Magnetic Reconnection during Turbulence and the Role it Plays in Dissipation and Heating

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Motivation

• Focus: Turbulence
  – Not reconnection generated turbulence

• Significant advances recently on the nature of plasma heating during magnetic reconnection
  – e.g., Phan et al., 2013, 2104; Yamada et al., 2014, Shay et al., 2014; Haggerty et al., 2015; Wang et al., and many more

• Kinetic simulations of turbulence: some inertial range to electron scales
  – e.g., Howes et al., Tenbarge et al., Karimabadi et al., Parashar et al, Gary et al., and many more.

• Can we apply our understanding of “simple” magnetic reconnection to turbulent heating?
  – Short Answer: Yes ..... But .....
Overview

• Background
• Laminar Reconnection Studies
  – Heating in Reconnection Exhausts
• Framework: Apply Heating Predictions to Turbulence
• Kinetic PIC Turbulence Simulations
  – Test Framework
• Statistics of Reconnection: Kinetic PIC Simulations
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Solar Wind Turbulence

Notice the Comet!
“Powerlaws everywhere”  

Broadband self-similar spectra are a signature of cascade

- Solar wind
- Corona
- Diffuse ISM
- Geophysical flows

Interstellar medium: Armstrong et al

SW at 2.8 AU: Matthaeus and Goldstein

Coronal scintillation results (Harmon and Coles)

Tidal channel: Grant, Stewart and Moilliet
Heating by turbulence cascade

Energy spectrum $E(k)$

- Heat the plasma,
- Increasing the pressure gradient
- Adding momentum → Producing the solar wind

Where the heating occurs is important!
Plasma Heating - Magnetic Dissipation?

- Something is heating the solar corona
- Something is heating the solar wind

Model of Photosphere/Corona Transition

Wang et al., JGR, 106, 29401, 2001
Physical Dissipation Mechanisms for Kinetic Turbulence

From SHINE conference, 2014

Howes/Shay Session Description

Three mechanisms have been proposed:

(1) Collisionless Wave-Particle Interactions (Landau damping)

(2) Stochastic Heating
   (Johnson & Cheng, 2001; Chen et al. 2001; White et al., 2002; Voitenko & Goosens, 2004; Bourouaine et al., 2008; Chandran et al. 2010; Chandran 2010)

(3) Dissipation in Current Sheets
   (Dmitruk et al. 2004; Markovskii & Vasquez 2011; Matthaeus & Velli 2011; Osman et al. 2012; Servidio 2011)

Key Goal:
- To compare and contrast the different turbulence theories
- To identify observational and numerical tests to distinguish these distinct models
Phan et al., Nature, 2018

- Reconnection in Turbulent Magnetosheath
  - “Electron-Only” Reconnection
MMS 1 and MMS 3 on opposite sides of the X-line: smoking gun evidence for reconnection

Magnetic-to-electron energy conversion
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Character of Reconnection Heating

- Heating Tends to Occur as beams
  - Especially: Ion Heating

Simulations

Solar Wind Observations

Gosling et al., 2005

Lottermoser et al., 1998
“Simple” Problem: Heating in Reconnection Exhausts

- Focus on Understanding Heating in Reconnection Exhausts

Heating Definition:

\[ T = \frac{1}{n} \int d^3v f(x, v)(v - u)(v - u) \]

\[ T = \frac{1}{3} \text{Tr}[T] \]

- Counter-streaming beams are considered “heating”.

- Systematic Kinetic PIC Simulations
\[ \frac{B^2}{4\pi} V_{in} D = \left[ \frac{1}{2} m_i n V^2_{out} + \frac{\gamma}{\gamma - 1} \Delta T_e n + \frac{\gamma}{\gamma - 1} \Delta T_i n \right] V_{out} \delta + Q_{ix} + Q_{ex} \]

- Magnetic Energy In:
- Flow Energy, Thermal Energy, Heat Flux out
Energy Budget: Heating

• Energy Conservation

\[
\frac{B^2}{4\pi} V_{inD} = \left[ \frac{1}{2} m_i n_{out} V_{out}^3 + \frac{\gamma}{\gamma - 1} \Delta T_e n_{out} V_{out} + \frac{\gamma}{\gamma - 1} \Delta T_i n_{out} V_{out} \right] \delta + Q_{ix} + Q_{ex}
\]

Divide eqn by left hand side

• \( 1 = \alpha_{flow} + \alpha_{Te} + \alpha_{Ti} + \alpha_{Qi} + \alpha_{Qe} \)

• \( \alpha_T = \% \) of released energy that heats a species.

• Important Questions
  – Is \( \alpha_T \) a constant? What does it depend on?
  – What is the value of \( \alpha_T \)?
  – What is \( \gamma/(\gamma - 1) \)? (5/2 for adiabatic)

\[
\alpha_T \approx \frac{\gamma}{\gamma - 1} \frac{\Delta T}{B^2 / (4\pi n)}
\]

Review in: Shay et al., 2014
Laminar Reconnection Simulations

- Reconnection heating depends strongly on parameters upstream of x-line.
  - $c_{Ar}$: Alfvén speed based on reconnection field
  - $B_r$: reconnection field
  - $B$: Total Field

\[
\Delta T_i = M_{Ti} \ c_{Ar}^2 \frac{B_r^2}{B^2}
\]

\[
\Delta T_e = M_{Te} \ c_{Ar}^2 \frac{B_r}{B}
\]

- $M_{Ti}$, $M_{Te}$ are constants
- $\Delta T_i$ consistent with Drake et al., 2009
- Relative heating is:

\[
\frac{\Delta T_i}{\Delta T_e} \propto \frac{B_r}{B}
\]

Dataset limited to:

- $B_{guide} > 0.2$
- $T_e/T_i < 1.25$
- $\beta_i < 2$
Question

• Can we take this knowledge about laminar reconnection and apply it to reconnection during turbulence?
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Heating in Turbulence Due to Reconnection?

- **Multifaceted problem**
  - Magnitude and Character of Heating due to Reconnection?
    - What parameters does the heating depend on?
  - Properties of Magnetic Reconnection in Turbulence?
    - How many x-lines? How many reconnecting x-lines?
  - Relative role of heating due to magnetic reconnection versus other sources of heating

- **Kinetic PIC Simulation Study**
  - Can we apply our understanding of “simple” magnetic reconnection to turbulent heating?
  - What are the statistics of X-lines in kinetic turbulence simulations?

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Magnetic Flux Contours with X-lines

Haggerty et al., 2017
Kinetic PIC Turbulence Simulation
Flux Bundles Reconnecting

- Energy released into ions:
  - Single Flux Bundle:
    \[ \varepsilon_x = 2\pi \Delta T \ell^< \ell^> n_r \]
    \[ \varepsilon_x = \frac{M_T}{2} \ell^< \ell^> B_r^2 \frac{B_{ir}^2}{B^2} \]

- Sum Over All Bundles:
  \[ \varepsilon = \frac{M_T}{2} \sum_{x\text{-line } i} \ell_i^< \ell_i^> B_{ir}^2 \frac{B_{ir}^2}{B^2} \]
  \[ \varepsilon = \left( \frac{M_T}{2} \sum_{x\text{-line } i} \ell_i^< \ell_i^> \right) \frac{B_{ir}^2}{B^2} \]
Determine $B_{ir}$?

- Assume mean field is constant and $B_0 \gg B_{ir}$
- First estimate: Width of reconnection sites typically $\sim d_i$
  - What are magnetic fluctuations at scale size $d_i$?
- Assume $\delta Z$ at $d_i$ scales like reconnection Alfven speed: $\delta Z_{di} \propto C_{ar}$

$$\frac{c_{Ar}}{c_A} = \frac{B_r}{B} = \frac{\delta Z_{di}}{c_A} \frac{d_i}{d_i} = \frac{\tau_{ci}}{\tau_{nl}(d_i)} \equiv \alpha_{nl}$$

- Where $c_A$ is Alfven speed based on global RMS $B$
- $\tau_{nl}(d_i)$ is nonlinear time at ion inertial scale
- $\tau_c$ is cyclotron time based on global RMS $B \approx B_0$

Protons: $$\varepsilon_p = \frac{\delta Z_{di}^4}{c_A^4} \left( \frac{M_T}{2B^2} \sum_{x\text{-line } i} \ell_i^< \ell_i^> \right) = \alpha_{nl}^4 \text{ (Flux Bundle Details )}$$

Electrons: $$\varepsilon_e = \frac{\delta Z_{di}^3}{c_A^3} \left( \frac{M_T}{2B^2} \sum_{x\text{-line } i} \ell_i^< \ell_i^> \right) = \alpha_{nl}^3 \text{ (Flux Bundle Details )}$$
Key Points

- Turbulent heating due to reconnection estimated to be:
  \[ \varepsilon_p = \alpha_{nl}^4 \text{ (Flux Bundle Details)} \]
  \[ \varepsilon_e = \alpha_{nl}^3 \text{ (Flux Bundle Details)} \]
  \[ \frac{\varepsilon_p}{\varepsilon_e} \propto \alpha_{nl} \]

- Will (Flux Bundle Details) remain invariant as we change turbulence properties?

- Proton to electron heating scaling expected to be more accurate.
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• **Kinetic PIC Turbulence Simulations**
  – Test Framework

• Statistics of Reconnection: Kinetic PIC Simulations
Kinetic PIC Turbulence Simulations

- Wu et al, 2013, Parashar et al., 2016.
- 2 1/2 Dimensions
- Initial uniform Bz = 5
- Initial Perturbation:

\[ Z_0^2 \equiv \langle v^2 \rangle + \langle \frac{B^2}{4\pi m_i n} \rangle \]
Turbulence Simulations

- Constant Mean field $B_0 = 5$, $B \gg B_r$

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Determining Nonlinear Time

- Estimate of $\tau_{nl}(d_i)$ based on von Karman-Kolmogorov phenomenology

\[ \delta Z_\ell = Z \left( \frac{\ell}{\lambda} \right)^{1/3} \]

\[ \tau_{nl}(\ell) = \frac{\ell}{\delta Z_\ell} = \tau_{nl} \left( \frac{\ell}{\lambda} \right)^{2/3} \]

- $\lambda$ is correlation or energy containing scale

- Is this estimate applicable to our system?
Turbulence Simulations: Scaling of Heating

Approximate Best Fit Not Consistent

\[ \varepsilon_p \propto \alpha_{nl}^3 \]
\[ \varepsilon_e \propto \alpha_{nl}^2 \]

Ratio of Heating Matches Well

\[ \frac{\varepsilon_p}{\varepsilon_e} \propto \alpha_{nl} \]
Conclusions: Heating

• Turbulence Simulations:
  \[ \frac{\varepsilon_p}{\varepsilon_e} \propto \alpha_{nl} \]
  \[ \varepsilon_p \propto \alpha_{nl}^3 \]
  \[ \varepsilon_e \propto \alpha_{nl}^{2/3} \]

• Theory Predictions:
  \[ \frac{\varepsilon_p}{\varepsilon_e} \propto \alpha_{nl} \]
  \[ \varepsilon_p \propto \alpha_{nl}^{4/3} \]
  \[ \varepsilon_e \propto \alpha_{nl}^{3/2} \]

• Why the difference?
  • Is \( \Delta B \) at \( d_i \) scale best measure of magnetic fields upstream of current sheets?
  • \( \tau_{nl}(d_i) \) determined ignoring intermittency. Justified?
  • Are the number of x-lines changing with changing parameters?
  • Filling factor of reconnection exhausts?
  • \( \varepsilon_p/\varepsilon_e \) matches reconnection prediction quite well.
    – Even if some details of scaling of reconnection parameters wrong, taking the ratio removes the discrepancy.