Dissipation and Kinetic Physics of Astrophysical Plasma Turbulence

NSF PRAC project #1614664

Vadim Roytershtein
Space Science Institute

Blue Waters Symposium, Sunriver, OR, May 15-19, 2017
Acknowledgements

Collaborators:

William Matthaeus University of Delaware
John Podesta, Space Science Institute
Stanislav Boldyrev, University of Wisconsin, Madison
Aaron Roberts, NASA Goddard
Yuri Omelchenko, Space Science Institute
Nikolai Pogorelov, University of Alabama, Huntsville
Gian Luca Delzanno, Los Alamos
Homa Karimabadi, CureMetrix, Inc
Heli Hietala, UCLA
William Daughton, Los Alamos
Hantao Ji, Princeton
Jack Scudder, University of Iowa
Seth Dorfman, UCLA

Funding: NASA, NSF
Plasma Turbulence is a Ubiquitous Phenomenon

Fusion: magnetically confined, inertially confined, hybrid

Solar corona

Solar wind, planetary magnetospheres

Heliosphere, interstellar Medium

Jets, accretion disks, other astrophysical objects

Local Interstellar Medium

Armstrong et al., 1995
Focus of This Project: Turbulence in Solar Wind & Magnetosphere

- Turbulence is of interest because of:
  - Local energy input (e.g. to explain famously anomalous temperature profiles)
  - Transport of energetic particles (solar energetic particles, cosmic rays, etc)
- Solar Wind is the best accessible example of astrophysical (=large scale) plasma turbulence

Kiyani et al., 2015
Kinetic Effects in Plasma Turbulence (i.e. the Plasma Physics Aspects)

Cross-scale coupling in the inertial range via

- intense current sheets and reconnection
- ion temperature anisotropies
- coupling between compressible and incompressible fluctuations

“dispersion range” or “dissipation range”:

- internal kinetic scales are encountered, leading to partial onset of dissipation, but also to change in fluctuation properties;
- in weakly collisional plasma, dissipation is a collective effect
A Variety of Models & Approximations Are Used to Tackle This Range of Scales

“First-Principle” description of weakly coupled plasmas:

\[
\frac{\partial_t f_s}{m_s} \left( E + \frac{1}{c} \mathbf{v} \times \mathbf{B} \right) \cdot \nabla \mathbf{v} f_s = C \{ f_s, f_s', \ldots \} + \text{Maxwell’s equations}
\]

\[ L: \text{system size, energy injection scale, correlation scale} \]

\[ \text{collisional scale (collisional)} \]

\[ \text{ion kinetic scales} \]

\[ \text{electron kinetic scales} \]

\[ \text{debye length} \]

\[ \text{collisional scale (c-less)} \]

\[ \text{smaller scales} \]

\[ \text{model complexity} \]

Magnetohydrodynamic approximation (MHD):
- incompressible, fully compressible, kinetic MHD...
- Hall MHD
- multi-fluid multi-moments models
- hybrid kinetic
- Landau Fluid
- Gyrokinetic
- Fully kinetic...

In many situations, cross-scale coupling play a role an important role global dynamics. Full understanding of global evolution may require multi-scale, multi-physics models.
Models

Fully kinetic simulations (microscopic model)

All species kinetic
code: VPIC

\[
\frac{\partial f_s}{\partial t} + \mathbf{v} \cdot \nabla f_s + \frac{q_s}{m_s} \left( \mathbf{E} + \frac{1}{c} \mathbf{v} \times \mathbf{B} \right) \cdot \nabla f_s = \sum_{s'} C\{f_s, f_{s'}\}
\]

\[
\nabla \times \mathbf{B} = \frac{4\pi}{c} \mathbf{j} + \frac{1}{c} \frac{\partial \mathbf{E}}{\partial t}
\]

\[
-\frac{1}{c} \frac{\partial \mathbf{B}}{\partial t} = \nabla \times \mathbf{E}
\]

\[
\nabla \cdot \mathbf{E} = 4\pi \rho
\]

\[
\nabla \cdot \mathbf{B} = 0
\]

Takizuka-Abe collisional model

\~ up to 10^{10} cells
\~ up to 4 \times 10^{12} particles
\~ 120 TB of memory
\~ 10^7 CPU-HRS (~10^3 CPU-YRS)

Hybrid simulations (mesoscale model)

kinetic ions + fluid electrons
codes: H3D, HYPERES

\[
0 = \frac{4\pi}{c} \left( \mathbf{j}_i + \mathbf{j}_e \right) - \nabla \times \mathbf{B}
\]

\[
0 = en_e \left[ \mathbf{E} - \eta \left( \mathbf{j}_i + \mathbf{j}_e \right) \right] - \frac{\mathbf{j}_e \times \mathbf{B}}{c} + \nabla p_e
\]

\[
\frac{1}{c} \frac{\partial \mathbf{B}}{\partial t} = -\nabla \times \mathbf{E}
\]

\[
en_e = q_i n_i, \quad \mathbf{j}_e = -en_e \mathbf{v}_e
\]

\[
p_e = n_e T_e \sim n_e^\gamma
\]

\~ up to 1.7 \times 10^{10} cells
\~ up to 2 \times 10^{12} particles
\~ 130 TB of memory

Blue Waters!
Sample the phase space with computational particles (markers) at $t=t_0$. Move the markers along the characteristics (single-particle equations of motion). Since $f(x,v)$ is constant along the characteristic, we obtain a representation of distribution function at finite $t>t_0$.

\[
\partial_t f_i + \mathbf{v} \cdot \nabla f_i + \frac{e}{m} \left( E + \frac{1}{c} \mathbf{v} \times \mathbf{B} \right) \cdot \nabla_v f_i = 0
\]

\[
\partial_t \mathbf{B} = -c \nabla \times \mathbf{E}
\]

\[
\mathbf{E} = -\frac{1}{ne} \nabla P_e - U_e \times \mathbf{B} - \frac{m_e}{e} \frac{d}{dt} U_e + \mathbf{F}_{ei}
\]
Problems Considered in Year 1

- Generation of intense current sheets at or above proton scales
- Turbulence in low-\(\beta\) plasmas \textit{in progress}
- Universality of decay \textit{in progress}

3D hybrid simulation of solar wind-like turbulence

3D hybrid simulation of decaying turbulence
Current sheets (regions of large gradients in magnetic field) are typically preferred sites of energy dissipation and reconnection.

C.S. evolution is an example of cross-scale coupling:

- C.S. are formed by large-scale dynamics
- Evolution of c.s. (e.g. their stability) depends on microscopic effects
- The first order of business is classification of c.s.
- What’s known: some observations, some MHD results, but no kinetic simulations (i.e. no simulations with adequate microscopic physics).

- Our goal:
  - validate techniques for interpreting spacecraft data
  - Make sure that our models reproduce observations

Podesta and Roytershteyn, under review in JGR
Example of Direct Comparison With Spacecraft Data:
Properties of Intense Currents Sheets

In many cases spacecraft data is 1D - a sample along spacecraft trajectory (with the exception of multi-spacecraft missions, e.g. MMS, CLUSTER, THEMIS, etc)

Plasma data from the Wind 3DP instrument and magnetic field strength data from the Wind MFI instrument for the two day interval (Podesta, 2017)

Remarkable agreements between simulation and data

Table 1. Characteristics of 5σ events in the simulation with $L_d = 128d_i$

<table>
<thead>
<tr>
<th>Property</th>
<th>Physical variable</th>
<th>$J_{\text{true}}$</th>
<th>$J_P$</th>
<th>$dB_x/d\lambda$</th>
<th>$dB_y/d\lambda$</th>
<th>$dB_z/d\lambda$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean (in units of $B_0/d_i$)</td>
<td>0.204</td>
<td>0.103</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Standard Deviation ($B_0/d_i$)</td>
<td>0.122</td>
<td>0.0649</td>
<td>0.0822</td>
<td>0.0562</td>
<td>0.0697</td>
<td></td>
</tr>
<tr>
<td>Number of events</td>
<td>365</td>
<td>459</td>
<td>244</td>
<td>168</td>
<td>197</td>
<td></td>
</tr>
<tr>
<td>Mean separation distance ($d_i$)</td>
<td>381</td>
<td>299</td>
<td>563</td>
<td>814</td>
<td>697</td>
<td></td>
</tr>
<tr>
<td>Median separation distance ($d_i$)</td>
<td>214</td>
<td>203</td>
<td>377</td>
<td>544</td>
<td>366</td>
<td></td>
</tr>
<tr>
<td>Mean event size ($d_i$)</td>
<td>1.80</td>
<td>1.75</td>
<td>1.5</td>
<td>1.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean peak value ($B_0/d_i$)</td>
<td>0.949</td>
<td>0.508</td>
<td>0.489</td>
<td>0.330</td>
<td>0.403</td>
<td></td>
</tr>
<tr>
<td>Maximum peak value ($B_0/d_i$)</td>
<td>1.68</td>
<td>0.922</td>
<td>0.864</td>
<td>0.761</td>
<td>0.584</td>
<td></td>
</tr>
</tbody>
</table>

Table 2. Characteristics of 5σ events in the simulation with $L_d = 256d_i$

<table>
<thead>
<tr>
<th>Property</th>
<th>Physical variable</th>
<th>$J_{\text{true}}$</th>
<th>$J_P$</th>
<th>$dB_x/d\lambda$</th>
<th>$dB_y/d\lambda$</th>
<th>$dB_z/d\lambda$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean (in units of $B_0/d_i$)</td>
<td>0.109</td>
<td>0.0746</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Standard Deviation ($B_0/d_i$)</td>
<td>0.0748</td>
<td>0.0479</td>
<td>0.0603</td>
<td>0.0416</td>
<td>0.0499</td>
<td></td>
</tr>
<tr>
<td>Number of events</td>
<td>2,881</td>
<td>4,249</td>
<td>2,522</td>
<td>1,349</td>
<td>2,033</td>
<td></td>
</tr>
<tr>
<td>Mean separation distance ($d_i$)</td>
<td>386</td>
<td>261</td>
<td>440</td>
<td>823</td>
<td>547</td>
<td></td>
</tr>
<tr>
<td>Median separation distance ($d_i$)</td>
<td>269</td>
<td>160</td>
<td>277</td>
<td>506</td>
<td>302</td>
<td></td>
</tr>
<tr>
<td>Mean event size ($d_i$)</td>
<td>2.83</td>
<td>1.95</td>
<td>1.7</td>
<td>1.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean peak value ($B_0/d_i$)</td>
<td>0.581</td>
<td>0.381</td>
<td>0.366</td>
<td>0.250</td>
<td>0.299</td>
<td></td>
</tr>
<tr>
<td>Maximum peak value ($B_0/d_i$)</td>
<td>1.36</td>
<td>1.06</td>
<td>0.818</td>
<td>1.36</td>
<td>0.799</td>
<td></td>
</tr>
</tbody>
</table>

Table 3. Characteristics of 5σ events in high speed solar wind data

<table>
<thead>
<tr>
<th>Property</th>
<th>Physical variable</th>
<th>$J_{\text{true}}$</th>
<th>$J_P$</th>
<th>$dB_x/d\lambda$</th>
<th>$dB_y/d\lambda$</th>
<th>$dB_z/d\lambda$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean (pA/cm²)</td>
<td>?</td>
<td>0.0952</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Standard Deviation (pA/cm²)</td>
<td>?</td>
<td>0.0725</td>
<td>0.0566</td>
<td>0.0698</td>
<td>0.0791</td>
<td></td>
</tr>
<tr>
<td>Number of events</td>
<td>?</td>
<td>1,336</td>
<td>660</td>
<td>977</td>
<td>879</td>
<td></td>
</tr>
<tr>
<td>Mean separation distance ($d_i$)</td>
<td>?</td>
<td>336</td>
<td>680</td>
<td>459</td>
<td>504</td>
<td></td>
</tr>
<tr>
<td>Median separation distance ($d_i$)</td>
<td>?</td>
<td>57.4</td>
<td>108</td>
<td>49.6</td>
<td>71.2</td>
<td></td>
</tr>
<tr>
<td>Mean event size ($d_i$)</td>
<td>?</td>
<td>3.2</td>
<td>3.1</td>
<td>2.8</td>
<td>3.1</td>
<td></td>
</tr>
<tr>
<td>Mean peak value (pA/cm²)</td>
<td>?</td>
<td>0.695</td>
<td>0.363</td>
<td>0.467</td>
<td>0.536</td>
<td></td>
</tr>
<tr>
<td>Maximum peak value (pA/cm²)</td>
<td>?</td>
<td>1.64</td>
<td>1.09</td>
<td>1.72</td>
<td>1.84</td>
<td></td>
</tr>
</tbody>
</table>
Universality of Decaying Turbulence

- Collisionless plasma dynamics approximately conserves important quantities (rugged invariants) magnetic helicity, kinetic helicity, energy

\[ H_c = \frac{1}{V} \int (\mathbf{v} \cdot \mathbf{B}) \, dV \]

\[ H_m = \frac{1}{V} \int (\mathbf{A} \cdot \mathbf{B}) \, dV \]

- In a real system, the rates of decay are typically different. This results in a decay towards “special” final states.

- The existing paradigms are based on idealized approximations.

- One way of interpreting these results is to say that we are putting constraints on how applicable those idealized models are to real plasmas.
Sub-Proton Range in low-$\beta$ plasma: Fully-Kinetic Simulations

Spectrum of Magnetic Fluctuations in the Earth's Magnetosheath

transition 1  transition 2

The nature of fluctuations changes

C. H. K. Chen and S. Boldyrev, 2017
Simulations Revealed Surprising Results

Puzzle:
- simplified analysis agrees with observations
- Simulations and “exact” analysis do not

**Something very interesting is going on**

“simple” analysis

fully kinetic simulation

k^{-2.8}

k^{-4.2}

observations

|B||/|B|

kinetic linear analysis

(“exact solution”)
1. Understanding of plasma turbulence is a grand challenge problem.
2. We are using Blue Waters to study some aspects of this problem, namely kinetic effects associated with turbulence dissipation.
3. Year 1 has yielded exciting results, some of them await explanation.

Publications & data products

J. Podesta and V. Roytershteyn, “The most intense electrical currents in the solar wind: Comparisons between single spacecraft measurements and plasma turbulence simulations”, *under review* in JGR

3 more manuscripts in preparation

1 new project has just began with the simulation data produced in BW

Database of large-scale simulations to be used for years to come (hopefully).