The impact of pressure anisotropy on magnetic reconnection and particle acceleration

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Observations of particle heating and acceleration

• Impulsive flares

- In solar flares energetic electrons to MeV 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)
 - Powerlaw spectra of energetic electrons with spectral indices as hard as -1.5 (Lin et al '03)
- Quiet time solar wind
 - Distribution functions of super Alfvenic ions in the quiet time solar wind take the form of powerlaws with spectral indices of -5 (Fisk and Gloeckler '06)
 - Correspond to energy fluxes with spectra of -1.5

Observations of ion heating and acceleration (cont.)

- The outer heliosphere
 - The Voyager observations reveal Anomalous Cosmic Rays peak deep within the heliosheath (Stone et al '05, '08)
 - Not at the termination shock
 - Fluxes with powerlaw spectra with indices of around -1.5

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



- 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!

Super thermal ions in the solar wind

• Powerlaw spectra of energetic ions are measured in the quiet solar wind (Fisk and Gloecker '06)



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

The source of ACRs

- The Voyager 1 & 2 spacecraft observations revealed that the ACRs do not peak at the TS but continue to increase in intensity as the spacecraft move further into the heliosheath
 - The local TS was not the source of the ACRs.



Main Points

- A single x-line model of reconnection can not explain the observations of particle acceleration in the corona, solar wind and outer heliosphere
 - Must explore reconnection and particle acceleration in a multi-x-line environment
- What is the dominant acceleration mechanism for particle acceleration in a multi-x-line reconnecting system?
 - Fermi reflection in contracting and merging islands
 - Generically during reconnection local relaxation in tension in a kinked field both releases magnetic energy and drives particle acceleration
- What is the dominant feedback of energetic particles on a reconnecting system?
 - Particle acceleration increases parallel pressure, driving anisotropy instabilities that profoundly alter magnetic field dynamics and particle acceleration.

- Can parallel electric fields in a single xline produce the large number of electrons seen in flares?
 - Around 10³⁷electrons/s

fields relax their stress

energetic electrons

Can't explain the large number of

—

- Downflow currents in a single x-line would be enormous
 - Producing 10^9 G fields for L ~ 10^4 km
- Parallel electric fields are shorted out except near the x-line

0.0 1.0 1.0 1.0 1.0

Single x-line model: the sun



Must abandon single x-line model!

Tsuneda 1997

SDO/AIA flare observations

- Super Arcade Downflows (SADs) are interpreted as signatures of magnetic islands from an overlying reconnection site (Sheeley et al 2004)
- Such SAD events are now considered typical and not anomalies.
- SADs result from spatiallylocalized 3-D reconnection (Cassak et al '13)
- Must abandon the classical single x-line picture!!

Savage et al 2012



Multi-island reconnection with a guide field



- Narrow current layers spawn multiple magnetic islands in reconnection with a guide field (Drake et al 2006; Daughton et al 2011)
- Multi-island reconnection in the corona is generic

Multi-island dynamics in stirre MHD simulations

 MHD simulations of Parker's nano-flare heating model lead to a multi-island reconnection configuration (Rappazzo et al 2008)



0.8

0.2

0.4

X 0.6

0.0





Sector structure of the heliospheric magnetic field

- Misalignment of solar rotation and magnetic axes causes the heliospheric current sheet to flap
- Periodic reversal of B_{ϕ}



B

λ

R



MHD model of the heliosphere

- 3-D MHD model
- Structure of the sectored 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 close to the heliopause is inevitable
- Where else does reconnection take place?

В



Opher et al 2011

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, Oka et al 2010, Drake et al '13)

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

- Increase in the parallel energy of particles

 \Rightarrow same for electrons and protons

Arises from the curvature drift in the direction of the reconnection electric field



Simulation of multi-island particle acceleration

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



Multi-island reconnection dynamics



- PIC simulations of multi-current systems
 - First have reconnection on individual current layers
 - Then merging of islands

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

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

⇒ Fermi mechanism

• Note: not a powerlaw



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}



Firehose instability during island contraction

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







- simulation
 - Each point corresponds to a grid point in the simulation
- As reconnection stronglyonsets both the firehoseand mirror stabilityboundaries are violated
- At late time the firehose and mirror conditions act as constraints



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Wind data on solar wind turbulence

- Solar wind turbulence bumps against the the firehose and mirror stability boundaries
- Very similar to the reconnection simulations
 - Why does this happen in the case of solar wind turbulence?



 $|\beta|$

Bale et al 2009

Development of anisotropy (guide field case)

- Simulation with a guide field (0.5 B₀)
- The Fermi mechanism drives the system towards the firehose threshold even in a system with very low initial β



Firehose condition

- Within islands bump against the firehose condition
 - This condition limits island contraction
 - No tension in magnetic fields when the firehose condition is violated

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

- Note the abnormally long islands compared with early time
- Self-consistency is crucial in exploring particle acceleration



Structure late-time magnetic islands

 $\beta_0 = 0.25$

 $\beta_0 = 4.8$



• Firehose halts island contraction during reconnection

Impact of firehose on reconnection evolution

- Fermi acceleration of electrons leads to firehose within island cores (Drake et al '06, '10, Schoeffler et al '11)
 - Quenches reconnection (see also Karimabadi et al '05)
 - Produces island growth at very long wavelength



Suppression of electron heating by anisotropy in

• Electron scattering by anisotropy instability suppresses acceleration $\beta = 0.2, 1.0, 2.0, 3.0, 4.8$. (Schoeffler et al '13)



3-D structure of magnetic islands

- Exploration of 3-D reconnection, particle acceleration and transport
 - Little change in particle acceleration but big change in transport characteristics



Particle dynamics in 3-D reconnetion

- Exploring particle acceleration in 3-D fields
 - Little change in particle spectra in 3-D versus 2-D
 - 3-D magnetic island trap particles for a finite time
 - Why so little change?



Measuring energy release during reconnection

- Energy release as field lines shorten
 - What is a measure of this in a general 3-D system?

$$\frac{\partial}{\partial t}\frac{B^2}{8\pi} = -\vec{J} \cdot \vec{E} + \dots = -\frac{B^2}{4\pi}\vec{K} \cdot \vec{V}_{E\times B} + \dots$$

- In a reconnecting system \vec{K} and $\vec{V}_{E\times B}$ are on average in phase
- This is the slingshot that drives reconnection
- Particle energy gain is linked to magnetic energy release

$$\frac{\partial}{\partial t}\varepsilon_{\parallel} = 2\varepsilon_{\parallel}\vec{\kappa} \bullet \vec{V}_{E\times B}$$

- First order Fermi acceleration in a reconnecting system
 - Ongoing exploration of $\vec{K} \bullet \vec{V}_{E \times B}$ during 2-D and 3-D reconnection

Fermi acceleration in contracting islands



• Area of the island Lw is preserved

\Rightarrow 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 \Rightarrow isotropic plasma
- Retaining anisotropy is critical for reconnection

Fermi acceleration in contracting islands



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

$$W = \frac{1}{2}mv_0^2 \left(\frac{2L}{3L_0} + \frac{L_0^2}{3L^2}\right)$$

- No energy gain for infinitesimal change in L \Rightarrow consistent with Parker
- Significant energy gain for finite contraction
 - Parker equation is missing some important physical processes
 - See also Cho and Lazarian 2006

Energy gain in merging islands

- Total area preserved
- Magnetic flux of largest island is preserved
- Particle conservation laws
 - Magnetic moment $\mu = m v_{\perp}^2 / B$
 - Parallel action

V_{II}L

• Field line shortening drives energy gain

$$\frac{dv_{\parallel}^{2}}{dt} \sim 2 \frac{0.1c_{A}}{r_{1} + r_{2}} v_{\parallel}^{2}$$

$$\frac{dv_{\perp}^{2}}{dt} \sim -\frac{0.1c_{A}}{r_{1} + r_{2}} v_{\perp}^{2}$$

- No energy gain when isotropic



Particle acceleration in a multi-island reconnecting system

- Average over the merging of a bath of magnetic islands
- Kinetic equation for $f(v_{\parallel}, v_{\perp})$ with $\zeta = v_{\parallel}/v$
 - Equi-dimensional equation no intrinsic scale
 - powerlaw solutions
 - Drake et al 2013

$$\frac{\partial f}{\partial t} + \vec{u} \cdot \vec{\nabla} f - \vec{\nabla} \cdot \vec{\vec{D}} \cdot \vec{\nabla} f + R \left(\frac{\partial}{\partial v_{\parallel}} v_{\parallel} - \frac{1}{2v_{\perp}} \frac{\partial}{\partial v_{\perp}} v_{\perp}^2 \right) f - \gamma \frac{\partial}{\partial \xi} \left(1 - \xi^2 \right) \frac{\partial}{\partial \xi} f = 0$$

$$R \sim 0.1 \left\langle \frac{\alpha^{1/2} c_A}{r} \right\rangle \qquad \text{merging drive} \qquad \text{pitch-angle scattering} \\ \alpha = 1 - \frac{1}{2} \beta_{\parallel} + \frac{1}{2} \beta_{\perp}$$

Benchmarking with simulations

- Model particle energy gain in simulations
 - No convective loss
 - No diffusive loss
 - Weak scattering



Energetic particle distributions

- Solutions in the strong drive limit
 - heating time short compared with loss time
 - feedback from the high pressure (firehose) and convective loss
 - Powerlaw solutions for the particle flux

$$j \sim v^2 f(v) \sim v^{-3} \sim E^{-1.5}$$

- Upper limit on spectral hardness

- Pressure of energetic particles rises until it is comparable to the remaining magnetic energy
 - Equipartitian
 - Consistent with flare and outer heliosphere observations

Conclusions

- Efficient particle acceleration to high energies requires multi-xline reconnection
- All electrons and ions with Alfvenic thermal speeds are accelerated by contracting and merging islands
 - Island contraction and merging drives strong anisotropy with p_{\parallel} > p_{\perp}
 - Firehose instability limits reconnection drive and controls the spectral index of the particle energy flux
- A transport equation describing particle heating and acceleration in a bath of merging magnetic islands generalizes the Parker transport equation to include anisotropy
- Powerlaw spectra from multi-x-line reconnection are consistent with energetic electron spectra in the strongest flares, ion spectra in the the quiet time solar wind and the ACR spectra in the outer heliosphere