High-speed fluid dynamics in magnetic reconnection in a low-beta plasma

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Motivation

• Magnetic reconnection expels a fast outflow jet at the upstream Alfvén speed
• How does the jet interact with an external medium?

\[ c_A = \frac{B}{\sqrt{4\pi \rho}} \]

• Key parameter

\[ \beta \equiv \frac{p_{\text{gas}}}{p_{\text{mag}}} = \frac{8\pi p}{B^2} \]
\[ \frac{1}{\beta} \sim \left( \frac{c_A}{c_s} \right)^2 \sim \left( \frac{V}{c_s} \right)^2 \sim M^2 \]

Typical velocity
Typical Mach number
Sound speed
Branches of fluid dynamics

Conventional fluid dynamics

- Incompressible fluids

Shock waves

- Compressible fluid dynamics
  - Adiabatic effects
  - Shocks
  - Shock-shock interaction

- High-speed fluid dynamics

Subsonic

Transonic

Supersonic

\[ \mathcal{M} = \frac{V}{C_s} \]
MHD simulation

Density

Symmetry

Reconnection point

Density

Plasma sheet

\( \beta = 0.2 \)

Outflow velocity \((V_x)\)

X

Z
Various shocks!

- Extensive analysis on shock conditions (Minimum variance analysis; MVA-B)

<table>
<thead>
<tr>
<th>No.</th>
<th>Location</th>
<th>$\xi$, $\eta$</th>
<th>$\xi_{sh}$</th>
<th>$\beta_{sh}$</th>
<th>$M_{sh}$</th>
<th>$M_{sh}$</th>
<th>$M_{sh}$</th>
<th>$M_{sh}$</th>
<th>$M_{sh}$</th>
<th>$M_{sh}$</th>
<th>$M_{sh}$</th>
<th>$T_{sh}/T_1$</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>(40, 0, 1.35)</td>
<td>$(-0.03, 1.35)$</td>
<td>0.00</td>
<td>86.3</td>
<td>0.22</td>
<td>0.06</td>
<td>0.98</td>
<td>2.49</td>
<td>0.04</td>
<td>0.69</td>
<td>0.69</td>
<td>2.72</td>
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<tr>
<td>2</td>
<td>(55, 0, 1.75)</td>
<td>$(-0.04, 1.00)$</td>
<td>-0.013</td>
<td>86.3</td>
<td>0.098</td>
<td>0.06</td>
<td>0.88</td>
<td>3.22</td>
<td>0.04</td>
<td>0.58</td>
<td>0.58</td>
<td>4.58</td>
</tr>
<tr>
<td>3</td>
<td>(61, 2, 0)</td>
<td>$(-1.00, 0.00)$</td>
<td>-0.40</td>
<td>90.3</td>
<td>0.30</td>
<td>1.41</td>
<td>0.77</td>
<td>1.38</td>
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<td></td>
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<tr>
<td>4</td>
<td>(51, 0, 6.0)</td>
<td>$(1.00, -0.04)$</td>
<td>0.31</td>
<td>9.4</td>
<td>0.12</td>
<td>0.41</td>
<td>0.42</td>
<td>1.34</td>
<td>0.33</td>
<td>0.34</td>
<td>0.78</td>
<td>1.33</td>
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<tr>
<td>5</td>
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<td>0.16</td>
<td>0.05</td>
<td>0.85</td>
<td>2.47</td>
<td>0.03</td>
<td>0.56</td>
<td>0.65</td>
<td>2.54</td>
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<tr>
<td>6</td>
<td>(110, 0, 8.5)</td>
<td>$(0.24, 0.97)$</td>
<td>0.19</td>
<td>84.9</td>
<td>0.21</td>
<td>0.06</td>
<td>0.76</td>
<td>1.99</td>
<td>0.05</td>
<td>0.53</td>
<td>0.64</td>
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<tr>
<td>7</td>
<td>(101, 2, 1.00)</td>
<td>$(0.94, 0.33)$</td>
<td>0.54</td>
<td>25.2</td>
<td>0.23</td>
<td>0.43</td>
<td>0.49</td>
<td>1.15</td>
<td>0.39</td>
<td>0.44</td>
<td>0.87</td>
<td>1.15</td>
</tr>
<tr>
<td>8</td>
<td>(110, 0, 1.5)</td>
<td>$(-0.06, -1.00)$</td>
<td>0.10</td>
<td>87.8</td>
<td>1.1</td>
<td>0.12</td>
<td>4.5*</td>
<td>6.5*</td>
<td>0.12</td>
<td>3.99</td>
<td>4.0*</td>
<td>1.55</td>
</tr>
<tr>
<td>9</td>
<td>(120, 0, 1.9)</td>
<td>$(0.43, -0.99)$</td>
<td>0.13</td>
<td>87.1</td>
<td>0.49</td>
<td>0.09</td>
<td>0.00</td>
<td>3.8*</td>
<td>3.8*</td>
<td>0.08</td>
<td>1.7*</td>
<td>1.9*</td>
</tr>
<tr>
<td>10</td>
<td>(120, 0, 1.0)</td>
<td>$(0.64, -0.77)$</td>
<td>0.50</td>
<td>46.8</td>
<td>2.63</td>
<td>1.22</td>
<td>3.00</td>
<td>3.40</td>
<td>0.88</td>
<td>2.66</td>
<td>3.06</td>
<td>1.18</td>
</tr>
</tbody>
</table>

* indicates unreliable results (see Sec. III F). The letter (S) indicates a slow shock, (F) is a fast shock, and (U) is unclassified.
Normal shock: Analogy to airfoil

- MHD slow shock
- Recovery/recompression shock

\[ V_{\text{jet}} \sim C_A \]

\[ \beta = 1.0 \]
\[ \beta = 0.2 \]

Subsonic \( (V \ll C_s) \)

Transonic \( (0.8C_s < V) \)

Supersonic \( (C_s < V) \)

See also https://www.youtube.com/watch?v=8OlfCTAZQo
Shock diamond

\[ v_{jet} \approx c_A > c_s \iff \beta < 1 \]
Supersonic nozzle problem

- (a) Over-expanded flow
  \[ c_s < V_{jet} \quad \text{and} \quad p_{jet} < p_{ambient} \]

- (b) Under-expanded flow
  \[ c_s < V_{jet} \quad \text{and} \quad p_{jet} > p_{ambient} \]
Shock diamonds in aeronautics

Shock diamonds in video game

Microsoft Flight Simulator X  https://www.youtube.com/watch?v=S8QGaiE4yWc
Shock diamonds in astrophysics

$2 \times 10^6$ light years

Hidden shock-diamonds

- Under-expanded shock-diamonds at the shock crossing point

- Triple-point structure is even more complicated (Zenitani 2015 PoP)
  - Contact discontinuity
  - Slow expansion fan

- Normal shock
- Petschek slow shocks

- $\beta = 0.1$
- $V_x$ and $V_z$
A digital catalog of the plasmoid structure

1. Petschek slow shock (Petschek 1964)
2. outer shell = slow shock (Ugai 1995)
3. intermediate shock (Abe & Hoshino 2001) or slow shock (Saito et al. 1995)
4a fast shock (Forbes & Priest 1983)
4b oblique shock & Mach disk (Takasao et al. 2015)
5. loop top front (Ugai 1987)
6. tangential discontinuity
7. post-plasmoid vertical slow shock (Zenitani et al. 2010)
8. outer vertical slow shock (Zenitani & Miyoshi 2011)
9. fast-mode wave front (Saito et al. 1995)
10. overexpanded shock-diamonds (Zenitani et al. 2010)
11. underexpanded shock-diamonds (Zenitani 2015)
12. contact discontinuity (Zenitani & Miyoshi 2011, 2015)
13. contact discontinuity (Zenitani 2015)
14. contact discontinuity (Zenitani 2015)
15. slow expansion wave front (Zenitani 2015)
16. region dominated by shocks
17. region dominated by shocks
18. region dominated by shocks

- In high Mach number, low-β regime, reconnection system is dominated by shocks
- This regime has long been unexplored!

\[
\frac{1}{\beta} \sim \left( \frac{c_A}{c_s} \right)^2 \sim \left( \frac{V}{c_s} \right)^2 \sim M^2
\]
OpenMHD code

• Simple, Scalable, and Shock-capturing MHD code
  • TVD Runge-Kutta method
  • TVD MUSCL scheme + HLLD solver
  • Hyperbolic divergence cleaning
  • Parallel-IO

• Search “OpenMHD” without a space

http://th.nao.ac.jp/MEMBER/zenitani/openmhd-e.html
Summary

• We have investigated the shock structure of a reconnection-plasmoid system

• In high Mach-number, low-\(\beta\) regime, several new structures are found:
  • Recompression shock
  • Over-expanded shock diamonds at the front
  • Under-expanded shock diamonds inside the jet

• They are outcomes of high-speed (compressible) fluid effects : \(M > 1\)

• Code publicly available

• References:
Thank you for your attention.
Have a safe return trip!