Asymmetric reconnection

不揃いなりリコネクション

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M’pause reconnection: asymmetry

Phan & Paschmann 1996

Phan+ 2013
Early predictions

- Rotational discontinuity (RD) and slow-mode expansion fan (SEF) are expected
- See Lin & Lee 1993 for detail.
Numerical development

- Shock structures are roughly confirmed
  - Minor details were difficult to tell: schemes, limited domain, and kinetic effects
- Steep RD and downstream bulge on the M’sheath side

Hoshino & Nishida 1983

Nakamura & Scholer 2000

Swisdak+ 2003
Renewed attention in late 00’s

- NASA MMS mission
  - 4 satellites
  - Extremely high resolution

- Everything is ON SCHEDULE
- Launch for Oct 2014
- During Phase 1 (2015-2016), MMS will probe RX sites at the M’pause
Basics properties in symmetric RX

Energy conservation

\[ \frac{B_{in}^2}{4\pi} L v_{in} \sim \left( \rho_{out} v_{out}^2 \right) \delta v_{out} \]

Continuity

\[ \rho_{in} L v_{in} = \rho_{out} \delta v_{out} \]

\[ R \sim V_{in} / V_{A,in} \sim 0.1 \]

\[ E \sim 0.1 V_{A,in} B_{in} \]

\[ \frac{B_{in}^2}{4\pi \rho_{in}} \sim v_{out}^2 \]

\[ V_{out} \sim V_{A,in} \]
Dawn of the new MHD theory

- Scaling analysis of different upstream densities
- Empirical hybrid relations

\[ v_{\text{Ah}} = B[I \frac{4\pi(0.5\rho_1 + 0.5\rho_2)]^{1/2} \]

Borovsky+ 2007
Cassak-Shay model (1/2)

- Immediate success
- Full asymmetry
- Conservation analysis
- Useful hybrid relations

\[ E \sim 0.1 \, v_A B_0 \]
\[ v_{out} \sim v_A \]

\[ E \sim \left( \frac{\delta}{L} \right) \left( \frac{v_{out}}{c} \right) \left( \frac{2B_1 B_2}{B_1 + B_2} \right) \]

\[ v_{out}^2 \sim \frac{B_1 B_2}{4\pi} \frac{B_1 + B_2}{\rho_1 B_2 + \rho_2 B_1} \]
• Too good to be true?
• Minor differences aside, the results were verified by many simulation works (Cassak & Shay 2007-2009, Malakit+ 2010)

<table>
<thead>
<tr>
<th>Physical quantity</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density of outflow, Eq. (17)</td>
<td>$\rho_{\text{out}} \sim (\rho_1 B_2 + \rho_2 B_1)/(B_1 + B_2)$</td>
</tr>
<tr>
<td>Outflow speed, Eq. (13)</td>
<td>$v_{\text{out}}^2 \sim [(B_1 B_2)/(4\pi)][(B_1 + B_2)/(\rho_1 B_2 + \rho_2 B_1)]$</td>
</tr>
<tr>
<td>Reconnection rate, Eq. (19)</td>
<td>$E \sim <a href="v_%7B%5Ctext%7Bout%7D%7D/c">(B_1 B_2)/(B_1 + B_2)</a>(2\delta/L)$</td>
</tr>
<tr>
<td>Location of X-line, Eq. (26)</td>
<td>$(\delta_x/\delta_{x_1}) \sim (B_2/B_1)$</td>
</tr>
<tr>
<td>Location of stagnation point, Eq. (27)</td>
<td>$(\delta_{s_2}/\delta_{s_1}) \sim (\rho_2 B_1/\rho_1 B_2)$</td>
</tr>
</tbody>
</table>
Compressibility debate

- Cassak=Shay balances

\[ L \left( \frac{B_1^2}{8 \pi} v_1 + \frac{B_2^2}{8 \pi} v_2 \right) \sim 2 \delta \left( \frac{1}{2} \rho_{out} v_{out}^2 \right) v_{out} \]

- We became aware of the roles of
  - Compressibility
  - Enthalpy flux
  - ==> Missing pieces in Sweet-Parker theories.

- Theory (Birn+ 2010, 2011, Hesse+2011)
- Simulation (Birn+ 2008, Aunai+ 2011)
- Observation (Eastwood+ 2013)
Consider the full balance equations, including the compressibility.

Near-equipartition

Compression factor

\[ r \equiv \frac{\rho_o}{\bar{\rho}} = \frac{\Gamma(B_1 + B_2)}{\lambda_1 B_2 + \lambda_2 B_1} \]

\[ E \sim \frac{\Gamma(B_1 + B_2)}{\lambda_1 B_1 + \lambda_2 B_2} \left( \frac{2B_1 B_2}{B_1 + B_2} \right) \frac{v_{out}}{c} \frac{\delta}{L} \]
Kinetic signatures in symmetric RX

- Flipping of the filed lines (Sonnerup 1979)
- Higher beta, stronger modulation

Zenitani et al., PoP 18, 122108 (2011)

Øerosat+ 2001 Nature
See also Nagai+ 2001 JGR
Kinetic signatures

- Many asymmetric signatures
- Few impacts to the global evolution
Kinetic feedback 1 - diamagnetic suppression

- Diamagnetic effect may suppress reconnection (Swisdak+ 2003, 2010)
- Derived a criteria
  \[ \Delta \beta > 2(L/\lambda_i)\tan(\theta/2) \]
- This remains controversial
  - Unclear theory: diamagnetic flow does not carry magnetic flux
  - No confirmation by other groups (i.e., Aunai+ 2013)
Observational support

The Swisdak criteria: $\Delta \beta > 2(L/\lambda_i)\tan(\theta/2)$
Kinetic feedback 2 - anomalous slow down

- $64.0 \, d_i \times 25.6 \, d_i$, periodic in $x$, reflecting in $z$
- $m_i : m_e = 25 : 1$
- Two runs: Coplaner ($B_y = 0$) vs Guide-field ($B_y \neq 0$)
Coplaner reconnection is slow!!

\[ E \sim \left( \frac{\delta}{L} \right) \sqrt{\frac{B_1 B_2}{\mu_0} \frac{B_1 + B_2}{\rho_1 B_2 + \rho_2 B_1} \left( \frac{2B_1 B_2}{B_1 + B_2} \right)} \]

- Guide-field usually makes RX slow
- Coplaner \((B_y=0)\) run is anomalously slow
- Consistent with previous work by Pritchett 2008

Zenitani+ 2010 unpublished
Hesse+ 2013, Aunai+ 2013
**Implications**

- Flux/energy/mass transfer by magnetopause reconnection can be intermittent.
Particle confinement?

- Larger bounce width
- Wider current channel $\Rightarrow$ Weaker $E$ can drive the current

Hesse+ 2013
Dissipation region

Nonideal energy dissipation

\[ D_e = j_\mu e^{\mu} = \gamma_{e} \left[ j \cdot (E + v_e \times B) - \rho_c (v_e \cdot E) \right] \]

Field reversal

Zenitani+ 2011
Electron distribution function

- Highly anisotropic, structured distribution
- The “half-ring” population is responsible for the energy dissipation
Lower-origin meandering electrons
Drifting electrons on the upper side
• Two current-carrying electrons
  • Meandering electrons (unconfined, dissipative)
  • drifting electrons (confined, non-dissipative)
• We are still trying to understand
  • How do they mix each other?
  • How to dissipate the energy?
Summary

• MHD properties
  – Shock structures
  – Cassak=Shay=Birn (CSB) model is successful

• Kinetic signatures
  – Bipolar Hall field, density-gradient mode etc.
  – Few impacts to global evolution

• Major unsolved issues - kinetic effects, related to $\Delta \beta$
  – Diamagnetic suppression (Swisdak+ 2003)
  – Anomalous slow down (Hesse+ 2013)

• More simulations needed, using realistic parameters
• Next-generation observations will come in 2015