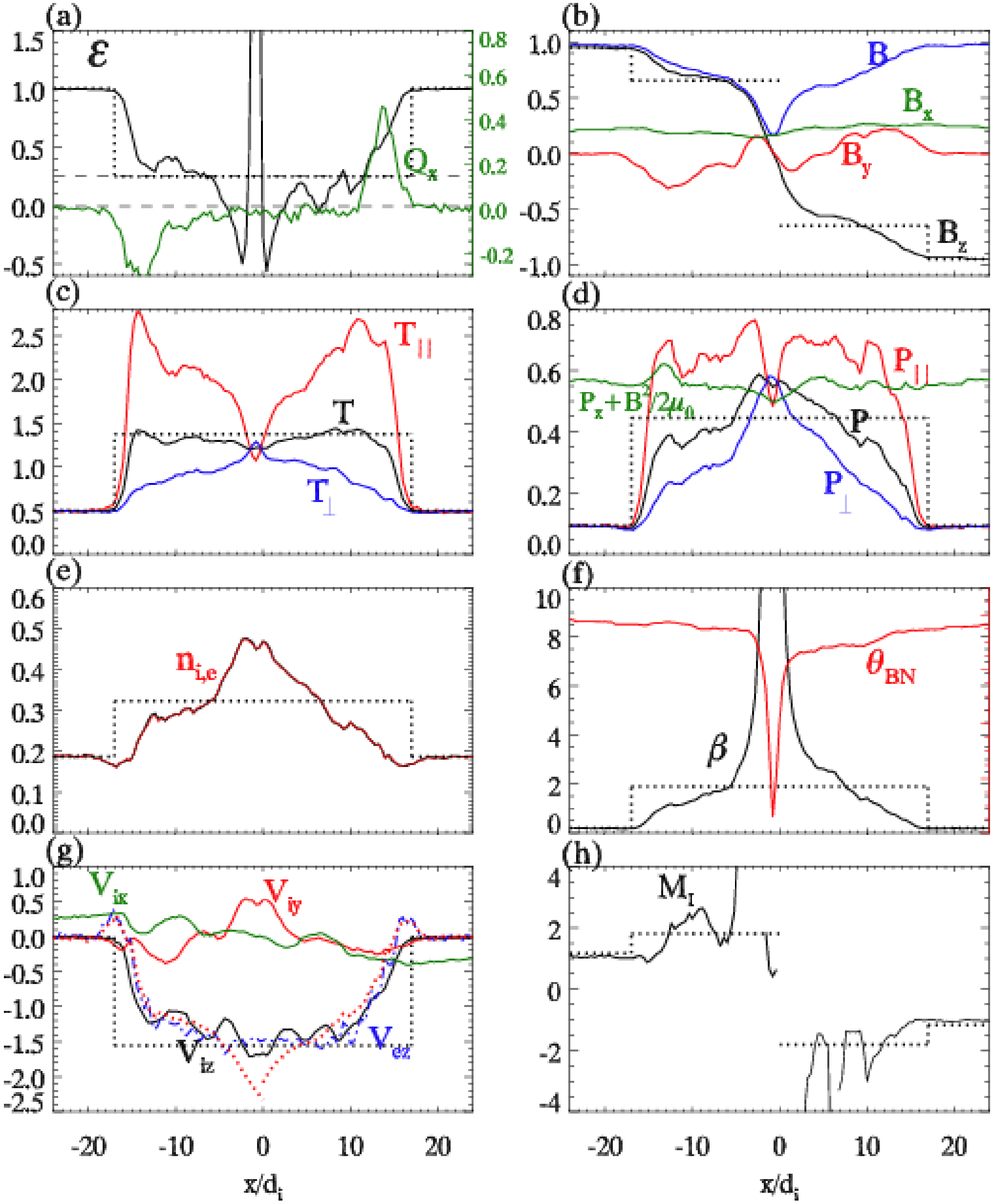




Structure of the reconnection exhaust: anti-parallel

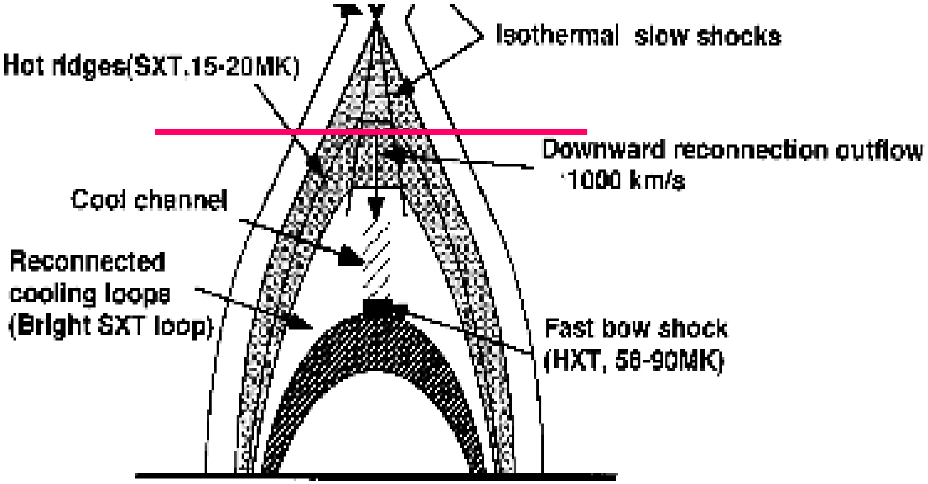
- Petschek slow shocks can’t exist because of the pressure anisotropy
  - Anisotropy reduces the speed of the intermediate mode below that of the slow mode
  - Firehose parameter

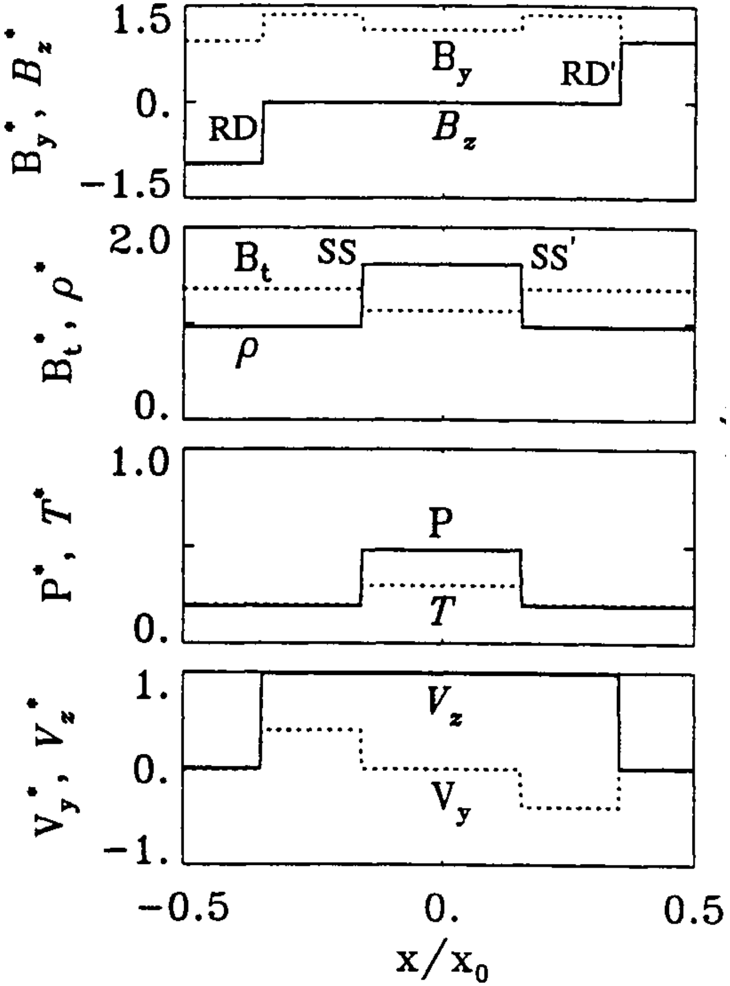
$$e^{o}\ 1 - \frac{1}{2} b_{\|} + \frac{1}{2} b_{\wedge}$$



The MHD description of slow shock heating: guide field case

- In the MHD model the reconnection exhaust boundary consists of a pair of rotational discontinuities followed by a pair of slow shocks

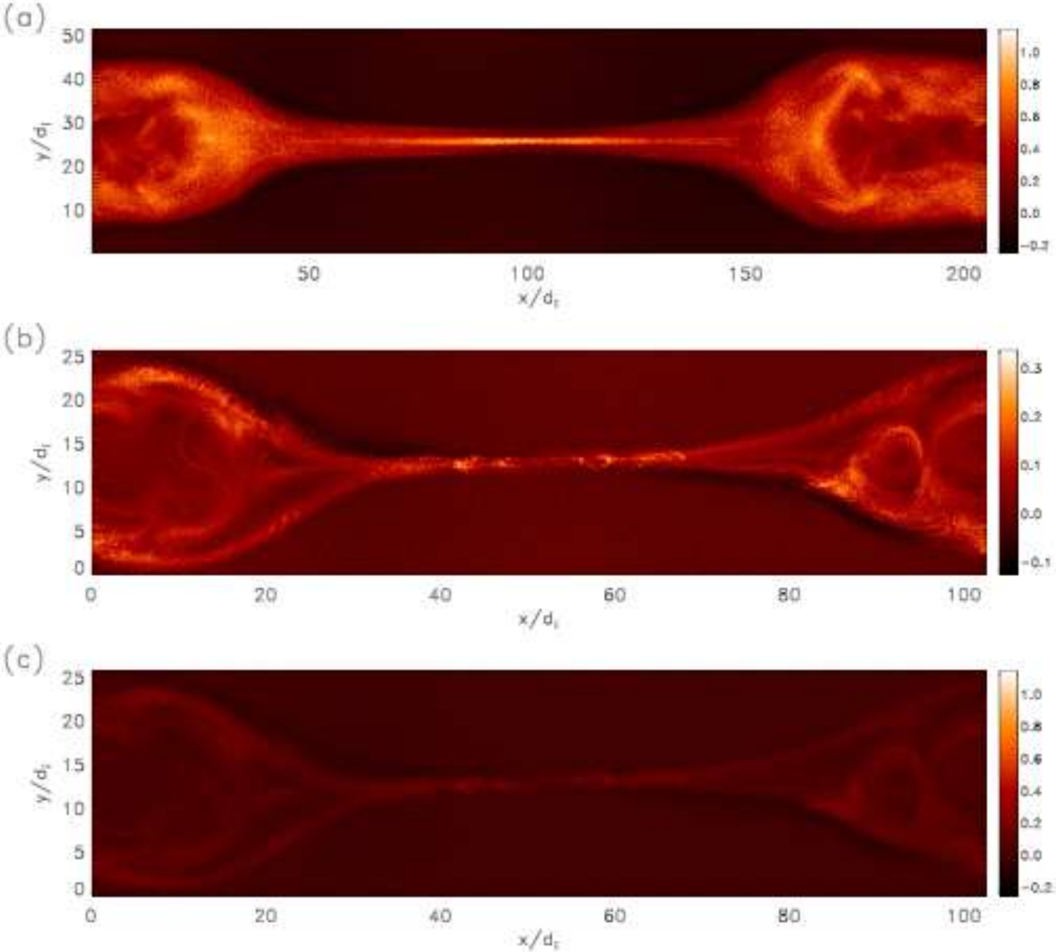




- MHD description fails because mean-free-path longer than the shock scale
  - Strong ion heating at the RD in the kinetic model

Ion temperature in reconnection outflows: anti-parallel versus guide field

- Comparison of PIC simulations with and without a guide field
- Temperature increments of protons
  - Little proton heating with strong guide field
  - Protons are adiabatic
  - Why?

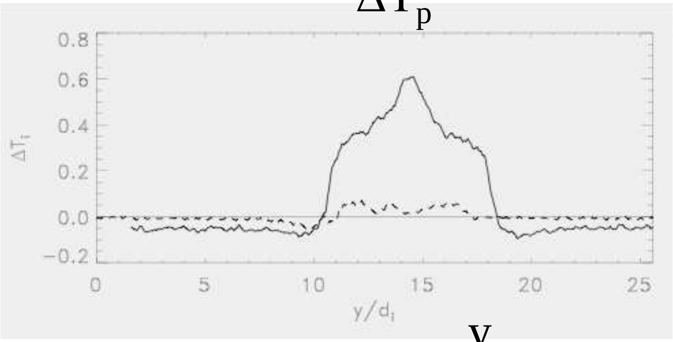


$B_{z0}=0$

$B_{z0}=2$

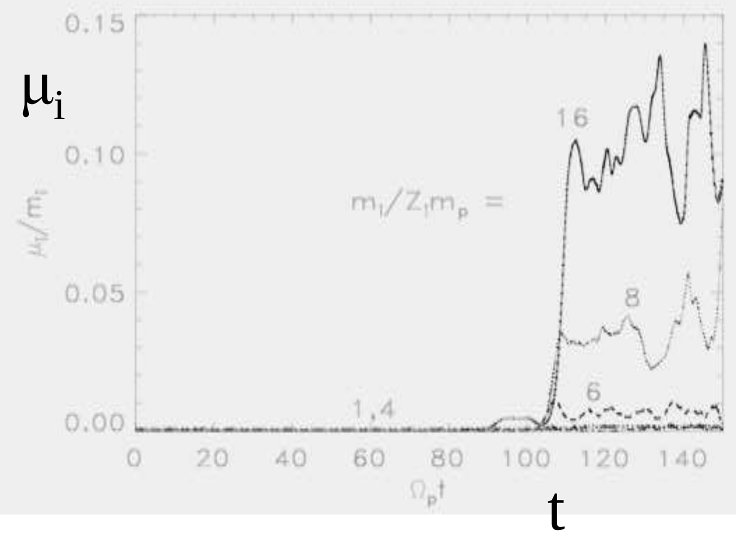
$B_{z0}=2$

ΔT_p

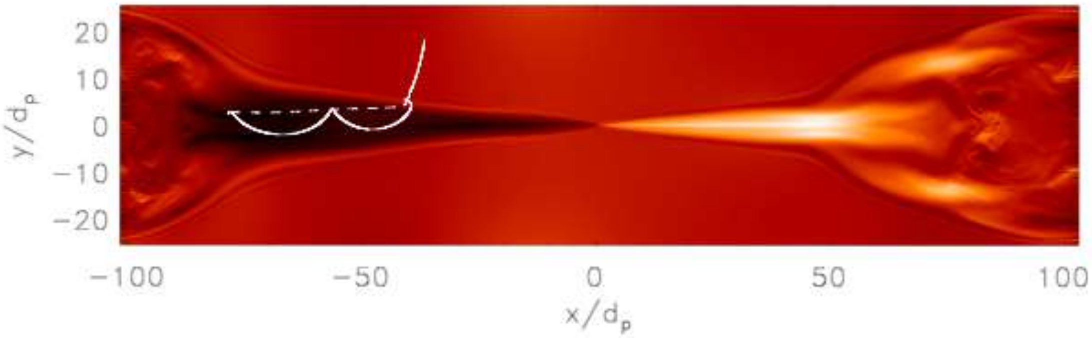


y

Pickup threshold: guide field



E_y



$B_{z0} = 5.0$

- Protons and alpha particles remain adiabatic (μ is conserved)
- Only particles that behave like pickup particles gain significant energy ⇒ threshold for pickup behavior

$$\frac{v_{iy}}{\Delta} \approx \frac{0.1 c_{Apx}}{r_{sp}} > \Omega_i \Rightarrow \frac{m_i}{Z_i m_p} > \beta_{px}$$

$$\Delta T_\perp = \frac{1}{2} m_i c_{Ax}^2 \qquad \Delta T_\parallel = 0$$

Reconnection with multiple ion species

- PIC simulations with a guide field 2.0 times the reconnecting field
  - Protons in the adiabatic regime

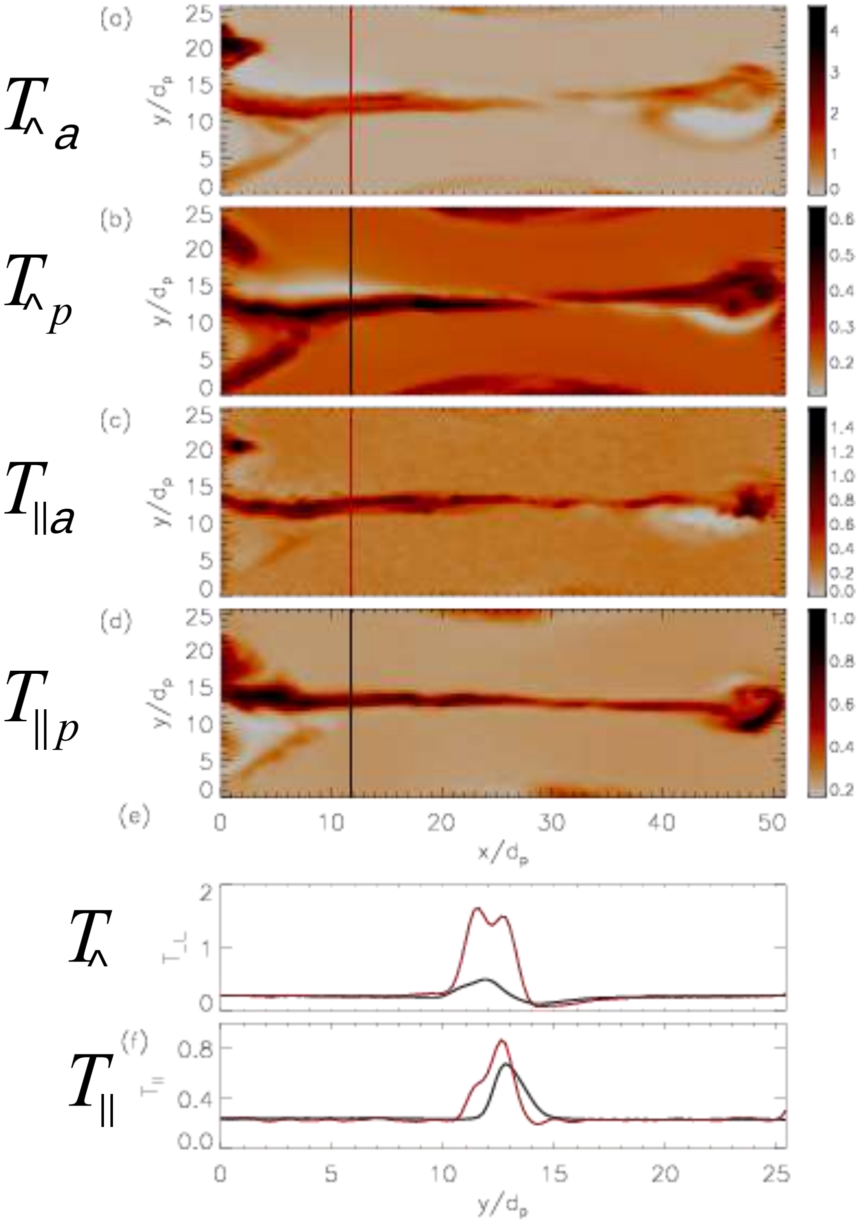
$$b_{px} > 1$$

  - Include 1% fully stripped alpha particles
    - In the pickup regime

$$\frac{m_a}{Z_a m_p} > b_{px}$$

Alpha and proton heating

- Strong enhancement of $T_{\wedge a}$
  $T_{\wedge a} >> T_{\parallel a}$
  - Very different from anti-parallel reconnection
- Strong alpha heating compared to that of protons
  - Consistent with predictions



$T_{\wedge a}$

$T_{\wedge p}$

$T_{\parallel a}$

$T_{\parallel p}$

$T_{\wedge}$

$T_{\parallel}$

Knizhnik et al ‘11

Reconnection exhaust heating

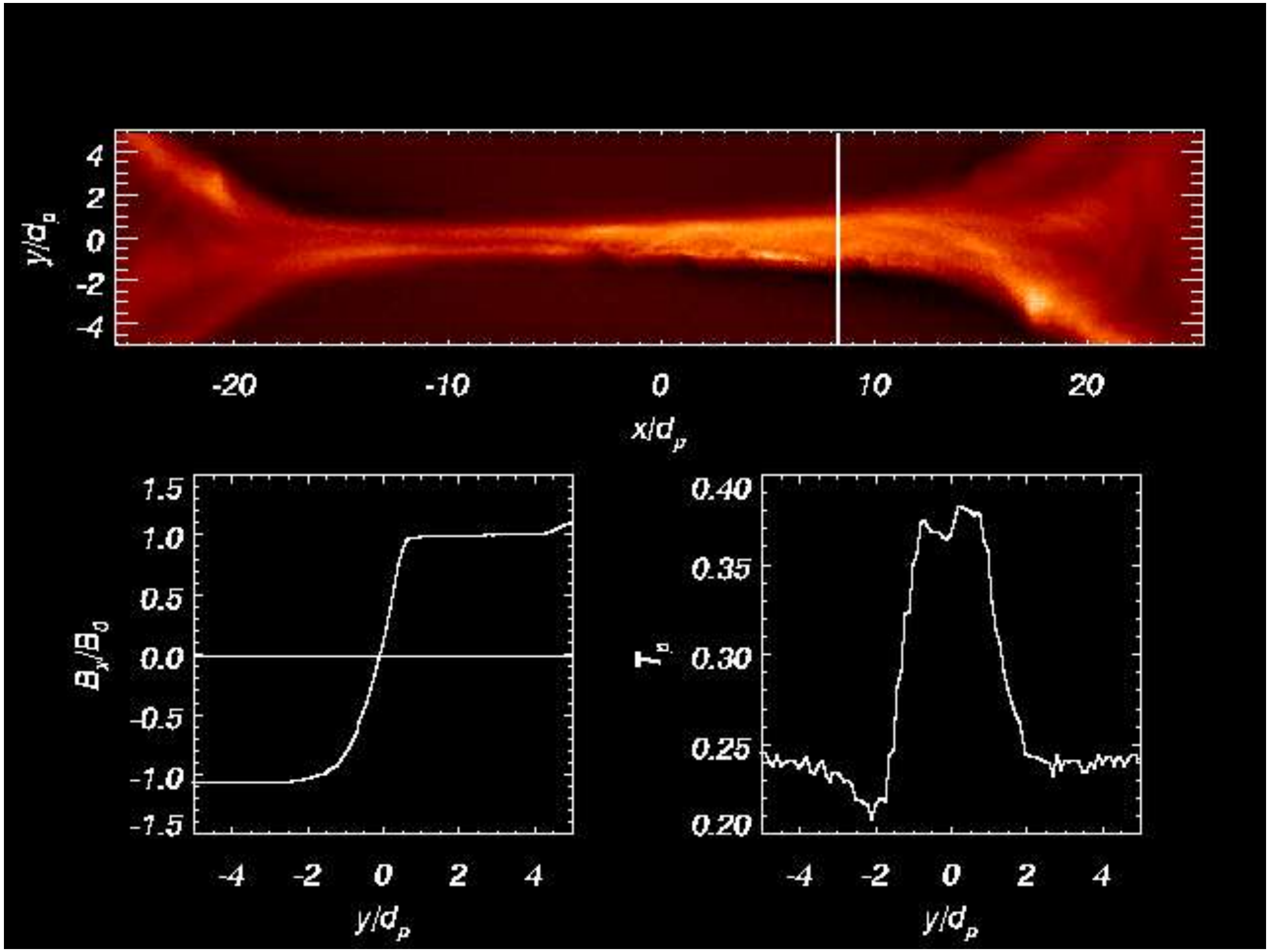
- For typical coronal parameters ($B \sim 50G$, $n \sim 10^9$), temperature increments ~ 25keV/nucleon
  - – Typical of thermal component in flare heating
- Ion heating scenario
  - – In a typically wide current sheet the reconnection magnetic field B_{0x} is very small ⇒ $\beta_{px} \sim 8\pi n T_p/B_{0x}^2 >> 1$
    - Adiabatic behavior for all ions
  - – As reconnection proceeds B_{0x} increases and β_{px} decreases and ions with progressively smaller $m_i/Z_i m_p$ behave like pickup particles and gain energy

$$\frac{m_i}{Z_i m_p} > b_{px}$$

  - – Mostly perpendicular heating
- Heavy impurity ions gain energy first
- Consistent with coronal observations with $T_{perp} > T_{||}$ and abundance enhancements in impulsive flares?

Onset of ion heating in a wide current layer

- PIC simulations with multiple ion species in a wide current layer
  - Onset of pickup behavior and heating of protons



Conclusions

- High energy particle production during magnetic reconnection requires the interaction with many magnetic islands
  - Not a single x-line
  - 1st order Fermi acceleration in contracting islands accelerates both ions and electrons
  - Island contraction is limited by the marginal firehose condition
  - Spectral indices of energetic particles take the form of powerlaws with spectral indices controlled by the firehose condition
- The heliospheric sectored field compresses across the termination shock and as it moves toward the heliopause
- Reconnection dominantly accelerates the interstellar medium pickup particles
  - Particle spectra are controlled by the firehose condition
  - Predicted spectra are consistent with observations

Conclusions (cont.)

- A seed mechanism is required to seed ions to super-Alfvenic velocities in the low beta corona.
  - Ions act as pickup particles as they enter reconnection exhausts gain most energy
    - M/Q threshold for pickup behavior in guide field reconnection
    - Gain a thermal velocity given by the Alfven speed
    - Most of temperature increase is in $T_\perp$
- Ions with super-Alfvenic velocities undergo Fermi acceleration in contracting and merging islands
- M/Q threshold for pickup behavior is a possible explanation of impulsive flare heavy ion abundance enhancements
- Can reconnection be responsible for the $T_\perp > T_\parallel$ coronal observations?