Kinetic aspects of the ion current layer in an outflow exhaust in magnetic reconnection

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Outline

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  – Kinetic structure of the reconnection site
• 2. Ion velocity distribution function
  – Composition of the VDF
  – Chaotic particle motion
• 3. Discussion
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1. Introduction
Kinetic structure of reconnection site

Electron-scale structure

Ion-scale structure

$E + \mathbf{v} \times \mathbf{B} \neq 0$

2D PIC simulations
Dissipation region

Generalized measure

\[ D_e = \gamma_e \left[ j \cdot (E + v_e \times B) - \rho_e (v_e \cdot E) \right] \]
\[ \approx j \cdot (E + v_e \times B) \]

[Zenitani et al. 2011 PRL]

Total energy transfer

\[ j \cdot E = (j \times B) \cdot \nu_{\text{mhd}} + D_e \]

Energy dissipation (resistive MHD)

Work by Lorentz force (Ideal MHD)

(a) anti-parallel

(b) guide-field \((B_g=0.8B_0)\)

Dissipation region

2D PIC simulations
Electron-scale structure

(A) Quadrupole magnetic field

(B) Hall current

(C) Electron current layer

(D) Dissipation region

(E) Super-Alfvénic electron jet

(F) Pedestal

Zenitani et al. 2011 PoP
Electron-scale structure

- The electron ideal condition is violated.
- Super-Alfvénic electron jet.

Zenitani et al. 2011 PoP

$$(E + U_e \times B)_y \neq 0$$

Karimabadi et al. 2007 GRL

Shay et al. 2007 PRL
Ion-scale structure

$E + \mathbf{v} \times \mathbf{B} \neq 0$

Electron-scale structure
- Hall current
- Dissipation region
- Electron current layer
- Super-Álveo electric jet
- Pedestal

Ion-scale structure
- Hybrid
  - Lottermoser et al. 1998 JGR
  - Arzner & Scholer 2001 JGR
  - Higashimori & Hoshino 2012
- Kinetic
  - Drake et al. 2009 JGR
  - Liu et al. 2011-2012 PoP

Zenitani et al. 2011 PoP
• Q1. Why is the ion ideal condition violated?
• Q2. Why is the ion flow sub-Alfvénic?
2. Ion velocity distribution function
Ion velocity distribution function

- 2D PIC simulation
- $m_i/m_e=100$
- $76.8 \times 38.4 \text{ [d]}$
- $10^9$ particles

- Non-Maxwellian
- Non-gyrotropic
- Non-ideal

\[ \mathbf{v}_i \neq \frac{\mathbf{E} \times \mathbf{B}}{B^2} \]

\[ \mathbf{E} + \mathbf{v}_i \times \mathbf{B} = \mathbf{R}(\mathbf{v}_i) \neq 0 \]
Ion velocity distribution function

- (1) global Speiser ions
- (2) local Speiser ions
- (3) trapped ions
(Global-type) Speiser orbit

Movie: X-line to outflow
Energetic tail rotates clockwise
(Local-type) Speiser orbit

Lottermoser et al. 1998 JGR
Nakamura et al. 1998 JGR
Arzner & Scholer 2001 JGR

Lyons & Speiser 1985 JGR
Speiser 1965 JGR
Hall effect

- Magnetic field lines are dragged out of the page (Sonnerup 1979, Mandt et al. 1994)
Two Speiser orbits

- Global-type (classical one)
- Local-type (local reflection)
Ion velocity distribution function

- (1) global Speiser ions
- (2) local Speiser ions
- (3) trapped ions
Nonlinear dynamics in 1980’s

- The night before kinetic PIC simulations
- Poincaré map: $(x, \dot{x})$ at $z=0$

One can visually classify particle orbits.

Chen & Palmadesso 1986 JGR
Ion velocity distribution function
Ion velocity distribution function

\[
\left( \frac{\partial}{\partial x} \right) \ll \left( \frac{\partial}{\partial z} \right)
\]
Ion velocity distribution function

Two of 5 variables \((x, y, V_x, V_y, V_z)\) at \(z=0\)
Distribution function $\Leftrightarrow$ Poincaré map

- $(x, \dot{x}) \Leftrightarrow (-\dot{y}, \dot{x})$

Speiser orbits
(Transient orbits)

Regular orbits

Chen & Palmadesso 1986 JGR
magnetic field lines

by T. Wada @ NAOJ

http://th.nao.ac.jp/MEMBER/zenitani/research-e.html
http://th.nao.ac.jp/MEMBER/zenitani/files/regular_orbits.mp4
Simulation vs Theory

PIC simulation

Chaos model

Regular motion in a moving, rotated frame
(Reconstructed) **Trapped-ion orbit**

- Decomposed to the regular motion and the frame motion
- First demonstration of regular orbits in a self-consistent PIC simulation
3. Discussion
Particle-orbit theory

Curvature radius of $B$

$$ \kappa = \sqrt{\frac{R_{\text{min}}}{\rho_{\text{max}}}} $$

Larmor radius

Büchner & Zelenyi 1989 JGR

$\kappa \rightarrow 0$

$\kappa \sim 1$

$\kappa \rightarrow \infty$

Bounce motion

Chaotic motion

Gyro motion ($\mu$-adiabatic)
Particle-orbit theory

Curvature radius of $B$

$$\kappa = \sqrt{\frac{R_{\text{min}}}{\rho_{\text{max}}}}$$

Larmor radius

Bounce motion

Chaotic motion

Gyro motion ($\mu$-adiabatic)

$\kappa \rightarrow 0$

$\kappa \sim 1$

$\kappa \rightarrow \infty$
Ideal condition

\[ E + v \times B \neq 0 \quad \text{and} \quad E + v \times B \approx 0 \]

- The ideal condition can be easily violated
- Particles no longer gyrate about \( B \)
- The nonidealness is necessary, but not sufficient for magnetic dissipation

\( \kappa \to 0 \quad \kappa \sim 1 \quad \kappa \to \infty \)

Bounce motion

Chaotic motion

Gyro motion (\( \mu \)-adiabatic)
Sub-Alfvénic ion flow

- Ion flow ($V_i$) is slower than the inflow Alfvén speed ($c_{A,in}$)
  - Typically 0.4-0.5 $c_{A,in}$
- Local Speiser ions in the rotated frame

Inflow Alfvén speed ($c_{A,in}$)

(a) Outflow velocity

$|V_i - U| \sin \alpha$
Super-Alfvénic electron jet

= Ensemble of the swing-by motion of local Speiser electrons

Dissipation region

Local Speiser electrons

Chen et al. 2011 PoP
Multiscale picture of the outflow region

- Curvature radius increases in the farther downstream
- We may eventually see MHD-like Alfvénic outflow

\[ V_x \]

\[ V_y \]

\[ V_z \]

\[ V_{\text{ExB}} \]

\[ \kappa_e \rightarrow 0 \]
\[ \kappa_e \lesssim 1 \]
\[ \kappa_i \rightarrow 0 \]
\[ \kappa_i \lesssim 1 \]

Super-Alfvénic electron jet in x

[\[E + v_e \times B\]_y < 0]

Sub-Alfvénic ion flow in x

[\[E + v_i \times B\]_y > 0]
Summary

• We have examined an ion velocity distribution function in the reconnection outflow:
  – (1) Global Speiser ions
  – (2) Local Speiser ions
  – (3) Trapped ions
    • Regular orbits in the chaos theory
    • First demonstration in PIC simulation

• Plasma ideal condition
  – Easily violated in the \( \kappa < 1 \) regime
  – Particles no longer gyrate

• Local-Speiser motion explains
  – Sub-Alfvénic ion flow
  – Super-Alfvénic electron jet

• Better understanding of the outflow region from the viewpoint of particle motion
Thank you for your attention!