Small scale solar wind turbulence: Recent observations and theoretical modeling

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Outline

- Motivations
- Solar wind turbulence: cascade vs dissipation below the ion scale $\rho_i$
- Different theoretical predictions on small scale plasma turbulence
- High resolution Cluster data to analyze small scale SW turbulence

1. *Clear evidence of a new inertial range below* $\rho_i$
2. *First evidence of a dissipation range* @ $\rho_e$
3. *Theoretical interpretation (KAW turbulence)*

- Conclusions
Turbulence in the Universe

is observed from cosmological to quantum scales!

Controls mass transport, energy transfers & heating, \textit{magnetic reconnection in plasmas(?)}, \ldots

- M100 galaxy $10^{23} m$
- Eagle nebula $10^{18} m$
- Sun-Earth $\sim 10^{11} m$
- Earth’s atmosphere $10^7 m$
- Clouds $10^3 m$
- Soap film $10^{-1} m$
Turbulent reconnection in the Magnetosphere

Can ULF turbulence drive transfers across the magnetopause?

Collisionless plasma $\Rightarrow$ role of waves & turbulence

- Large scale ULF turbulence ($\sim 10^4 km$) in the magnetosheath may drive reconnection at small scales ($\sim km$) via a cascade process
- Reconnection as a mechanism to dissipate small scale turbulence (Sundkvist et al., PRL, 07) dissipates

$\sim 10^4 km$

$\sim 10 km$
Phenomenology of turbulence

NS equation:

\[ \partial_t \mathbf{V} + \mathbf{F}_i = \mathbf{V} \cdot \nabla \mathbf{V} - \nabla P - \nu \nabla^2 \mathbf{V} \]

- Idealistic image (even in NS): e.g., doesn’t account for intermittency
- More complex situation in plasmas: - several eigenmodes/observables \( \mathbf{V}, \mathbf{B}, \mathbf{E} \)…
  - breaking of the scale invariance assumption at \( \rho_{i,e} d_{i,e} \)
Solar wind turbulence

Typical power spectrum of magnetic energy at 1 AU

What happens to the energy at and below the ion scale?

Dissipation at $f_{ci}$ (or $\rho_i$)

Leamon et al. 98; Goldstein et al. JGR, 94

Cascade below $f_{ci}$ (or $\rho_i$)

Alexandrova et al., 08, Bale et al., 05
Theoretical predictions on small scale turbulence

\[ \mathbf{E} + \mathbf{V} \times \mathbf{B} = \frac{1}{en} \mathbf{J} \times \mathbf{B} - \frac{\nabla P_e}{en} + ... \]

1. Fluid models (Hall-MHD)
   - Whistler turbulence (E-MHD): (Biskamp et al., 99, Galtier, 08)
   - Weak Turbulence of Hall-MHD (Galtier, 06; Sahraoui, 07)

2. Gyrokinetic theory: \( k_{//} \ll k_\perp \) and \( \omega \ll \omega_{ci} \) (Schekochihin et al. 06; Howes et al., 08)
The Cluster mission

Four identical satellites of ESA

Objectives:

- **3D exploration** of the Earth magnetosphere boundaries (magnetopause, bow shock, magnetotail) & SW

- **Fundamental physics**: turbulence, reconnection, particle acceleration, …

Different orbits and separations (100 to 20000km) depending on the scientific goal
View of a single spacecraft

42 experiments provide wave & particle data since December 2000
Wave consortium

STAFF (LPP/LESIA, France)

EFW (IRFU, Sweden)

DWP (UK)

WBD

WHISPER, LPCE, France
The data used here

Flux Gate magnetometer ⇒ magnetic field data up to ~1Hz

STAFF-Search Coil ⇒ magnetic field fluctuations

EFW ⇒ Electric field data

Ion spectrometer ⇒ Ion moments: $N_i$, $V_i$, $T_i$ (4sec)

Electron Analyser ⇒ Electron moments: $N_e$, $V_e$, $T_e$ (4sec)

Two modes:
- 12Hz
- 225Hz
Small scale solar wind turbulence

Position of the Quartet on March 19, 2006

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FGM data (CAA, ESA)

Proton plasma data from CIS (AMDA, CESR)
1. Two breakpoints, corresponding to $\rho_i$ and $\rho_e$, are observed.

2. A clear evidence of a new inertial range $\sim f^{-7/3}$ below $\rho_i$

3. First evidence of a dissipation range $\sim f^{-4}$ at electron scale $\rho_e$
Zoom on small scales

From $\Delta T_1$

From $\Delta T_2$
Further investigation: (B+E) field data

1. Large scales (L>\(\rho_i\)): strong correlation of \(E_y\) and \(B_z\) in agreement with \(E=-VxB\)

2. Small scales (L<\(\rho_i\)): steepening of \(B^2\) and enhancement of \(E^2\) (however, strong noise in \(E_y\) for f>5Hz)

⇒ Good agreement with GK theory of Kinetic Alfvén Wave turbulence

Howes et al.
PRL, 08
k-spectra determination using the k-filtering technique

Interferometric method: it provides, by using a NL filter bank approach, an optimum estimation of the 4D spectral energy density $P(\omega, k)$ from simultaneous multipoints measurements

$P(\omega, k)$ can be used to

1. Calculate experimental dispersion relations $\Rightarrow$ plasma mode identification (Sahraoui et al., 03a, 04, Tjulin et al., 05)
2. Determine 3D k-spectra (anisotropies, power laws, …)

Sahraoui et al., PRL, 06; Narita et al. 06
k-spectra at large scale

Cluster separations $d$ limit the interval of study to $[f_{\text{min}}, f_{\text{max}}]$

$f_{\text{max}} \sim k_{\text{max}} V/2\nu \sim V/d$ (otherwise aliasing occurs)

$\Rightarrow$ turbulence at large scale is quasi-2D

Assumption used below: turbulence at small scales remains 2D
Theoretical interpretation of the small scales

Solutions of the Maxwell-Vlasov equations using the observed plasma parameters:

1. The Kinetic Alfvén Wave extends **down to** $k\rho_e \sim 1$ with $\omega_r < \omega_{cp}$

2. Only a slight damping @ $k\rho_i \sim 1$ (\(|\gamma| \sim 0.1 \omega_r\)) \(\Rightarrow\) may explain the slight steepening to $f^{-7/3}$

3. Strong damping @ $k\rho_e \sim 1$ (\(|\gamma| \sim \omega_r\)) \(\Rightarrow\) may explain the strong steepening to $f^{-4}$
E/B observations

E/B estimation from KAW theory and from Cluster observations

- Lorentz transform: \( \mathbf{E}_{\text{sat}} = \mathbf{E}_{\text{plas}} + \mathbf{V} \times \mathbf{B} \)
- Taylor hypothesis to transform the spectra from \( f \) (Hz) to \( k \rho \)

1. Large scale (\( k \rho_i < 1 \)): \( E/B \sim V_A \)
2. Small scale (\( k \rho_i > 1 \)): \( E/B \sim k^{1.1} \) ⇒ in agreement with GK theory of KAW turbulence \( E^2 \sim k_{\perp}^{-1/3} \) & \( B^2 \sim k_{\perp}^{-7/3} \) ⇒ \( E/B \sim k \)
3. The departure from linear scaling (\( k \rho_i > 20 \)) is due to noise in Ey data

Sahraoui et al., PRL 102, 231102 (2009)
Journey of the energy through scales:

2D cascade

Injection

1st cascade

k^{-5/3}

Strong dissipation

Slight dissipation

e-Landau damping

2nd KAW cascade

k^{-7/3}

p-Landau damping

Dissipation range

1. Turbulence
2. e-Acceleration
3. Heating
4. Reconnection
Conclusions

- Evidence of a second inertial range of SW turbulence below the ion gyroscale $\rho_i$ with the scaling $\sim f^{-7/3}$.
- First evidence of dissipation below the electron gyroscale $\rho_e \Rightarrow \text{electron heating by turbulence cascade}$
- Remarkable agreement with the prediction of the Gyro-kinetic theory of the Kinetic Alfvén Wave turbulence.
- Consequences on solar wind heating and on modeling of magnetic reconnection.