Ion acceleration during magnetic reconnection

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GORDON RESEARCH CONFERENCES
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June 20 - 24, 1977
"Magnetic Reconnection in Space and Laboratory Plasmas"
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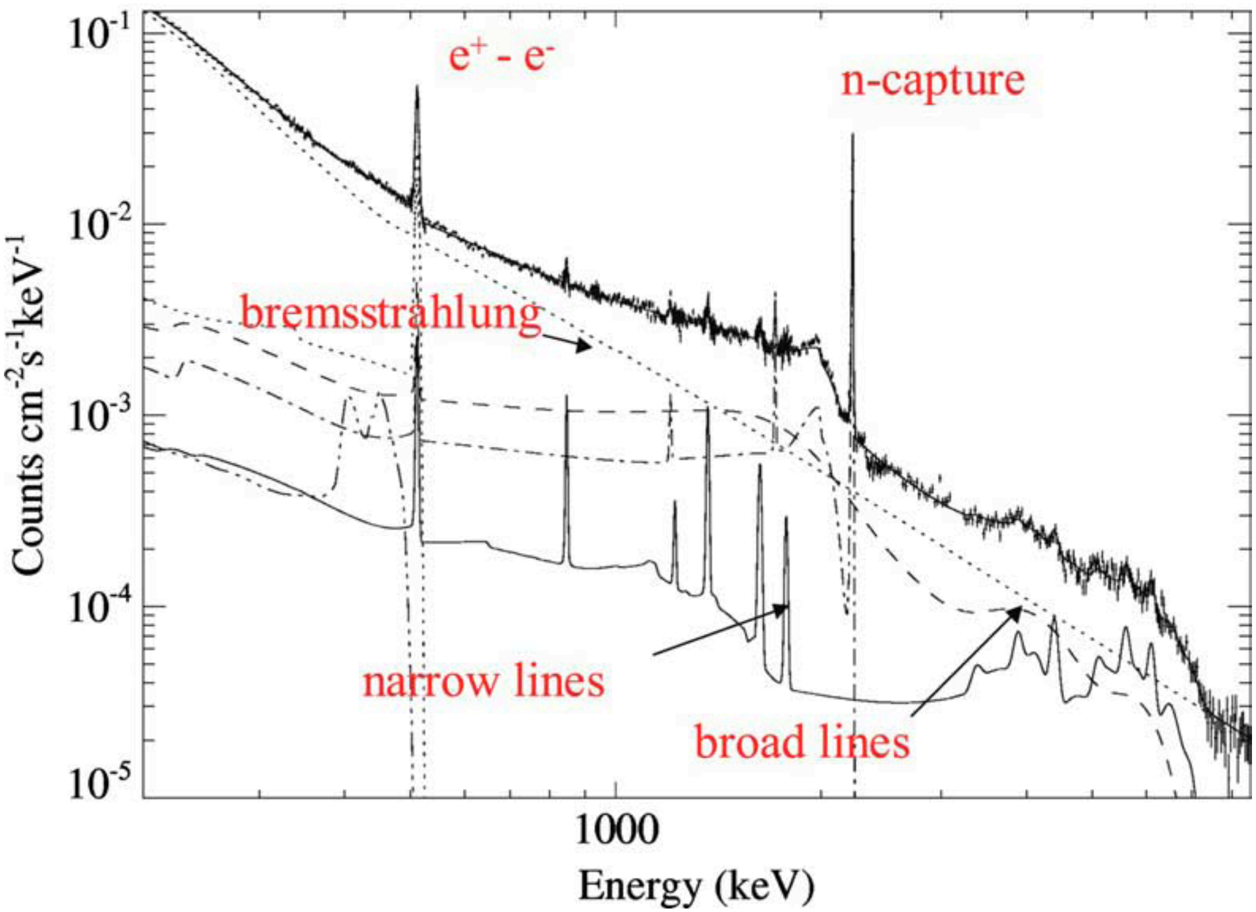
Some energetic ion observations in the heliosphere

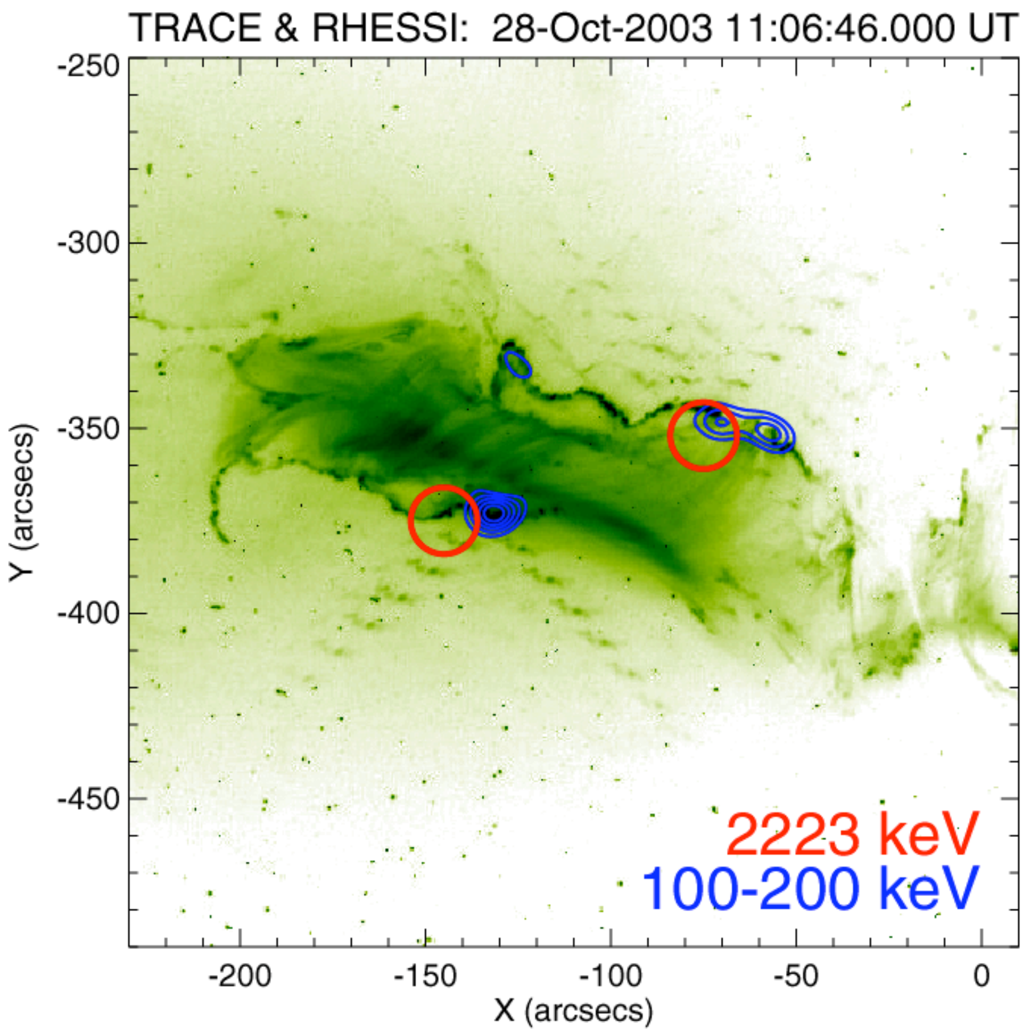
- Flare observations
  - In solar flares energetic electrons up to MeVs and ions up to GeVs have been measured
    - A significant fraction of the released magnetic energy appears in the form of energetic electrons and ions (Lin and Hudson '76, Emslie et al '05)
    - Correlation between > 300keV energetic electrons and > 30 MeV ions (Shih et al 2008) ⇒ common acceleration mechanism
  - In impulsive flares see enhancements of high M/Q ions (Mason '07)
- Ion heating in solar wind reconnection exhausts (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)
- Anomalous Cosmic Rays -- ions with energy 10-100MeV whose source is in the vicinity of the heliospheric termination shock/heliosheath

Rhessi γ -ray spectrum



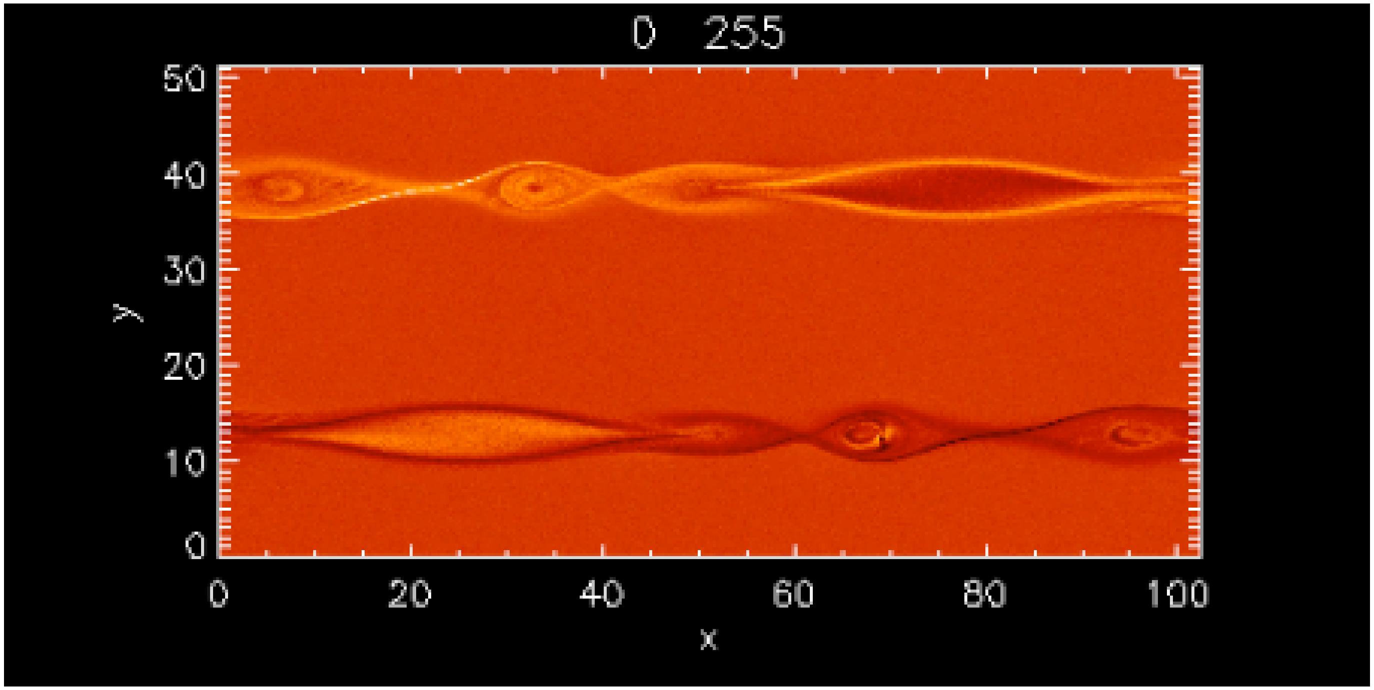
- Time-average γ-ray spectrum from Oct 28 2003 X-17 flare

RHESSI Gamma ray observations



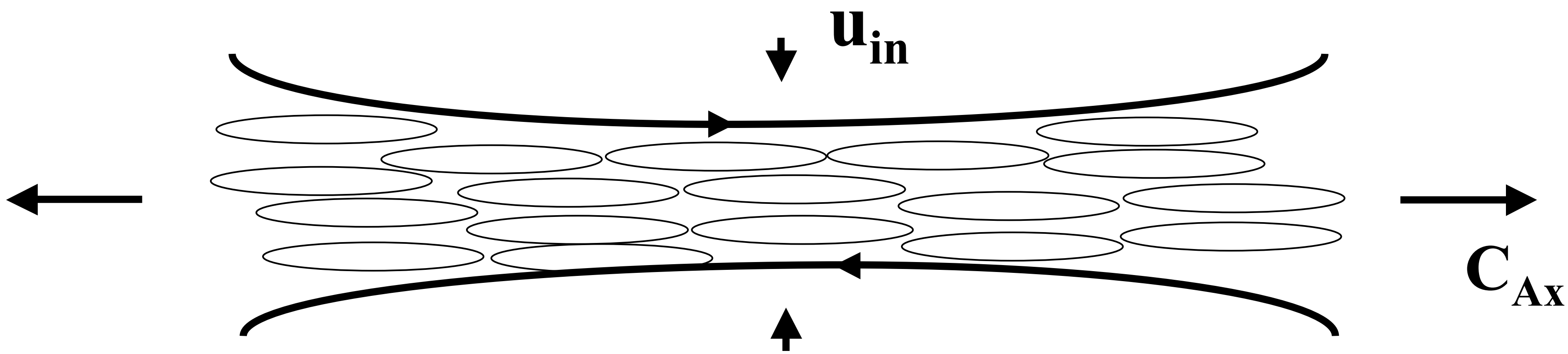
- October 28 2003 flare - x-rays in blue and gamma rays in red.

A multi-island acceleration model

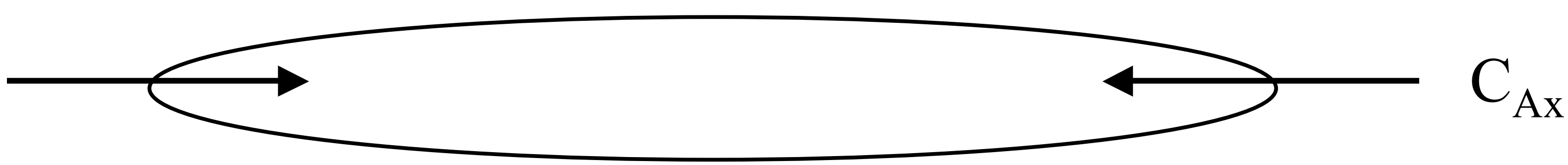


- A single x-line line model can not explain the high fraction of energy going into electrons and ions in flares
  - Parallel electric fields are strongly localized around the x-line -- energetically unimportant
- Narrow current layers spawn multiple magnetic islands in reconnection with a guide field
  - Must abandon the classical single x-line picture!!

Multi-island reconnection



- Consider a reconnection region with multiple islands in 3-D with a stochastic magnetic field (e.g., Onofri et al 2006)
- How are electrons and ions accelerated in a multi-island environment?
  - Fermi reflection in contracting magnetic islands (Kliem 94, Drake et al 2006)

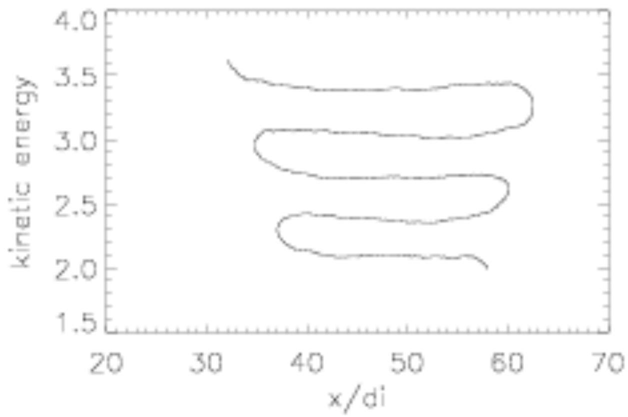


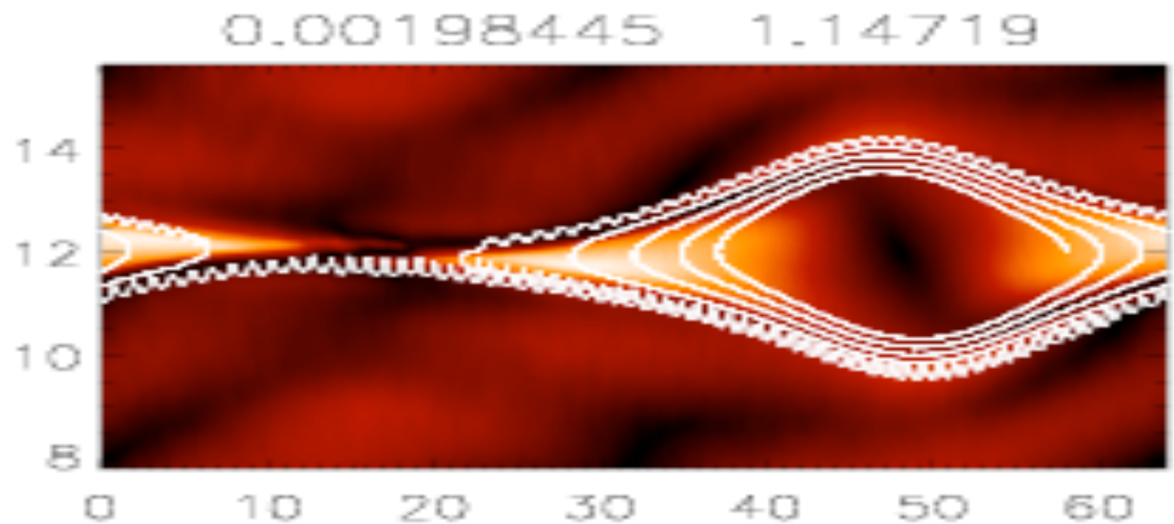
– Rate of energy gain independent of particle mass

⇒ same for electrons and protons

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

Electron Dynamics in simulation fields





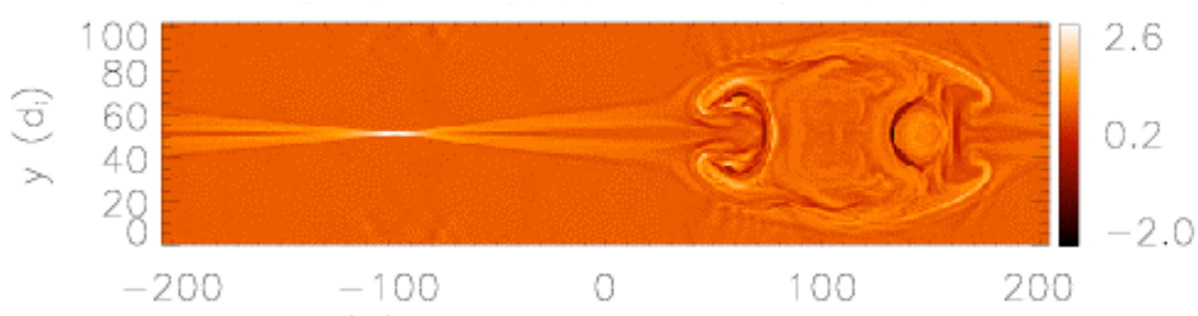
- Electrons gain energy during each reflection from contracting island
  - Increase in the parallel velocity

Ion acceleration during reconnection

- Fermi acceleration through island contraction is efficient only for super-Alfvenic ions
  - Need seed heating mechanism for ions
- Ions gain significant energy through large-scale Alfvenic flows
  - Does not facilitate the production of particles in the 100MeV to GeV range in the corona ⇒ energy gain is reversible
- Parallel electric fields are inefficient accelerators of ions
- Ion "pickup" in magnetic reconnection exhausts is the dominant seed heating mechanism.

Seeding super-Alfvenic ions through pickup in reconnection exhausts

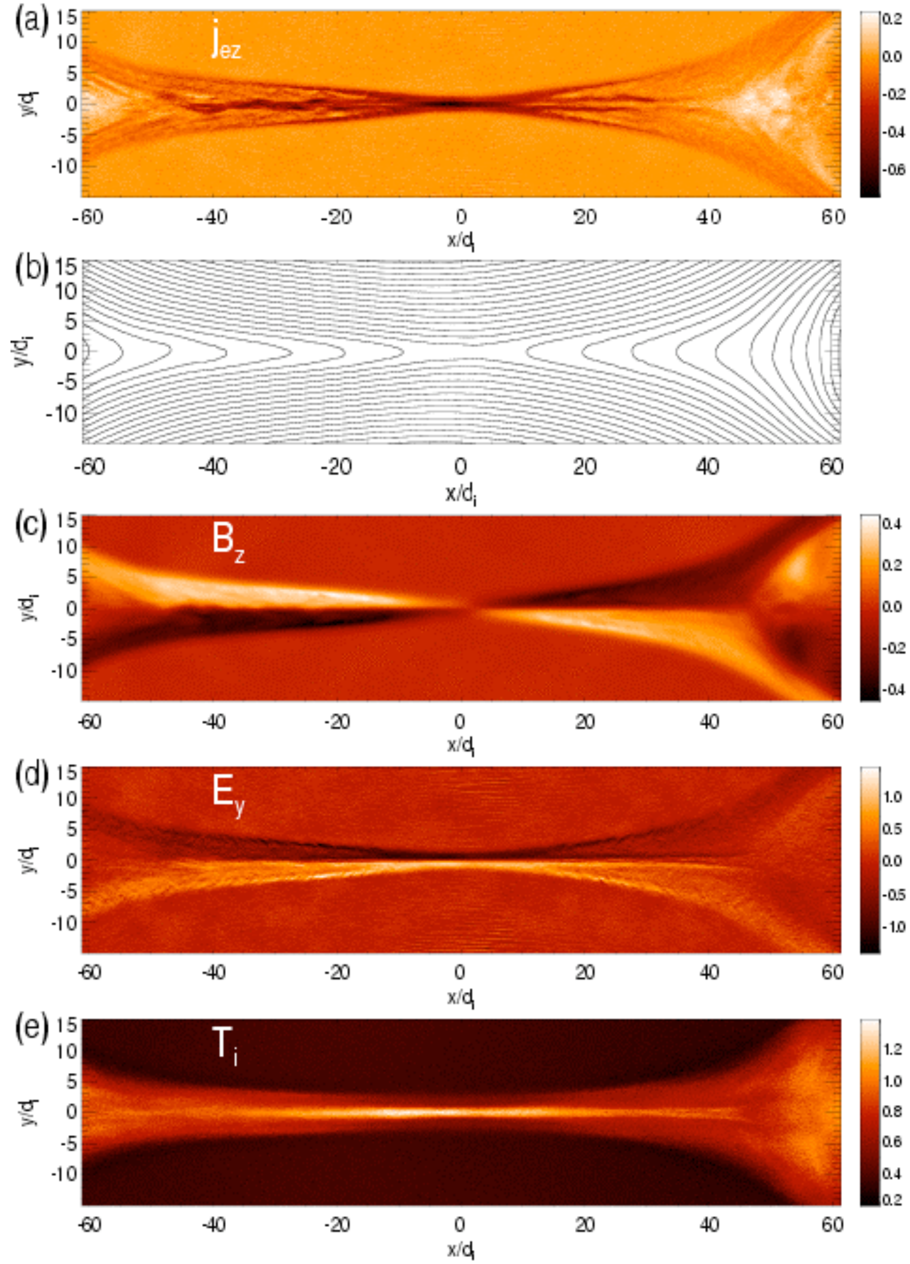
- Ions moving from upstream cross a narrow boundary layer into the Alfvenic reconnection exhaust
- The ion can then act like a classic "pick-up" particle, where it gains an effective thermal velocity equal to the Alfvenic outflow $T_i \sim m_i c_A^2$
    - Energy proportional to mass (Fujimoto and Nakamura, 1994)



Ion acceleration during anti-parallel reconnection

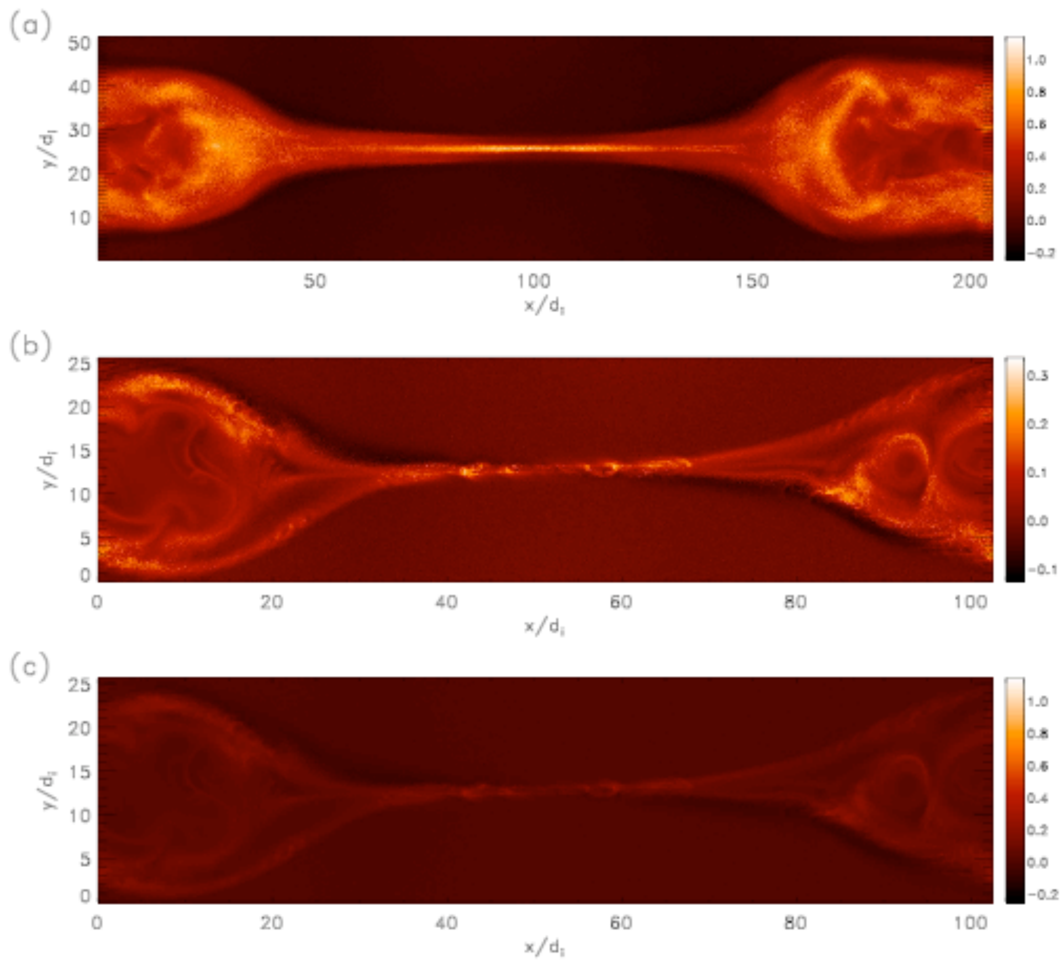
- PIC simulation with $m_i/m_e=25$
- Sharp increase of T_i in the exhaust
- In pickup picture

$\Delta T_i \sim m_i \Delta v^2/3 \sim m_i c_A^2/3$



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. Why?

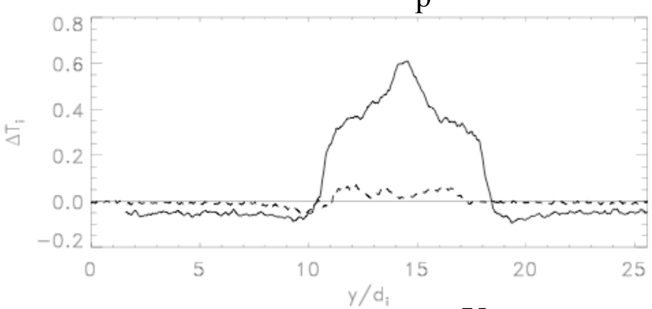


$B_{z0}=0$

$B_{z0}=2$

$B_{z0}=2$

ΔT_p



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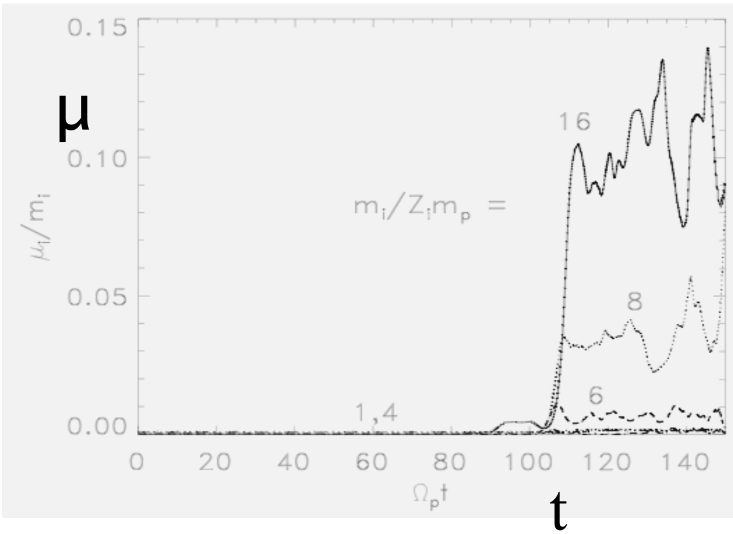
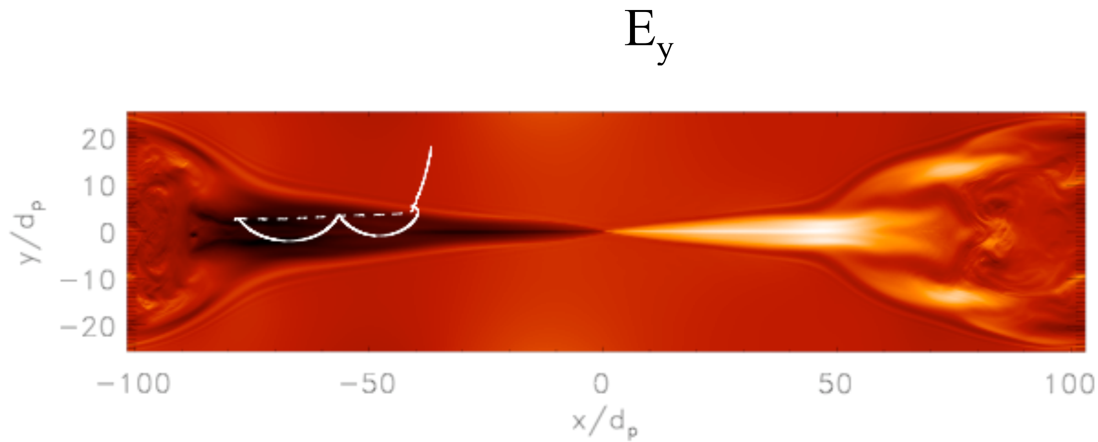
Pickup threshold: guide field





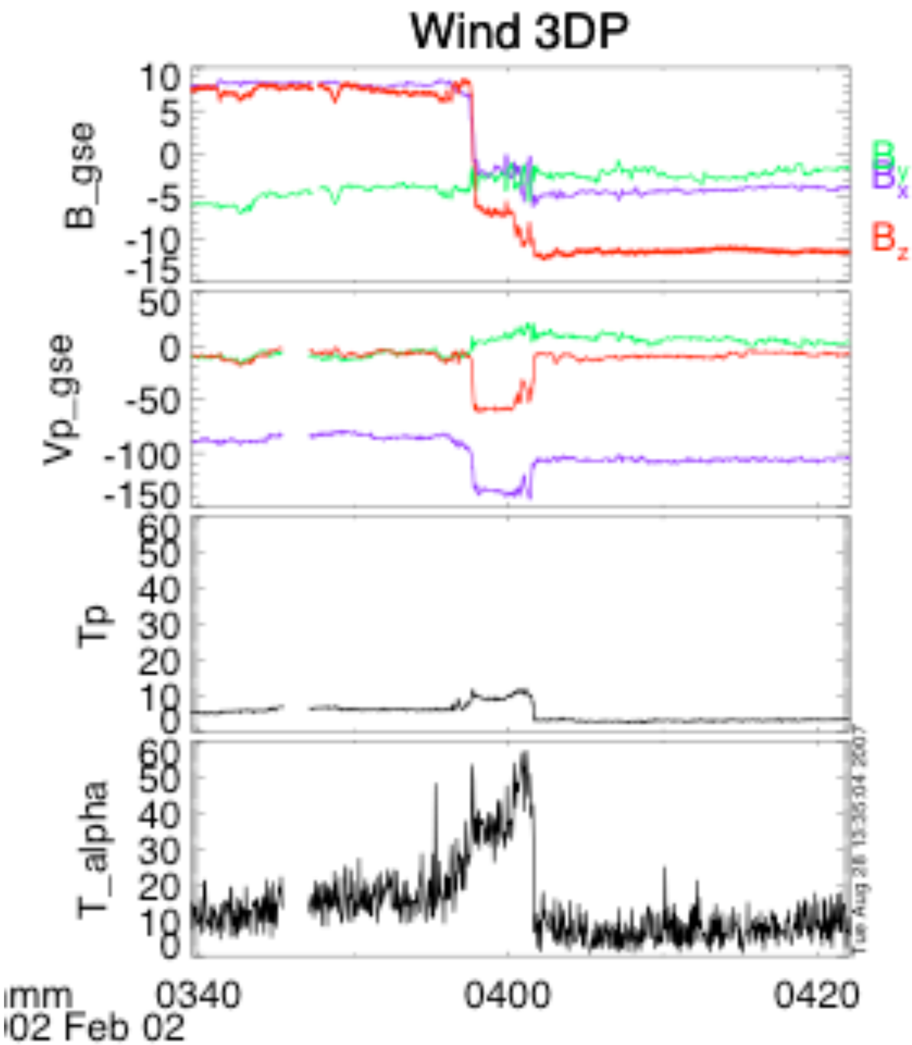
$B_{z0} = 5.0$

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

$$\frac{v_{iy}}{\Delta} \approx \frac{0.1 c_{Apx}}{\rho_{sp}} > \Omega_i \Rightarrow \frac{m_i}{Z_i m_p} > 10 \frac{c_{ps}}{c_{Apx}}$$

For a given ion mass and charge this is a threshold in the reconnecting magnetic field B_x

Wind observations of solar wind exhaust



- $300R_E$ event (Phan et al., 2006)
- Exhaust velocity ~ 70km/s
- $\Delta T_p \sim 7$eV
- $\Delta T_\alpha \sim 30$eV

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

- Same for higher mass ions

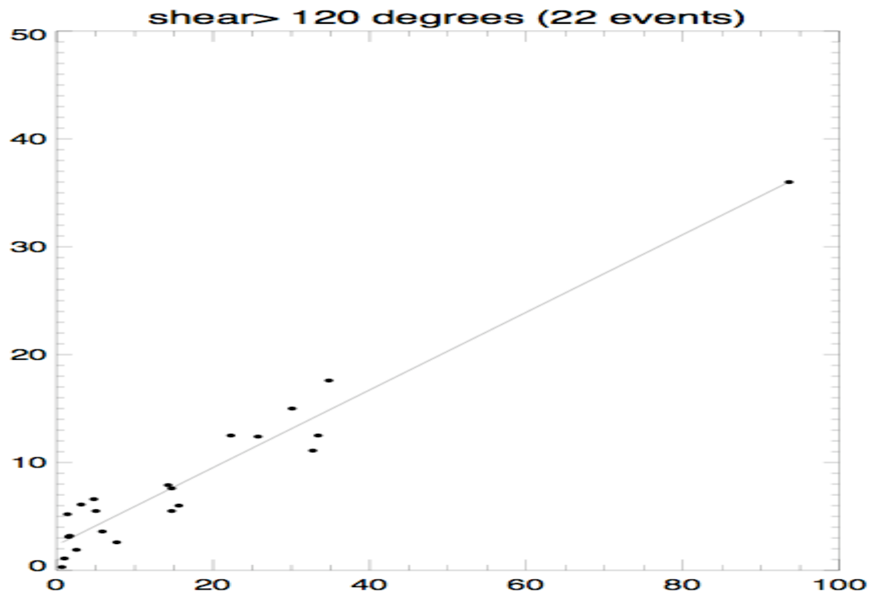
Wind solar wind exhaust data

- Wind data from 22 high-shear, solar-wind reconnection exhaust encounters
- Proton temperature increase in exhaust is given by

$$3\Delta T_p \simeq 0.39 m_p \Delta v^2$$

  – Correct scaling but below expected values

$3\Delta T_p(\mathrm{eV})$

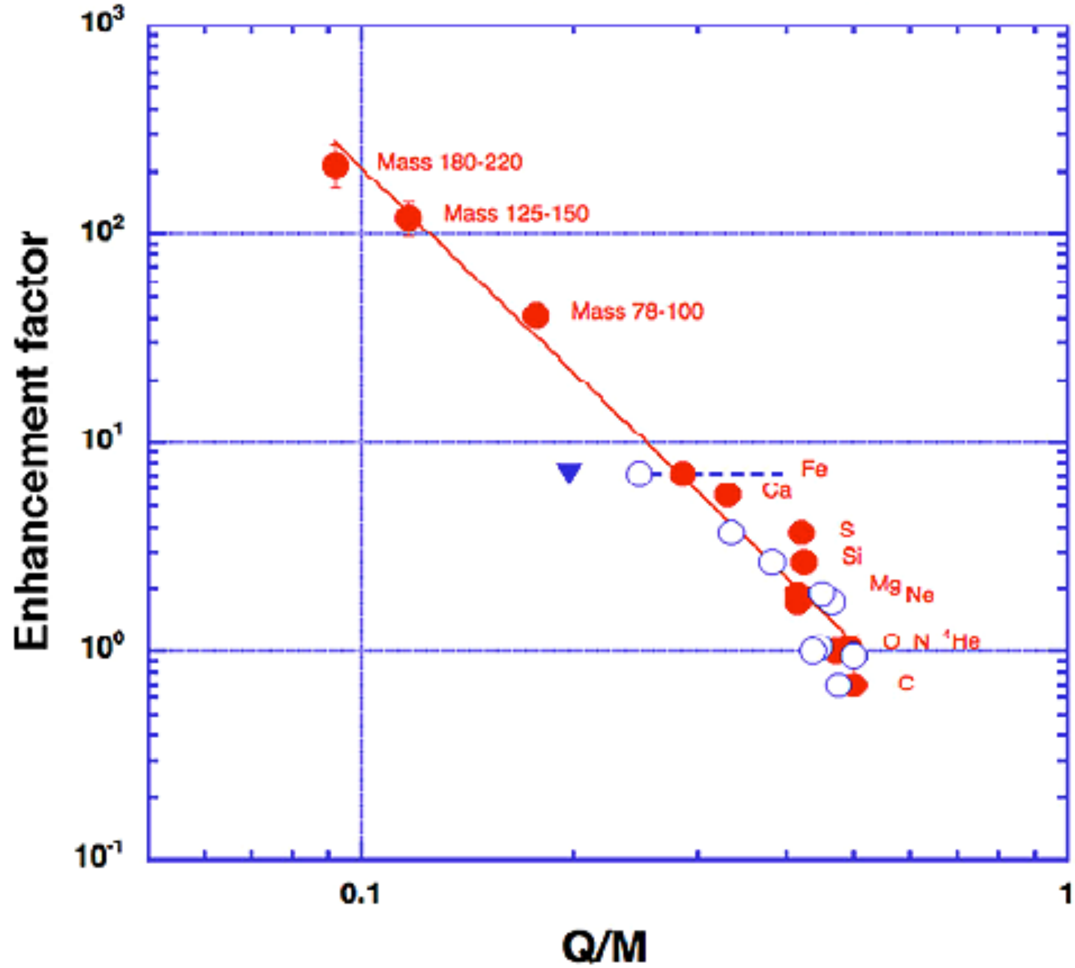


$m_p \Delta v^2(\mathrm{eV})$

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

Abundance enhancement of ions during impulsive flares

- In impulsive flares see an abundance enhancement of high M/Q ions compared with nominal coronal values.
- Ions are seeded to super-Alfvenic velocities through interaction with reconnection exhausts
- Once the ions are super-Alfvenic the Fermi island contraction mechanism acts on all ions
- Is the abundance enhancement linked to the pickup threshold?

Abundance enhancements in impulsive flares

- Ion pickup criterion can be rephrased as a threshold on magnetic island width w_c.

$$\frac{m_i}{Z_i m_p} > 10 \frac{c_{sp}}{c_{Axp}} \qquad c_{Axp} \simeq c'_{Axp} w_c > 10 c_{sp} \left(\frac{Z_i m_p}{m_i} \right)$$

  - Higher M/Q ions have lower island width thresholds
- Rate of production of pickup ions

$$\frac{dN_i}{dt} \sim \sum_{w>w_c} 0.1 c_{Ax} L_w \sim \sum_{w>w_c} w^2 \sim \int_{w_c}^{\infty} dw w^2 P(w)$$

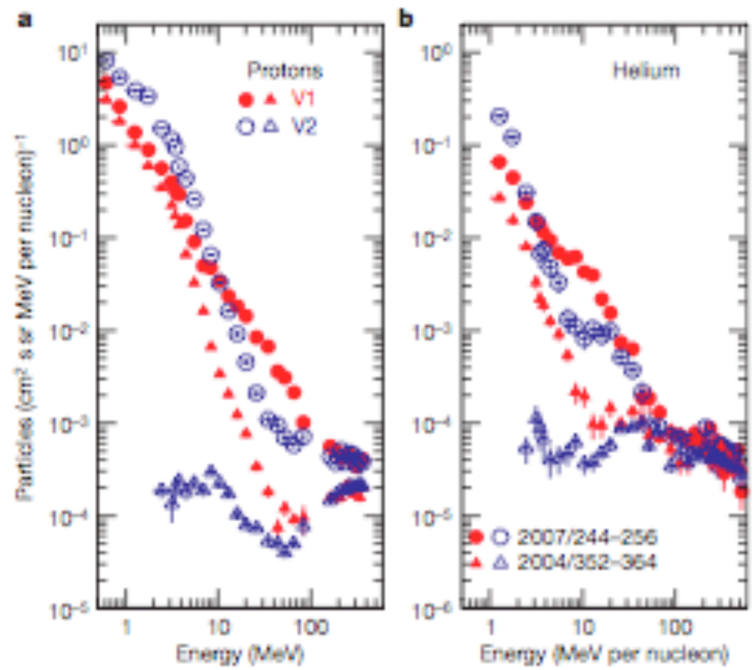
  - Take powerlaw distribution of island widths: $P(w) \sim w^{-\alpha}$

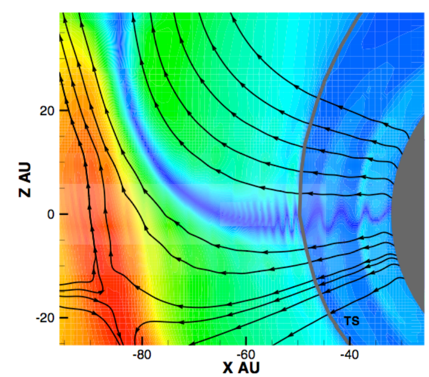
$$\frac{dN_i}{dt} \sim w_c^{3-\alpha} \sim \left(\frac{Z_i m_p}{m_i} \right)^{3-\alpha}$$

  - Match the Mason '07 observations if $\alpha \sim 6.26$

Anomalous Cosmic Rays (ACRs)

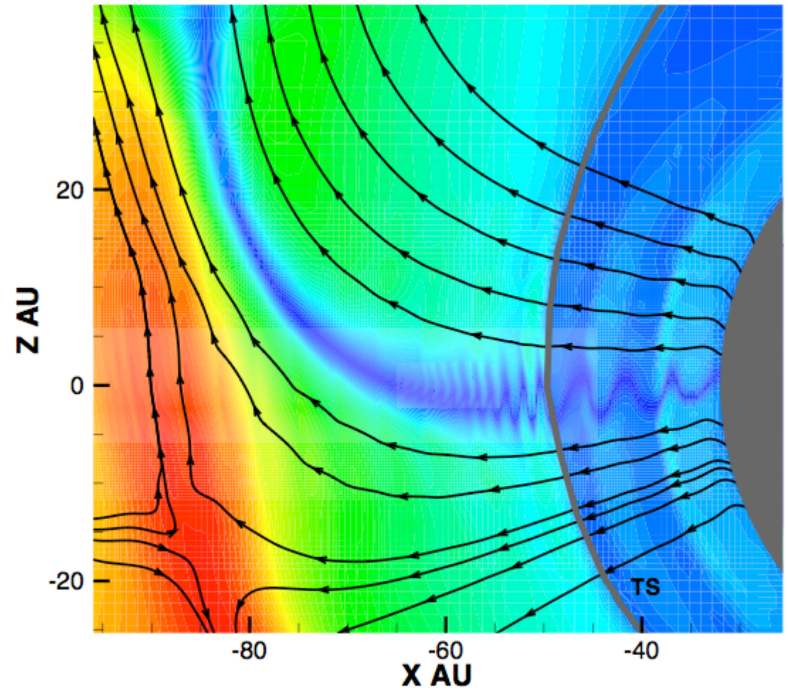
- 10-100MeV/nucleon particles
- Local interstellar medium neutrals are ionized and picked-up deep in the heliosphere and carried back out to the heliospheric termination shock (TS) where they are accelerated
  - The Voyager 1 & 2 spacecraft observations revealed that the local TS was not the source of the ACRs.
  - Produced by the TS at the flanks of the heliosphere (McComas and Schwadron 2006)?

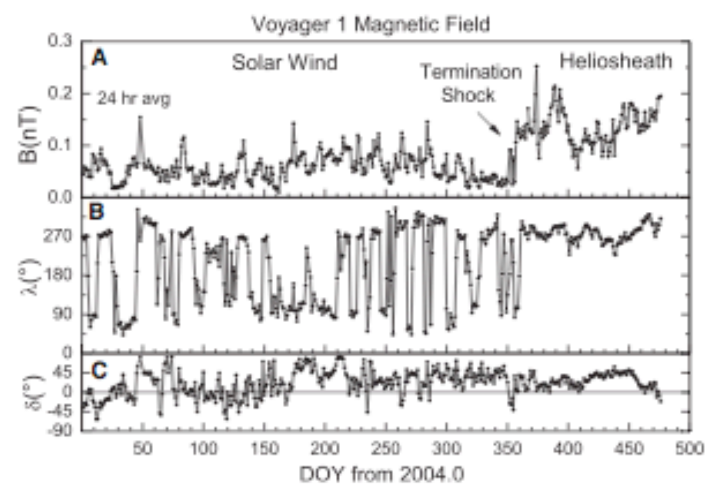




MHD model of the heliosphere

- Supersonic solar wind becomes subsonic at the termination shock
- The heliospheric toroidal field B_ϕ changes sign across the heliospheric current sheet
- The tilt of the solar magnetic field with respect to the rotation axis generates a sectored magnetic field
  - Latitudinal extent depends on solar cycle ~ 30 degrees
  - Sectors are compressed across the TS and as the flow slows as it approaches the heliopause

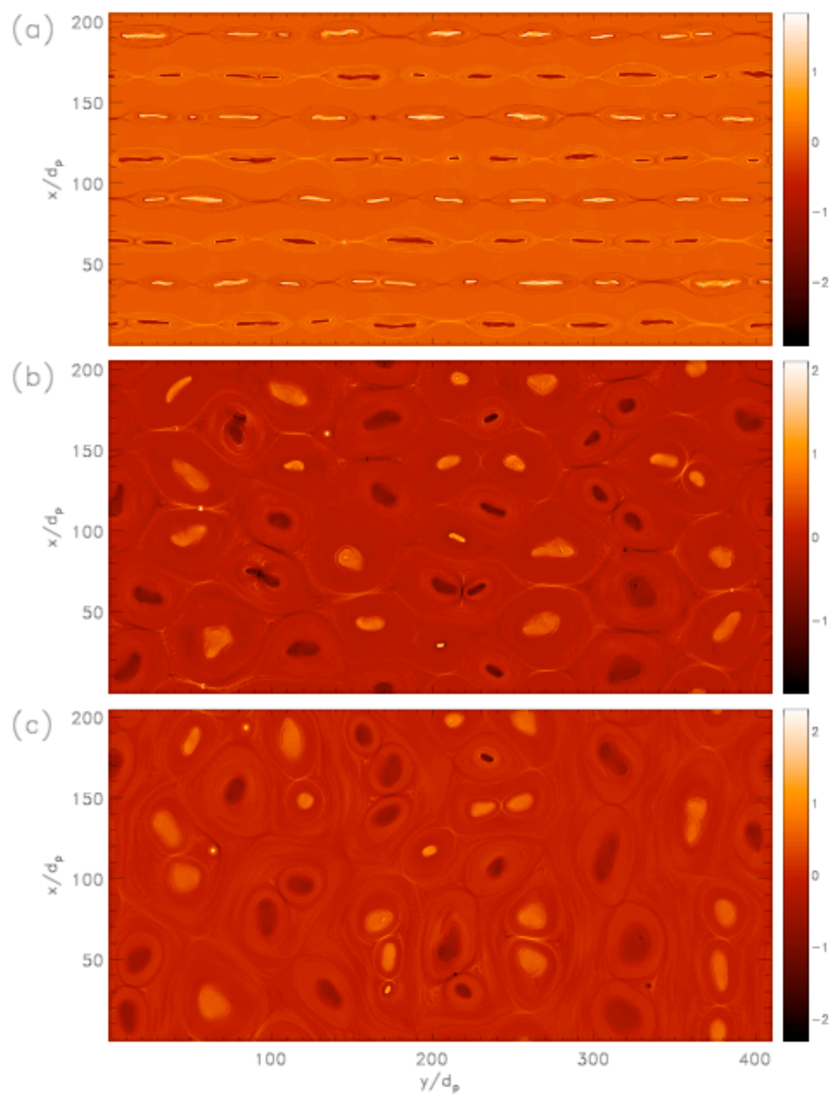




Collisionless reconnection of the sectored heliospheric field

- The sectored field is stable to reconnection upstream of the TS because the width of the current sheet is much wider than c/ω_{pi}.
  - Collisionless reconnection is very weak
- The current layers compress on their approach to the heliopause
  - Inevitably have the onset of collisionless reconnection
  - Dissipation of nearly all of the magnetic energy

J_{ez}

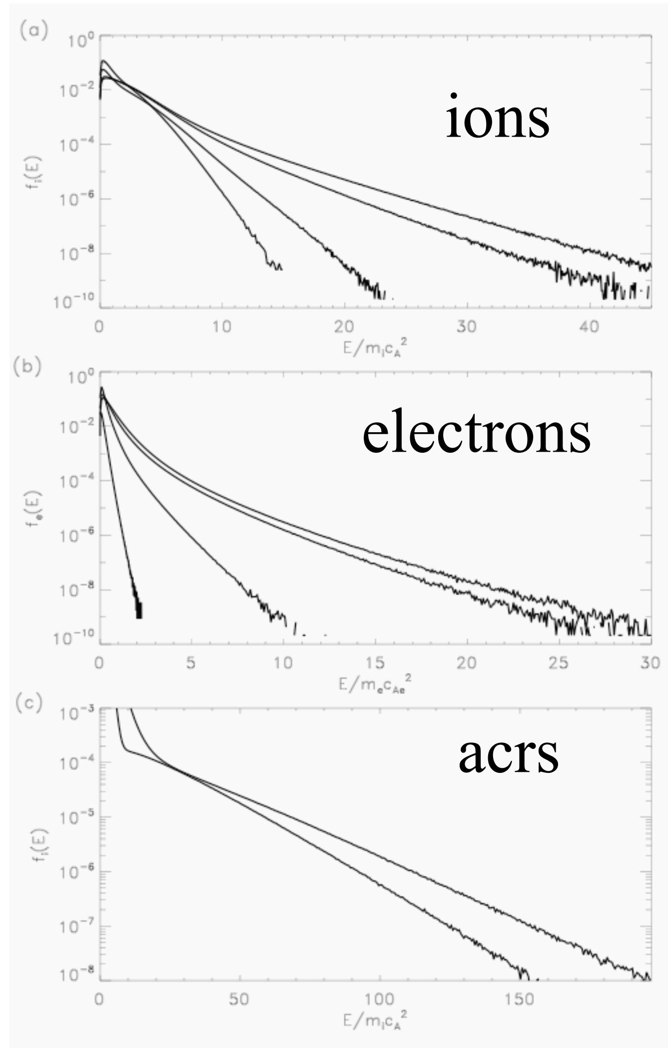


Electron and ion energy spectra

- Both ions and electrons gain energy
- Include 5% population of pickup particles to simulate the production of ACRs
- A key feature is that the rate of energy gain of particles increases with energy

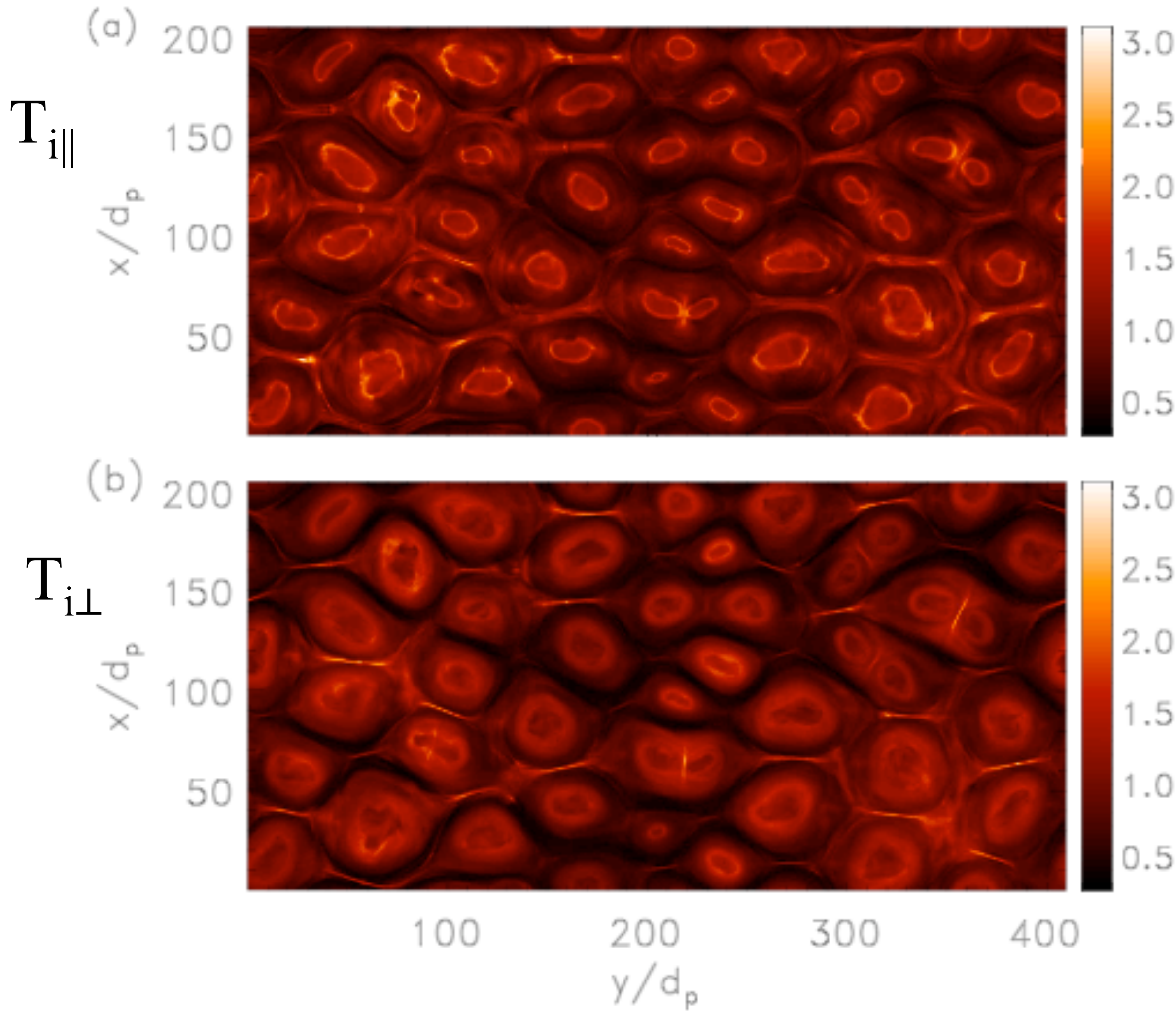
$$\frac{d\varepsilon}{dt} \propto \varepsilon$$

$\Rightarrow$ first order Fermi



Proton temperature

- Within islands
  $T_{i||} > T_{i\perp}$
- In exhaust regions
  $T_{i||} < T_{i\perp}$
- Violate marginal firehose condition within the islands
  - Self-consistency is crucial
- Energetic electron pressure in flares can approach the magnetic pressure (Krucker et al 2009)



1-D Model equations

- Rate of energy gain: first order Fermi

$$\dot{v} = \frac{dv}{dt} = \frac{1}{\tau_h}\left(1 - \frac{4\pi p}{B^2}\right)^{1/2} v$$

- Model equation for the omnidirectional distribution function

  $F(v,t) = 4\pi v^2 f\,(v,t)$

$$\frac{\partial F}{\partial t} + \frac{\partial}{\partial v}\dot{v}F = -\frac{1}{\tau_L}\left[F - F_0(v)\right]$$

- Above the source energy this is an equidimensional equation

  $\Rightarrow$ powerlaw solutions

Distributions and spectral indices

- Exact steady state solutions for F(v)

$$F(v) = (\gamma - 1) v^{-\gamma} \int_0^v ds s^{\gamma-1} F_0(s)$$

- Spectral index

$$(\gamma - 1)\left(1 - \frac{4\pi p_0}{B^2}\frac{\gamma - 1}{\gamma - 3}\right)^{1/2} = \frac{\tau_h}{\tau_L}$$

- Heliopause limit $\tau_h << \tau_L$

$$\gamma = 3 + \beta_0$$

⇒ spectral index controlled by marginal firehose condition

Implications for ACRs

- Squeezing of plasma near the HP causes β to drop (similar to the magnetopause)

  $\Rightarrow \beta_0 \approx 0.5$

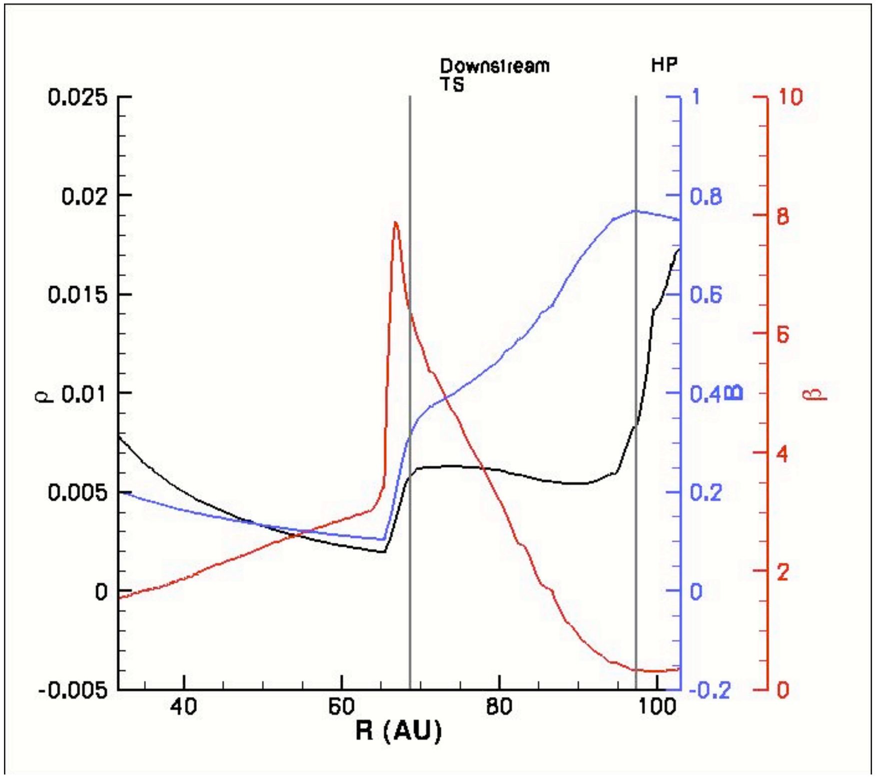
- For ACRs

  $F \sim \epsilon^{-1.75}$

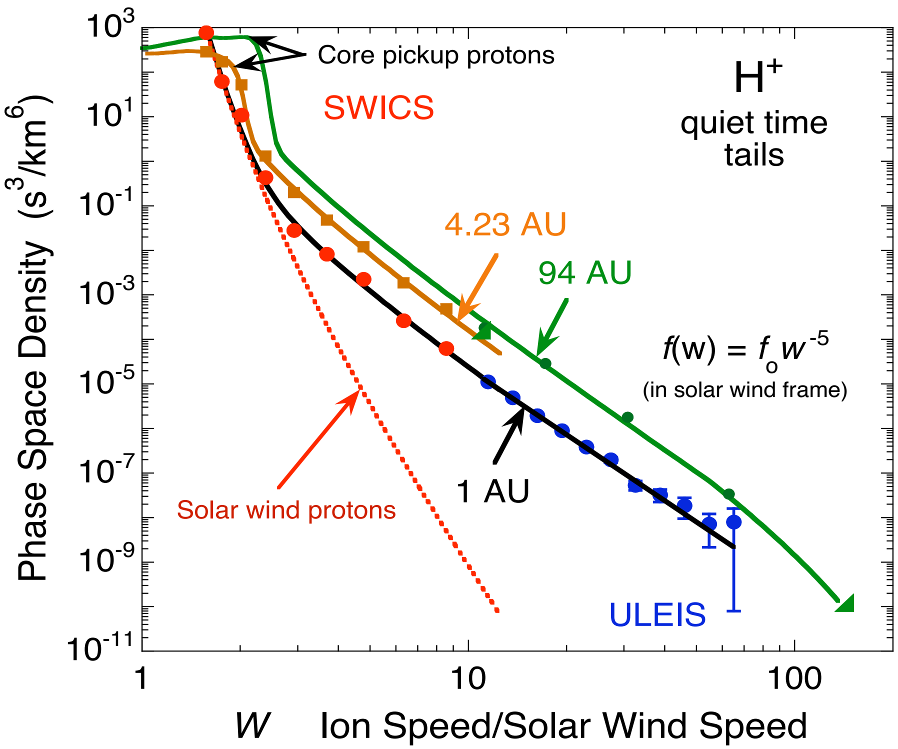
- The minor species have the same form when written on a per nucleon basis
- Background plasma also acts like a minor species $f \sim v^{-5.5}$

Is the heliosheath the source of the Fisk/Gloeckler v^{-5} distributions?

MHD model



Universal super-Alfvenic ion spectrum in the quiet solar wind



Fisk and Gloeckler, 2006

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

Conclusions

- High energy particle production during magnetic reconnection involves the interaction with many magnetic islands
  - Not a single x-line
- Ion interaction with the reconnection exhaust seeds them to super-Alfvenic velocities.
  - Ions that act as pickup particles as they enter reconnection exhausts gain most energy
    - M/Q threshold for pickup behavior
    - Gain a thermal velocity given by the Alfven speed
    - Wind and ACE observations support this picture
- Interaction with reconnection exhausts should enable energetic ions to be accelerated through Fermi contraction
- M/Q threshold for pickup behavior is a possible explantation of impulsive flare heavy ion abundance enhancements

Conclusions (cont.)

- The sectored heliospheric field is compressed as it approaches the heliopause
  - Collisionless reconnection inevitably onsets and dissipates the sectored field energy
    - Enormous reservoir of energy
    - Preferential heating of pickup particles
- Efficient heating of pickup ions through magnetic island contraction
  - Balance of contraction drive and convective loss yields powerlaw solutions
  - Spectral indices are controlled by the approach to firehose stability
- Minority ions have similar spectra to the main He and H
- Background protons are strongly heated and have spectra similar to those seen by Fisk/Gloeckler

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