Kinetic effects in Solar Wind low frequency Turbulence: Vlasov Simulations vs Data Analysis

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Proton temperature anisotropy in the solar wind

The role of kinetic instabilities has been extensively investigated to understand the physical mechanisms which limit the development of the Temperature anisotropy

\[ T_{\parallel p} \text{ and } T_{\perp p} = \text{parallel and perpendicular proton temperatures with respect to ambient magnetic field} \]

\[ \beta_{\parallel p} = \text{parallel plasma beta (ratio between kinetic and magnetic pressure)} \]

Hellinger et al. GRL (2006); Kasper et al. JGR (2006); Kasper et al., (2002)
Proton temperature anisotropy in the solar wind

Is it possible to understand if and how anisotropy is produced inside a turbulent collisionless medium?

...we need Vlasov-Maxwell simulations!

The solar wind is a turbulent and weakly collisional system.

Nonlinear kinetic processes may locally occur in turbulence!
Basic equations (dimensionless units)

Hybrid Vlasov-Maxwell (HVM) equations:

\[
\begin{align*}
\frac{\partial f}{\partial t} + \mathbf{v} \cdot \nabla f + \left[\mathbf{E} + \mathbf{v} \times \mathbf{B}\right] \cdot \nabla_v f &= 0 \\
\mathbf{E} &= -\mathbf{u} \times \mathbf{B} + \frac{1}{n} \mathbf{j} \times \mathbf{B} - \frac{1}{n} \nabla P_e + \eta \mathbf{j} \\
\nabla \times \mathbf{E} &= -\frac{\partial \mathbf{B}}{\partial t} \\
\nabla \times \mathbf{B} &= \mathbf{j} \\
\end{align*}
\]

Characteristic quantities:

\[
V_A = \frac{B}{(4\pi \rho_p)^{1/2}}; \quad \Omega_p = \frac{eB}{m_p c}; \quad d_p = \frac{V_A}{\Omega_p}
\]

Simulations have been performed on FERMI at CINECA, within the European Project “3D-3V Vlasov simulations of plasma turbulence”, PRACE (Partner for advanced computing in Europe).
Setup of 2D-3V simulations

Numerical Domain 2D - 3V (2 dimensions in physical space and 3 in velocity space)

Phase space discretization

Periodic boundary conditions in physical space

The initial Maxwellian equilibrium is perturbed by a 2D spectrum of fluctuations for magnetic and proton velocity fields. No density disturbance is imposed at t=0

\[ f = f(x, y, v_x, v_y, v_z) \]

\[ f(|v| > v_{\text{max}}) = 0 \]

\[ v_{\text{max}} = 5v_{\text{th},p} \]

\[ L = 2\pi \times 20d_p \]

\[ k = \frac{2\pi m}{L} \quad 2 \leq m \leq 6 \]

\[ 0.05 \leq k \leq 0.3 \]

\[ T_e/T_p = 1 \]

\[ 0.25 \leq \beta_p = \frac{2v_{\text{th},p}^2}{V_A^2} \leq 5 \]

\[ \delta B/B_0 = 1/3, 2/3 \]
Simulations of kinetic turbulence

In analogy with fluid models (MHD, Hall MHD, etc.) of decaying turbulence (Mininni & Pouquet 2009), it is possible to identify an instant of time at which the turbulent activity reaches its maximum value. The turbulent pattern is similar to 2D MHD: vortices, islands, current sheets....

\[ t = t^* \sim 40 \]

\[ \delta B/B_0 = 1/3; \quad \beta_p = 2 \]

\[ \langle j_z^2 \rangle = \langle (\nabla \times B)_z^2 \rangle \]
In turbulence, reconnection locally occurs (at the X-points)


Bifurcation (Hall effect)

Thickness ~ few proton skin depths
Power spectra

- Large scale Alfvénic correlations
- Kolmogorov-like spectrum
- Low compressibility (density fluct. 8%)
- Intense electric activity at small scales
- Steepening of the magnetic spectrum at $kd_i \sim 1$

...several features commonly observed in space plasmas!
A measure of temperature anisotropy

Velocity distribution functions display strong deformations in velocity space.

Stress Tensor

\[ A_{ij}(r) = \frac{1}{n} \int (v_i - \langle v_i \rangle)(v_j - \langle v_j \rangle) f(r, v) \, d^3v \]

Eigenvectors

\[ e_1, e_2, e_3 \]

Eigenvalues (Temperatures)

\[ \lambda_1 > \lambda_2 > \lambda_3 \]

Minimum Variance Frame (MVF)

For a Maxwellian

\[ \lambda_1 = \lambda_2 = \lambda_3 = 1 \]

(Maximum) Temperature anisotropy

\[ \equiv \frac{\lambda_1}{\lambda_3} \]
Velocity distributions in turbulence

Anisotropy with respect to local magnetic field can be either $>1$ or $<1$

Distribution Functions are strongly affected by turbulence (Elongated potato-like structures)
Anisotropy direction with respect to local $B$

$\cos \theta = e_1 \cdot B$

$e_1$ is mainly found along or across local $B$. Because of turbulence, a broad distribution of angles is observed.

Note: If $e_1$ and $B$ were spatially random and uncorrelated, $PDF(\cos \theta) \sim \text{const. (}=0.5)$
Where are kinetic effects located?

Out of plane current density

Temperature anisotropy

\[ \frac{\lambda_1}{\lambda_3} \propto |\nabla j_z| \equiv |\nabla^2 b_\perp| \]

Kinetic effects (temperature anisotropy) are localized adjacent to regions with high magnetic field gradients (current sheets).

Trying to reproduce the solar-wind anisotropy plot

We considered an ensemble of simulations with different values of the plasma $\beta$ parameter and evaluated the temperature anisotropy with respect to the local magnetic field.

Pisa 2014
Trying to reproduce the solar-wind anisotropy plot

In the solar wind plot different levels of fluctuations are mixed together.

Let us try additional simulations with increased level of turbulence!

\( \frac{dB}{B_0} = 0.66 \)

The anisotropy depends on the level of turbulence.

SIMULATIONS

The higher is the level of the initial fluctuations the higher is the anisotropy generated at the turbulence saturation,

Different initial values of the plasma beta and of the fluctuation level cover almost all the observed values of temperature anisotropy.
Temperature anisotropy is generated during the turbulent cascade

As turbulence develops, smaller and smaller scale structures are generated and larger and larger values of temperature anisotropy are reached.
From 2D-3V to 3D-3V simulations

3D-3V runs with resolution:
- 128x128x128 space
- 51x51x51 velocity

European PRACE project
- 25.000.000 CPU hours on FERMI.

2D-3V runs

3D-3V runs
The small scale most intermittent coherent structures (current sheets, velocity shears, pressure balanced structures) are mainly localized at the boundaries of the region where temperature anisotropy is found, both in solar wind and in the simulations.

\[ f(s) = \frac{\Delta f}{\sqrt{\Delta f^2}} \]

Summary and Conclusions

Using Hybrid Vlasov-Maxwell simulations we modeled the complex Solar Wind dynamics that produces temperature anisotropy in the proton velocity distributions.

Our numerical results in 2D-3V and 3D-3V configuration suggest that:

- Along the turbulent cascade, small scale structures (current sheets, velocity shears etc.) are generated;
- In correspondence to these small scale structures, large temperature anisotropy with respect to the local magnetic field is recovered;
- The temperature anisotropy plot from the simulations display many features significantly comparable to those observed in the solar wind data;
- Both the generation of this temperature anisotropy and the shaping of the temperature anisotropy plot are driven by the turbulent cascade.