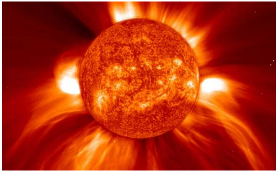

Particle Acceleration in Imbalanced Resistive Turbulence

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[ESA / NASA].

Cross-Helicity in the Solar Wind

- Solar-wind turbulence characteristics are consistent with Alfvénic turbulence
- Positive cross-helicity ($\mathcal{H}^c = \langle \mathbf{u} \circ \mathbf{b} \rangle$) signifies a dominance of outward-propagating Alfvén waves
- However, the magnitude of cross-helicity is not constant throughout the solar wind:
  $\mathcal{H}^c$

[Marsch & Tu, JGpR 1990].

Cross-Helicity in the Solar Wind

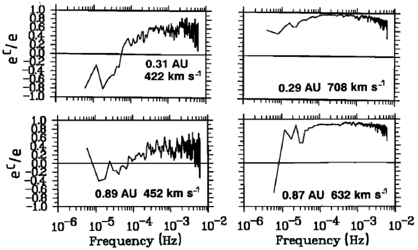


Fig. 4. Normalized cross helicity as a function of heliocentric distance and solar wind flow speed as indicated.

- However, the magnitude of cross-helicity is not constant throughout the solar wind:
  $\mathcal{H}^c$
  - decreases at greater radial distances from the sun
  - is greater in the fast wind than in the slow wind
  - decreases in regions with a high energy cascade rate or high compressibility

[Marsch & Tu, JGpR 1990].

Energy Cascade & Cross-Helicity

- In the Elsasser formulation ($\mathbf{z}^{\pm} = \mathbf{u} \pm \mathbf{b}$), the incompressible MHD equations are:

$$\partial_t \mathbf{z}^{\pm} = -[(\mathbf{z}^{\mp} \mp \mathbf{B}_0) \circ \nabla]\mathbf{z}^{\pm} + \frac{\nu + \eta}{2}\nabla^2 \mathbf{z}^{\pm} + \frac{\nu - \eta}{2}\nabla^2 \mathbf{z}^{\mp} - \nabla p.$$

- Nonlinear interactions (and hence the energy cascade rate ε) disappear if either of $\mathbf{z}^{\pm}$ is zero ($\hat{=}\sigma^c = \mathcal{H}^c/\mathcal{E} = \mp 1$)

Motivation

- If cross-helicity affects the cascade rate, how does it influence the stochastic heating of charged particles?
- Dung & Schlickeiser, A&A (1990): heating goes down;
  Chandran et al., ApJ (2010): heating barely affected;
  Beresnyak et al., ApJ (2011): spatial diffusion unaffected

- First step: compare test-particle acceleration in incompressible 3D MHD simulations for
  - **Balanced** turbulence (zero cross-helicity)
  - **Strongly imbalanced** turbulence (high cross-helicity)

MHD code Turbo

- Pseudospectral code for incompressible resistive MHD

$$\partial_t \mathbf{u} = -(\mathbf{u}\cdot\nabla)\mathbf{u} + [(\mathbf{B}_0+\mathbf{b})\cdot\nabla]\mathbf{b} + \nu\,\nabla^2\mathbf{u} + \mathbf{f}^u - \nabla\tilde{p},$$
$$\partial_t \mathbf{b} = -(\mathbf{u}\cdot\nabla)\mathbf{b} + [(\mathbf{B}_0+\mathbf{b})\cdot\nabla]\mathbf{u} + \eta\,\nabla^2\mathbf{b} + \mathbf{f}^b$$

[Teaca et al., 2009].

MHD code Turbo

- Pseudospectral code for incompressible resistive MHD

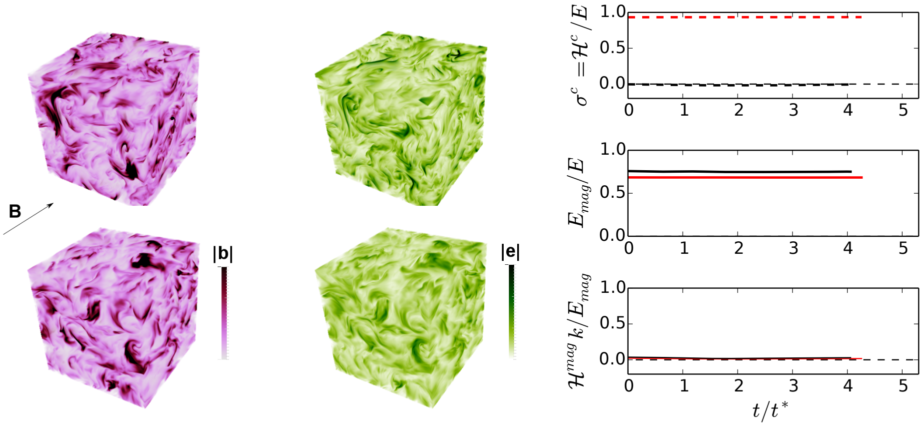
$$\partial_t \mathbf{u} = -(\mathbf{u}\cdot\nabla)\mathbf{u} + [(\mathbf{B}_0+\mathbf{b})\cdot\nabla]\mathbf{b} + \nu\,\nabla^2\mathbf{u} + \mathbf{f}^u - \nabla\tilde{p},$$
$$\partial_t \mathbf{b} = -(\mathbf{u}\cdot\nabla)\mathbf{b} + [(\mathbf{B}_0+\mathbf{b})\cdot\nabla]\mathbf{u} + \eta\,\nabla^2\mathbf{b} + \mathbf{f}^b$$

- Tracking of test-particles subject to Lorentz force

$$\ddot{\mathbf{x}}_n = q_n\left(\underbrace{\eta\nabla\times\mathbf{b} - \mathbf{u}\times(\mathbf{B}_0+\mathbf{b})}_{\mathbf{e}} + \dot{\mathbf{x}}_n\times(\mathbf{B}_0+\mathbf{b})\right)$$

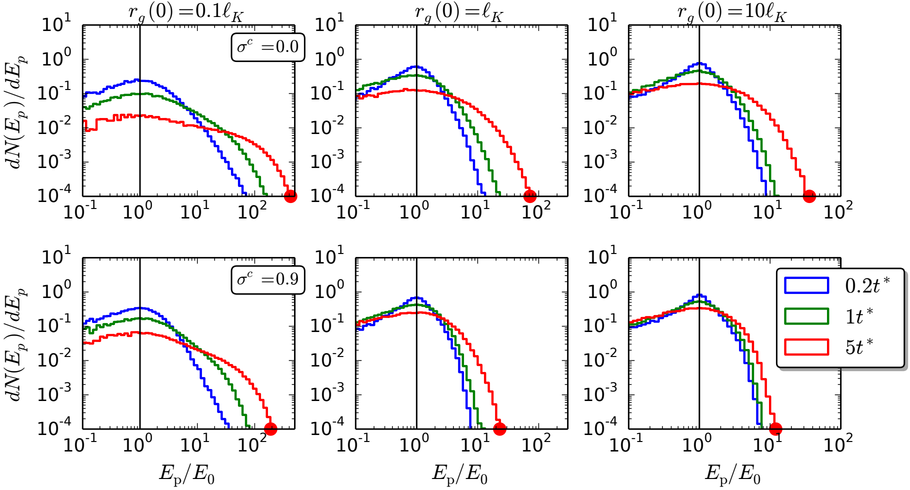
[Teaca et al., 2009].

Balanced vs. imbalanced



- **Balanced** (top) and **imbalanced** (bottom) MHD turbulence with otherwise identical parameters

Heating in imbalanced turbulence



- Particle heating is reduced in imbalanced turbulence

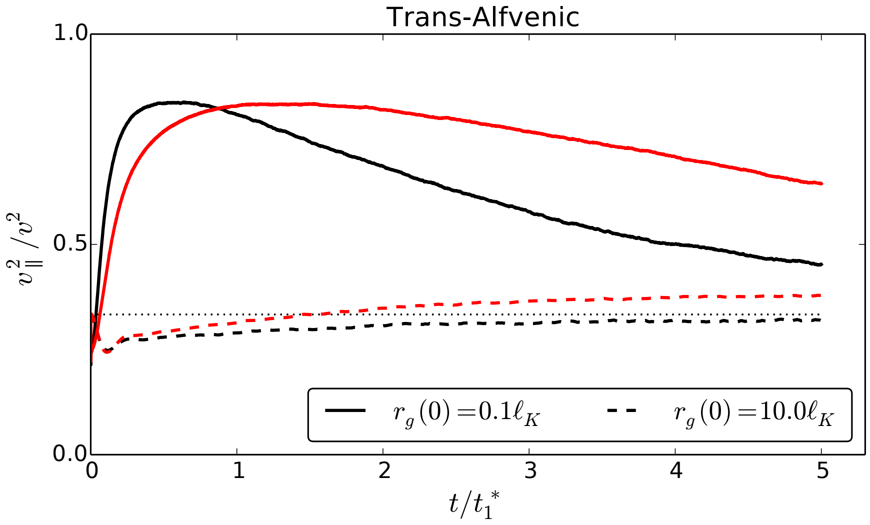
[Teaca, msw+, in press].

Two-stage acceleration

- Particles with small gyroradius experience strong unidirectional acceleration in current sheets ($\mathbf{e}_{\parallel} = \eta \mathbf{j}_{\parallel}$)
- Pitch-angle scattering and energy gain cause the gyroradius to exceed the transverse extent of the current sheet
- Large-gyroradius particles pass through current sheets too quickly to be accelerated, leaving only $\mathbf{e}_{\mathrm{mot}} = -\mathbf{u} \times \mathbf{b}$ as acceleration mechanism

[Dalena et al., ApJ 2014].

Pitch-angle evolution



- Imbalance reduces perpendicular heating

[msw, Teaca+, in prep].

Quasi-linear momentum diffusion

Quasi-linear theory

for imbalanced slab turbulence describes particle heating as diffusion in momentum space

$$\frac{\partial}{\partial t} f(p,t) = p^{-2} \frac{\partial}{\partial p} \left[p^2 D_{pp} \frac{\partial}{\partial p} f(p,t) \right]$$

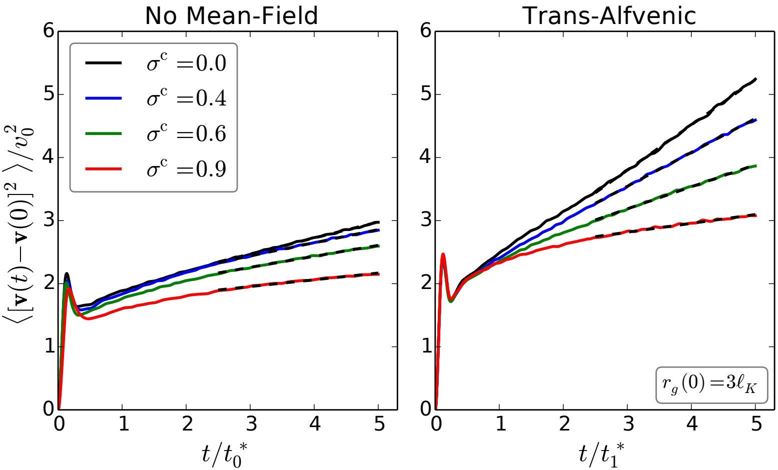
and predicts that momentum diffusion scales as :

$$D_{pp} \sim \frac{p^2}{\tau} \frac{v_A^2}{v^2} \times [1 - (\sigma^c)^2]$$

with the scattering timescale $\tau \propto r_g^{2-s}$ for $v \gtrsim v_A$

[Dung & Schlickeiser, A&A 1990].

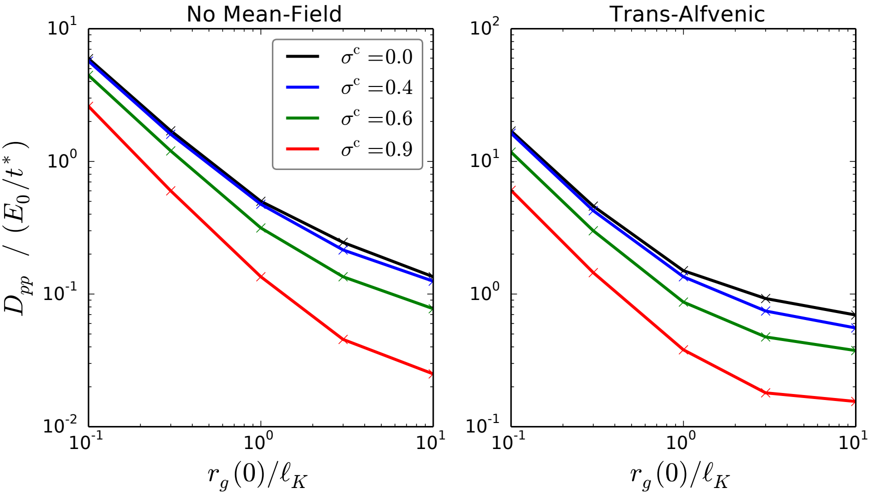
Momentum diffusion



$$D_{pp} = \frac{1}{2}\frac{d}{dt}\langle|\mathbf{v}(t) - \mathbf{v}(0)|^2\rangle$$

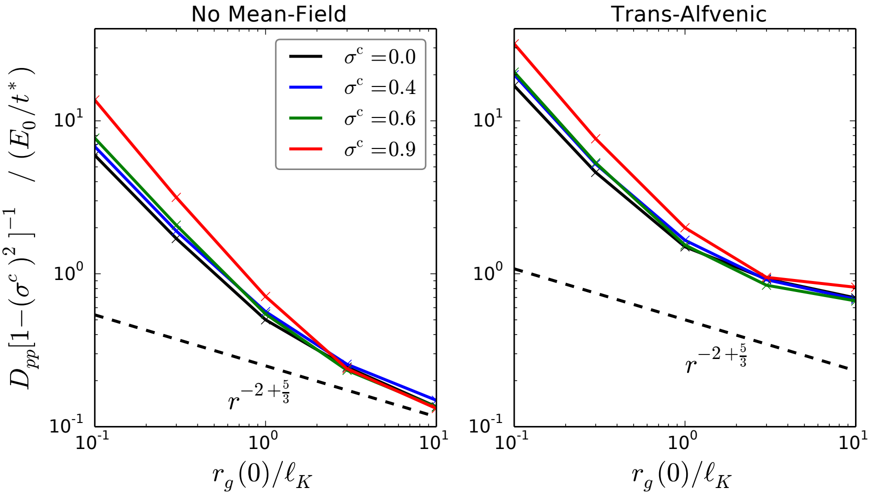
[Teaca, msw+, in press].

Heating in imbalanced turbulence



[Teaca, msw+, in press].

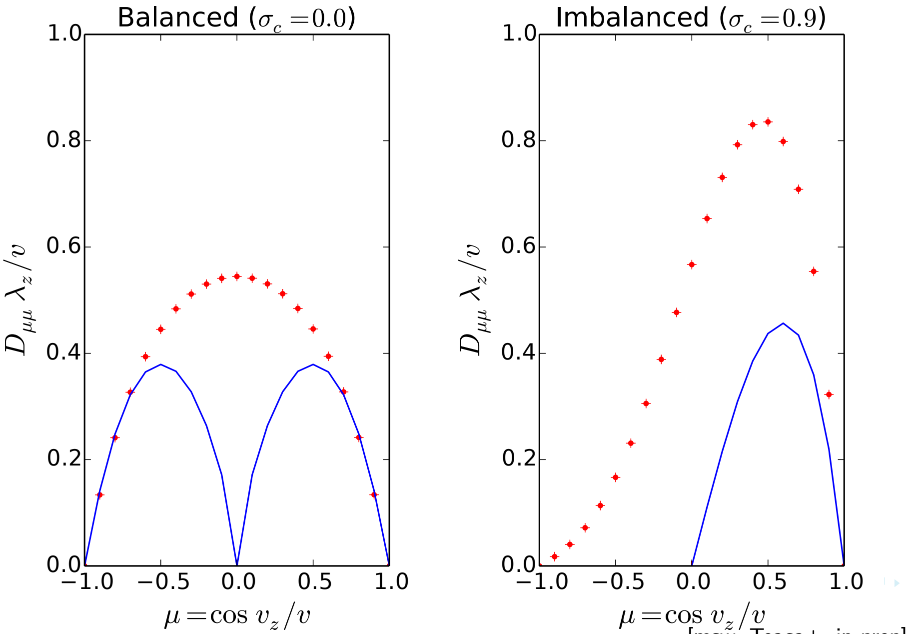
Heating in imbalanced turbulence



$$D_{pp} \sim [1 - (\sigma^c)^2] r_g^{-2+s}$$

[Teaca, msw+, in press].

Pitch-angle diffusion without Ohmic heating



[msw, Teaca+, in prep].

Summary

- We have compared test-particle acceleration in time-dependent MHD turbulence at various degrees of imbalance, with and without magnetic mean-field
- Strong imbalance (non-zero cross-helicity) inhibits the efficiency of ion heating in MHD turbulence
- At gyroradii in the inertial range, the observed scaling agrees with $D_{pp} \sim [1 - (\sigma^c)^2] r_g^{-2+s}$
- For smaller gyroradii, momentum diffusion is increased by Ohmic heating (independent of cross-helicity) until the inertial range is reached

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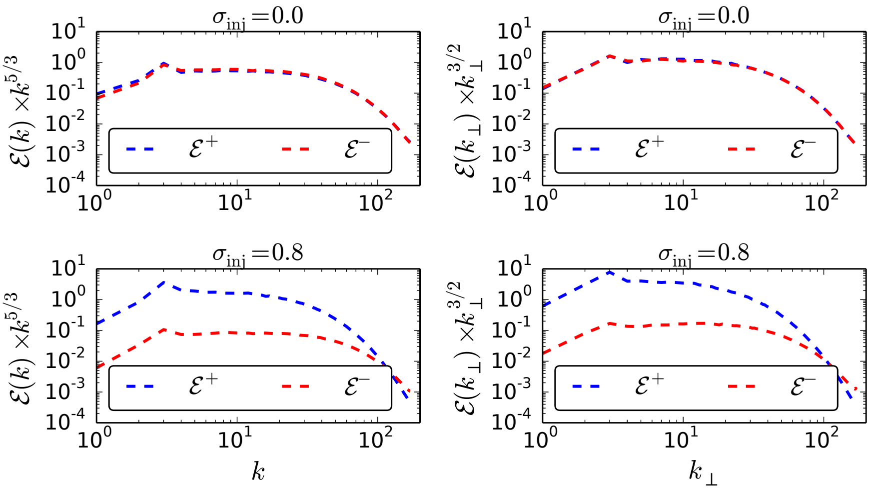
Comparison of Elsasser spectra

Isotropic ($\mathbf{B}_0 = 0$) — Trans-Alfvénic ($\mathbf{B}_0 = \langle \mathbf{b}^2 \rangle^{1/2} \hat{\mathbf{z}}$)



- Steady-state Elsasser energy spectra ($\mathcal{E}^{\pm} = (\mathbf{u} \pm \mathbf{b})^2/4$) both with and without mean-field