"Physics of Auroral Phenomena", Proc. XXXIX Annual Seminar, Apatity, pp. 70-73, 2016
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FINE STRUCTURE OF THE INTERPLANETARY SHOCKS OBSERVED BY BMSW EXPERIMENT ONBOARD THE SPEKTR-R

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Abstract. Interplanetary (IP) shocks are one of the main factors influencing the space weather. The fine structure of the front of collisionless shock has been investigated for planetary shocks from magnetic field measurements whereas IP shocks are less often studied. BMSW [1] plasma spectrometer onboard the SPEKTR-R satellite, launched in 2011, measures the ion moments with high-time resolution – 0.031 s and it allowed us to study ramp region of the IP shocks using ion moments, which were completed by magnetic field measurements from ACE, WIND, THEMIS and CLUSTER spacecraft.

All registered IP shocks were studied and their main characteristics were calculated: β (the ratio of the solar wind thermal to the magnetic pressure), $\boldsymbol{\theta}_{Bn}$ (the angle between the upstream magnetic field and shock normal direction), Mms (Magnetosonic Mach number – the ratio of the IP velocity to the propagation speed of magnetosonic waves), IP shock velocity. The study shows that the ramp thickness defined from plasma measurements roughly corresponds to the ramp thickness derived from the magnetic field measurements and lies within interval from 40 to 600 km. In some cases the precursor waves were observed in the front of subcritical shocks both in plasma and magnetic measurements. It was found that their wavelengths varied from 70 to 400 km.

1. Introduction

Interplanetary shock waves which are generated by solar flares and the emission of coronal material are one of the major sources of perturbation in the solar wind [2, 3, 4]. On the front of a shock wave there are a redistribution of energy of directed plasma motion into thermal energy, and the acceleration of the part of particles to significant energies that leads to a large growth of all kinetic parameters of plasma and magnetic field of solar wind.

The most important parameters that characterize the shock wave structure are: the parameter β (ratio of thermal pressure to magnetic pressure), the angle $\boldsymbol{\theta}_{Bn}$ (angle between the normal to the wave front and the direction of magnetic field in the unperturbed solar wind), magnetosonic Mach number [5, 6]:

$$\beta = \frac{P_t}{P_{mag}}, \text{ где } \quad P_{mag} = \frac{H^2}{8\pi}; \quad P_t = kTN;$$

$$M_{ms} = \frac{V_{IP} - V_{sw}}{C_{ms}}, \text{ где } \ C_{ms} = \sqrt{C_a^2 + C_s^2} \ ; \ C_a = \sqrt{\frac{\gamma RT}{M}} ; \ C_s = \frac{H}{\sqrt{4\pi\rho}} \ ;$$

where P_{mag} – magnetic pressure, P_t – thermal pressure, V_{IP} – shock wave front speed, C_{ms} – magnetosonic speed, C_a – Alven speed, Cs – sound speed

The shock front is a thin transition layer (or ramp) from the unperturbed to the perturbed solar wind. Many works were devoted to study the thickness of the wave front according to magnetic measurements [7, 8, 9, 10] with high time resolution.

The thickness of the wave front according to plasma measurements was investigated in [11] and depends to excessively steep spatial gradients, and their steepening is determined by the interaction between nonlinear processes of dispersion and dissipation. The definition of the characteristic scale of the shock front is an important task, because it allows us to determine the dominant processes in the interaction mechanism and its characteristics.

2. Experimental data

For research we used measurements of the plasma spectrometer BMSW (Fast Monitor of Solar Wind) installed on the SPEKTR-R satellite with a time resolution 3 s for the velocity, temperature and concentration, and 0.031 s for the ion flux (magnitude and two angles). According to the BMSW device measurement it was identified interplanetary shock waves registered by the device from August 2011 to March 2016.

The BMSW data was complemented by magnetic and plasma measurements at other satellites, which were in the solar wind at the same time with the highest possible time resolution. We usually used data from following satellite devices:

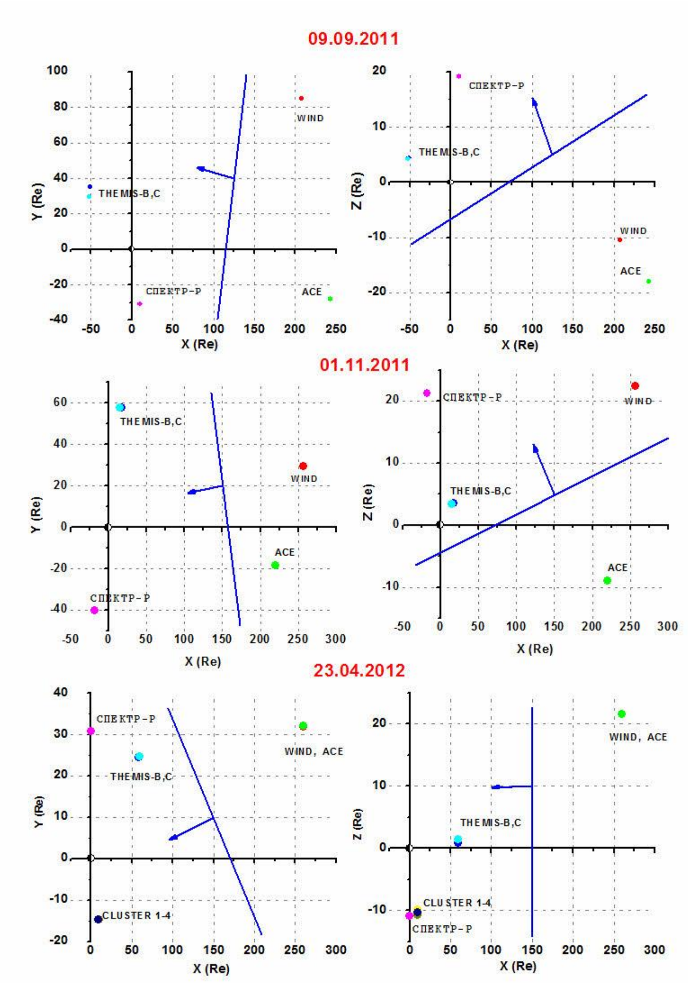


Figure 1. The satellites position on 09.09.2011, the front normal projection on Y(X) and Z(X) planes, GSE coordinate

-WIND (MFI instrument - Magnetic Fields Investigation; 3DP instrument - Three-Dimensional Plasma Analyzer)
-ACE (MFI instrument)
-THEMIS-B (P1/ARTEMIS-P1) (FGM instrument - Flux Gate Magnetometer)
-THEMIS-C (P2/ARTEMIS-P2) (FGM instrument)
-CLUSTER 1 – 4 (instrument)

3. Example of IP shock

On the 9th September, 2011 five satellites - WIND, ACE, THEMIS-B, THEMIS-C and SPEKTR-R were simultaneously in the solar wind and consistently recorded the passage of an interplanetary shock wave. The position of satellites in space, in the interval 11:30 – 13:30 UT, shown on Fig. 1. Using the location of the satellites and the time delay between the registrations of the IP wave, the orientation of the normal to the IP front was determined: **n** = (-0.916; 0.12; 0.38). Its projection on the planes X-Y and X-Z are also shown in Fig. 1.

Fig. 2 illustrates the behavior of velocity and temperature of protons, the concentration of ions. Similarly, Fig. 3 illustrates the behavior of components of the magnetic field vector, simultaneously measured on different satellites from 11:30 to 13:20 UT. IP shock was registered at 11:45:37 on the WIND and at 12:41:16 on the SPEKTR-R.

There was a sharp increase of all solar wind parameters at the time of shock passage. Solar wind speed rose up on 35-40 km/s. The temperature of protons increased by 2 times after the passage of the wave. The ion concentration also increased by 2 times. Angle θ_{Bn} was about 26º, according to that the interplanetary shock was determined as quasiparallel. Magnetosonic Mach number Mms was about 2.3, which corresponds to a supersonic wave. The ratio of thermal to magnetic pressure $\beta > 10$.

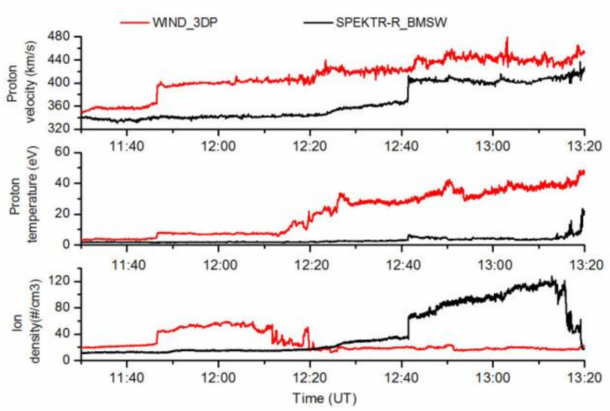


Figure 2. Plasma parameters: velocity and temperature of protons, the concentration of ions (09.09.2011 11:30-13:20 UT).

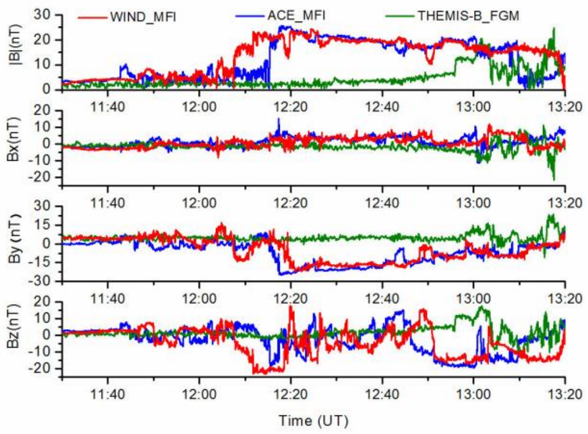


Figure 3. Magnetic field vector parameters (09.09.2011 11:30-13:20 UT).

4. Fine structure of the IP ramp region

An example of the front fine structure is illustrated on Fig. 4 taken from 09.09.2011 event. The figure shows its parameters: the duration of the front by plasma measurements: tδ=0.37; magnetic field measurements: tδ=0.48 s; thickness: δ=161 km; front speed: IP_{vel}=410 km/s.

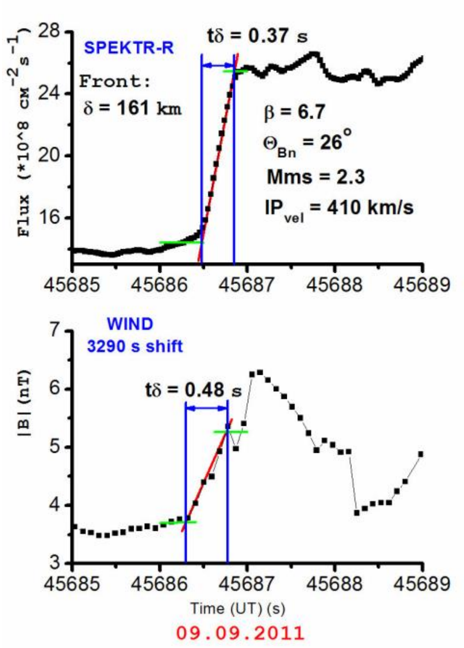


Figure 4. Ion flux and magnetic field measurements for 09.09.2011. Main classification parameters are given.

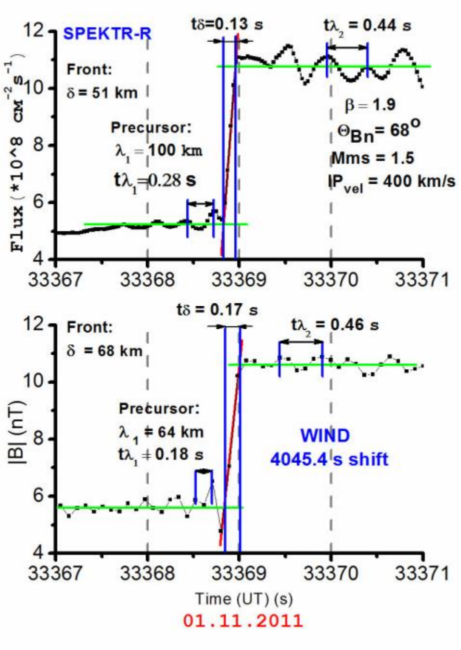


Figure 5. Ion flux and magnetic field measurements for 01.11.2011. Main classification parameters are given.

An example of the precursor wave presented on Fig. 5 (01.11.2011 event). 4 peaks are clearly visible in the flow before front, with an amplitude rising up while approaching to the front. This oscillations was also observed in magnetic field.

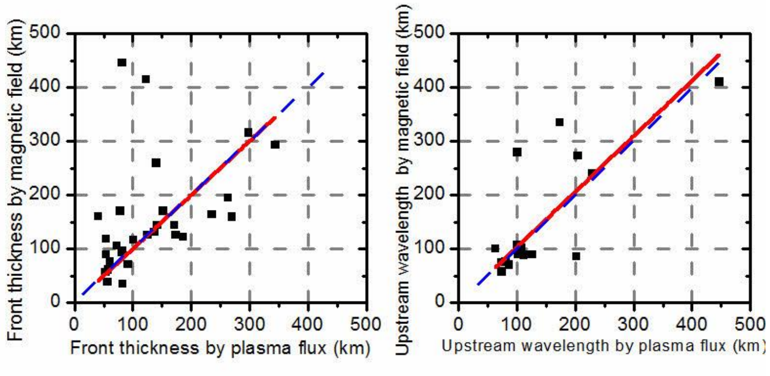
Fig. 6a shows comparison of front thickness by plasma flux and front thickness by magnetic field module. There is a good mutual alignment in common. Figure 6b presents the same for precursor waves.

5. Conclusion

The SPEKTR-R (highly elliptical orbit satellite) was launched in 2011, with plasma spectrometer BMSW onboard it. Device BMSW was designed to achieve the high time resolution [12] for plasma parameters of the solar wind – 0.031 s for measurements of magnitude and direction of the solar wind ion flux. According to the BMSW instrument the study of the fine structure of the IP waves fronts was carried out, and with other spacecrafts' data a wide range of IP waves characteristics was received.

Classifying IP shocks parameters were determined: β (ratio of thermal pressure to magnetic pressure), the angle θ_{Bn} - angle between the normal to the wave front and the direction of the vector magnetic field in the unperturbed solar wind, magnetosonic Mach number Mms; the IP shocks propagation speed was calculated.

The fine structure of IP shock fronts and precursors was studied. According to the fronts duration and their velocity, the fronts thickness was determined (lying in range from 40/35 up to 350/450 km) (by the plasma/magnetic field parameters); the length of precursors was calculated (from 65/60 to 450/410 km).



a **b**

Figure 6. Comparison of measurements by plasma flux and by magnetic field module.

Acknowledgments. The reported study was funded by RFBR according to the research project No. 16-32-00818. N. Borodkova and G. Zastenker were funded by RFBR according to the research project No. 16-02-00669.

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