Multi X-line magnetic reconnection and particle acceleration

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Astrophysical reconnection

- Solar flares
- Pulsar magnetospheres, winds, PWNe
- AGN (e.g., blazar) jets, radio-lobes
- Gamma-Ray Bursts (GRBs)
- Magnetar flares
RHESSI observations

- 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
  – A large fraction of 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!

30-50keV
17GHz

Krucker et al 2010
The importance of the reconnection outflow

- Most of the magnetic energy release during reconnection takes place downstream of the x-line where newly reconnected field line relax their tension
  - Not around the x-line

- Magnetotail observations suggest that the ions carry most of the released magnetic energy (Eastwood et al 2013)
  - Bulk Alfvenic flow
  - Ion heating – enthalpy flux
Ion energy gain during reconnection

- Wind spacecraft observations in the solar wind (Phan et al 2006)
- What is the mechanism for ion heating?
Counter-streaming ions within reconnection exhausts

• In the exhaust outflow frame
• Counter-streaming ions are measured throughout the magnetosphere (Hoshino et al ’98, Gosling et al ’05, Phan et al ’07)
• Basically a Fermi reflection mechanism
  - curvature drift along the reconnection electric field

\[ \Delta T_{||} \sim m_t c_A^2 \]

Phan et al ‘07
Basic mechanisms for electron energy gain during reconnection

- Electron heating and acceleration less well understood
- In the guiding center limit

\[
\frac{d\epsilon}{dt} = \frac{\mu}{\gamma} \frac{\partial B}{\partial t} + q v^\parallel E^\parallel + q \vec{v}_c \cdot \vec{E} + q \vec{v}_B \cdot \vec{E}
\]

- Curvature drift
  - Slingshot term (Fermi acceleration) increases the parallel energy

\[
v_c = \frac{\gamma v^\parallel}{\Omega} \vec{b} \times (\vec{b} \cdot \nabla \vec{b})
\]

- Grad B drift
  - Betatron acceleration increases (or decreases) perpendicular energy

\[
v_B = \frac{\gamma v^\perp}{2\Omega} \vec{b} \times \frac{\vec{\nabla} B}{B}
\]

- Magnetic moment

\[
\mu = \frac{m\gamma^2 v^2}{2B}
\]
Electron heating during reconnection

- Carry out 2-D PIC simulations of electron-proton system with a weak and strong guide fields (0.2 and 1.0 times the reconnection field)
  - $819.2d_i \times 409.6d_i$
  - Mass-ratio $m_i/m_e=25$
  - Compare all of the heating mechanisms
Electron heating mechanisms: weak guide field

- Slingshot term dominates (Fermi reflection)
- Parallel electric field term small – a surprise
- Grad B term is an energy sink
  - Electrons entering the exhaust where B is low lose energy because $\mu$ is conserved.

![Graph showing heating over time](image)
Spatial distribution of heating: weak guide field

- The distribution of Fermi and $E_\parallel$ heating
Electron heating mechanisms: strong guide field

- Fermi and parallel electric field term dominate
Spatial distribution of heating: strong guide field

• The distribution of Fermi and $E_\parallel$ heating
• Longer current layers and electron holes (Buneman)
  – Not much heating from electron holes

Fig. 6.— Simulation B ($b_g = 1.0$), $t = 350 \Omega - 1$ c.i. Most intense heating occurs at the ends of islands for the curvature term, and at X-lines for the $E \cdot J$ term.
Electron energy spectra

- Electron energy spectrum from guide field unity simulation
- Most rapid electron energy gain early in time when many small islands develop and merge
- No powerlaws – no loss mechanism in periodic system
Electron spectral anisotropy

- The dominant acceleration mechanisms accelerate electrons parallel to the local magnetic field – Fermi slingshot and $E_{||}$
  - Extreme anisotropy in the spectrum of energetic electrons
  - More than a factor of $10^3$
  - What limits the anisotropy?
Fermi acceleration

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

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

Schoeffler et al 2011
Multi-island particle acceleration

• How does a multi-island environment develop?
• What is the size distribution of magnetic islands? (Fermo ‘10, Uzdensky ‘10)
• How does a bath of growing and merging islands accelerate particles?
  – Need a generalized Parker transport equation to describe reconnection driven particle acceleration
• How do energetic particles feed back on island growth?
  – firehose
• What is the upper limit on electron acceleration in a multi-island system?
  – Gyro-synchrotron radiation is significantly reduced in a system with extreme anisotropy – guide field case
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, Fermo et al 2012)
- Multi-island reconnection is generic
Development firehose limits reconnection

- The Fermi mechanism drives the system towards the firehose threshold even in a system with very low initial $\beta$
- At the firehose threshold magnetic fields have no tension
  - No reconnection drive
Firehose instability during island contraction

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

Schoeffler et al 2011
Fermi acceleration in contracting islands

- Area of the island $Lw$ is preserved
  \[ \Rightarrow \text{nearly incompressible dynamics} \]
- Magnetic field line length $L$ decreases
- Parker’s transport equation
  \[
  \frac{\partial F}{\partial t} + \nabla \cdot u F - \nabla \cdot \kappa \cdot \nabla F - \frac{1}{3} (\nabla \cdot u) \frac{\partial}{\partial p} pF = 0
  \]
  - Only compression drives energy gain. Why?
  - Parker equation assumes strong scattering \(\Rightarrow\) isotropic plasma
- Retaining anisotropy is critical for reconnection
Energy gain in merging islands

- Total area preserved
- Magnetic flux of largest island is preserved
- Particle conservation laws
  - Magnetic moment $\mu = \frac{p_{\perp}^2}{2mB}$
  - Parallel action $p_{\parallel}L$
    - Field line shortening drives energy gain

\[
\frac{dp_{\parallel}^2}{dt} \sim 2 \frac{0.1c_A}{r_1 + r_2} p_{\parallel}^2 \\
\frac{dp_{\perp}^2}{dt} \sim -\frac{0.1c_A}{r_1 + r_2} p_{\perp}^2
\]

- 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 $f(p_\parallel, p_\perp)$ with $\zeta = p_\parallel/p$
  - Equi-dimensional equation – no intrinsic scale
  - Powerlaw solutions
  - Drake et al 2013

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

$R \sim 0.1 \left\langle \frac{\alpha^{1/2} c_A}{r} \right\rangle \equiv \frac{1}{\tau_h}$  merging drive  pitch-angle scattering

$\alpha = 1 - \frac{1}{2} \beta_\parallel + \frac{1}{2} \beta_\perp$
Energetic particle distributions

- Solutions in the strong drive limit – balance between drive and loss
  - Characteristic times
    - Heating time based on characteristic island size \( w \): \( \tau_{\text{heat}} = \frac{w}{c_A} \)
    - Loss time based on characteristic system size \( L \): \( \tau_{\text{loss}} \sim \frac{L}{c_A} \)
  - Typically heating time short compared with loss time (\( w \ll L \))
  - Require feedback from the high pressure (firehose)

- Pressure of energetic particles rises until it is comparable to the remaining magnetic energy
  - Equipartition
  - Powerlaw solutions for the particle flux
    - Non-relativistic
      \[ j \sim p^2 f(p) \sim p^{-3} \sim E^{-1.5} \]
    - Relativistic
      \[ j \sim E^{-2} \]
An upper limit on energy gain during reconnection

• Magnetic reconnection dominantly increases the parallel energy of particles, depending on the degree of magnetization
  – Traditional synchrotron emission may not limit particle energy gain
• An upper limit on energy comes from a balance between the energy gain due to the magnetic slingshot ($\sim \gamma/R$) and the particle radiation due to its motion along the curved field line ($\sim \gamma^4$)

\[ \gamma < \left( \frac{R}{R_c} \right)^{1/3} \]

– Where $R_c = e^2 / mc^2$ is the classical electron radius and $R$ is the field line radius of curvature.
Conclusions

• The magnetic curvature and associated Fermi reflection is the dominant driver of electron acceleration during reconnection of anti-parallel fields

• Both Fermi and parallel electric fields dominant drivers of electron acceleration during guide field reconnection

• Significant acceleration requires electron interaction with multiple islands

• Energetic particles exhibit extreme anisotropy for reconnection with a guide field
  – What mechanism limits this anisotropy?
Conclusions (cont.)

• A transport equation describing particle heating and acceleration in a bath of merging magnetic islands generalizes the Parker transport equation to include anisotropy
  – Powerlaw solutions controlled by feed back from the pressure anisotropy
  – Can be used to explore particle acceleration in large-scale systems