Waves and Electron Acceleration in the Separatrix Regions of Magnetic Reconnection

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Waves in MRX Region: Obs.
EC (Electron cyclotron: Whistler) → Electromagnetic
Langmuir (plasma oscillation) → Electrostatic
ESW (Electrostatic Solitary Wave) → Electrostatic

- Previous simulations were unable to reproduce them.
- Generation mechanisms?
- Their roles in reconnection?

[Viberg et al., GRL, 2013]
Electron Energetics: Observations

- High energy electrons around separatrices
- “Flat-top” electrons

Maxwellian with Isotropic supra-thermal flat-top accelerated components distribution beam (thermalization) (scattering) (acceleration)

4 – 10keV

[Asano et al, JGR, 2008]
Purpose of This Study

- To understand the generation mechanisms of the waves in the separatrix regions of anti-parallel reconnection using particle-in-cell simulations, and

- To clarify the roles of the waves in reconnection, in particular, in electron acceleration.
Strategy of the PIC Simulation

\begin{equation}
V_{e,\text{out}} \sim V_{Ae} = \left(\frac{m_i}{m_e}\right)^{1/2} \left(\frac{n_b}{n_0}\right)^{-1/2} V_{A0} \propto \frac{1}{\sqrt{\beta_e}}
\end{equation}

- More realistic parameters
  - $m_i/m_e$: 100 $\rightarrow$ 400
  - $n_b/n_0$: 0.2 $\sim$ 0.3 $\rightarrow$ 0.04
- AMR-PIC
- Long-time evolution:
  - Periodic $\rightarrow$ Open boundary

$N_p: \sim 10^{10}$
- Memory: $\sim$ 1TB
Wave Activities Around Separatrices

[Fujimoto, GRL, 2014]
Wave Activities

- Weak waves
- Strong e⁻ acceleration due to double layer
- Intense wave activities
- Electron heating
Wave Generation Mechanisms

Electron-electron 2-stream instability

Beam-driven whistler instability

Linear analyses

$$\omega = \omega_r + i\gamma$$
Roles of the Waves

- **Buneman** 2-stream instability
- **Electron-electron** 2-stream instability
- **Beam-driven** whistler instability
- A few 100eV to ~5keV
- Flat-top
- Non-thermal component
Electron Acceleration Mechanism

Acceleration due to localized double layer

Ion-electron decoupling motion determines the potential structure.

\[-e\phi_A \sim \frac{1}{2} m_e V_{Ae}^2 = \frac{1}{2} m_i V_A^2\]

\[r_{gi} \sim \delta_H \sim c / \omega_{pi} \Rightarrow v_{th,i} \sim \alpha V_A\]

\[\alpha = B_i / B_e > 1\]

\[-e\phi_C \sim (\alpha^2 - 1) m_i V_A^2 / 2 < 0\]
Electron Acceleration Mechanism

At point C

\[ V_e \parallel \approx \sqrt{\frac{2e\phi_C}{m_e}} \]

\[ \sim \sqrt{\alpha^2 - 1} V_{Ae} \]

\[ \propto \beta_e^{-1/2} \]

At point C
Summary [Fujimoto, GRL, 2014]

The generation mechanisms of the waves in the separatrix regions have been identified for anti-parallel reconnection.

Key parameters are realistically low plasma beta.

The waves are responsible for “flat-top” and non-thermal electrons.

The waves are useful to diagnose the electron dynamics in the reconnection region by means of on-going and/or up-coming satellite observations.

Guide-field cases will be investigated as a next step.