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SPECTRAL PROPERTIES OF UPSTREAM ULF TURBULENCE/WAVES

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Abstract. The high-resolution magnetic and plasma data from Interball satellite during its crossing of the dayside bow shock are analyzed. We examine how the basic spectral properties of the ULF turbulence change upon the transition from the foreshock region into the magnetosheath.

Introduction: Waves/turbulence in the foreshock/magnetosheath

The alterations of a magnetized plasma flow when passing through the earth's bow shock (BS) are commonly described with the single-fluid MHD Rankine-Hugoniot (R-H) jump conditions. These equations describe the downstream state of the plasma in terms of the upstream parameters, and stem from the conservation of mass, momentum, and energy of the flow through a shock. However, the statistical study of ISEE-1 BS crossings found that the downstream conditions are well approximated by R-H model with a polytropic index 5/3 only for quasi-perpendicular shocks (when the angle between the upstream magnetic field and shock normal $\theta_{Bn} > 45°$) [*Winterhalter et al.,* 1984]. For quasi-parallel shocks, i.e. $\theta_{Bn} < 45°$, the predicted downstream field values were generally larger than those observed. This disagreement indicates an essential role of turbulence generated by kinetic effects, in energy/momentum transfer through a BS.

The Interball-Tail (IB) observations showed the occurrence of intense variations of ion flux and magnetic field in a frequency range of 0,02–1 Hz in the magnetosheath (MSH) and the upstream foreshock region (FSH) [*Shevyrev et al.,* 2005]. The level of MSH turbulence grew upon an increase of the solar wind (SW) fluctuations, however the MSH turbulence could be rather intense even at the quiet SW background. Thus, all intense disturbances of the SW manifest themselves in the MSH, but MSH turbulence is not directly proportional to the SW variations. The IMF orientation controls the level of ULF magnetic and plasma turbulence not in the FSH only, but in the MSH too.

In this paper, using the magnetic field and plasma flux observations onboard IB we continue the examination of the change of basic spectral properties of the field/plasma turbulence upon trespassing the dayside BS.

Satellite magnetic and plasma data

We analyze the high-resolution (1-sec) magnetic and plasma IB data. We examine six events listed in Table 1, when IB moves across the BS flanks from the MSH into the FSH (or vice-versa). The magnetic field data (*B*) are given in the GSE coordinates. Ion flux (*F*) measurements are made by the plasma trap oriented Sunward. To discriminate various regimes of the BS, the angle θ_{Bn} between the upstream field and the shock normal has been calculated using WIND and ACE spacecraft data. Among 6 events under analysis there are 2 cases corresponding to the quasi-parallel FSH (N=1,3), while in other cases the value of θ_{Bn} vary near the boundary value ~ 50° for quasi-parallel regime.

Three regions have been identified from the analysis of IB data: the regions unambiguously corresponding to the MSH and the FSH, and the intermediate region with multiple BS crossings due to the irregular motion of the BS, further marked as BS (thin line on plots).

Table 1: List of events and mean θ_{Bn} values

N	Data/time of event	MSH	FSH
1	25 May 1997 0000–0400 UT	49.8° ± 13.9°	24.0° ± 3.3°
2	21 March 1997 0700–1500 UT	57.3° ± 21.7°	55.7° ± 12.9°
3	12 July 1997 0700–1500 UT	36.4° ± 20.3°	27.5° ± 3.1°
4	16 July 1997 0300–1100 UT	40.6° ± 9.3°	32.0° ± 14.0°
5	26 May 1999 1000–2100 UT	55.2° ± 15.9°	55.6° ± 16.9°
6	14 June 1999 1200–2000 UT	50.5° ± 1.3°	50.2° ± 2.0°

The change of turbulence spectra upon transition through the bow shock

We examine how the spectral properties of the plasma and magnetic field turbulence in the ULF frequency interval 0.0001–0.5 Hz change upon the transition from the FSH to MSH. The turbulence power spectral density form *S(f)* is commonly approximated as power-law "colored-noise" spectrum from the raw non-filtered data [*Shevyrev et al.,* 2005]. However, observed spectra from IB data look as straight lines in the log-log coordinates only in a frequency range above some cut-off frequency $f > f_0$, and f_0 varies from event to event in the interval 0.001–0.05 Hz. Therefore, we have applied another approximation which fits better the observational data:

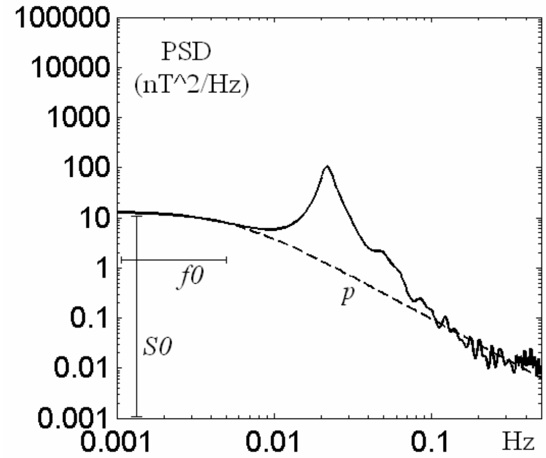

Fig. 1. An example of MEM power spectrum of *By* component (solid line) in the log-log scale and the approximation curve (dashed line) for June 14, 1999, 1200–1220 UT. The parameters of the approximation (1) are as follows: S_0=12.87 nT^2/Hz, f_0 = 0.005 Hz, P = 1.7.

$$S(f) = S_0\left[1+(f/f_0)^2\right]^{-P/2} \qquad (1)$$

where the parameter P characterises the slope of the spectra in the inertial scale interval, S_0 stands for turbulence intensity, and f_0 is the cut-off frequency. The parameters of the approximation (1) has been determined with the use of the nonlinear least square fit based on the trust-region algorithm embodied in the MATLAB Fitting Toolbox. The example of the power spectrum of *By* component and its approximation in the FSH region are shown in Fig. 1. This plot shows the occurrence of narrow-band spectral peak (~20-30 mHz) corresponding to the upstream waves. The possible transmission of these waves into the MSH will be considered elsewhere.

Spectra have been estimated in a running 20-min window with the 10 min overlapping, using the maximum entropy method (MEM). As compared with Fourier transform, MEM provides more smooth spectral forms. The variations of the estimated spectral parameters: $\log_{10}S_0$ (further denoted as S_0), P, and f_0 are shown for the field magnitude B (Fig. 2), *By* component (Fig. 3), and plasma flux F (Fig. 4) for all 6 passes. The values of S_0 and P have been averaged over the regions adjacent to the BS, and are given in Tables 2,3 for both the MSH and the FSH sides. The averaging intervals vary from 50 min to 1 h 40 min and are marked in Figs. 2-4 by thick vertical lines.

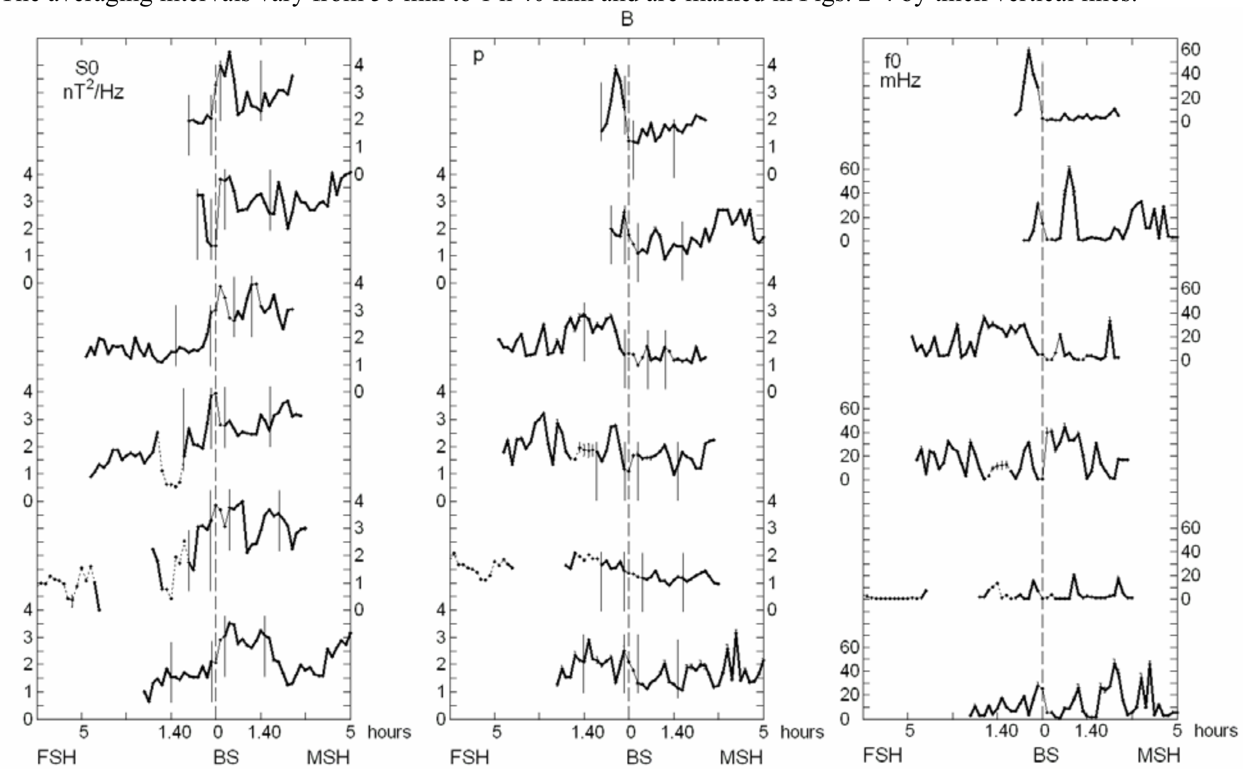

Fig. 2. Spectral parameters S_0, P, f_0 for field B spectra for events from 1 to 6 (up to down). The regions corresponding to the BS are marked with a thin line, the MSH and FSH regions are marked with thick lines. The dashed line denotes the onset of the BS region. The regions corresponding to SW are marked with dotted line. Thick grey vertical lines show the time averaging intervals used in Tables 2,3.

The examination of Figs. 2-4 and Table 2 shows that during all events both the magnetic and plasma turbulence level on the MSH side of the BS is higher (on average, the ratio of log$S$ ~1.5) that those on the FSH side.

Moreover, not only the level, but the form of the turbulence changes also (Figs. 2-4 and Table 3). The spectral index P is mainly larger in the FSH than in the MSH, that is the FSH turbulence spectra are steeper than those in the MSH. The indices for the magnetic *(B, By),* and plasma (*F*) turbulence are somewhat different, though this difference is within the dispersion of the estimate.

The cut-off frequency f_0 experiences rather strong variations in both regions and demonstrates no consistent regularities upon the transition across the BS. The parameter f_0 for magnetic and plasma turbulence varies from few mHz to few tens of mHz.

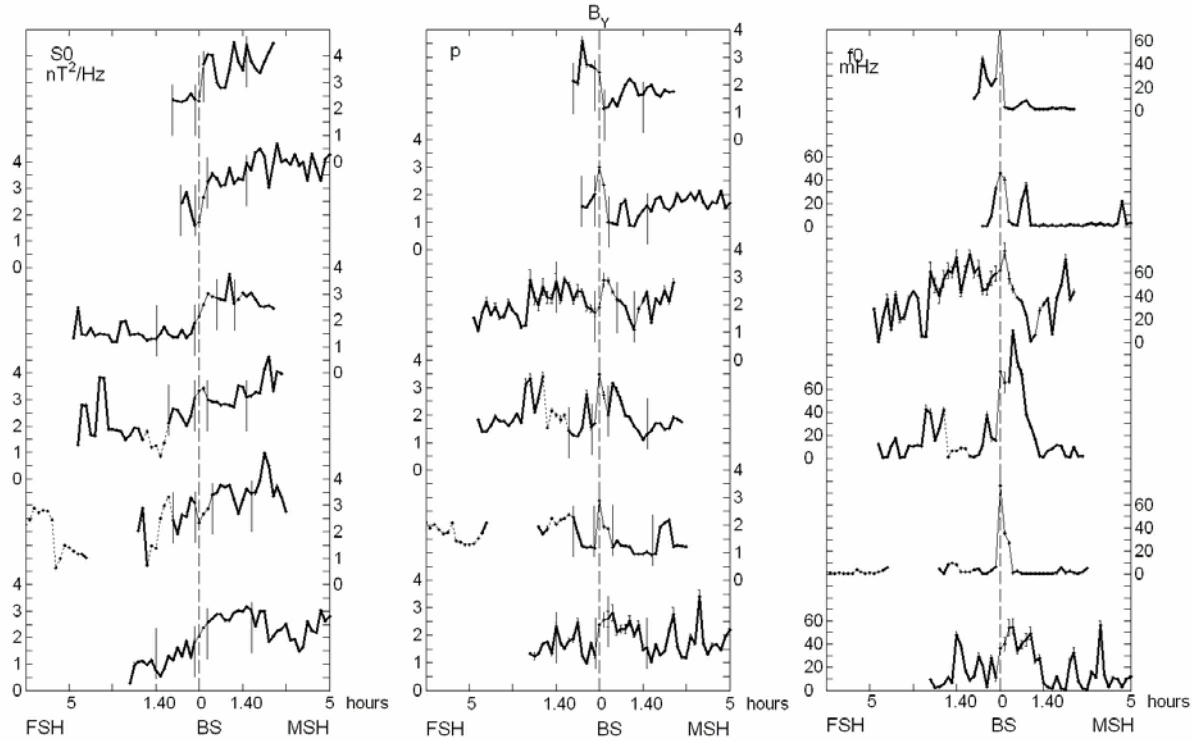

Fig. 3. The same as Fig.2, but for *By* component.

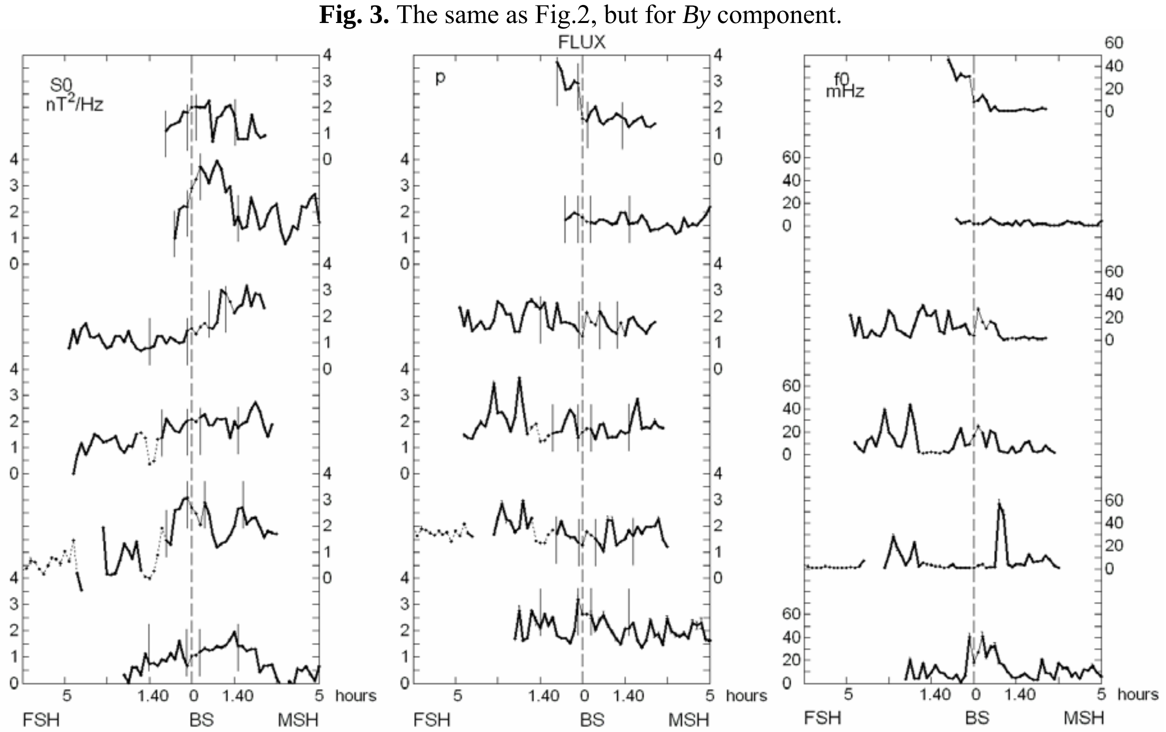

Fig. 4. The same as Fig.2, but for plasma flux *F*.

Table 2: Turbulence intensity $\log_{10}S_0$

N	*B*			*By*			*F*		
	FSH	MSH	MSH /FSH	FSH	MSH	MSH/FSH	FSH	MSH	MSH/FSH
1	1.9±0.1	3.0±0.8	1.5	2.3±0.1	3.6±0.6	1.6	1.5±0.3	1.8±0.4	1.2
2	2.3±1.0	3.1±0.4	1.3	2.2±0.5	3.4±0.3	1.5	1.9±0.6	3.1±0.6	1.6
3	1.7±0.4	3.1±0.5	1.9	1.5±0.2	3.0±0.4	2.0	1.1±0.2	2.2±0.7	2.0
4	2.2±0.4	2.7±0.2	1.2	2.3±0.3	3.0±0.3	1.3	1.7±0.3	1.9±0.2	1.1
5	2.6±0.7	3.2±0.6	1.4	2.7±0.5	3.4±0.3	1.3	2.3±0.8	2.0±0.6	0.9
6	1.6±0.2	3.0±0.3	1.8	1.2±0.4	2.8±0.2	2.3	0.9±0.3	1.4±0.2	1.6
mean			**1.5±0.2**			**1.7±0.4**			**1.4±0.4**

Table 3: Spectral index *P*

N	*B*		*By*		*F*	
	FSH	MSH	FSH	MSH	FSH	MSH
1	2.6±0.9	1.5±0.3	2.6±0.5	1.6±0.4	3.0±0.4	1.6±0.2
2	2.0±0.4	1.4±0.3	1.7±0.2	1.2±0.4	1.8±0.1	1.6±0.2
3	2.4±0.5	1.4±0.2	2.3±0.4	1.7±0.5	1.9±0.4	1.7±0.4
4	2.1±0.5	1.6±0.3	1.6±0.6	2.0±0.7	1.9±0.3	1.6±0.2
5	1.6±0.2	1.1±0.1	1.5±0.5	1.1±0.2	1.7±0.3	1.5±0.4
6	2.2±0.4	1.4±0.3	1.6±0.4	2.2±0.4	2.2±0.5	2.1±0.4
mean	**2.1±0.3**	**1.4±0.2**	**1.9±0.5**	**1.6±0.4**	**2.1±0.5**	**1.7±0.2**

Discussion

This study confirms the basic conclusion of previous IB studies [e.g., *Shevyrev et al.*, 2007] that spectral properties of the MSH fluctuations and FSH turbulence do differ. Both the magnetic and plasma turbulences in the MSH are more intense than those in the FSH. The spectral slope of the MSH magnetic noise is close within error range to the spectral index of the Kolmogorov turbulence, $P \sim 1.67$, while the FSH turbulence spectra are steeper than those in the MSH. Moreover, the spectral indices for the magnetic *B* and *By,* and plasma *F* turbulence are somewhat different. However, this difference is within the dispersion of the estimate, so it does not give an answer to the question whether the magnetic and plasma fluctuations are manifestation of the same turbulence, or these turbulences are uncoupled. The difference between the spectral properties of *B* and *By* spectra is also within the error limits, so the difference between the compressive and Alfvenic (non-compressive) turbulence cannot be resolved. The determined cut-off frequency f_0 may correspond to the largest turbulence scale k_0, $f_0 \sim k_0V_{sw}$. This frequency in the FSH corresponds to the scale $\lambda \sim V_{SW} / f_0$ ~ 400 km/s / 0.03 Hz ~ $1.3 \cdot 10^4$ km. This scale is about the typical correlation scale λ ~ 2 Re found in [*Eiges et al.,* 2000]. Thus, MSH fluctuations are not just FSH fluctuations, amplified upon transmission through the BS, but the manifestation of intrinsic processes in the MSH and its boundaries.

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