Electron dynamics surrounding the X line in asymmetric magnetic reconnection

Seiji ZENITANI

Hiroshi Hasegawa
Tsugunobu Nagai
Magnetic reconnection in near-Earth space

Electron-scale measurement with MMS

We try to understand electron-physics signatures in magnetopause reconnection
2D particle-in-cell (PIC) simulation

- Asymmetry in plasma properties
  - Density variation \( n_1 : n_2 = 3 : 1 \)
  - Magnetic variation \( B_1 : B_2 = 1 : 3 \)
- Ion-electron mass ratio
  - \( m_i : m_e = 25 : 1 \)
Electron-physics signatures near the X line

1. Sphere-side
2. Sheath-side
3. Outflow region
4. Electron mixing
5. Guide-field effects
Sphere-side: Crescent-shaped VDF

Electron velocity distribution function

MMS observation (Burch+ 2016 Science)

See also
Hesse+ 2014 GRL
Bessho+ 2016 GRL
Shay+ 2016 GRL
Sphere-side: Crescent-shaped VDF

- Sheath-origin meandering electrons
- Sphere-origin core component
- Meandering electron

[Image of a crescent-shaped VDF with labels and a croissant image]

https://commons.wikimedia.org/wiki/File:Rogalik.jpg
Sphere-side: Crescent-shaped VDF

• Generic crescent formula
  (see also Bessho+ 2016)

\[ v_y < -\left( \frac{1}{2e}mv_z^2 - \frac{1}{2m}eA_y^2(z) - \phi(z) \right) / A_y(z) \]

\[ A_y(z) \equiv -\int_{z_0}^{z} B_x dz \]
\[ \phi(z) \equiv -\int_{z_0}^{z} E_z dz \]

Color and radius = Crossing numbers of \( B_x \)-reversal
Sheath-side: Nonadiabatic electrons

- Curvature parameter (Buchner & Zelenyi 1989 JGR)

\[ E'_y = \left[ E + V_e \times B \right]_y \]

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

- Magnetic curvature radius

\[ \kappa \equiv \frac{R_c}{\rho} \]

- Electron Larmor radius

Nonadiabatic (\(\kappa < 2.5\))

- \(\varrho \sim R_c\)
- Chaotic motion
- We no longer expect the ExB drift!

\[ E + v_e \times B \neq 0 \]
Sheath-side: Nonadiabatic electrons

\[
E'_y = [E + V_e \times B]_y
\]

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

- Curvature parameter
  (Buchner & Zelenyi 1989 JGR)

\[
\kappa \equiv \sqrt{\frac{R_c}{\rho}}
\]

Magnetic curvature radius
Electron Larmor radius

Sharp magnetic curvature in 3D
Outflow region: Magnetic topology

- After an appropriate 3D rotation, the sharpest curvature is located at the $B_L$-reversal ($\neq B_x$-reversal)
Outflow region: Poincaré map analysis

(c) $E'_y = [E + V_e \times B]_y$

(g) Ensemble curvature parameter

Nonadiabatic

Adiabatic

Electron mixing
(Brute-force way to identify the EDR)
Quantifying electron mixing

$+\Delta t$

$M_f(t_0, \Delta t)$

"Forward" mixing
Quantifying electron mixing
Quantifying electron mixing
Quantifying electron mixing

$M_b(t_0, \Delta t)$

"Backward" mixing
Quantifying electron mixing

See also Haller 2015 Annu. Rev. Fluid Mech
Finite-time mixing fraction (FTMF)

\[ \mathcal{M}_R(t_0, \Delta t) \equiv \mathcal{M}_f(t_0, \Delta t) \times \mathcal{M}_b(t_0, \Delta t) \]

- \( t_0 \): time of interest
- \( \Delta t \): an electron-scale time interval

\[ \mathcal{M}_R(t_0, \Delta t) \]

\[ \mathcal{M}_f(t_0, \Delta t) \]

\[ \mathcal{M}_b(t_0, \Delta t) \]
Finding appropriate $\Delta t$

$$\mathcal{M}_R(t_0, \Delta t) \equiv \mathcal{M}_f(t_0, \Delta t) \times \mathcal{M}_b(t_0, \Delta t)$$

$t_0$ : time of interest

$\Delta t$ : an electron-scale time interval

$\Delta t = 0.1$

$\Delta t = 3.0$

$\Delta t = 1.0 \, \Omega_{ci}^{-1} = 25 \, \Omega_{ce}^{-1}$

Sufficiently small $\Delta t$ that satisfies $2\pi \Omega_{ce}^{-1} \ll \Delta t$
Mixing measure
Zenitani+ 2017 JGR

Asymmetric RX

Energy dissipation
Zenitani+ 2011 PRL

\[ M_R(t_0, \Delta t) \]

\[ D_e \simeq j \cdot (E + v_e \times B) \]

Asymmetric RX

Asymmetric RX with a guide-field

\[ B_y \]
Guide-field reconnection: VDFs

- Sphere/sheath-origin electrons are separate in VDFs (Hesse+ 2017 PRL)
Guide-field reconnection: electron orbits

• Signatures are enhanced by parallel acc. near the X line
Guide-field reconnection: Shannon entropy

\[-\sum_{i} p_i \log p_i\]

$p_i$: probability in the 3D velocity space

- High-entropy sphere-side layer with unmixed electrons
Online viewer (public version)

- http://rish.kyoto-u.ac.jp/~zenitani/DFX/
- Antiparallel reconnection
- http://rish.kyoto-u.ac.jp/~zenitani/MRA/
- Asymmetric reconnection
Summary

• 2D PIC simulation of magnetopause-type asymmetric reconnection

• Electron-physics signatures
  – Sphere-side: Crescent-shaped distribution functions
  – Sheath-side: Nonadiabatic/nonideal layer
  – Outflow-region: Nonadiabatic/nonideal layer near the B_L-reversal

• Electron mixing
  – We have introduced finite-time mixing fraction (FTMF)
  – It marks the energy-dissipation region

• Guide-field reconnection
  – We have confirmed Hesse (2017)’s finding of unmixed electrons
  – Shannon entropy marks the sphere-side unmixed layer

• Reference