Turbulence, Transport, and Thermodynamics in Collisionless Space and Astrophysical Plasmas

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with and on behalf of: Matthew Kunz (PI), Lev Arzamasskiy, Archie Bott, Alisa Galishnikova, Eliot Quataert, Stephen Majeski, Alex Schekochihin, Jonathan Squire, Himawan Winarto, Evan Yerger, Muni Zhou

(Frontera users thus far marked in orange)
We use kinetic and MHD simulations to study turbulence, transport, and thermodynamics in space/astrophysical plasmas.
Articles from our group that used Frontera time:

- Tearing instability and current-sheet disruption in the turbulent dynamo
  Galishnikova, Kunz & Schekochihin 2022, Physical Review X

- High-frequency heating of the solar wind triggered by low-frequency turbulence
  Squire et al. 2022, Nature Astronomy

- Triggering tearing in a forming current sheet with the mirror instability
  Winarto & Kunz 2022, Journal of Plasma Physics

- Microphysically modified magnetosonic modes in collisionless, high-\(\beta\) plasma
  Majeski, Kunz & Squire 2023, Journal of Plasma Physics

- Electron-ion heating partition in low-\(\beta\), imbalanced turbulence
  Squire, Meyrand & Kunz, in prep. (submission in Aug 2023)

- Collisionless conduction in a high-\(\beta\) plasma: collision operator for whistler turbulence
  Yerger, Kunz, Bott, Spitkovsky, in prep. (submission in Aug 2023)
Elongated current sheets naturally produced by the turbulent dynamo become disrupted by tearing instability during the nonlinear stage of dynamo, change geometry and spectrum of field. Large-scale fields produced.

Galishnikova, Kunz & Schekochihin 2022, PRX
Microphysically regulated conductive heat transport in collisionless, high-\(\beta\) plasma

heat flux excites \textbf{whistler instability},
creates bath of scattering magnetic fluctuations,
regulates heat flux through
\[
\nu_e \sim \left| \nu_{th,e} \nabla \ln T \right| \beta_e
\]
\[
\Rightarrow \quad q_{||,e} \sim \frac{1}{\beta_e} n T_e v_{th,e}
\]

Yerger et al. (2023, in prep) verifies this result up to \(L_T = 2000 \rho_e\), then uses a several methods to obtain an \textbf{effective collision operator} for whistler-e\(^-\) interactions
\[ k \perp \rho_i = 1 \]
\[ k \parallel d_i = 0.8 \]

\[ E_{\perp} = \left( E_x^2 + E_y^2 \right)^{1/2} \]

St-Onge & Kunz 2018

kinetic Alfvénic turbulence at high \( \beta \)

Squire, Meyrand, Kunz, Arzamasskiy, Schekochihin & Quataert 2022

imbalanced solar-wind turbulence and ion heating: “helicity barrier”
Fast solar wind heating observations

- Ions heated dominantly over electrons
- Heated more in the perpendicular direction
- Heating spatially extended out to several solar radii

\[ \beta \equiv \frac{8\pi nT}{B^2} \]

- Electron heating
- Proton heating
- adiabatic
- perpendicular heating

Figure: Temperature anisotropy
Mechanism must dominantly heat ions perpendicularly

**Alfvénic turbulence**

+ Converts magnetic to thermal energy
+ Observed (Belcher & Davis etc.) and sufficient power to heat corona and solar wind (e.g., De Pontieu et al. 2007, Tomczyk et al. 2007)

- Balanced, low amplitude, low beta turbulence dominantly heats electrons
- Ion Landau damping at higher beta heats in parallel direction

**ICW heating**

+ Heats perpendicularly
+ ICWs are observed in solar wind

- Source of ICWs? Propagation of ICWs to large radii mostly ruled out (Hollweg 2000)

**Stochastic heating**

+ Heats perpendicularly
+ Heats at lower frequencies, at larger amplitudes in magnetic spectra

- Requires sufficient fluctuation amplitude above a critical value

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Cranmer et al. 2017
Bowen et al. 2022
Hoppock et al. 2018
Mechanism must dominantly heat ions perpendicularly

- **Alfvénic turbulence**
  - Converts magnetic to thermal energy
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- Heats perpendicularly
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**Stochastic heating**
- Heats perpendicularly

Compatible! (2022)

High-frequency heating of the solar wind triggered by low-frequency turbulence

Jonathan Spitzer,1,2 Renée Miroveo,1 Matthew W. Kaiser,1,3 Les Azumutskiy,4 Alexander A. Schekochihin,3,5 Elise Quataert2

ICWs are observed in solar wind (e.g., De Pontieu+ 2007, Tomczyk+ 2007)

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Bowen et al. 2022

Hoppock et al. 2018

Cranmer et al. 2017
Helicity barrier blocks electron heating in imbalanced turbulence...

$$\int d^3x \left( \frac{\rho u^2}{2} + \frac{B^2}{8\pi} \right) = \text{const} \quad \text{(energy flux conserved during cascade)}$$

$$\sigma_c = 0$$

if cross-helicity is not zero

$$z^\pm \equiv u \pm B/\sqrt{4\pi \rho}$$

$$H(k_\perp) = E(k_\perp)/v_{ph}(k_\perp)$$

$$\ell \gg \rho_i \quad \int d^3x \left( \frac{|z^+|^2}{2} - \frac{|z^-|^2}{2} \right) \propto \int d^3x (u_\perp \cdot B_\perp) = \text{const}$$

$$\ell \ll \rho_i \quad \int d^3x \delta B_\parallel \delta A_\parallel = \text{const}$$

$$\sigma_c \neq 0$$

(a) injection range \hspace{5mm} inertial range \hspace{5mm} kinetic range

- $\varepsilon_0$
- $\varepsilon(k_\perp) = \varepsilon_0 = \text{const}$
- $E(k_\perp) \propto k_\perp^{-5/3}$
- $Q_i + Q_e = \varepsilon_0$

(b) injection range \hspace{5mm} inertial range \hspace{5mm} kinetic range

- $\varepsilon_0$
- $\varepsilon(k_\perp) \neq \text{const}$
- $H(k_\perp) \propto E(k_\perp)$
- $Q_i + Q_e = \varepsilon_0$

$L^{-1} \hspace{5mm} \rho_i^{-1} \hspace{5mm} \rho_e^{-1}$
...and can lead to ICW heating of ions

Pegasus++ hybrid-kinetic imbalanced turbulence simulations on Frontera (Squire, Meyrand, Kunz, Arzamasskiy, Schekochihin & Quataert 2022)
Minor ions are heated even more strongly than protons

How much are minor ions heated in balanced vs. imbalanced turbulence? Heated by ICWs? Stochastically heated?
Minor ions in Pegasus++

Hybrid-kinetics lets us drop electron scales (less computationally expensive than full kinetic PIC)

\[
\frac{\partial f_i}{\partial t} + v \cdot \nabla f_i + \frac{Ze}{m_i} \left( E + \frac{1}{c} v \times B \right) \cdot \frac{\partial f_i}{\partial v} = \left( \frac{\partial f_i}{\partial t} \right)_{\text{coll}}
\]

\[
E = -\frac{1}{en_e} \nabla \rho_e - \frac{1}{c} u_e \times B + \eta j = \sum_i q_i n_i u_i - j
\]

- Minor ions stored in separate particle list (modular from main code)
- Can treat actively/passively
Simplified version of the original loop

start from $E$, $B$

takes >90% of computational time

update particle positions and velocities (mover)

compute moments of the distribution function (deposit)

update $B$, recompute $E$

$E$ is a quasi-neutrality constraint: hybrid-kinetics is implicit!

\[
\frac{dv_p}{dt} = \frac{q}{m} \left( E + \frac{v_p}{c} \times B \right)
\]

\[
\frac{dr_p}{dt} = v_p
\]
Pegasus++ loop with minor ions

start from $E$, $B$

update particle positions and velocities (separate movers)

compute moments of the distribution function (separate deposits)

update $B$, recompute $E$

\[
\frac{dv_p}{dt} = \frac{q}{m} \left( E + \frac{v_p}{c} \times B \right) \quad \frac{dv_i}{dt} = \frac{q_i}{m_i} \left( E + \frac{v_i}{c} \times B \right) \quad \frac{dr_p}{dt} = v_p \quad \frac{dr_i}{dt} = v_i
\]
Example of a Pegasus++ minor ion test

1D ion cyclotron wave test - observed heating of resonant minor ion species

\[
\frac{q_i}{q_p} = 1, \quad \frac{m_i}{m_p} = 4, \quad \frac{n_i}{n_p} = 0.03, \quad \frac{T_i}{T_p} = 36
\]

\[
\beta_p = 1, \quad k_{||} = \frac{2\pi}{100}
\]

(Unnormalized)
Upcoming frontera runs

- Minor ion imbalanced turbulence runs
  - Study the impact of imbalance and beta on the helicity barrier and associated heating of different solar-wind ions
- High-beta turbulence run with compressive driving (Stephen Majeski)
- Dynamo run to test the idea of an explosive phase of plasma dynamo (Muni Zhou)