Solar-Terrestrial Physics. 2025, vol. 11, iss. 3, pp. 50–58. DOI: 10.12737/stp-113202507. © 2025 S.A. Starodubtsev. Published by INFRA-M Academic Publishing House

Received February 28, 2025
Accepted May 22, 2025

DOI: 10.12737/stp-113202507

MHD WAVES IN THE PRE-FRONT REGION OF THE INTERPLANETARY SHOCK ON MAY 10, 2024

S.A. Starodubtsev
Yu.G. Shafer Institute of Cosmophysical Research and Aeronomy SB RAS,
Yakutsk, Russia, starodub@ikfia.ysn.ru

Abstract. The article reports on the study of the dynamics of the IMF turbulent component from the quiet period on May 7, 2024 to the arrival of an interplanetary shock wave in the second half of May 10, 2024. To achieve the stated goal, 1-minute direct measurements of interplanetary medium parameters on the *ACE*, DSCOVR, and WIND spacecraft are involved in the analysis. Spectral analysis methods are used to study the evolution of power spectra of fluctuations in IMF modulus and MHD waves in the inertial portion of the SW turbulence spectrum at frequencies $\sim 2.5 \cdot 10^{-4}$–$8.3 \cdot 10^{-3}$ Hz. The contribution of Alfvén, fast, and slow magnetosonic waves to the observed power spectrum of the IMF modulus measured by each of the three spacecraft is determined, and power spectra of MHD waves of these types are identified. It is shown that the power of the spectra of fluctuations in the IMF modulus and MHD waves increases by more than an order of magnitude as the shock wave approaches the point of its recording on the spacecraft. It is concluded that this is due to the generation of MHD waves by fluxes of storm particles — cosmic rays with energies ~1 MeV, observed in the region ahead of the interplanetary shock wave front. Analysis of all measurement data allows for the assumption that a significant increase in low-energy CR fluxes (~1 MeV) and SW turbulence levels may lead to a change in the IMF direction in the region adjacent to the IPS front.

Keywords: MHD waves, solar wind, interplanetary magnetic field, interplanetary shock.

INTRODUCTION

Nowadays, space weather forecasting is one of the most relevant areas of research in space physics. For this purpose, observations from various ground- and spaced-based instruments are used and diverse predictive models are being developed. When making a forecast, it is necessary to take into account the current state of the interplanetary medium and have an idea about the physical processes that occur in the solar wind plasma under certain conditions.

The interplanetary magnetic field (IMF) is an important component in space plasma. It plays a significant role in the generation and propagation of cosmic rays (CRs) in the heliosphere, as well as in the occurrence of geomagnetic storms and the formation of pulsations of various types in Earth's magnetosphere. In many cases, its turbulent component is also important.

Properties of turbulence in SW, in particular in the vicinity of interplanetary shock (IPS) fronts, are widely discussed in the scientific literature. Various characteristics of fluctuations in IMF magnitude and components, density, and velocity in different parts of observed SW turbulence spectrum are studied (see, e.g., [Li et al., 2005; Hu et al., 2013; Borovsky, 2020; Pitna et al., 2021; Sapunova et al., 2024; Kim, Oh, 2024; Smith, Vasquez, 2021, 2024]). In these works, in particular, it is noted that in the region ahead of IPS fronts an increase in the intensity of fluctuations in various interplanetary medium components is often observed in a wide range of frequencies corresponding to the energy, inertial, and dissipative parts of the SW turbulence spectrum. At the same time, there are changes in the slopes of spectra at the corresponding inflection points of the spectra. In addition, Smith and Vasquez [2021] draw attention to the fact that, despite the constant improvement in the quality of spacecraft data, the fundamental questions of plasma physics concerning energy dissipation and observed heating of thermal plasma still remain largely unanswered. Moreover, one of the reasons for this is the insufficient number of multipoint measurements of IMF and SW parameters by SC, which are located close enough to each other to better study the three-dimensional dynamics of turbulent phenomena, which underlies many physical processes in SW plasma.

In this regard, of particular interest is to delve into the powerful heliogeophysical events that occurred in early May 2024. At that time, after a series of X-class solar flares accompanied by multiple coronal mass ejections [Ram et al., 2024; Lazzús, Salfate, 2024], significant changes in space weather and, as a consequence, various geophysical phenomena were observed in Earth's orbit. In particular, the passage of an intense IPS in the second half of May 10, 2024 caused a strong geomagnetic storm with sudden commencement (SSC) (Figure 1, *a*). It started on May 10 at 17:05 UT [https://www.obsebre.es/php/geomagnetisme/vrapides/ssc_2024_p.txt] and was the most powerful in the last two decades after the famous event on November 20, 2003, known as the Halloween Event in the scientific

This is an open access article under the CC BY-NC-ND license

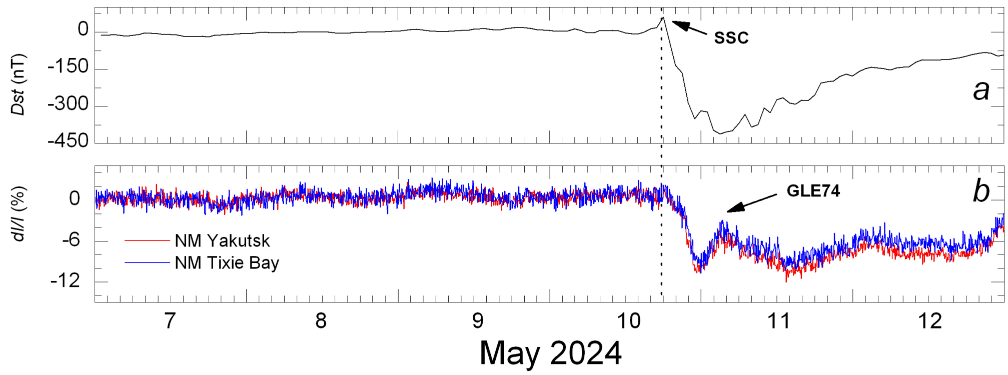

Figure 1. Geomagnetic activity index *Dst* (*a*) and CR intensity as measured by neutron monitors (NM) at the stations Yakutsk and Tixie Bay (*b*) on May 7–12, 2024. The dotted line shows the beginning of the geomagnetic storm and the Forbush effect on May 10, 2024; arrows indicate the sudden commencement (SSC) of the magnetic storm and the ground-level enhancement of CRs (GLE74)

literature. This storm was followed by a major Forbush effect (see Figure 1, *b*), powerful auroras even at low latitudes [Lazzús, Salfate, 2024], and an unusual response from the low-latitude ionosphere near the equatorial anomaly in India [Jain et al., 2025]. In addition, on May 11, 2024, the worldwide neutron monitor network recorded a ground-level enhancement of cosmic rays (GLE74) [https://www.nmdb.eu]. Thus, this extraordinary heliogeophysical event requires a comprehensive study.

This paper is a sequel to our previous work [Starodubtsev, Shadrina, 2024] and is devoted to experimental study of generation, properties, and evolution of SW MHD turbulence in the IPS pre-front region, which was recorded by a constellation of three spacecraft, located at a relatively short distance from each other in the second half of May 10, 2024, and caused a number of vivid manifestations of space weather on Earth.

1. DATA AND METHOD

The work uses one-hour data on the geomagnetic disturbance index *Dst* [https://omniweb.gsfc.nasa.gov/form/dx1.html] and one-hour pressure-corrected data on CR intensity from the stations Yakutsk and Tixie Bay [https://www.ysn.ru/ipm], as well as one-hour data on CRs recorded on board ACE SC by a detector LEMS120 during the EPAM experiment. This detector is designed to measure low-energy CR fluxes (mainly protons) in eight different differential energy channels: 0.047–0.068, 0.068–0.115, 0.115–0.195, 0.195–0.321, 0.321–0.580, 0.587–1.06, 1.06–1.90, and 1.90–4.80 MeV [https://izw1.caltech.edu/ACE/ASC/level2/index.html].

In order to study properties of the IMF turbulent component and to identify MHD waves, we have used one-minute direct measurements of IMF and SW parameters from three spacecraft: the Deep Space Climate Observatory (DSCOVR), Advanced Composition Explorer (ACE), and WIND, located near the libration point L1. Detailed information about these spacecraft and data on various interplanetary medium parameters are publicly available at [https://omniweb.gsfc.nasa.gov/ftpbrowser/wind_min_merge.html; https://services.swpc.noaa.gov/json/rtsw/rtsw_mag_1m.json; https://services.swpc.noaa.gov/json/rtsw/rtsw_wind_1m.json]. Especially noteworthy is that SC measurements are initial, contain small gaps and failures, so they should be used with caution.

When analyzing the SC measurement data, the location of each of the spacecraft in near-Earth space was also taken into account [https://sscweb.gsfc.nasa.gov/cgi-bin/Locator.cgi].

Using the entire set of spacecraft data, IMF and MHD-wave spectral characteristics and their dynamic changes in the inertial part of the spectrum of SW turbulent fluctuations at frequencies ~$2.5 \cdot 10^{-4}$–$8.3 \cdot 10^{-3}$Hz were examined. Note that the first of the frequencies roughly corresponds to the boundary between the energetic and inertial parts of the spectrum of SW turbulent fluctuations, which changes little with solar cycle [Kovalenko, 1983], and the second is determined by the Nyquist frequency $\nu_N=1/(2\Delta t)$, where Δt=60 s is the sampling increment of the data in use. Spectral analysis methods based on the Blackman—Tukey algorithm with the Tukey correlation window were employed to gain useful information from direct measurements [Jenkins, Watts, 1971; Otnes, Enoxon, 1982]. Its application made it possible to estimate the IMF fluctuation power spectra with a 95 % confidence interval corresponding to the number of degrees of freedom equal to 66.675 [Jenkins, Watts, 1971]. All original time series of data were preliminarily subjected to the standard procedure of preparation for analysis. At this stage, observed failures and outliers were excluded from the data, with gaps in the initial series filled in with values obtained by interpolating adjacent measurements. Further, all time series of data were reduced to the zero mean, and then they were filtered by a digital bandpass filter in the frequency band indicated above [Otnes, Enokson, 1982].

Note that when studying properties of IMF fluctuations, the spectral characteristics of its magnitude and components are often examined. This is due to the fact that from the type of spectra we can draw a definite and reasonable conclusion about the presence of longitudinal or transverse waves and oscillations in SW during the time periods of interest. In particular, it is known that for transverse Alfvén waves there are fluctuations in the field direction rather than in its magnitude. In this case, the difference between the power spectra of IMF components and strength may be as great as an order of magnitude. For the fast mode (compression waves), the power spectra of IMF components and strength are of the same order, which indicates fluctuations in both the IMF direction and magnitude [Kovalenko, 1983]. However, from these IMF fluctuation power spectra it is impossible to conclude about the contribution of MHD waves of a certain type to the spectra observed in SW. But all of them contribute to the IMF magnitude in any way. Therefore, when identifying spectral characteristics of MHD waves of different types, their known properties were taken into account. They consist in that Alfvén waves (AW) are characterized by a correlation between the IMF magnitude B and the SW velocity V; for fast magnetosonic waves (FMSW), between B and the plasma density n; and for slow magnetosonic waves (SMSW), between n and V [Neugebauer et al., 1978; Toptygin, 1983]. Nonetheless, since this work deals with spectral properties of IMF fluctuations, the coherence coefficient is used which is a generalization of the concept of correlation to the frequency domain rather than the correlation coefficient that characterizes the relationship between certain physical quantities in the time domain [Luttrell, Richter, 1986, 1987; Starodubtsev et al., 2023]. Note that, by definition, the coherence coefficient is a positive value of the square root of the coherence function. It varies from 0 to 1 and is a function of frequency. The procedure adopted in this work for estimating the spectral characteristics of fluctuations in IMF and SW plasma parameters, the corresponding coherence coefficients, as well as the method for identifying MHD waves, and their difference from oscillations are described in detail in [Starodubtsev et al., 2023].

2. RESULTS AND DISCUSSION

Figures 2–4 display the IMF magnitude B and B_z component (*a*), density n (*b*), velocity V (*c*), and temperature T (*d*) recorded by each of the three spacecraft on May 7–12, 2024. The dotted line indicates the arrival time of IPS for each spacecraft. Its arrival at DSCOVR was recorded on May 10, 2024 at 16:35 UT (see Figure 2); at ACE, at 16:37 UT (see Figure 3); at WIND, at 17:05 UT (see Figure 4). It is apparent (see Figures 2–4) that from May 7 until the arrival of the large-scale SW disturbance (coronal mass ejection accompanied by IPS) at Earth's orbit in the second half of May 10, conditions in near-Earth space were relatively quiet, and IMF and SW parameters did not experience any significant changes despite sufficiently high SW n, V, and T [Toptygin, 1983].

Figure 5, *a–c* in the GSE coordinate system shows the location of the constellation of three spacecraft relative to Earth on May 7, 2024. The distance is given in Earth radii R_E. Blue segments represent the direction of the mean IMF vector in different projections on the YX (*a*), ZX (*b*), and ZY (*c*) planes. Compared to the distance from the Sun to Earth (1 AU≈285185 R_E), all SC are located quite close to each other. Nevertheless, it can be noted that WIND is located somewhat away from Earth; and the other two SC, at a distance of ~100 R_E (*a*, *c*). However, the direction of mean IMF during this time period is seen to be nearly the same for all spacecraft.

Let us now examine the spectral characteristics of SW turbulence, using the results of analysis of one-minute direct measurements of interplanetary medium parameters from the three spacecraft. We will begin with the quiet period of May 7, 2024. Figure 6, *a–c* presents calculated coherence coefficients $\Gamma_{BV}(\nu)$, $\Gamma_{Bn}(\nu)$, and $\Gamma_{Vn}(\nu)$ as function of frequency ν. Their values determine the contribution of MHD waves of one type to the observed power spectrum of IMF fluctuations at a certain frequency ν. The coherence values are seen to be not very high, except for $\Gamma_{Vn}(3.5\cdot10^{-3}$ Hz)=0.86 and $\Gamma_{BV}(3.4\cdot10^{-4}$ Hz)=0.55 (panel *b*), which means a significant contribution of SMSW and AW to the observed power spectrum of IMF fluctuations at these frequencies (panel *e*) during the period considered. As for the contribution of other types of MHD waves at other frequencies, it is much smaller and does not exceed 50 % as a whole. In general, in order to establish the frequency spectra of MHD waves of a certain type, it is necessary to multiply the power spectra of IMF fluctuations $P(\nu)$ by the corresponding values of the coherence coefficient $\Gamma(\nu)$, which are calculated for each SC. Panels *d–f* exhibit the observed power spectra of IMF fluctuations, their approximation by the least square method, and the corresponding power laws that describe them. Note that the corresponding powers for DSCOVR and ACE are greater than –1, whereas for WIND, on the contrary, they are much smaller than –1. From May 8 as the IPS front is approached, the spectral indices calculated from ACE and DSCOVR data gradually decrease, tending to the well-known Kolmogorov turbulence spectrum of –5/3, and for WIND they abruptly reach this value and remain almost the same up to the shock front. Perhaps this is somehow related to the location of WIND with respect to Earth and other spacecraft, from which it is at a distance of ~100 R_E along the Y-axis outside the boundary of the magnetosphere (

es 6, *d–f* also presents the established MHD wave spectra of all three types — AW, FMSW, and SMSW. As expected, they do not exceed the IMF fluctuation power spectra, and their sums within 95 % confidence intervals are comparable to the fluctuation power spectra of the IMF magnitude measured by each spacecraft. At the same time, the maximum power spectra in the frequency range considered correspond well to quiet conditions in SW [Kovalenko, 1983] and even at a low frequency $2.5\cdot10^{-4}$ Hz they do not exceed 10^2 nT^2/Hz.

Another pattern is observed just before thsee Figures 5 and 9).

Figure arrival of IPS. In Figure 7, *a–f* is the same information for the time interval before the arrival of IPS as in Figure 6, *a–f*. Values of all coherence coefficients $\Gamma(\nu)$ are seen to change; and the IMF fluctuation power spectrum, to increase by an order of magnitude, becoming steeper with powers less than –1. This also fully applies to each spectrum characterizing an MHD wave of a certain type (see Figure 7, *d–f*). Moreover, behind the IPS front in the transition turbulent region, the spectral indices on the three spacecraft drop sharply to –(2.0÷2.2) within 2–3 hrs, and then slowly tend to recover to –5/3.

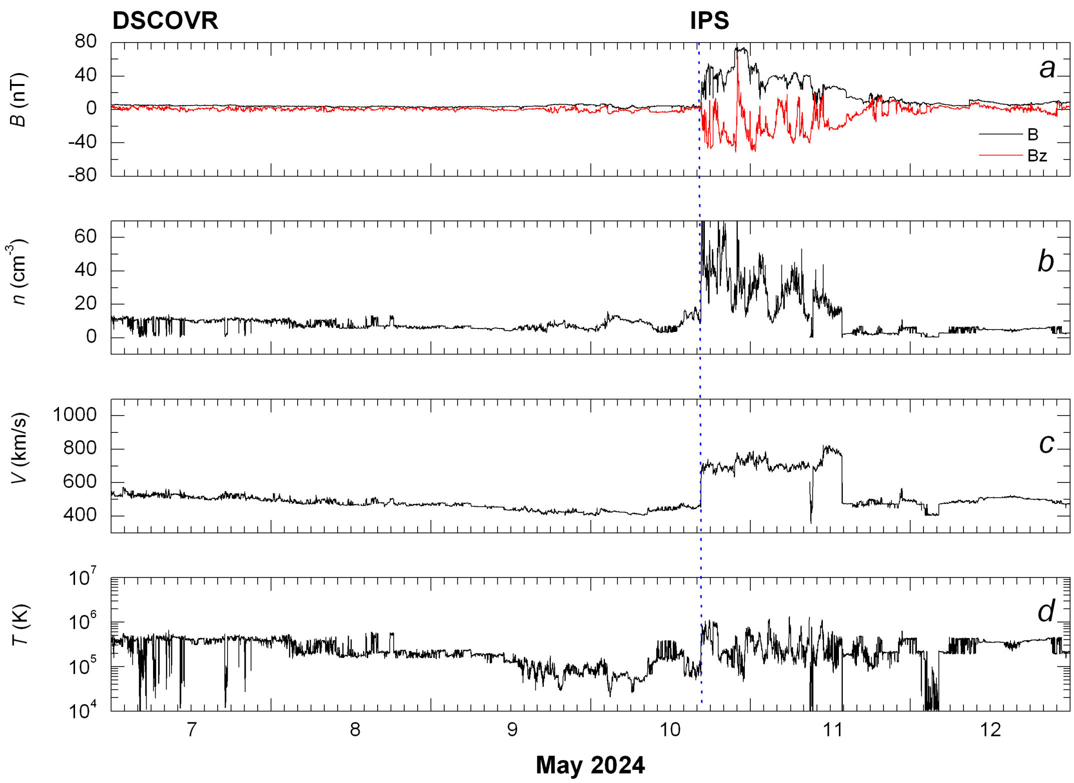

Figure 2. IMF B and B_z(*a*), SW density *n (b)*, velocity *V (c)*, and temperature *T* (*d*) measured by DSCOVR on May 7–12, 2024. The dotted line is the IPS arrival time

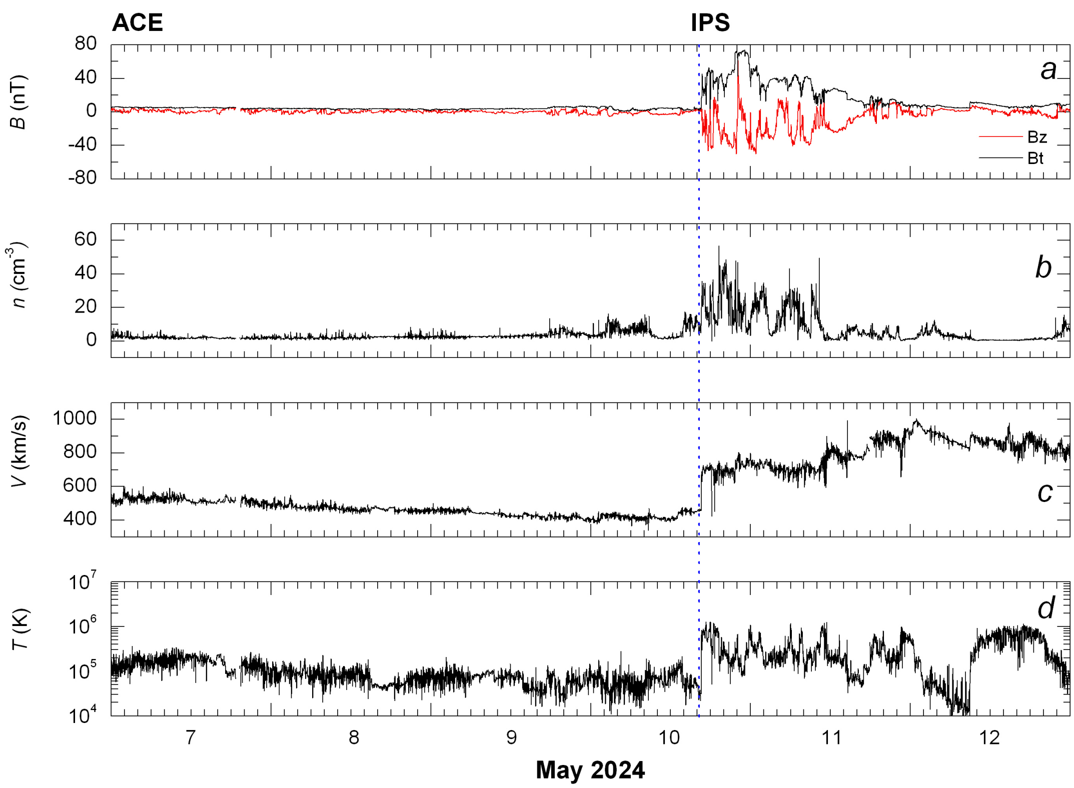

Figure 3. The same for ACE

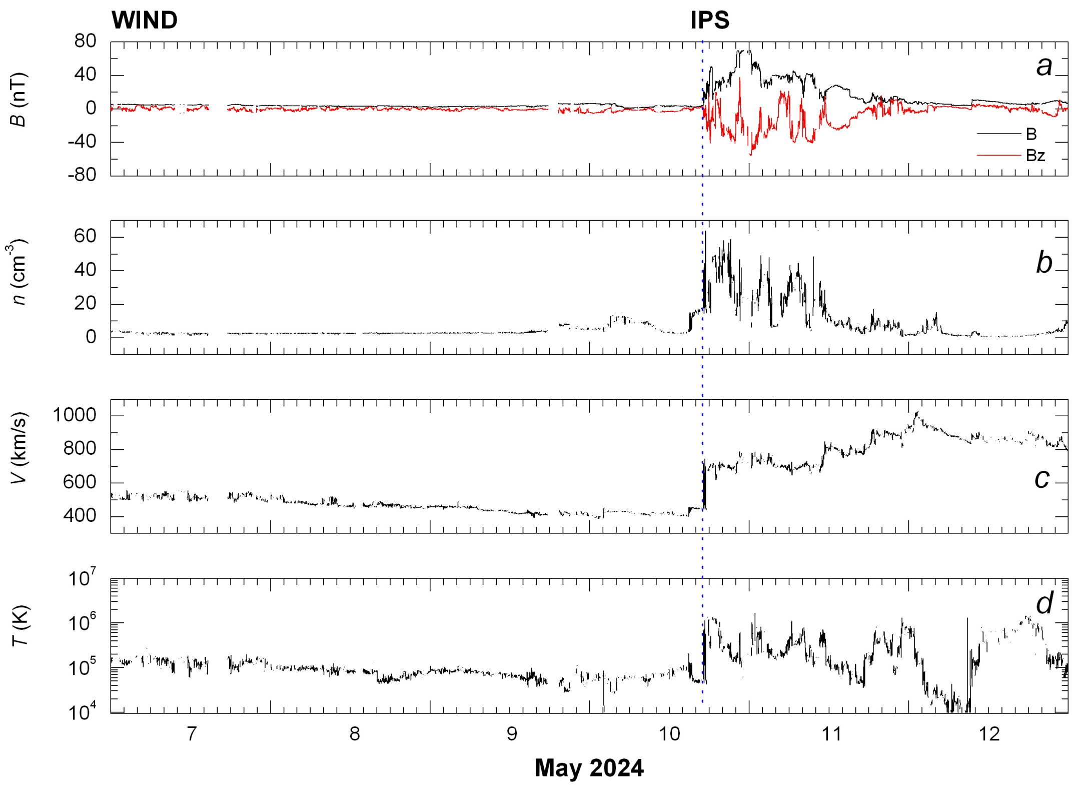

Figure 4. The same for WIND

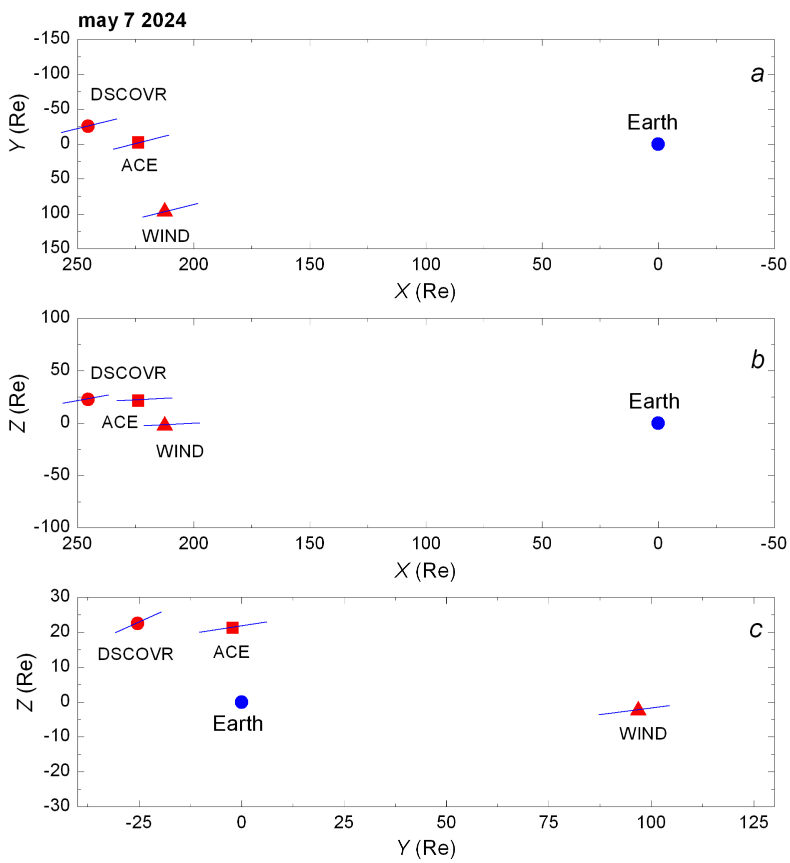

Figure 5. Location of the constellation of three spacecraft DSCOVR, ACE, and WIND during the quiet period on May 7, 2024 relative to Earth in projection on different planes in the GSE coordinate system. Blue segments represent the direction of the mean IMF in each spacecraft on that day

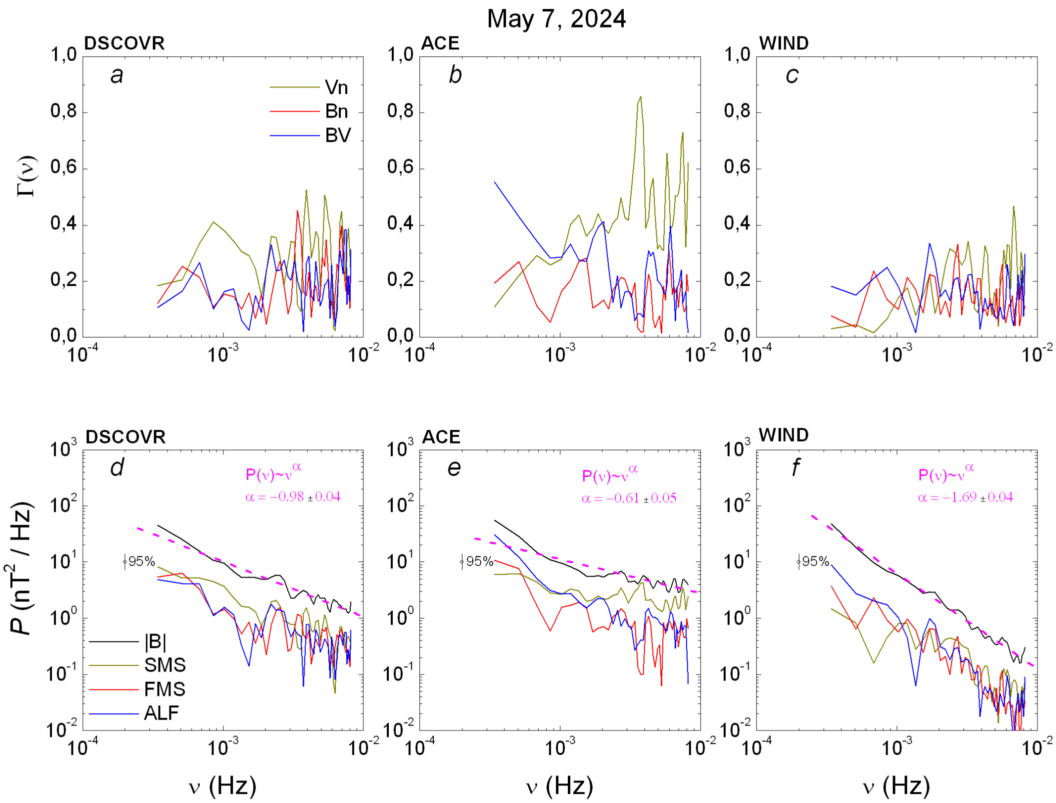

Figure 6. Coherence coefficients $\Gamma_{BV}(\nu)$, $\Gamma_{Bn}(\nu)$, and $\Gamma_{Vn}(\nu)$ *a–c*), as well as the power spectra of IMF fluctuations and the established power spectra of MHD waves (*d-f*) for the quiet period on May 7, 2024. The dashed line is an approximation of power spectra of IMF fluctuations; a power law describing them is given. The corresponding legends (*a*, *d*) for coherence and power spectra and 95 confidence intervals for power spectra are shown. Above each panel are names of SC

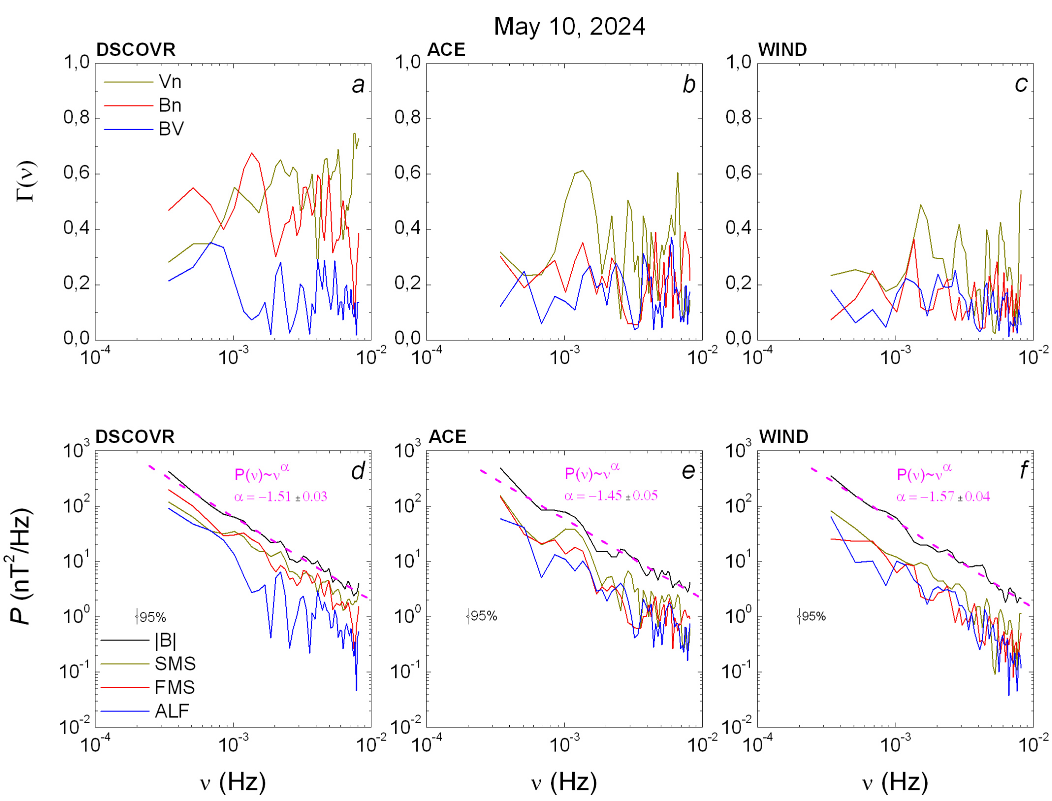

Figure 7. The same for the IPS pre-front region on May 10, 2024

Noteworthy is the shape of the IMF fluctuation power spectrum calculated from WIND data (see Figures 6, *f* and 7, *f*). In the IPS pre-front region, it also increases by an order of magnitude, but in both cases its index $\alpha<-1$. This raises a certain question, but may be due to the IMF spaghetti structure in front of the IPS front or due to the wavy structure of the IPS front itself, as we have assumed earlier in [Starodubtsev, Shadrina, 2024].

More detailed analysis of the dynamics of power spectra of IMF fluctuations and MHD waves shows that as IPS approaches SC the spectra become steeper and their power increases. Why this happens can be understood by considering the theoretical works [Berezhko, 1986, 1990; Chalov, 1988; Berezhko, Starodubtsev, 1988; Reames, 1989; Vainio, 2003], which suggest that MHD waves can be generated by low-energy CR fluxes. These authors have developed mechanisms for the generation of Alfvén and magnetosonic waves due to the formation of plasma instabilities in the interplanetary medium by low-energy solar CRs or particles accelerated at IPS fronts, which are called energetic storm particles in the scientific literature. The determining factor in these processes is the presence of low-energy (~1 MeV) CRs in the interplanetary medium, which feature large fluxes and gradients. Indeed, at the time in question there were such CR fluxes after a series of powerful solar flares in Earth's orbit. Figure 8, as Figures 2–4, shows raw data. From May 8, 2024, as ACE is approached, the low-energy CR flux, which consists of solar and energetic storm particles with a maximum at the IPS front and is characterized by a large spatial gradient, is seen to increase by many orders of magnitude. Taking into account the results of the above-mentioned studies, this allows us to draw a reasonable conclusion about the cause for the observed increase in the level of IMF fluctuations, which occurs due to generation of MHD waves by these particles in the IPS pre-front region on May 10, 2024.

An interesting fact is that, in contrast to the situation depicted in Figure 5, mean IMF changes direction, as observed in all three spacecraft located relatively close to each other. This is illustrated in Figure 9.

. It can be assumed that the presence of significant storm particle fluxes with an energy of ~1 MeV and a corresponding increase in the SW turbulence level cause the mean IMF to change direction in the region of space directly adjacent to the IPS front. It is, however, still too early to make certain conclusions about the reasons for this since very few statistics of observations of such events from sufficiently closely located spacecraft have been collected (only 35 cases).

CONCLUSIONS

Thus, studying the May 10, 2024 IPS event recorded by three spacecraft located near the libration point L1 allows the following conclusions to be drawn.

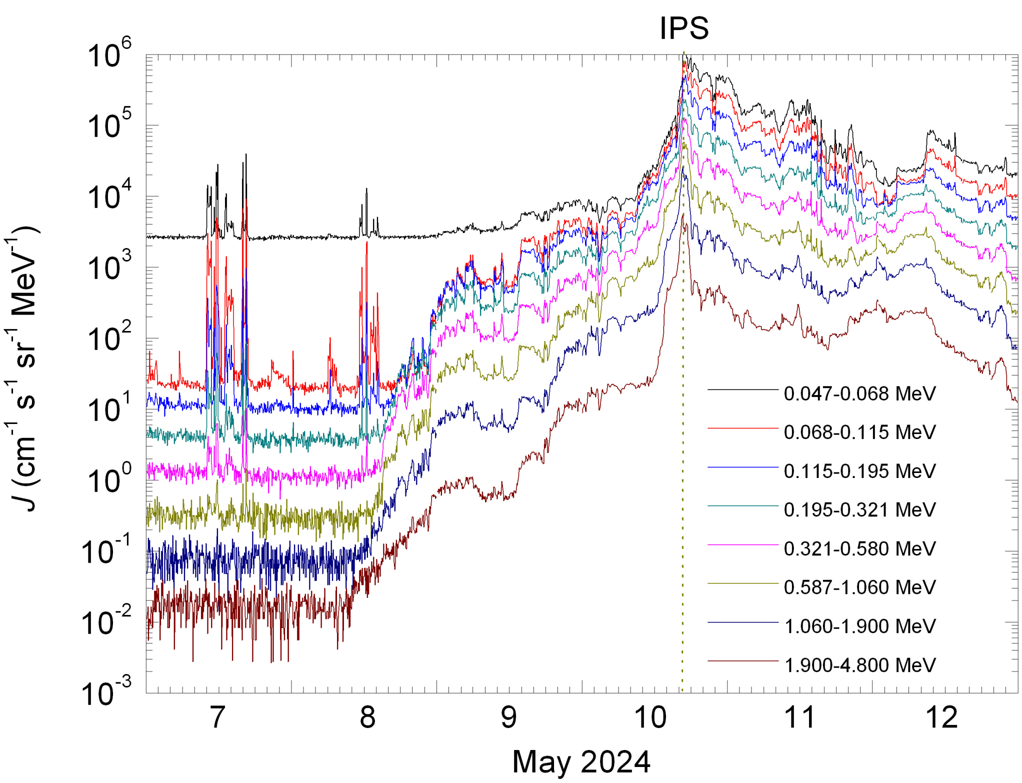

Figure 8. Low-energy CR fluxes in eight different differential channels recorded on board ACE during the EPAM experiment (LEMS120 detector) on May 7–12, 2024. A legend for the differential energy channels is shown. The dashed line is the time of IPS arrival at ACE, which coincides with the maximum CR flux of different energies

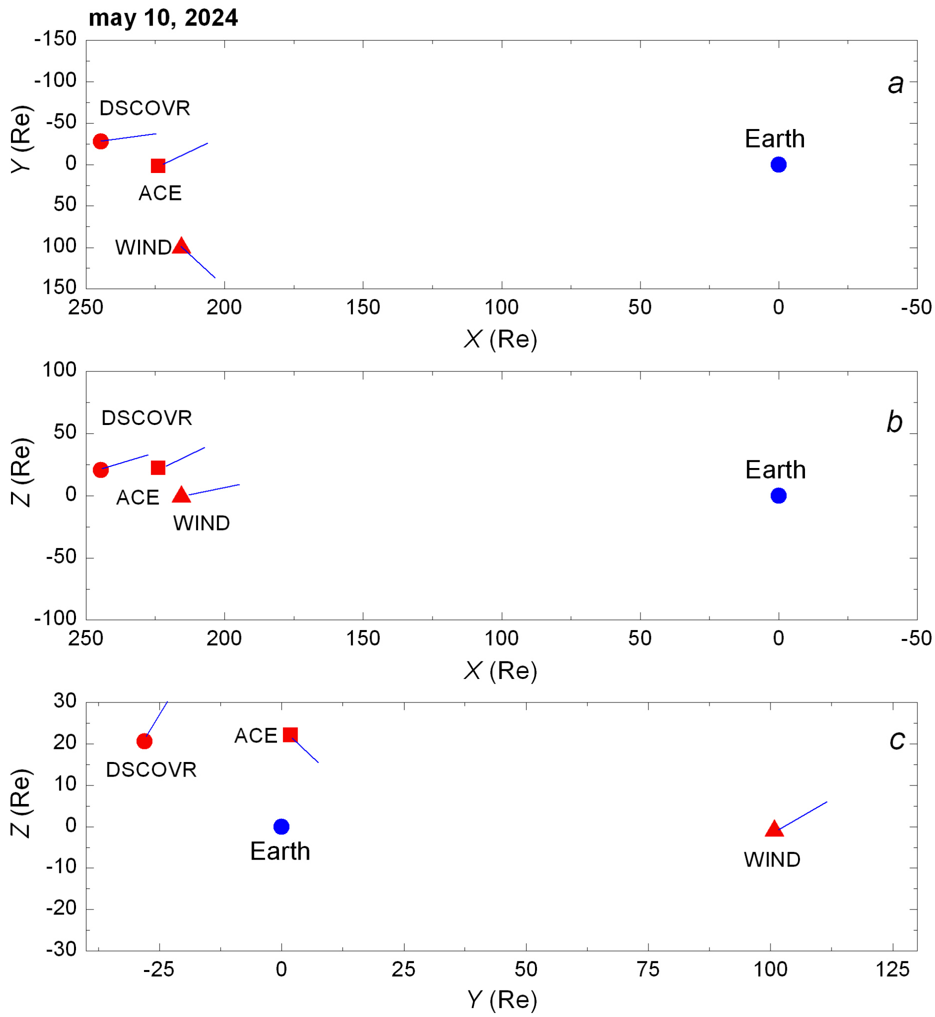

Figure 9. The same as in Figure 5 for the pre-front region of IPS recorded by three spacecraft on May 10, 2024

1. Using spectral analysis methods with direct measurements of IMF and SW plasma parameters from DSCOVR, ACE, and WIND spacecraft, we have identified MHD waves of three types: Alfvén, fast, and slow magnetosonic waves observed during the period of interest in the inertial part of the SW turbulence spectrum in the frequency range ~$2.5 \cdot 10^{-4}$–$8.3 \cdot 10^{-3}$ Hz.

2. It has been shown that during this event there is a significant increase, by about an order of magnitude, in the power of fluctuations in the IMF strength and MHD waves of all three established types in the IPS pre-front region.

3. The reason is low-energy CRs of solar and interplanetary origin, characterized by large fluxes and gradients whose presence in the IPS pre-front region led to the generation of MHD waves.

4. It is assumed that a significant increase in low-energy CR fluxes (~1 MeV) and the SW turbulence level can cause IMF to change direction in the region of space directly adjacent to the IPS front.

I would like to thank the teams of the Space Weather Prediction Center of the National Oceanic and Atmospheric Administration, NASA/Goddard Space Flight Center, ACE Science Centers and the Data Analysis Center for Geomagnetism and Space Magnetism (Kyoto University) for providing free access to DSCOVR, ACE, and WIND data and information on the geomagnetic activity index *Dst*.

The work was carried out as part of the Government assignment from SHICRA SB RAS FWRS-2021-0012.

REFERENCES

Berezhko E.G. Instability in a shock wave propagating in a gas with cosmic rays. *Pis'ma v Astronomicheskii Zhurnal.* 1986, vol. 12, pp. 842–847. (In Russian).

Berezhko E.G. Generation of MHD waves in interplanetary plasma by fluxes of solar cosmic rays. *Pis'ma v Astronomicheskii Zhurnal.* 1990, vol. 16, pp. 1123–1132. (In Russian).

Berezhko E.G., Starodubtsev S.A. Nature of the dynamics of the cosmic-ray fluctuation spectrum. *Izvestiya Akademii Nauk SSSR. Ser. Fizicheskaya* [Bull. Academy of Sciences of USSR. Ser. Physics]. 1988, vol. 52, pp. 2361–2363. (In Russian).

Borovsky J.E. A statistical analysis of the fluctuations in the upstream and downstream plasmas of 109 strong-compression interplanetary shocks at 1 AU. *J. Geophys. Res.: Space Phys.* 2020, vol. 125, iss. 6, article id. e27518. DOI: 10.1029/2019JA027518.

Chalov S.V. Instability of a diffusive shock wave in a plasma with cosmic rays. *Pis'ma v Astronomicheskii Zhurnal.* 1988, vol. 14, pp. 272–276. (In Russian).

Hu Q., Zank G.P., Li G., Ao X. A Power Spectral Analysis of Turbulence Associated with Interplanetary Shock Waves. *in AIP Conf. Ser. 1539, Proc. of the Thirteenth International Solar Wind Conf.*, ed. G. P. Zank et al. 2013. 175, DOI: 10.1063/1.4811016.

Jain A., Trivedi R., Jain S., Choudhary R.K. Effects of the super intense geomagnetic storm on 10–11 May, 2024 on total electron content at Bhopal. *Adv. Space Res.* 2025, vol. 75, iss. 1, pp. 953–965. DOI: 10.1016/j.asr.2024.09.029.

Jenkins G.M., Watts D.G. *Spectral Analysis and Its Applications.* San Francisco, Cambridge, London, Amsterdam, Holden-Day, 1968, 525 p.

Kim S., Oh S. Characteristics of interplanetary shock sheath regions in the solar wind inducing the Forbush decreases. *J. Korean Astron. Soc.* 2024, vol. 57, no. 2, pp. 173–182. DOI: 10.5303/JKAS.2024.57.2.173.

Kovalenko V.A.. *Solnechy veter* [Solar Wind]. Moscow, Nauka Publ., 1983, 272 p. (In Russian).

Lazzús J.A., Salfate I. Report on the effects of the May 2024 Mother's day geomagnetic storm observed from Chile. *J. Atmospheric and Solar–Terr. Phys.* 2024, vol. 261, 106304. DOI: 10.1016/j.jastp.2024.106304.

Li G., Hu Q., Zank G.P. Upstream turbulence and the particle spectrum at CME-driven shocks. *Proc. AIP Conf. "Physics of Collisionless Shocks*". 2005, vol. 781, pp. 233–239. DOI: 10.1063/1.2032702.

Luttrell A.H., Richter A.K. Power spectra of low frequency MHD turbulence up- and downstream of interplanetary fast shocks within 1 AU. *Ann. Geophys*. 1986, vol. 4, pp. 439–446.

Luttrell A.H., Richter A.K. Study of MHD fluctuations upstream and downstream of quasiparallel interplanetary shocks. *J. Geophys. Res*. 1987, vol. 92, pp. 2243–2252.

Neugebauer M., Wu C.S., Huba J.D. Plasma fluctuations in the solar wind. *J. Geophys. Res*. 1978, vol. 83, pp. 1027–1034.

Otnes R., Enokson L. *Prikladnoi analiz vremennykh ryadov. Osnovnye metody.* [Applied Time Series Analysis. Vol. 1. Basic Techniques.] Moscow, Mir Publ., 1982, 430 p. (In Russian).

Pitna A., Safrankova J., Nemecek Z., Durovcova T., Kis A. Turbulence upstream and downstream of interplanetary shocks. *Front. Phys*. 2021, *Frontiers in Physics.* 2021, vol. 8, id. 654. DOI: 10.3389/fphy. 2020.626768.

Ram T., Veenadhari S., Dimri B., et al. Super-intense geomagnetic storm on 10–11 May 2024: Possible mechanisms and impacts. *Space Weather.* 2024, vol. 22, iss. 12, e2024SW004126. DOI: 10.1029/2024SW004126.

Reames D.V. Wave generation in the transport of particles from large solar flares. *Astrophys. J. Lett.* 1989, vol. 342, no. 1, Part 2, pp. L51–L53.

Sapunova O.V., Borodkova N.L., Yermolaev Yu.I., Zastenker G.N. Spectra of fluctuations of solar wind plasma parameters near a shock wave. *Cosmic Res*. 2024, vol. 62, iss. 1, pp. 1–9. DOI: 10.1134/S0010952523700843.

Smith C.W., Vasquez B.J. Driving and dissipation of solar-wind turbulence: What is the evidence? *Front. Astron. Space Sci.* 2021, vol. 7, id. 114. DOI: 10.3389/fspas.2020.611909.

Smith C.W., Vasquez B.J. The unsolved problem of solar-wind turbulence. *Front. Astron. Space Sci.* 2024, vol. 11, id. 1371058. DOI: 10.3389/fspas.2024.1371058.

Starodubtsev S.A., Shadrina L.P. MHD waves at the pre-front of interplanetary shocks on September 6 and 7, 2017. *Sol.-Terr. Phys*. 2024, vol. 10, iss. 3, pp. 50–57. DOI: 10.12737/stp-103202406.

Starodubtsev S.A., Zverev A.S., Gololobov P.Yu., Grigoryev V.G. Cosmic ray fluctuations and MHD waves in the solar wind. *Sol.-Terr. Phys*. 2023, vol. 9, iss. 2, pp. 73–80. DOI: 10.12737/stp- 92202309.

Toptygin I.N. *Kosmicheskie luchi v mezhplanetnykh magnitnykh polyakh* [Cosmic rays in interplanetary magnetic fields]. Moscow, Nauka Publ., 1983, 304 p. (In Russian).

Vainio R. On the generation of Alfven waves by solar energetic particles. *Astron. Astrophys.* 2003, vol. 406, pp. 735–740.

URL: https://www.obsebre.es/php/geomagnetisme/vrapides/ssc_2024_p.txt (accessed February 27, 2025).

URL: https://www.nmdb.eu (accessed February 27, 2025).

URL: https://omniweb.gsfc.nasa.gov/form/dx1.html (accessed February 27, 2025).

URL: https://www.ysn.ru/ipm (accessed February 27, 2025).

URL: https://izw1.caltech.edu/ACE/ASC/level2/index.html (accessed February 27, 2025).

URL: https://omniweb.gsfc.nasa.gov/ftpbrowser/wind_min_merge.html (accessed February 27, 2025).

URL: https://services.swpc.noaa.gov/json/rtsw/rtsw_mag_1m.json (accessed February 27, 2025).

URL: https://services.swpc.noaa.gov/json/rtsw/rtsw_wind_1m.json (accessed February 27, 2025).

URL: https://sscweb.gsfc.nasa.gov/cgi-bin/Locator.cgi (accessed February 27, 2025).

The paper is based on material presented at the 20th Annual Conference on Plasma Physics in the Solar System, February 10–14, 2025, Space Research Institute of the Russian Academy of Sciences, Moscow, Russia.

Original Russian version: Starodubtsev S.A., published in Solnechno-zemnaya fizika. 2025, vol. 11, no. 3, pp. 56–64. DOI: 10.12737/ssf-113202507. © 2025 INFRA-M Academic Publishing House (Nauchno-Izdatelskii Tsentr INFRA-M).

How to cite this article

Starodubtsev S.A. MHD waves in the pre-front region of the interplanetary shock on May 10, 2024. *Sol.-Terr. Phys*. 2025, vol. 11, iss. 3, pp. 50–58. DOI: 10.12737/stp-113202507.