Observations of solar wind turbulence at plasma kinetic scales

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Space plasmas:

- no collisions $\Rightarrow$ dissipation?
- Characteristic scales and frequencies
- $B_0 \Rightarrow$ anisotropy
- Turbulence?
Turbulent spectrum in the solar wind

∃ a spectral break close to $f_{ci}, \frac{V_{sw}}{\lambda_i}, \frac{V_{sw}}{R_{Li}}$

$\lambda_i = \frac{c}{\omega_{pi}}$

Below the spectral break:
Kolmogorov-like inertial range
On the spectral break?
- onset of dissipation range
- starting point of another cascade

If it is a dissipation range ⇒
- Why a power law and not an exponential cut-off?
- What happens at higher frequencies (where FGM instrument is not sensitive...)?

\[ \text{psd} \sim f^{-s}, s \in [2, 4[ \]

Dissipation range $\sim \exp$
Turbulence at electron scales: Cluster observations

- Solar wind: \(\sim\text{exponential spectrum for } \Delta f\sim[10,100] \text{ Hz (} k\rho_e = [0.1,1]) \)
- Foreshock region: spectral break at \( k\rho_e = k\lambda_e = 1 \)
- Magnetosheath: \(\sim\text{exponential + whistlers [Alexandrova et al., 2008, AnGeo]} \)

**Universality of solar wind spectrum?**
7 solar wind spectra for different plasma parameters

\[ V \in [360, 670] \text{ km/s}, \ \beta_i \in [0.4, 2], \ \beta_e \in [0.2, 1.6], \ \Theta_{BV} \in [65, 85] \degree \]

Is there a universal spectrum \( g \) such as any observed spectrum \( P(f) \) is

\[ P(f) = P_0 g(\lambda f) \]

[Pedrosa, et al., 1999, PRL]
Quasi-universality of SW spectrum

We arrive to one clear spectrum $g(k)$

2 clear inertial ranges: (i) -$5/3$ ; (ii) -$8/3$

There are 2 break points: (i) at ion scales; (ii) at electron ones

Rescaled spectra:

$$P(f)/P_0 = g(\lambda f)$$

- Assuming the validity of the Taylor’s hypothesis:
  $$\lambda = 2\pi/V$$

- Factor $P_0$ (relative spectral level):
  $$P_{0j} = \langle S_j/S_1 \rangle_{k \in [10^{-4}, 10^{-1}] km^{-1}}$$
  \[ j = 1, \ldots, 7 \]
Spectral level (factor $P_0$) and plasma parameters

$P_0$-factor depends on
- Mean magnetic field (cyclotron periods)
- Dynamical and thermal (not shown) pressures
- Electron Larmor radius

$$\rho_e = \frac{V_{\perp e}}{\Omega_{ce}}$$

$$\Omega_{ce} \sim B_0$$
$$V_{\perp e} = V_{th,e} \sim \sqrt{T_{\perp e}}$$
What does it mean that turbulence level $P_0$ is related to a particular scale?

HD: in the vicinity of the dissipation scale $L_d$

$$ \nu \cdot \nabla \nu \sim \eta \nabla \nu $$

$$ \frac{\nu^2}{L_d} \sim \eta \frac{v}{L_d^2}, \quad \tau^{-1} \sim \frac{v}{L_d} \sim \frac{\eta}{L_d}, \quad \nu \sim \frac{\eta}{L_d} $$

Energy transfer rate $\varepsilon \sim L_d^{-4}$

Kolmogorov: $P_0 \sim \varepsilon^{2/3} k^{-5/3}$

$P_0 \sim L_d^{-8/3}$

For a fixed $k$, at intermediate scales (inertial-dissipation rage)

No HD-like viscosity in the solar wind, so the $P_0(L_d)$ should be different…

Dependence of $P_0$ on the electron gyroradius indicates that this scale is the dissipation scale of space plasma turbulence.
Universal Kolmogorov’s function $\sim L_d E(k)/\eta^2$

From the balance between the energy input and the dissipation:

$$E(k)\ell_d/\eta^2 \sim (k\ell_d)^{-5/3}$$

- Assumption: $\eta=$Const
- $k\rho_i$ & $k\lambda_i$ - normalizations are not efficient to collapse the spectra together
- $k\rho_e$ & $f/f_{ce}$ ($f/f_{ci}$) - normalizations bring the spectra close to each other.
- There is a correlation between $\rho_e$ & $B_0$ ($& f_{ce}$)
- In terms of spatial scale, we could singled out for the 1st time with the observations the importance of $\rho_e$ for the dissipation.

[Alexandrova et al., 2009, PRL]
Dimensionless spectra $P(kr)/B_0^2$

$$k \rightarrow kr, \quad P(k) \rightarrow P(kr) = P(k) \frac{1}{r}.$$ 

- $k\rho_e$ - normalization => all the spectra collapse at scales smaller than the spectral break at ion scales

- This distinguishes $\rho_e$ from the other spatial plasma kinetic scales as $\lambda_{i,e} & \rho_i$

[Alexandrova et al. 2010, SW12]
Conclusions-I

- We have analyzed 7 spectra for 1h time intervals in the free solar wind, which cover MHD to electron scales.

- We have shown:
  - 1) Quasi-universal spectral shape: Kolmogorov -5/3 spectrum at MHD scales, -2.8 spectrum at ion scales (f=[0.2,10]Hz) and a curved (~exponential) spectrum at f=[10,100] Hz, indicating an onset of dissipation.
  - 2) Turbulence intensity depends on magnetic, kinetic and thermal energy of the solar wind (i.e. on energy input).
  - 3) Turbulence intensity depends on the electron Larmor radius $\rho_e$. This indicates that $\rho_e$ plays a role in the dissipation of turbulent energy in the collisionless plasma.
II. Statistical study of magnetic turbulence spectra at electron scales in the solar wind

(Cluster-4/STAFF-SA)

173 time periods of 10 minutes are considered
- 19 cases with parallel RH whistlers
- 154 time periods without whistlers (136 are 3 times more intense than the background noise)
Detection of whistler waves in the solar wind by Cluster/STAFF-SA

- The phase difference between $B_x$ and $B_y$ (in the plane perp to $B_0$) = 90°. That indicates the Right Hand polarization of the waves.
- The wave vectors are determined to be quasi-∥ to $B_0$. 
Spectra without whistlers
(as a function of satellite-frame frequency)

- All magnetic spectra at these scales are very similar (left plot).
- Simple translation along y-axes gives a nice superposition (right plot).
**k-spectra (k||V _sw_)**

The Taylor hypothesis is used for the time intervals where whistler waves are not observed.

- **Doppler shift**: \( k = 2\pi f/V \) and \( S(k) = S(f)V/2\pi \)

Confirmation of universality of the spectral shape at electron scales.
The superposition of k-spectra is better than the one of f-spectra.
This indicates that we really measure the Doppler shifted k-spectra
(frequencies of the fluctuations in the plasma frame are very small, ~zero).
Turbulence intensity and ion thermal pressure in the solar wind

Large scale turbulence level depends on the ion thermal speed in the solar wind (Cor=0.8) [Grappin, Mangeney, Marsch, 1990, JGR].

Turbulence intensity depends as well on
- kinetic pressure $\sim \rho V^2$ (Cor=0.8)
- magnetic pressure $\sim B^2$ (Cor=0.7)
- electron thermal pressure $\sim nT_e$ (Cor=0.5)

But all the pressures are cross-dependent in the solar wind:
- Cor(Pthi,Pmag)=0.7
- Cor(Pthi,Pthe)=0.6
- Cor(Pthi,Pkin)=0.5

The same dependences are present for the k-spectra (however, all the correlations are lower), but not for normalized $k\rho_e$-spectra.
Turbulence intensity vs temperature anisotropy & collisional age

Turbulence intensity at 0.3 Hz ~ ion temperature anisotropy (and collisional age) [Bale et al. 2009, PRL]:

- There is a +/- dependence on ion temp. anis. (Cor=0.6)
- No dependence on the collisional age
Turbulence intensity and electron scales

In fluids, turbulence intensity (in the vicinity of $k_d$) depends on $k_d$

Both scales control turbulent spectrum independently?
Rescaled spectra (dimensionless x-axis)

\[ k \to kr, \quad P(k) \to P(kr) = P(k) \frac{1}{r}. \]

- Dispersion is less for \( k_{\lambda_e}\)-superposition
- Shape is better for \( k_{\rho_e}\)-superposition
- … difficult to choose one scale
- May be both scales are important for dissipation in the solar wind?
- (To do the same analysis but for the complete spectrum (MHD-ion-electron scales), before a final conclusion… )
Spectral shape: curvature or succession of 2 power-laws?

- We calculate the 1st derivative of the 136 PSD.
- For each PSD, it is not constant.

Spectra are curved!
Spectral shape: exponential/polynomial

Dissipation range spectrum in fluid turbulence

[Chen, Doolen, Herring, Kraichnan, Orszag, She, 1993, PRL]:

\[ E(k) \sim k^\alpha \exp(-ck/k_d) \]

In our previous study [Alexandrova et al. 2009] we have shown that \( \alpha = -2.8 \) and \( k_d = 1/\rho_e \). In the present study we show that inertial length can be important as well.

\[ E(k) = Ak^\alpha \exp(-k/k_d), \ k_d = 1/\rho_e, \ k_d = 1/\lambda_e \]

- Fluids dissipation range spectrum coincide with solar wind data without any particular fitting for \( k_d = 1/\rho_e \) & \( k_d = 1/\lambda_e \)

- Fitting with 136 spectra => the same result!

- Advantage in comparison with polynomial fitting : only 1 parameter to fit (A) and we describe the whole spectrum from ion to electron scales.
Conclusions II

- 173, 10min averaged spectra at f > 8Hz in the free solar wind are analysed.
- During 19 (/173) intervals we observe whistler emissions (around fce/10).
- The other 154 intervals have very similar spectra

- The analysis of the spectra >3*noise (136/154) =>
  - Confirmation of a universal spectral shape
  - Turbulence level ~ $P_{thi}$ and $\rho_e$ and $\lambda_e$; but no dependence on $\rho_i$
  - Dissipation range is fluid like, with the law $\sim k^{-2.8} \exp(-k/k_d)$ !
    (With $1/k_d$=electron plasma scales.)

- Why? How it works? The exact mechanism of dissipation seems to be not so important as far as we arrive to the same spectrum as in fluids…?

- $k_d=\rho_e$ or $\lambda_e$ ? Small scale dissipation structures at $\rho_e$ and $\lambda_e$ ?