Kinetic simulations of electron-scale magnetic reconnection in space plasma turbulence (pr27ta)

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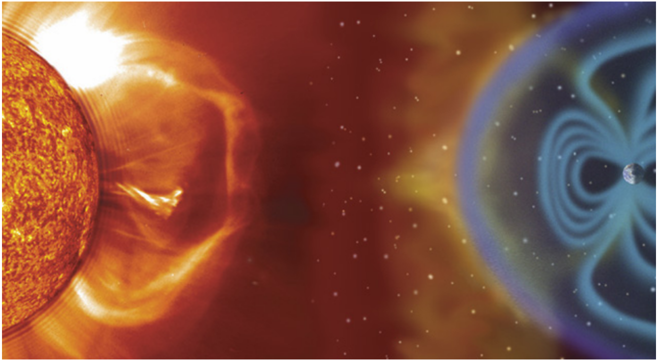
Space plasmas

- Most of our space environment, solar corona, solar wind, planetary magnetospheres is a collisionless plasma.
- Collisionless plasmas have particles with large mean free path $\Rightarrow$ Large deviations from thermal equilibrium $\Rightarrow$ Kinetic (not fluid) approach is necessary.



Turbulence in space plasmas

- Space plasmas are often turbulent, with features deviating from fluid (MHD: Magnetohydrodynamic models) at particle scales.

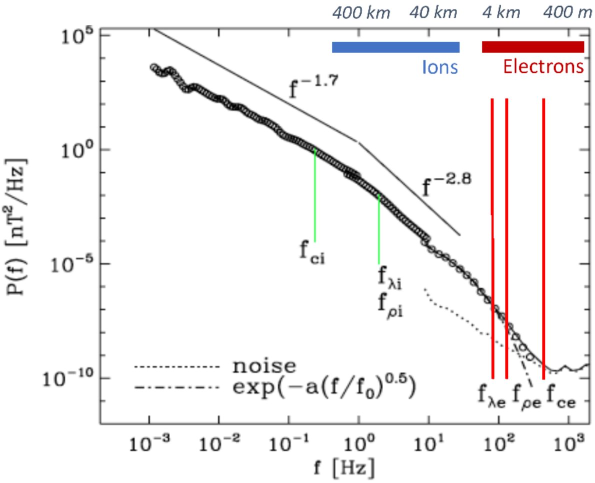


Figure 1: Turbulent magnetic spectra in the solar wind measured with the Cluster spacecraft [Verscharen 2019]

Magnetic Reconnection

Magnetic Reconnection

- Fast ($\ll$ diffusive τ) magnetic energy release.
- Change of magnetic field topology.
- Conversion of magnetic energy to particle energy (flows, heating, acceleration)

- Responsible for solar flares, magnetic storms in planetary magnetospheres, but also present in plasma turbulence.

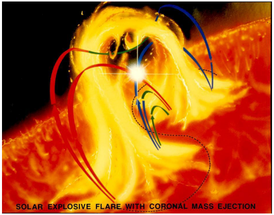


Figure 2: Schematics of a solar flare

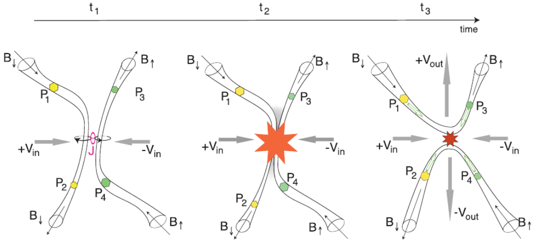


Figure 3: Schematics of Reconnection [Treumann and Baumjohann, 2013]

Turbulence and Magnetic Reconnection

Turbulence and Magnetic Reconnection

- Turbulence ⇒ magnetic reconnection through current sheets.
- This phenomena has been observed in MHD simulations since the 80s.

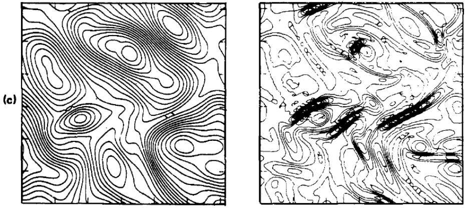


Figure 4: Decaying MHD turbulence. Left: Magnetic field lines. Right: Current density. [Matthaeus and Lamkin, 1986]

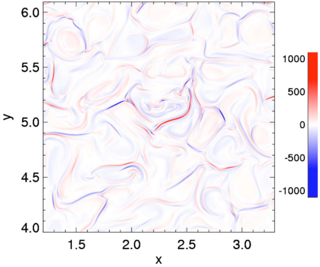


Figure 5: Current density of decaying MHD turbulence [Servidio et al., 2010]

Spacecraft missions

- Recent in-situ measurements in turbulent space plasmas revealed the key role of electrons (before, mainly ions).
- Magnetospheric Multiscale Mission (MMS) measuring the plasmas of the Earth's magnetosphere
- Parker Solar Probe (PSP) measures the solar wind near the Sun.

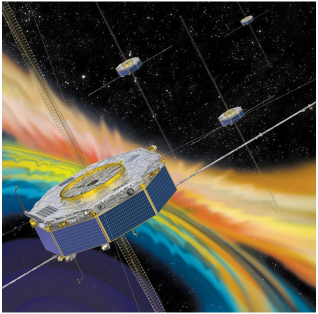


Figure 6: MMS

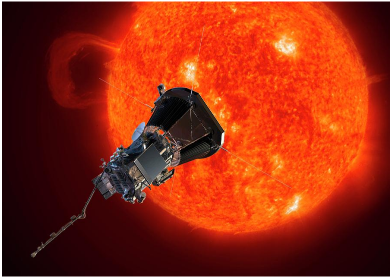


Figure 7: PSP

Reconnection in turbulence

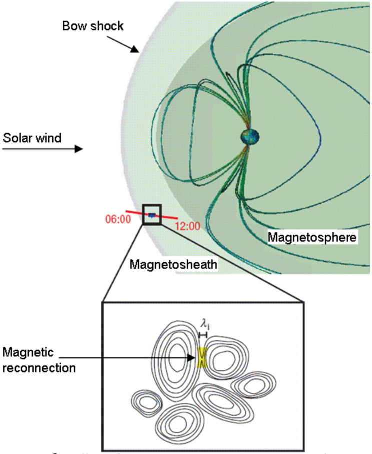


Figure 8: Small-scale magnetic reconnection in the turbulent magnetosheath

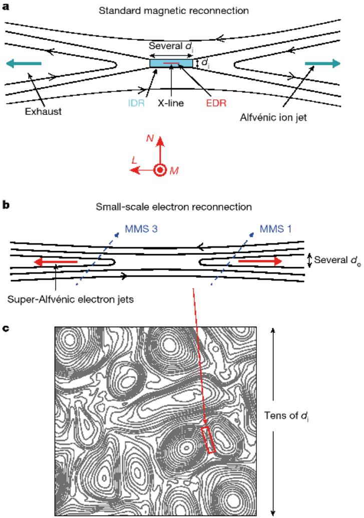


Figure 9: Schematics of electron-scale magnetic reconnection [Phan et al 2018]

Open questions and purpose of this work

Questions

1. Relevance of electron kinetic effecs for the current sheet formation/magnetic reconnection in turbulence (dissipation/heating via instabilities)
2. Role of plasma-beta (thermal/magnetic pressure) on those effects (PSP can observe different plasma regimes near the Sun).

Contents

Numerical methods: Fully kinetic PIC code

Fully kinetic PIC code

- Fully kinetic Vlasov-Maxwell system of equations.
- Particle-in-Cell Code ACRONYM (Advanced Code for Relativistic Objects, Now with Yee-Lattice and Macroparticles) [Kilian et al., 2012].
- 2nd order Maxwell solver, Boris pusher to advance particles, higher-order interpolation schemes.
- MPI parallelization, parallel HDF5 output.

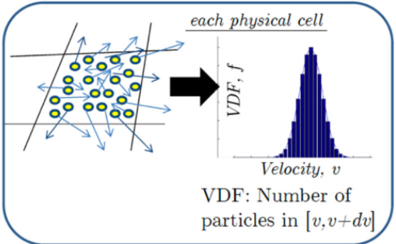
Fully-kinetic equations

$$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}$$

$$\nabla \times \vec{B} = \mu_0 \vec{J} + \mu_0 \epsilon_0 \frac{\partial \vec{E}}{\partial t}$$

$$\left[\frac{\partial}{\partial t} + \vec{v} \cdot \frac{\partial}{\partial \vec{x}} + \frac{q_\alpha}{m_\alpha}\left(\vec{E} + \vec{v} \times \vec{B}\right) \cdot \frac{\partial}{\partial \vec{v}}\right] f_\alpha = 0$$

+ Maxwell equations $\nabla \cdot \vec{E}$ and $\nabla \cdot \vec{B}$ and definitions of the sources ρ and $\vec{J}$ as function of f



PiC loop

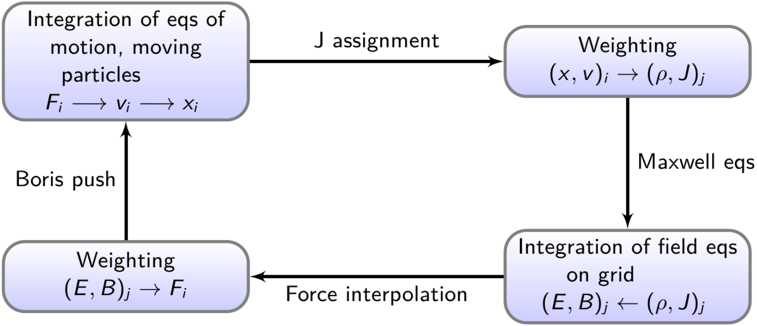


Figure 10: PiC loop

Simulation setup of decaying collisionless turbulence

- 2D decaying turbulence simulations with out-of-plane background magnetic field $\vec{B} = B_0\hat{z}$
- Uncorrelated Alfvénic fluctuations $\delta\vec{V}_\perp$ and $-V_A\delta\vec{B}_\perp/B_0$, wave modes initially excited: $kd_i < 0.2$, initial fluctuation amplitud $B_{\mathrm{RMS}} = 0.24B_0$.
- $m_i/m_e = 25$, $\beta_e = \beta_i = 0.1$ and $\beta_e = \beta_i = 2.0$
- Up to 9600^2 grid points, 5.5×10^{10} particles. Resources: 9.4k cores, 0.9M core-hours. Storage: 4.5 TB particle data per time snapshot.

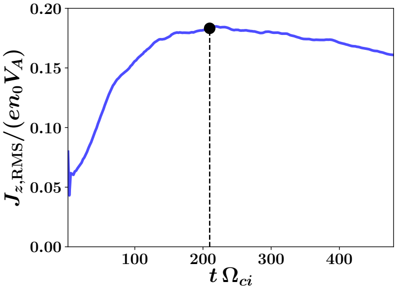


Figure 11: Time history of the RMS values of J_z

Contents

Electron kinetic effects: low-beta

- A way to assess regions where electron kinetic effects are larger is the non-gyrotropy of the electron pressure tensor $\bar{P}_e$, $D_{ng} = \sqrt{\sum_{i,j}(P_{ij,e} - G_{ij,e})^2}/\mathrm{Tr}(\bar{P}_e)$ (method by [Aunai et al., 2013]. $G_{ij,e}$ is the equivalent gyrotropic tensor.

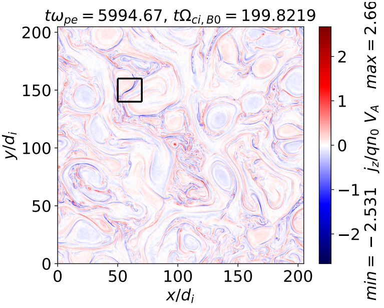


Figure 12: J_z

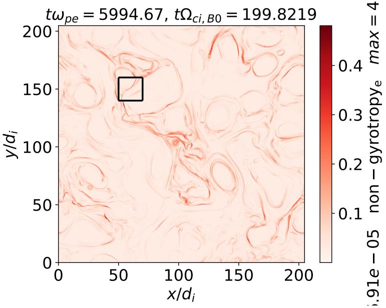


Figure 13: D_{ng}

Electron kinetic effects: low-beta

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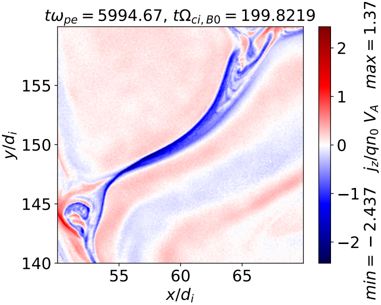

Figure 14: Zoomed-in J_z

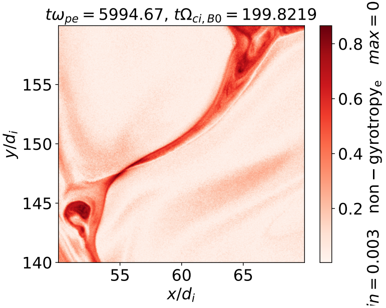

Figure 15: Zoomed-in D_{ng}

Distribution functions in the zoomed-in region

- Field-aligned double-peaked distribution functions with long plateaus near X-point. No streaming instabilities are possible though.
- The field-aligned double-peaked distribution functions with long plateaus can also be found in strong guide-field (3D) reconnection, but they are unstable!
- Non-field-aligned double peaked distribution functions near the downstream region

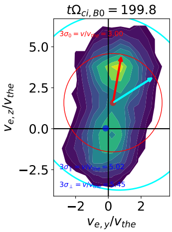

Figure 16: Near X-point @(56.6, 148.6)d_i

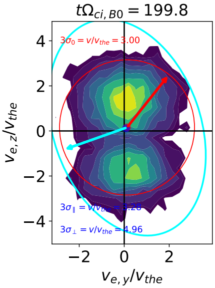

Figure 17: Downstream region @(65.6, 157.2)d_i

Plasma-beta effects

- Histograms of distribution of current-density and non-gyrotropy
- Higher plasma-beta tends to decrease the non-Maxwellian features and the current sheet strength (associated with smaller reconnection rates), temperature anisotropies, etc.

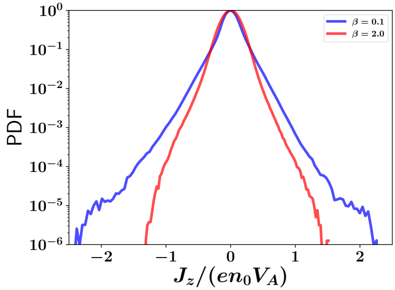

Figure 18: J_z

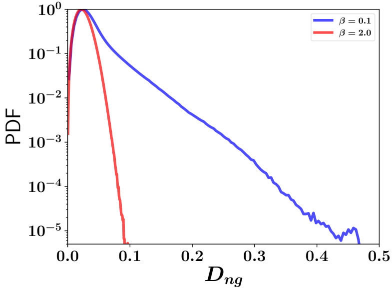

Figure 19: D_{ng}

Plasma-beta effects

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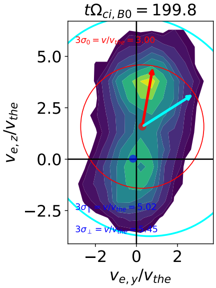

Figure 20: Near X-point, low-β

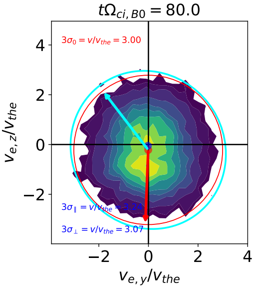

Figure 21: Near X-point, high-β

Turbulent spectra

- What is the relation with turbulence?
- At kinetic scales the spectral index is 2.6 below ion-scales for the low beta plasma case, the same that is measured in space plasmas.
- Spectral power is enhanced at typical current sheet scales for the low-beta case.

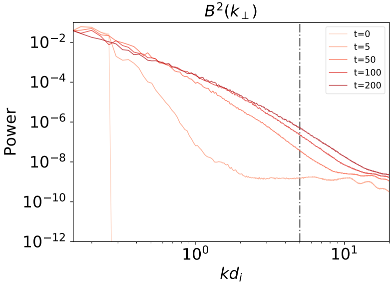

Figure 22: Low β evolution

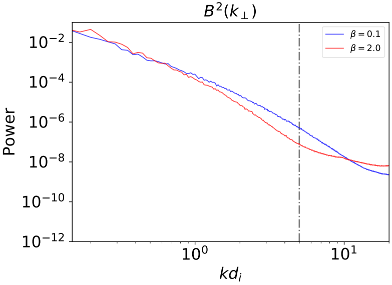

Figure 23: Comparison low vs high β

Contents

Conclusions

Conclusions

- Fully kinetic (collisionless) decaying turbulence led to electron-scale current sheet formation
- Field-aligned double-peaked distribution functions in the neighborhood of current sheets, typical from strong-guide field reconnection, but no signatures of micro-instabilities.
- Higher plasma-beta tends to decrease the current sheet strength/peak values, the efficiency of magnetic reconnection in turbulence, and the non-Maxwellian features.

THE END

Thank you very much
for your attention

Questions/Comments?

Contents

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