The electron-frame dissipation measure in collisionless magnetic reconnection

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Outline

1. Introduction
   - Recent debates on the electron diffusion region (EDR)

2. Theory
   - Introducing a new measure $D_e$

3. Numerical tests & discussions
   - 2D kinetic PIC simulations
   - What’s wrong with the frozen-in and why $D_e$ works?

4. Applications
   - Closer look at antiparallel symmetric reconnection
Magnetic reconnection

- Explosive topological change of magnetic field lines
- Beyond ideal-MHD

$$E + v \times B \neq 0$$

Solar flare
CME
Magnetopause
Magnetotail
Our magnetosphere
The dissipation region

- The ideal condition
  \[ E + v_s \times B = 0 \]

- We expected a multi-scale structure

- We are interested in the innermost EDR
  - It is traditionally identified by
    \[ E'_y = (E + v_e \times B)_y \neq 0 \]
EDR in 2D kinetic PIC simulations

- Large-scale PIC simulations

- A two-scale structure
  - Inner region attached to the reconnection point
  - Outer region elongated in the outflow (X) direction. A fast electron jet outruns the field lines.

\[ (E + U_e \times B)_y \]

Inner EDR: \( E'_y > 0 \)

Outer EDR: \( E'_y < 0 \)

Karimabadi+ 2007 GRL
Magnetic field lines are “flipped” (Hall field)
From a different angle

Quasi-ideal convection in X'-Z
Is this really EDR?

Hesse+ 2008 Phys. Plasmas
EDR in asymmetric Rx (1/2)

- Asymmetric reconnection
- All three components of $[E+v\times B]$ are puzzling

solar wind

- $B_z$
- $+B_z$

dipole field

- Magnetopause

Pritchett & Mozer 2009 Phys. Plasmas

$$(E + U_x B)_x$$
$$(E + U_x B)_y$$
$$(E + U_x B)_z$$

$X$ $Z$

$-2.2$ $0$ $2.2$

$-0.13$ $0$
The situation is worse for asymmetric reconnection with a guide field.

Any quantities to characterize the EDR-like region surrounding the reconnection site?
The violation of the electron ideal condition \((E + v_e x B \neq 0)\) may not identify the critical region.

- The controversial outer EDR
- No EDR signature in asymmetric reconnection
A new measure “D”

- Let us construct a new measure “D” to identify the critical region.

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

- We derive our formula from scratch, considering three basic requirements.
Desirable conditions for “D” (1/3)

1. Physical meaning
2. Scalar quantity
3. Insensitive to observer motion

- Reconnection consumes the magnetic energy
- Magnetic energy consumption or similar quantities should characterize the reconnection region

Diagram:
- Magnetic energy
- Plasma energy
  - Heat
  - Bulk flow
  - Nonthermal particles
Desirable conditions for “D” (2/3)

1. Physical meaning
2. Scalar quantity
3. Insensitive to observer motion

- If we employ a scalar quantity, we don’t need to worry about the coordinate. The Y direction or the Y’ direction do not matter.
Desirable conditions for “D” (3/3)

1. Physical meaning
2. Scalar quantity
3. Insensitive to observer motion

- There is always relative motion between the observer (satellite) and the reconnection site

X-line retreat (NENL)

Plasma sheet flapping
Desirable conditions

1. Physical meaning
2. Scalar quantity
3. Insensitive to observer motion

“The reconnection measure $D$ should be a Lorentz-invariant.”

A. Einstein
Making a Lorentz invariant

- 4-vector quantities

\[ a^\mu = (a_0, \mathbf{a}) = (a_0, a_1, a_2, a_3) \quad a'^\mu = \Lambda^\mu_\nu a^\nu \]

- Contracting two, we obtain an invariant scalar.

\[ a_\mu b^\mu = -a_0 b_0 + a_1 b_1 + a_2 b_2 + a_3 b_3 \]
\[ a'_\mu b'^\mu = a_\mu b^\mu = \text{const.} \]

- We list up all 4-vector quantities in the system.
- We find out a good combination(s) from all possible patterns.
Our choices: $j^\mu$ and $e^\mu$

- Spacelike current

$$j^\mu = J^\mu - c^{-2}(-J^\nu u_{e,\nu})u_e^\mu$$

- Covariant electric field

$$e^\mu = F^{\mu\nu}u_{e,\nu} = \left(\frac{\gamma_e \mathbf{v}_e \cdot \mathbf{E}}{c}, \gamma_e (\mathbf{E} + \mathbf{v}_e \times \mathbf{B})\right)$$

Lorentz factor for $v_e$.

4-current

$$J^\mu = (\rho c^2, \mathbf{j})$$

Electron fluid 4-velocity

$$u_e^\mu = \gamma_e(c, \mathbf{v}_e)$$

Electromagnetic tensor

$$F^{\mu\nu} = \begin{pmatrix}
0 & E_x/c & E_y/c & E_z/c \\
-E_x/c & 0 & B_z & -B_y \\
-E_y/c & -B_z & 0 & B_x \\
-E_z/c & B_y & -B_x & 0
\end{pmatrix}$$
... in the moving frame of electrons

- Spacelike current
  \[ j'^\mu = \Lambda^\mu_\nu j^\nu = (0, j') \]
  Electric current in this frame

- Covariant electric field
  \[ e'^\mu = \Lambda^\mu_\nu e^\nu = (0, E') \]
  Electric field in this frame

- Their contraction
  \[ j'_\mu e'^\mu = j' \cdot E' \]
  Energy transfer from the electromagnetic field to plasmas
We introduce the **electron-frame dissipation measure**

- The energy transfer in the electron frame

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

\[ \equiv \dot{j}_\mu e'^\mu = \dot{j}' \cdot E' \]

- This has a very good physical meaning.

**Desirable conditions**

1. Physical meaning
2. Scalar quantity
3. Insensitive to observer motion
Nonrelativistic formula

• Electric current in the electron’s frame

\[ j' = e n_i v'_i = e(n_i v_i - n_e v_e) - e(n_i - n_e) v_e \]
\[ = j - \rho_c v_e. \]

• Electric field in the electron’s frame

\[ E' = E + v_e \times B \]

• The energy transfer in the electron frame (= a unique frame)
  – The relativistic formula in the limit of \( \gamma_e \to 1 \)

\[ D_e = j' \cdot E' = j \cdot (E + v_e \times B) - \rho_c v_e \cdot E \]
2D PIC simulation (1/2): Symmetric Rx

- Mass ratio $m_i/m_e = 25$
- $10^9$ particles

Our Dissipation Region

- Inner EDR
- Outer EDR

The New Measure $D_e$

Minor fluctuations, no strong dissipation
• $D_e$ accurately locates the reconnection site
• The field reversal line is located inside the dissipation region
Why \((E+v_{e} \times B)\) does not work?

- The ideal condition assumes the \(E \times B\) drift motion.

\[ E + v_s \times B = 0 \]

- Diamagnetic, grad \(B\), curvature ... drifts violate the ideal condition.

- Example: \(\nabla B\) drift in zero-\(E\)
  - Particles don’t consume the field energy neither in this frame nor in the electron frame: \(D_e=0\)
Energy budget

- Resistive MHD (e.g. Birn & Hesse 2005)
  \[ E + \mathbf{v}_{\text{mhd}} \times \mathbf{B} = \eta \mathbf{j} \]
  \[ \mathbf{j} \cdot \mathbf{E} = (\mathbf{j} \times \mathbf{B}) \cdot \mathbf{v}_{\text{mhd}} + \eta \mathbf{j}^2 \]
  work by Lorentz force
  Non-ideal

- Kinetic neutral plasma
  \[ \mathbf{j} \cdot \mathbf{E} \approx (\mathbf{j} \times \mathbf{B}) \cdot \mathbf{v}_{\text{mhd}} + D_e \]
  Non-ideal

\[ D_e = \text{nonideal energy transfer} \]
• Our dissipation region is controlled by the electron physics
• Scales like \( (m_e/m_i)^{1/4} \) [bounce width] \( \sim (m_e/m_i)^{1/2} \) [inertia]
Closer look at the dissipation region (2/2)

\[(E + v_e x B)_y : \frac{m_i}{m_e} = 100\]

\[D_e : \frac{m_i}{m_e} = 100\]

\[\begin{align*}
D_e &\approx j \cdot (E + v_e \times B) \\
J_x &E'_x \\
J_y &E'_y \\
\end{align*}\]

- The dissipation region is usually longer than the classical inner EDR of \((E + v_e x B)_y > 0\).
- The x-component is important, too.
In a neutral plasma, $D_e = D_i = D_{\text{mhd}}$
The "outer EDR" is anti-dissipative.
It is not appropriate to call it "dissipation" nor "diffusion" region.

The "outer EDR" is anti-dissipative.
It is not appropriate to call it "dissipation" nor "diffusion" region.
Closer look at the “outer EDR” (2/3)

- Electron jet
  - Oblique projection of the electron current sheet (Hesse+ 2008)

\[ D_e \approx j \cdot (E + v_e \times B) \]
Closer look at the “outer EDR” (3/3)

Magnetic cavities

Reconnected $B_z$

Electron velocity $v_{ex}$

Quick heating

Electron temperature

“Electron shock”
Summary (1/2)

• The ideal frozen-in condition does not always work, however, we paid too much attention to the ideal condition.
• We were frozen-in to the ideal condition!

• We have introduced the electron-frame dissipation measure.

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

– Lorentz invariant scalar
– Energy transfer in the electron’s frame
– Nonideal energy conversion
– Verified by PIC simulations in various configurations

We propose to redefine the dissipation region by \( D_e \)
Further analysis

- Generic, electron-scale dissipation region
- “Outer EDR” is anti-dissipative jet, terminated by a shock
- Electron shock-heating is responsible for magnetic cavity signature

References

Ion DR

Electron DRs

Inner EDR : \( E'_y > 0 \)

Outer EDR : \( E'_y < 0 \)

Symmetric

Asymmetric
New picture

Symmetric

Asymmetric

Antiparallel

Guide-field

Dissipation Region