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Kinetic-scale plasma turbulence evolving in the magnetosheath: case study

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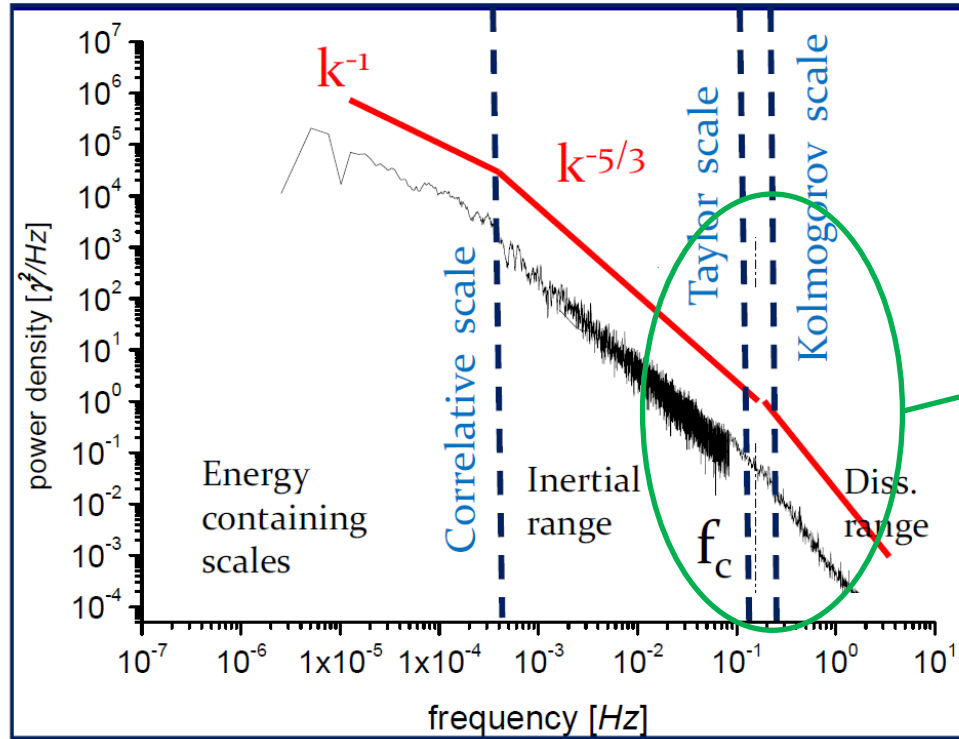
Motivation:

- Turbulence in the Earth's magnetosheath (MSH) develops behind the bow shock (BS), which may contribute to the formation of the turbulent cascade inside the MSH;
- Statistical studies indicate that position with respect to the BS does affect the turbulent cascade: at **MHD scales** spectra do not follow Kolmogorov-like scaling, at the **kinetic scales** steepening of spectra occurs in the vicinity of the BS (see e.g. *Czaykowska et al., 2001; Huang et al., 2017; Rakhmanova et al., 2018 a,b*).

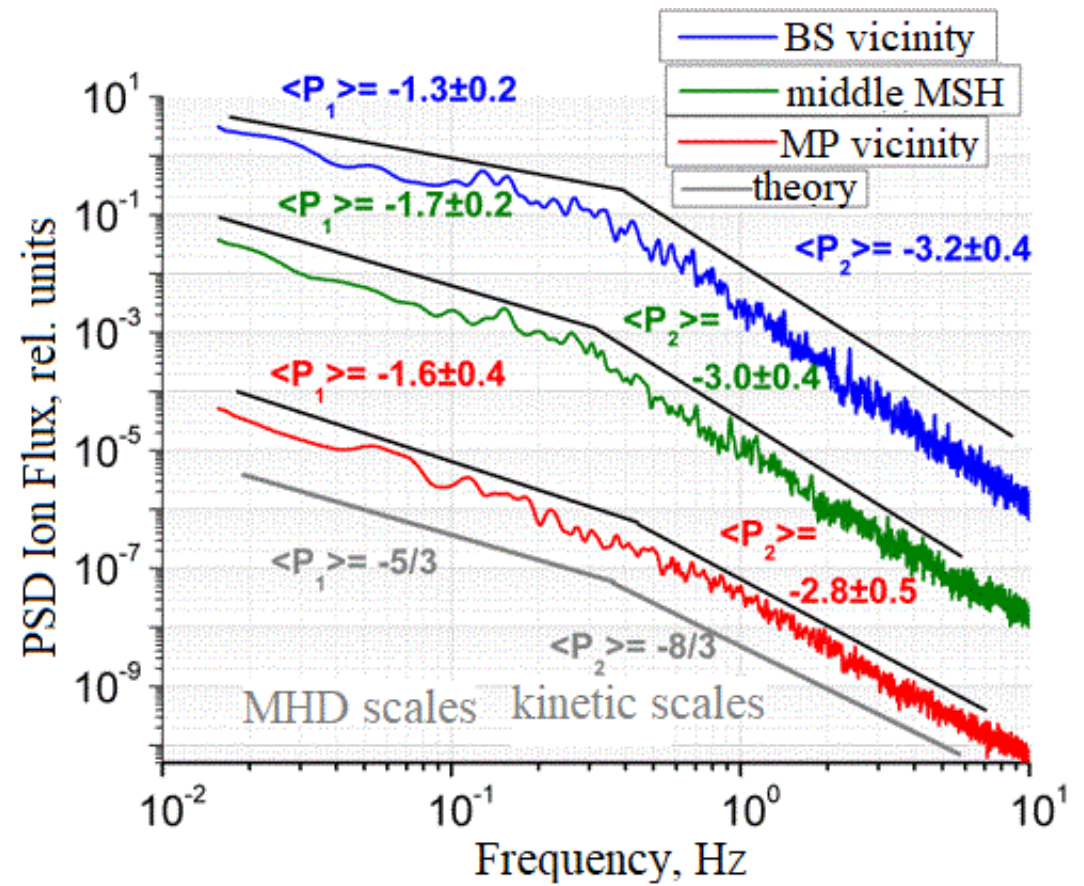
Aims:

- To consider the same volume of plasma **at two discrete points** behind the bow shock to find out **how the turbulent spectrum evolves** while plasma propagates through the magnetosheath;
- To consider if upstream **solar wind parameters affect** evolution of the **turbulent cascade** behind the bow shock.

Object of interest:



Typical spectrum of the interplanetary magnetic field fluctuations (from Bruno&Carbone, 2013).



Typical ion flux fluctuation spectra and their mean parameters in different regions inside the MSH: close to BS (blue), in the middle MSH (green) and close to the MP (red) (statistics from Rakhmanova et al., 2018a,b).

The study focuses on the range of scales where kinetic processes become significant, i.e. the scales around the ion spectral break.

Comparison between spectra of ion flux value and magnetic field magnitude is performed to focus on direct registration of compressible fluctuations.

Data:

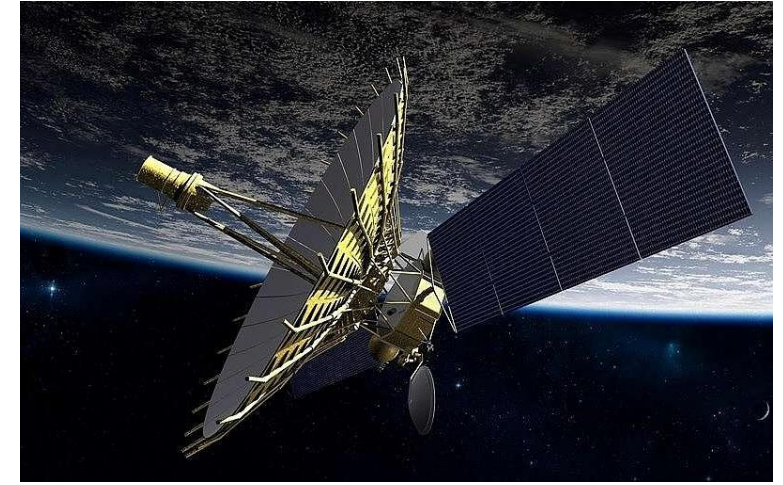
We considered **3 intervals**, when simultaneous measurements by two spacecraft were performed which satisfied the **following criteria**:

- Spacecraft were located at the **same flank** of the MSH;
- Separation between the spacecraft pair lied **within 30 R_E** ;
- Measurements of plasma parameters and/or magnetic field fluctuations with **high enough time resolution** were available.

We use ion flux measurements with time resolution **0.031 sec** provided by the Fast Monitor of Solar Wind (**BMSW**) instrument onboard the Spektr-R spacecraft (Šafránková *et al.*, 2013, Zastenker *et al.*, 2013).

*Ion flux fluctuations represent mostly fluctuations of the ion density (e.g. Neugebauer *et al.*, 1978; Pitňa *et al.*, 2016)*

Also **Themis** mission data were used in the second point. **FGM** (Auster *et al.*, 2008) measurements of the magnetic field vector with 0.25 sec time resolution were used together with **ESA** (McFadden *et al.*, 2008) measurements of ion parameters with 4 sec resolution. Data were downloaded from cdaweb.gsfc.nasa.gov web source.

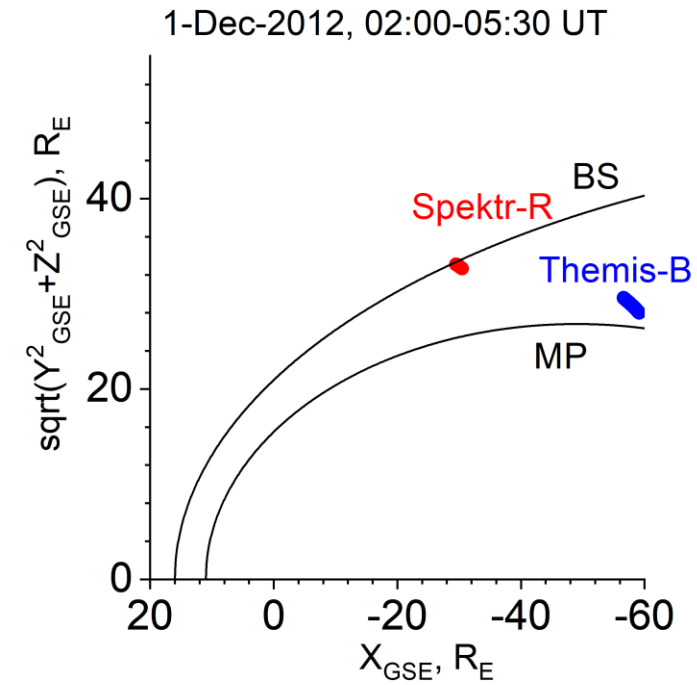


Spektr-R spacecraft

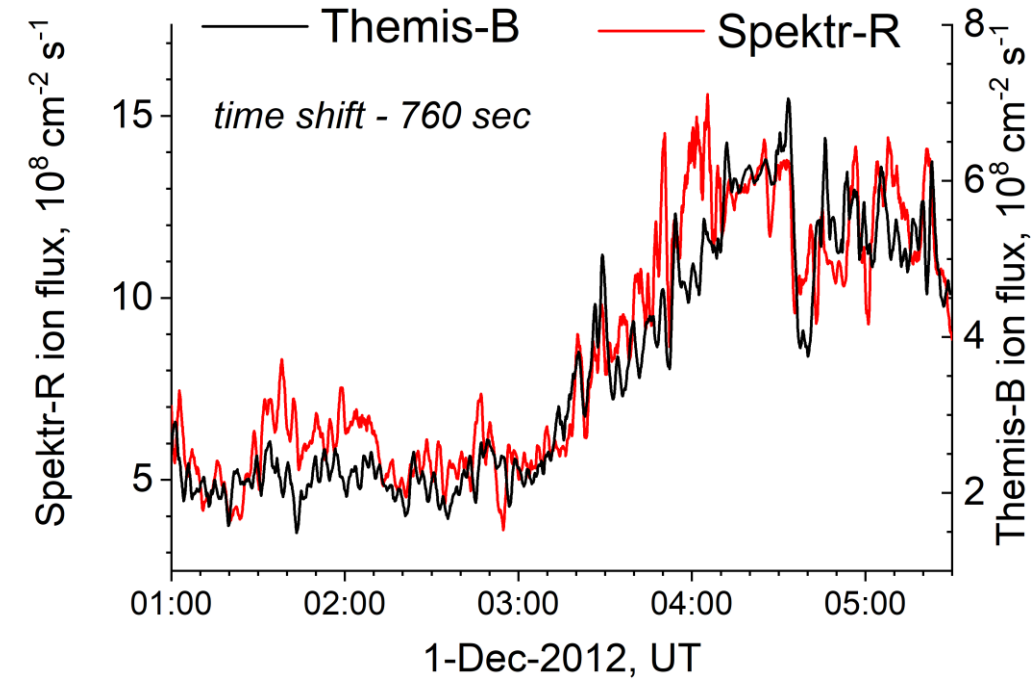


Themis spacecraft

Case study 1: December 1, 2012



Spacecraft orbits during analyzed event. BS and MP are shown schematically.

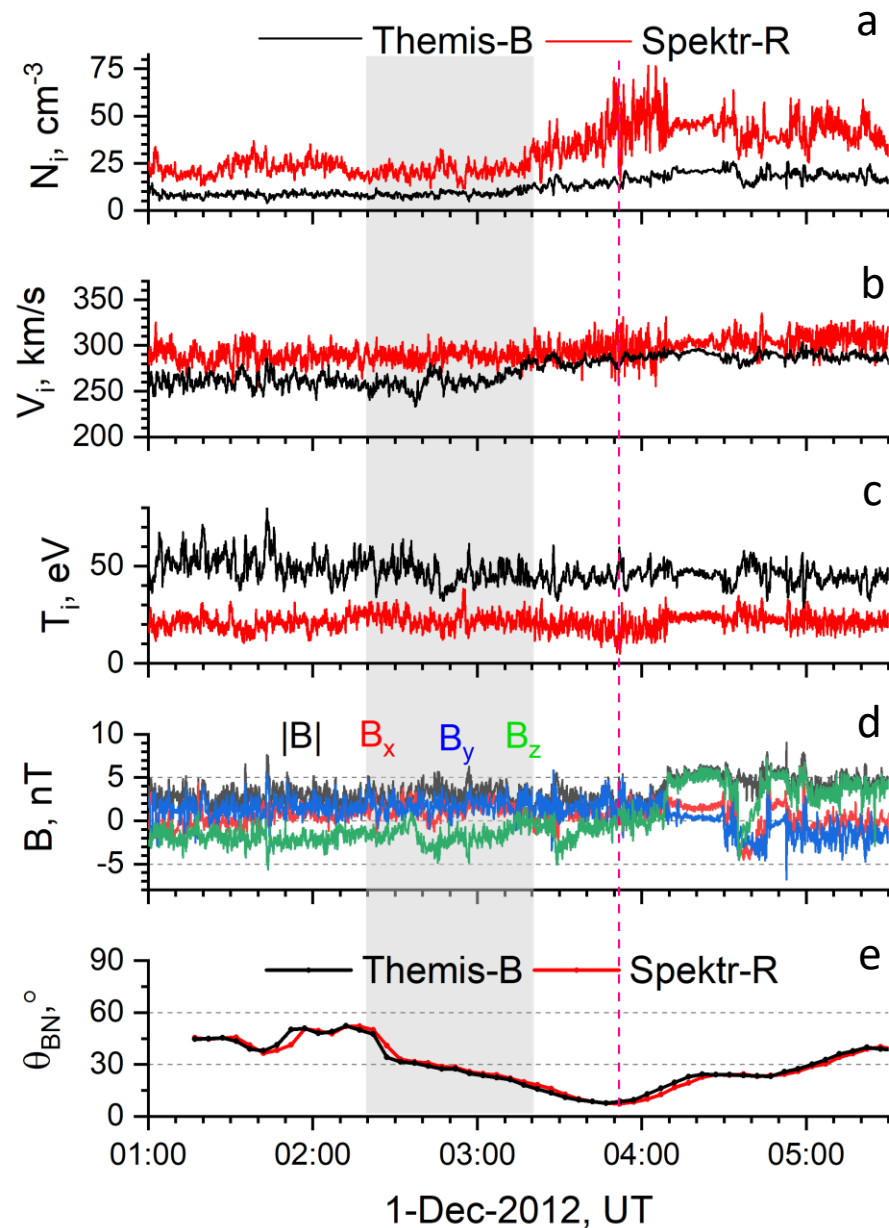


Example of ion flux measured at two spacecraft: Spektr-R (red line) and Themis-B (black line). Spektr-R time series was shifted in time by 760 sec.

Correlation coefficient between two data series was 0.7.

- 1) Determination of plasma propagation time between two spacecraft** was based on cross-correlation analysis of the smoothed by 100 sec data series. Thus, one can find the same volume of plasma at different spacecraft, i.e. consider it at different locations in the magnetosheath.

Case study 1: December 1, 2012



2) Selection of the time interval for the Fourier analysis was made taking into account stationarity of data rows and s/c positions.

- For the present case study, Spektr-R was in the vicinity of the BS (crossed it shortly at 03:52 UT), Themis-B was in the middle part of the MSH (12 hours after BS crossing and 10 hours before MP crossing); during 04:10-04:30 the spacecraft were moving through the heliospheric current sheet;
- The interval 02:20-03:20 was selected in order to compare the spectrum in the vicinity of the BS with the one in the middle MSH and to avoid shock-induced waves and high-frequency fluctuations;
- θ_{BN} angle, calculated upstream of the s/c at the BS, demonstrated that the event took place behind the quasi-parallel BS.

Ion (a) density, (b) bulk velocity, (c) temperature measured by Spektr-R (red) and Themis-B (black), (d) magnetic field components and magnitude by Themis-B, (e) θ_{BN} angle; vertical magenta line denotes short BS crossings by Spektr-R

Case study 1: December 1, 2012

3) Calculation of the spectra was performed with the help of the fast Fourier transform with smoothing in frequency domain.

- Spectra of ion flux value and magnetic field magnitude were considered, i.e. both quantities represented compressive component of the fluctuations;
- PSDs were normalized to the mean value of the quantity during the interval.

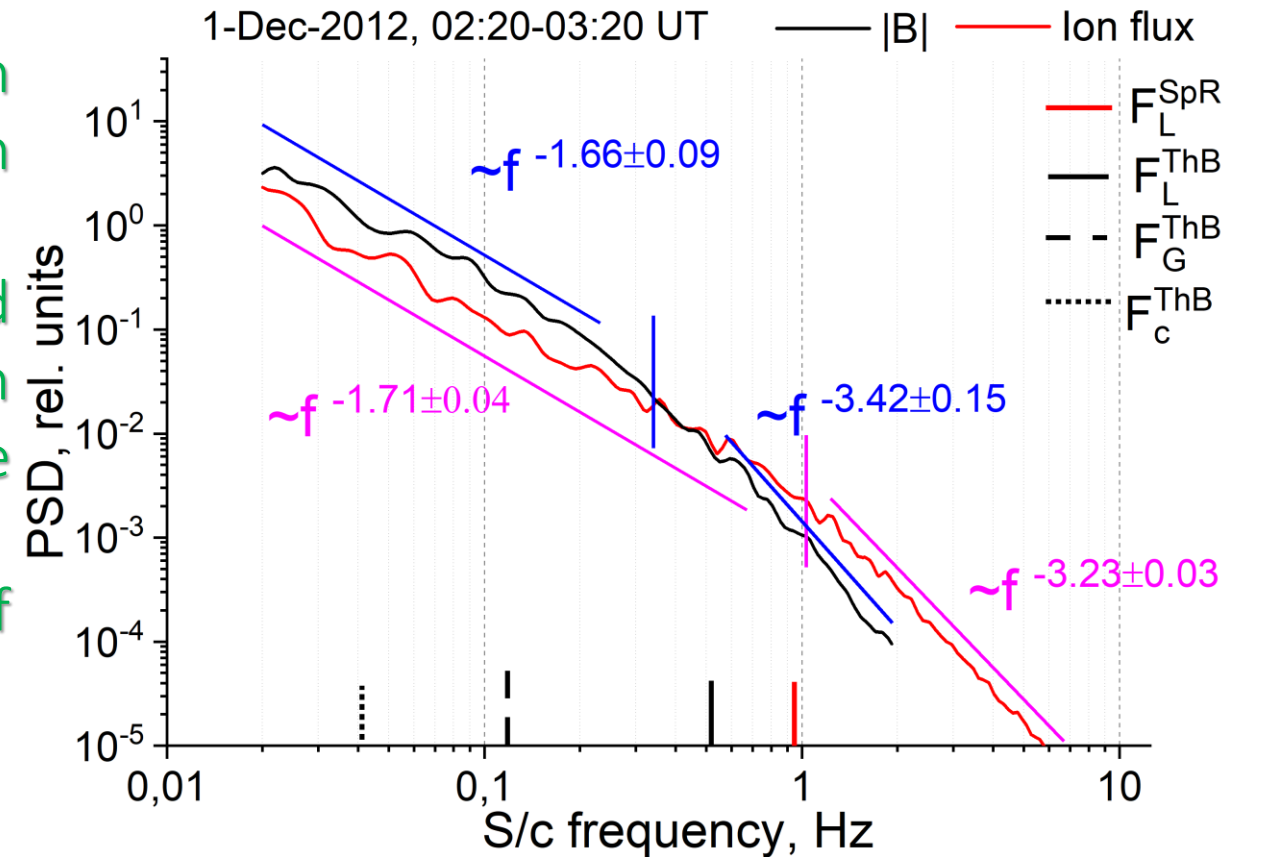
FINDINGS:

- Both spectra have very close slopes P_1 and P_2 , though breaks occur at different frequencies;
- For both spectra the breaks occur at scales close to ion inertial lengths (assuming Taylor hypothesis valid) F_L .

$$F_L = V/2\pi L, L = \omega_p/c'$$

$$F_G = V/2\pi R, R = V_{th}/\omega_c$$

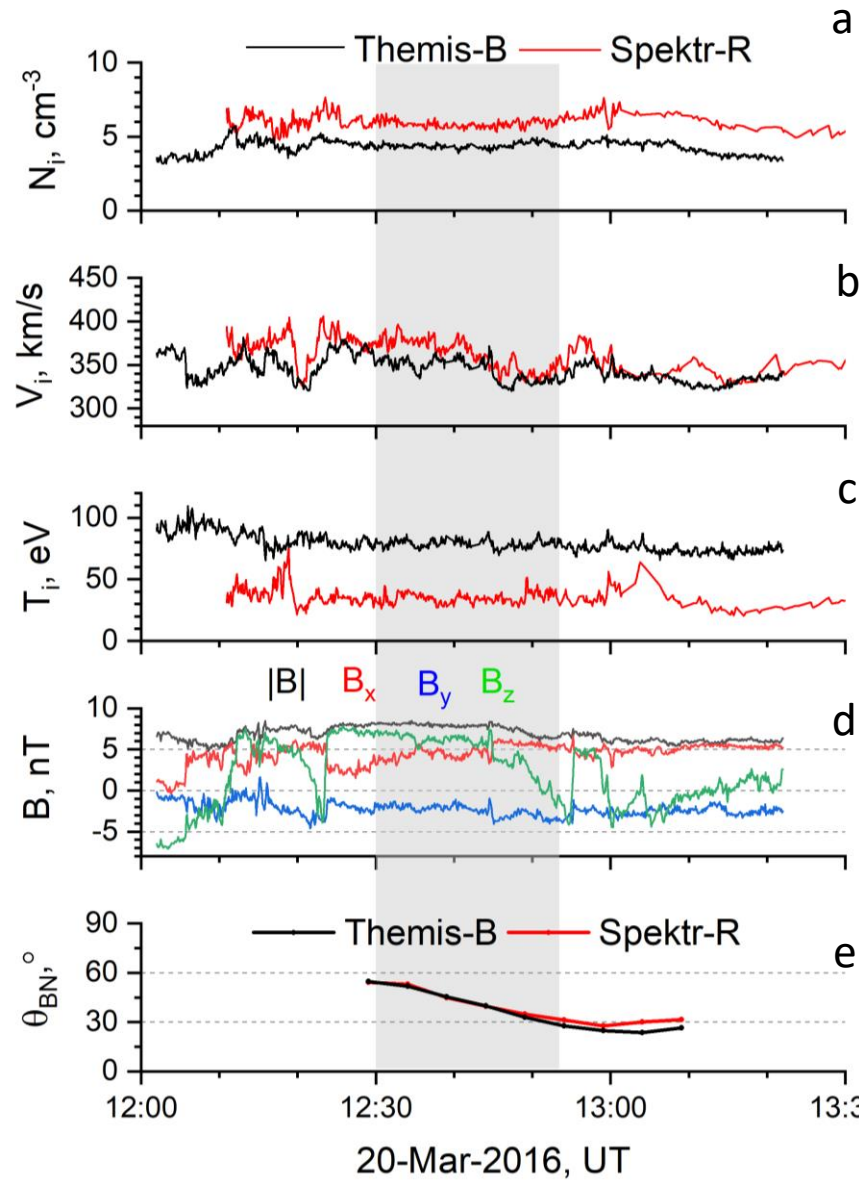
$$F_c = \omega_c/2\pi$$



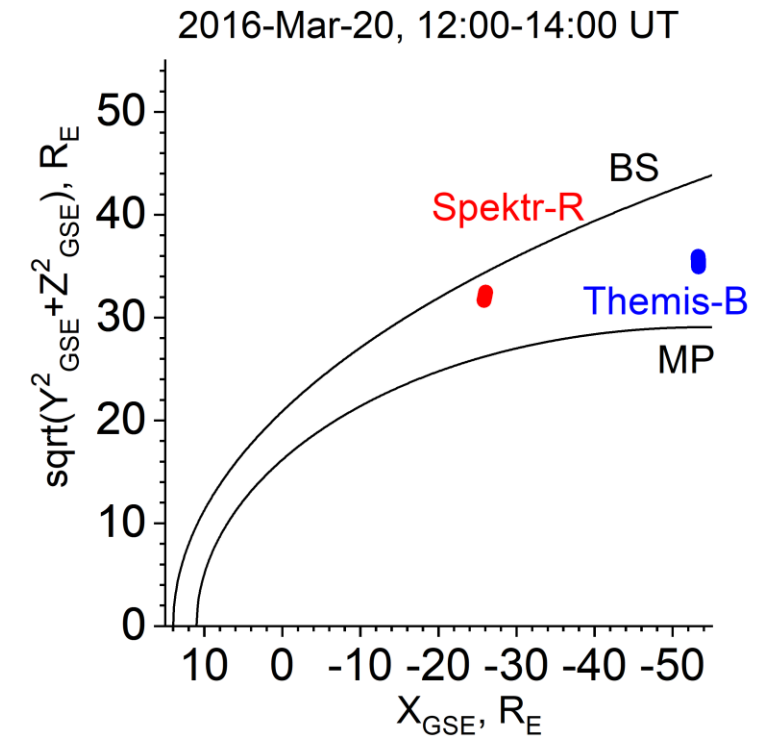
Spectra of ion flux (red) and magnetic field magnitude (black) fluctuations; results of approximation are shown in magenta/blue lines and symbols for ion flux/magnetic field)

No flattening at MHD scales occurs in the vicinity of the bow shock

Case study 2: March 20, 2016



Spacecraft orbits during analyzed event. BS and MP are shown schematically.



- Both spacecraft were located in the middle MSH mostly behind the quasi-parallel BS;
- Plasma propagation time between the s/c was 420 sec.

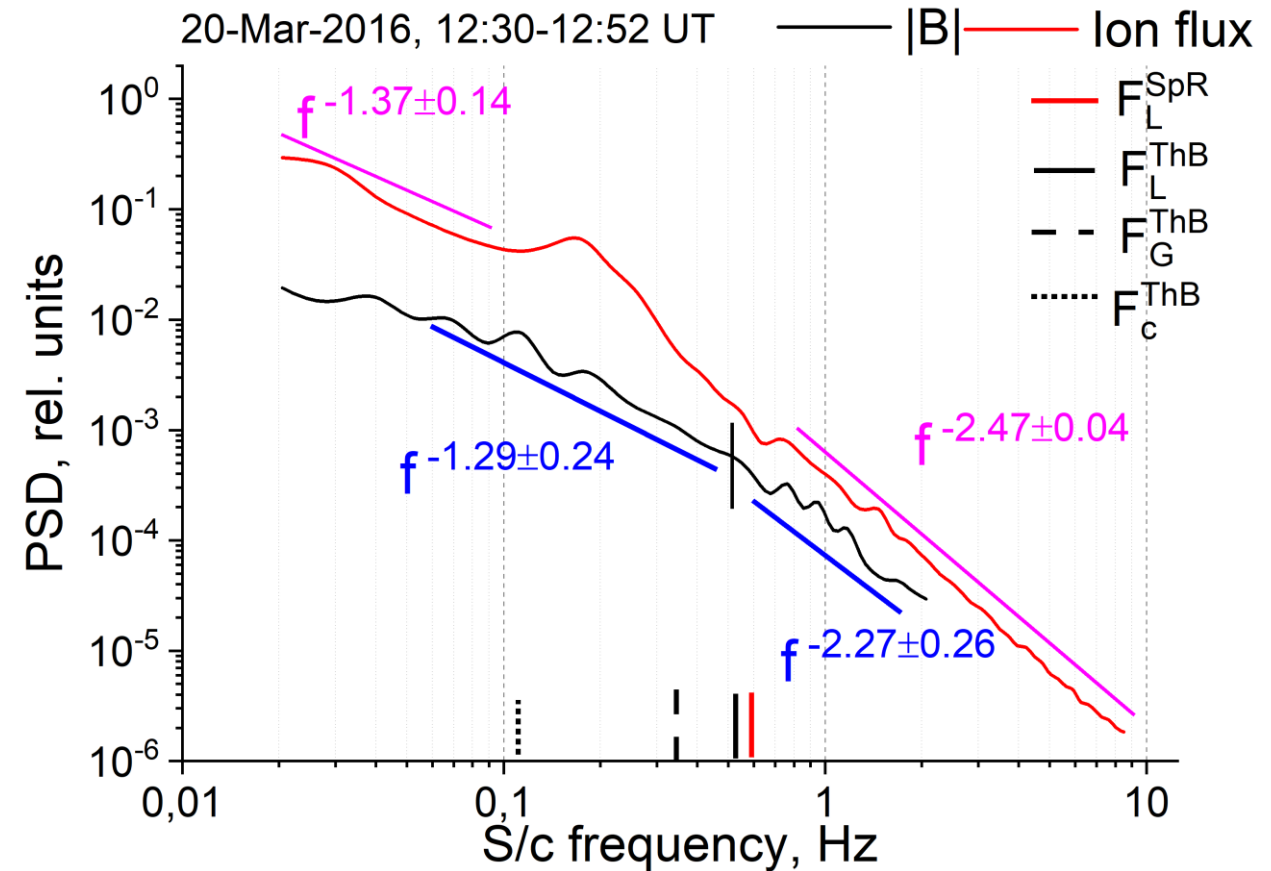
Ion (a) density, (b) bulk velocity, (c) temperature measured by Spektr-R (red) and Themis-B (black), (d) magnetic field components and magnitude by Themis-B, (e) ϑ_{BN} angle.

Case study 2: March 20, 2016

- Spectrum of ion flux value exhibits bump at scales of transition; no similar bump can be found in corresponding magnetic field magnitude spectrum;
- Break of the spectrum of magnetic field magnitude fluctuations occur at frequency close to the inertial length frequency F_L ;
- Taking errors into account, spectra at both spacecraft have similar slopes both at MHD and kinetic scales.

FINDINGS:

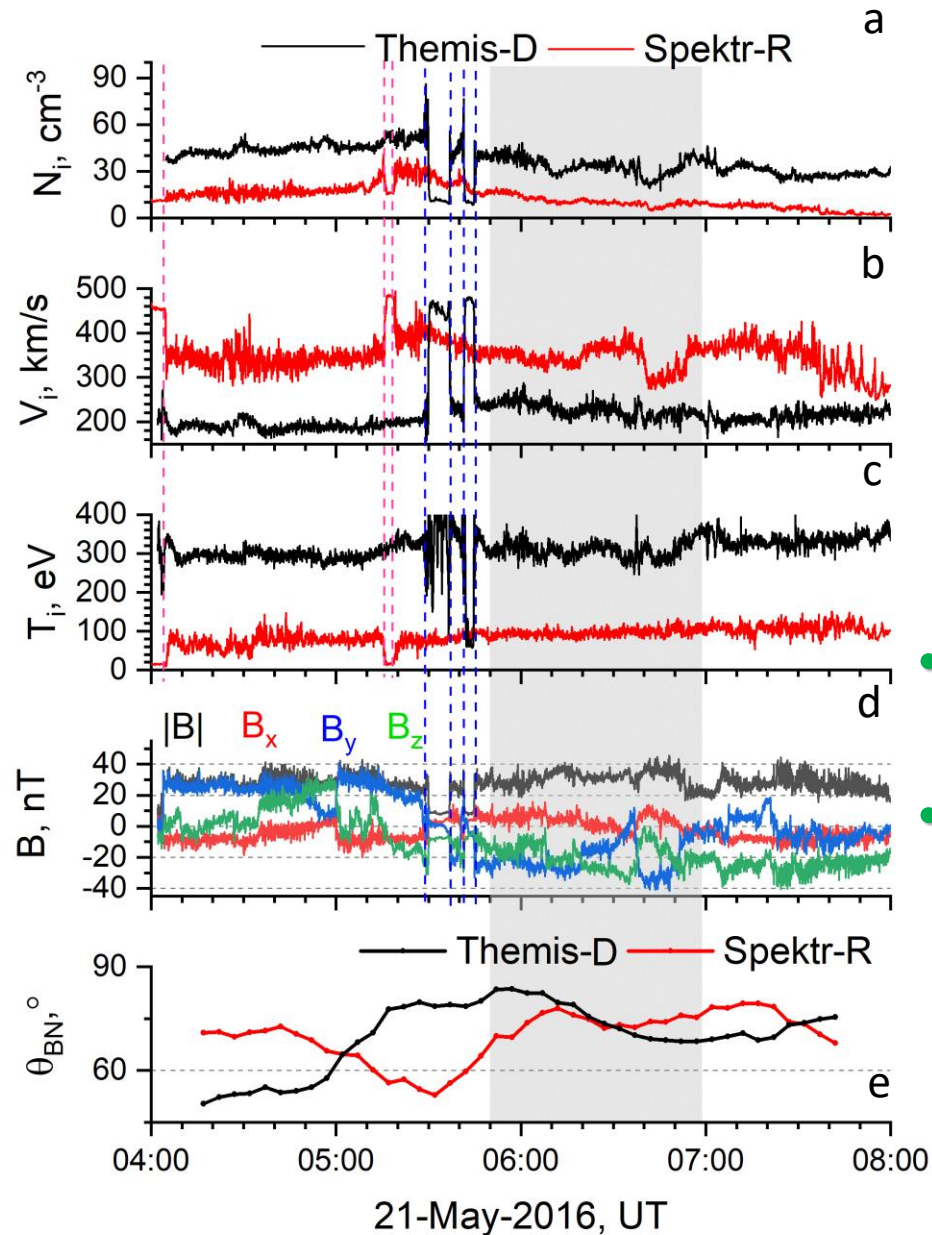
- Shallower (comparing to Kolmogorov-like) spectra can be found in the middle MSH far away tailward from the BS;
- Spectral slopes of the ion flux and magnetic field magnitude fluctuations are similar at distances $\sim 30 R_E$.



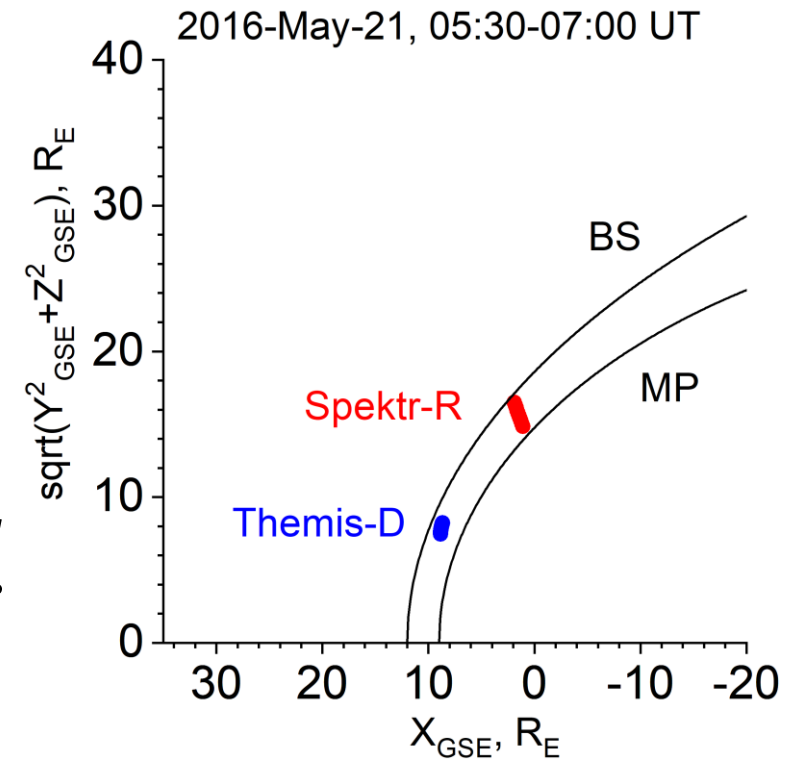
Same format as in slide 7

Flattening occurs in the middle MSH
far away from subsolar region

Case study 3: May 21, 2016



Spacecraft orbits during analyzed event. BS and MP are shown schematically.



- Both spacecraft were located in the dayside MSH in the vicinity of the quasi-perpendicular BS;
- Significant differences in velocity, temperature and density is likely to be due to Themis-D location closer to subsolar region.

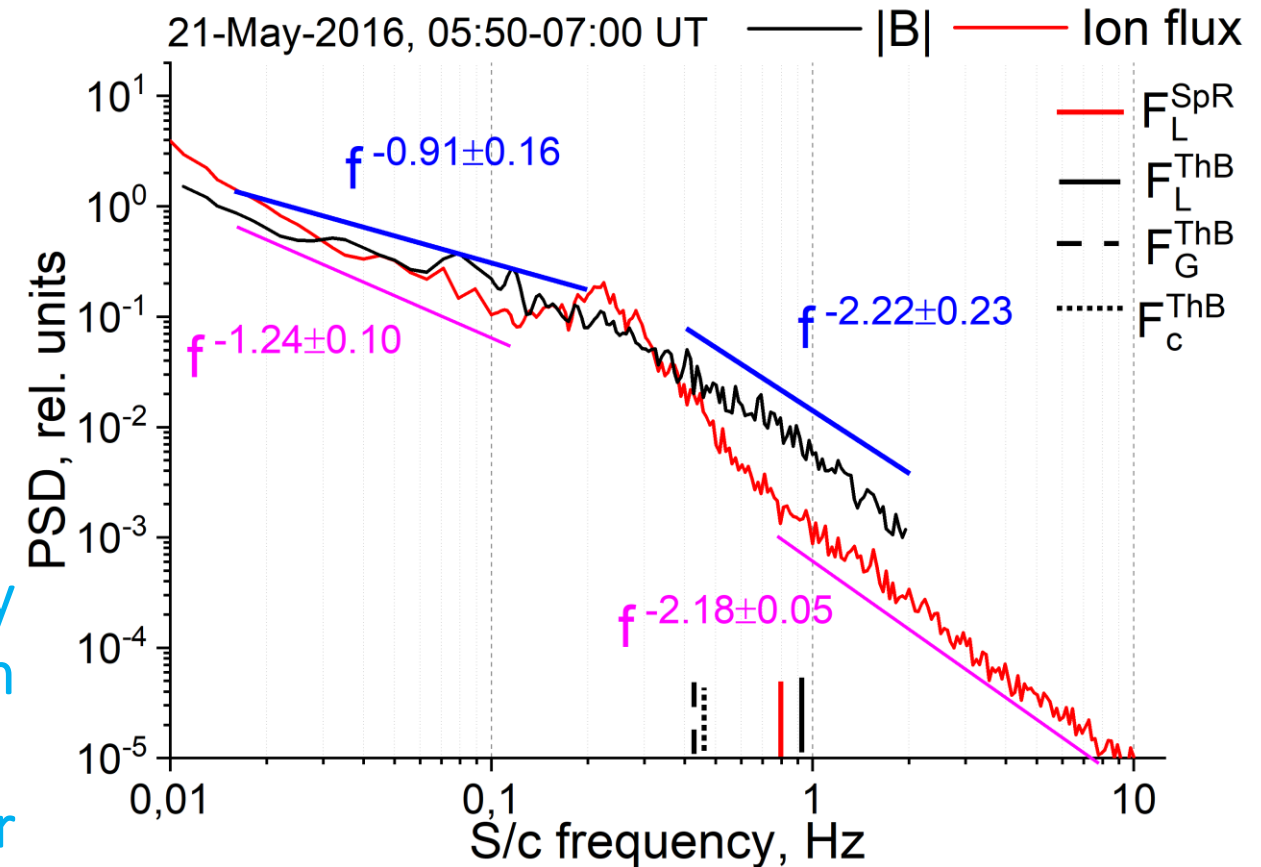
Ion (a) density, (b) bulk velocity, (c) temperature measured by Spektr-R (red) and Themis-D (black), (d) magnetic field components and magnitude by Themis-D, (e) ϑ_{BN} angle; vertical magenta/blue lines denote BS crossings by Spektr-R/Themis-D

Case study 3: May 21, 2016

- Spectrum of ion flux fluctuations exhibits bump at transition scales (likely to be due to mirror mode waves);
- Ratio $V_A/V = 2$ at Themis-D, thus Taylor hypothesis cannot be applied.

FINDINGS:

- At MHD scales the spectrum measured by Themis-D differs significantly from Kolmogorov-like $\sim f^{-5/3}$ spectrum;
 - Spektr-R was located farther from subsolar region and registered steeper spectrum at MHD scales than Themis-D; however, the spectrum is still flatter than $\sim f^{-5/3}$;
 - At kinetic scales spectra have similar slopes despite of the differences of their MHD parts.
- Same format as in slide 7*
- Significant flattening of spectra at MHD scales occur in the vicinity of subsolar BS; the effect gets less significant toward the flanks.



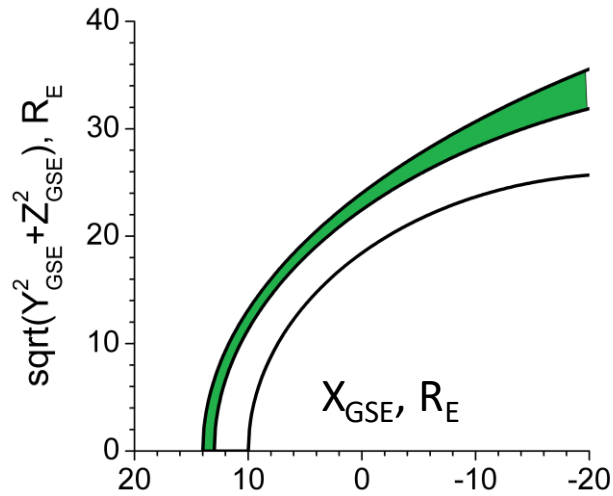
Summarizing case studies

Positions of the spacecraft with respect to the bow shock (BS), type of the bow shock and the spectral slopes P_1 and P_2 for all the analyzed events are summarized in the table:

Event	Position of Spektr-R	Position of Themis -B/-D	Type of the bow shock	Slope P_1 at MHD scales		Slope P_2 at kinetic scales	
				Spektr-R	Themis -B/-D	Spektr-R	Themis -B/-D
1-Dec-2012	BS vicinity	Middle MSH	Quasi-parallel	-1.71 ±0.04	-1.66 ±0.09	-3.23 ±0.03	-3.42 ±0.15
20-Mar-2016	Middle MSH	Middle MSH	Quasi-parallel	-1.37 ±0.14	-1.29 ±0.24	-2.47 ±0.04	-2.27 ±0.26
21-May-2016	BS vicinity (closer to the flank)	BS vicinity (closer to the dayside MSH)	Quasi-perpendicular	-1.30 ±0.18	-0.91 ±0.16	-2.17 ±0.08	-2.22 ±0.23

SW parameters' influence the MSH turbulence

Though it have been shown statistically that in the vicinity of the BS spectra usually deviates from the view, typical for developed turbulence (Kolmogorov-like power law at MHD scales and $f^{-7/3}$ or $f^{-8/3}$ power law at kinetic scales), this effect cannot be found in all of the events (see Case 1 of the present study and Rakhmanova et al., 2018b, 2020)

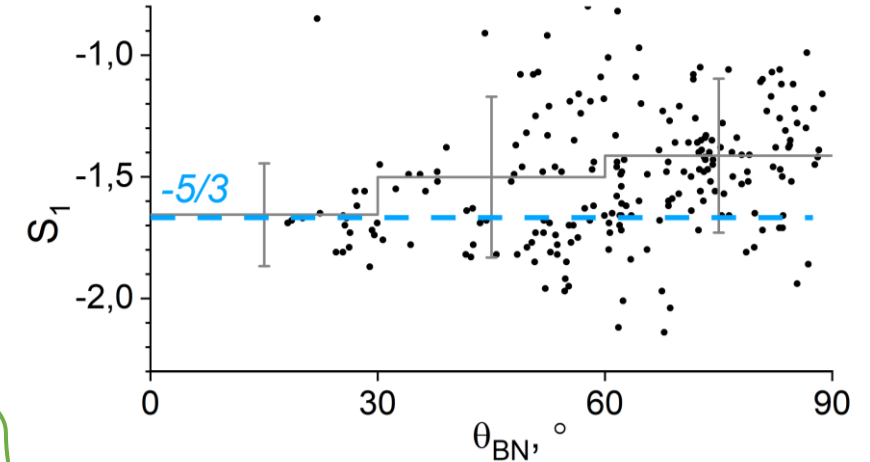


250 spectra of the ion flux fluctuations were analyzed in the vicinity of the BS

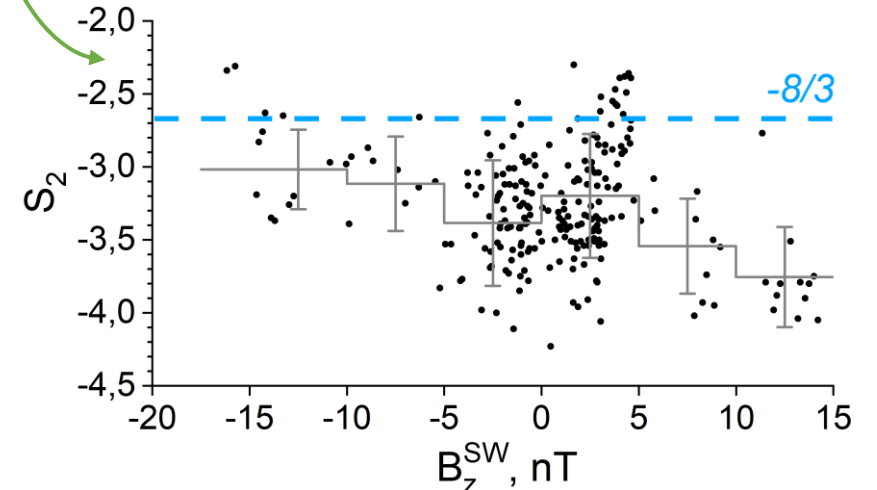
Slopes of the chosen spectra were plotted versus the BS and the solar wind parameters

The most significant deviations of spectra behind the BS from typical shape, given by theoretical predictions, occur usually for the quasi-perpendicular BS and during strong northward IMF

What else can influence the turbulent spectrum behind the BS?



Slope of the spectra at MHD scales vs ϑ_{BN}



Slope of the spectra at kinetic scales vs IMF B_z

RESULTS:

- Comparison of the spectrum of compressive fluctuations measured at 2 points inside the magnetosheath reveals that:
 1. Fluctuations of ion flux value and magnetic field magnitude exhibit similar slopes of the spectra, though spectral breaks occur at different frequencies;
 2. While plasma crosses the bow shock, the turbulent spectrum is likely to flatten at MHD scales; **significance of the flattening decreases with distance** from the subsolar region toward tail;
 3. **The slope** of the spectrum at **the kinetic scales survives** while plasma propagates as far as $30 R_E$ (e.g. ~ 1000 inertial lengths) tailward in the MSH, so the dissipation is likely to be due to the local processes involved into the plasma flow.
- Besides the influence of the bow shock presence, upstream solar wind parameters also influence features of the spectrum just behind the boundary: the most significant deviation of the spectrum from theoretical predictions and typical view in the MSH is likely to take place during high-magnitude northward IMF and behind the quasi-perpendicular bow shock.

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