Solar wind and bow shock parameters affecting turbulence development inside the magnetosheath

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Motivation

• Magnetosheath is known to be a significant part of solar wind – magnetosphere interactions.

• Magnetosheath region contains turbulent plasma and magnetic field and features of the turbulence are somewhat different from those observed in the undisturbed solar wind (particularly, in the dayside region).

• Mean properties of the magnetosheath turbulence were explored at scales of transition from MHD to kinetic regimes (i.e. at scales from ~10 to ~10⁴ km) thanks to the spacecraft measurements by AMPTE, ISEE, Cluster, Themis, Spektr-R and MMS.

Open questions:

• How does turbulence evolve behind the bow shock?

• Which factors of the interplanetary medium do affect the development of the turbulent cascade behind the bow shock?
Object of interest – transition from MHD to kinetic scales

Spectrum of turbulent fluctuations usually can be described with several power-law segments.

At scales above proton gyroradii the MHD description of plasma works effective; this ranges of scales forms inertial range of turbulent cascade and usually is described with so-called Kolmogorov law - power law with -5/3 power exponent (or slope) – see reviews by Bruno&Carbone 2013; Alexandrova et al. 2013.

At scales below proton gyroradii (ion kinetic scales) the spectrum breaks and give rise to the new dissipation range which is characterized with power exponent of -[7/3 – 8/3] according to theoretical frameworks (see e.g. Schekochihin et al. 2009; Boldyrev&Perez 2012) and -[2.7 – 3.0] according to in situ measurements (e.g. Chen et al. 2012; Huang et al. 2014; Riazantseva et al. 2015; Rakhmanova et al., 2016).
1. Substantial deviation of the spectra of both compressive and incompressive component occurred in the regions close to the bow shock (BS) in the dayside magnetosheath (MSH)

Values of MHD-scale slope throughout the dayside magnetosheath obtained with help of Cluster magnetic field measurements (Huang et al. 2017, figure 3)

2. Unchanged or steepened spectra at the kinetic scales in the regions close to the BS

Values of kinetic-scale slope throughout the dayside magnetosheath obtained with help of Cluster magnetic field measurements (Huang et al. 2017, figure 4)

Values of kinetic-scale slope throughout the flank quasi-perpendicular and quasi-parallel magnetosheath obtained with help of Spektr-R ion flux measurements (Rakhmanova et al. 2018a)
3. Behind the quasi-parallel BS spectra follow Kolmogorov scaling while behind the quasi-perpendicular BS spectra usually follow $\sim f^{-1}$ scaling at the MHD scales.

4. During slow undisturbed solar wind flow (type “Slow” in the catalog of large-scale solar wind events by Yermolaev et al. 2009) the turbulent cascade at the flanks of the MSH is modified slightly while for compressed solar wind flow (type “Sheath”) the spectra are substantially deviated from Kolmogorov scaling.

Spectra of magnetic and electric field fluctuations behind the quasi-perpendicular (left panel) and quasi-parallel (right panel) BS according to MMS data (Yordanova et al. 2020, figure 5)

MHD-scale slopes of ion flux fluctuation spectra observed by Spektr-R behind the BS of different types (from Rakhmanova et al. 2020b).

MHD-scale spectra slopes of ion flux fluctuation spectra observed by Spektr-R behind in the MSH close to the BS for different types of the upstream solar wind flow (from Rakhmanova et al. 2020a).
DATA

1. To observe the dynamics of the turbulent parameters the data were taken from two distinctly located spacecraft:

- **Themis** FGM measurements of the magnetic field magnitude with 0.25 s time resolution, and
- **Spektr-R** BMSW measurements of ion flux value with 0.031 s time resolution.

*Note.* Both magnetic field magnitude and ion flux fluctuations represent the compressive component of the fluctuations and can be compared in relative units (see Rakhmanova et al. 2020b for more detailed discussion of the topic).

2. To find out the difference in influence of the disturbed and undisturbed solar wind flow on the turbulence evolution behind the bow shock:

- First, several intervals were analyzed which took place during slow undisturbed solar wind, and then
- Second, several intervals occurred during different large-scale solar wind phenomena were considered.

For the study the solar wind types were distinguished according to the catalog by Yermolaev et al. 2009.

Three types of the disturbed solar wind flows were considered:

1. **EJECTA** – interplanetary manifestation of the coronal mass ejection;
2. **SHEATH** – compressed plasma in front of the EJECTA or magnetic cloud;
3. **CIR** – corotating interaction region.
Comparison between ion flux time rows for the two considered spacecraft.

1. Find appropriate mutual location – at the same flank, not too far away from each other, at different distances from the BS.

2. Take into account the time shift and check if the same plasma is measured at both spacecraft.

3. Compare the fluctuation spectra

Undisturbed SW. Example of the analyzed event: December 1, 2012.
Undisturbed SW: The set of the events

Looks like a local instability (peak + substantial steepening)
Undisturbed SW: Conclusions

Quasi-perpendicular bow shock:

• At the MHD scales spectra always deviate from the Kolmogorov scaling with -5/3 power law at the dayside MSH even in the vicinity of the magnetopause; when plasma moves toward flanks the spectra “recover” and follow Kolmogorov scaling.

• At the kinetic scales spectra usually have typical slopes of –[2.7-2.9] which survive during plasma propagation toward the flanks if there is no local instabilities.

Quasi-parallel bow shock:

• At the MHD scales at the flanks spectra follow Kolmogorov scaling regardless the distance to the bow shock.

• Kinetic scales are characterized by steepening of the spectra at different distances from the bow shock (which may be the signature of the higher dissipation rate).
Disturbed SW: The set of the events

**SHEATH**
- Date: 2017 Jul 2, 07:10-07:50 UT
- Events: BS, Spektr-R, Themis-E
- Angles: $\theta_{BN} \approx 45^\circ$, $\theta_{BN} \approx 15^\circ$

**CIR**
- Date: 22 Nov 2011, 00:00-00:17 UT
- Events: BS, Spektr-R, Themis-E
- Angles: $\theta_{BN} \approx 60^\circ$, $\theta_{BN} \approx 30^\circ$

**EJECTA**
- Date: 7 Nov 2011, 16:53-17:28 UT
- Events: BS, Ejecta, Themis-E
- Angles: $\theta_{BN} \approx 78^\circ$, $\theta_{BN} \approx 35^\circ$

**Power Spectral Density (PSD)**
- Sheath: $f = -0.73 \pm 0.02$
- CIR: $f = -1.20 \pm 0.06$
- Ejecta: $f = -1.21 \pm 0.05$

**Signatures**
- $\Sigma(y^2 \text{GSE} + z^2 \text{GSE}) R_E$
- $X_{GSE}, R_E$
Disturbed SW: Conclusions

For the considered events:

- Solar wind of type **EJECTA** and **CIR** are characterized by **deviation** of the MHD-scale spectra from Kolmogorov scaling behind the BS which survives **throughout the MSH** (unlike the cases of undisturbed SW);
- For the **EJECTA** and **CIR** solar wind types the **steepening** of spectra occurs in the subsolar MSH at the **kinetic scales** and this steepening **survives** when plasma moves toward the flanks; thus, interaction of these types of the SW with the BS results in increased dissipation rate at various distances from the BS and from the subsolar region.
- Interaction of the compressed solar wind flow of type **SHEATH** with the BS results in **deviation** of spectra at MHD scales from Kolmogorov scaling in the subsolar region and their “recover” toward the flanks;
- At the same time, at the **kinetic scales** spectra become **shallower throughout the MSH** than typically observed in the space plasma, e.g. compressed fluctuations in the MSH are **enhanced** in the MSH during **SHEATH** solar wind flow.
- **However** to understand physical mechanisms of the obtained differences between different disturbed flows more cases are required.
Results:

• Interaction of the **steady slow solar wind** with the **quasi-perpendicular** bow shock results in deviation of the fluctuation spectra from **Kolmogorov** scaling at the **MHD** scales in the dayside MSH and their **recovery toward the flanks**; in the same time, **kinetic-scale** spectra stay **unchanged** in the absence of local instabilities.

• For the **steady slow solar wind** spectra may stay **Kolmogorov-like** behind the **quasi-parallel** bow shock at various distances from the bow shock; on the other hand at the **kinetic** scales **steepening** of spectra occurs which implies increased dissipation behind the quasi-parallel bow shock.

• Interaction of the **disturbed solar wind** with the bow shock results in deviation of the fluctuation spectra from **Kolmogorov** scaling at the **MHD** scales which is likely to **survive throughout the magnetosheath**.

• For the **disturbed solar wind** the changes in the spectra occur at the **kinetic scales** behind the bow shock which implies changes in the dissipation mechanisms.
References:


