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COSMIC RAY FLUCTUATIONS AND MHD WAVES IN THE SOLAR WIND

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Abstract. During large-scale solar wind disturbances, variations in galactic cosmic rays with periods from several minutes to 2–3 hours, which are called cosmic ray fluctuations in the scientific literature, often occur. Such fluctuations are not observed in the absence of disturbances. Since cosmic rays are charged particles, their modulation in the heliosphere occurs mainly under the influence of the interplanetary magnetic field, or rather its turbulent part — MHD waves. In order to adequately describe the relationship between their fluctuation spectra, it is necessary to be able to isolate a certain type of MHD waves from direct measurements of the interplanetary medium parameters. In this paper, we consider some methods for determining the contribution of three solar wind MHD turbulence branches, namely, Alfvén, fast, and slow magnetosonic waves corresponding to the turbulence spectrum inertial region frequencies $10^{-4}<\nu<10^{-1}$ Hz, at which cosmic ray fluctuations are observed, to the observed power spectra of interplanetary magnetic field modulus fluctuations. To do this, we apply the methods of spectral and polarization analysis. In the absence of measurement data on SW parameters, to identify the type of MHD turbulence we use the known wave polarization properties that Alfvén and magnetosonic waves are polarized in different planes relative to the plane containing the average IMF vector $\vec{B}_0$ and wave vector $\vec{k}$.

Our results show that with the correct determination of the spectra of three MHD wave types, their sum, within the limits of errors, agrees well with the observed spectra of the interplanetary magnetic field modulus, and a small difference can be attributed to static inhomogeneities and oscillations frozen into plasma, as well as to various discontinuities that are always inevitably present in the solar wind.

Keywords: cosmic rays, interplanetary magnetic field, solar wind, MHD waves.

INTRODUCTION

It is well known that galactic cosmic rays (CRs), when propagating in the heliosphere, are subject to modulation in the collisionless solar wind (SW) plasma. This results in CR variations with periods from several minutes to 2–3 hours, also known as CR fluctuations, which often occur during large-scale SW disturbances. In this case, interplanetary magnetic field (IMF) fluctuations determine the conditions for CR propagation in the heliosphere and hence the mechanism for modulation of their distribution function. Currently, there are two different viewpoints on this subject in the scientific literature. The first is that CR fluctuations occur when the particle flux interacts with Alfvén waves. In this case, a small (less than 1 %) anisotropic component of the CR distribution function is modulated [Owens, 1974]. According to the second viewpoint, a much larger (about 99 %) isotropic component is modulated, which is caused by the interaction of CRs with fast magnetosonic waves [Berezhko, Starodubtsev, 1988]. Note that the theory adequately describes the observed relationship between CR and IMF fluctuation spectra [Berezhko, Starodubtsev, 1988; Transkii, Starodubtsev, 1991; Starodubtsev et al., 1996], which supports the latter viewpoint. At the same time, the problem of identifying the IMF fluctuations observed in the experiment with known MHD wave types has not yet been completely solved. Identification difficulties arise first from the fact that IMF and SW plasma fluctuations are generally a combination of waves of different frequencies and types, and second from an incomplete set of measured field and plasma parameters or insufficient measurement quality. The linear theory of MHD waves in plasma establishes their basic properties according to which a high degree of correlation (or coherence) between IMF strength B and SW velocity U suggests the presence of Alfvén waves in the observed SW turbulence spectra; between B and SW density n, fast magnetosonic waves; and between U and n, slow magnetosonic waves [Neugebauer et al., 1978; Toptygin, 1983].

Below we examine some methods of analyzing data from direct satellite measurements to identify the type and contribution of three SW MHD turbulence branches: Alfvén, fast, and slow magnetosonic waves, to the observed power spectra of IMF modulus fluctuations. To identify them, we apply spectral and polarization analysis methods. In the latter case, we determine the MHD turbulence type from the well-known wave polarization properties such that Alfvén and magnetosonic waves have different polarization planes relative to the plane containing the average IMF vector $\vec{B}_0$ and the wave vector $\vec{k}$ [Kulikovskii, Liubimov, 1962].

The purpose of this paper is to analyze ground-based measurements of CR intensity fluctuations and direct measurements of IMF and SW parameters to identify a certain MHD turbulence type.

1. DATA AND METHODS

In our work, we use one-minute measurement data, corrected for pressure, from neutron monitors of the Yakutsk and Tixie Bay Cosmic Ray Stations [https://ysn.ru/ipm], as well as one-minute direct measurement data on IMF modulus and components in the GSE coordinate system and on SW velocity and density from the WIND spacecraft instruments [https://omniweb.gsfc.nasa.gov/form/sc_merge_min1.html]. Note that this site presents data already reduced to the near-Earth bow shock nose.

To estimate the spectral power of the CR, IMF, and SW intensity fluctuations corresponding to the turbulence spectrum inertial region in the frequency range $10^{-4}<\nu<10^{-2}$ Hz, we employ the standard Blackman—Tukey method with a Tukey correlation window [Jenkins, Watts, 1971; Otnes, Enochson, 1982]. The realization length was 24 hrs, i.e. 1440 reads of one-minute measurements. In order to reduce the initial data to a quasi-stationary form, as well as to exclude low-frequency trends and possible distortion of the power estimates from them, all the initial information had been previously subjected to a standard procedure of reduction to zero mean and bandpass filtering in the above frequency range. When constructing confidence intervals for estimating the power of fluctuations of various quantities, we took into account that the number of degrees of freedom with the Tukey correlation window DoF =2.667L, where L is the cutoff covariance function coefficient [Jenkins, Watts, 1971].

Below we present the main general formulas and relations for spectral description of random processes, which we have used for analyzing measurement data.

If there is only one random variable x, its one-sided power spectrum density [Jenkins, Watts, 1971; Otnes, Enochson, 1982] is defined as

$$P_{xx}(\nu)=2\int_0^m w(\tau)R_{xx}(\tau)\cos(2\pi\nu\tau)\,d\tau, \quad (1)$$

here $R_{xx}(\tau)$ is the autocovariance function; $w_T(\tau)=\frac{1}{2}\left(1+\cos\frac{\pi\tau}{m}\right),\ \tau\le m$, where $w_T(\tau)=0,\ \tau>m$ is the Tukey correlation window we selected. The standard set of frequencies is defined as $\nu_i=\frac{i}{2m\Delta t}$, i=0, 1, ..., m, where i is the number of the corresponding harmonic, Δt is data increment.

If there are two realizations of random variables X and Y, we can calculate their cross-spectrum density. Its values can be written in terms of the sum of the real and imaginary parts of the power spectrum $P_{xy}(\nu)=C_{xy}(\nu)+jQ_{xy}(\nu)$. Then, the absolute cross-spectrum density will be written as

$$|P_{xy}(\nu)|=\sqrt{C_{xy}^2(\nu)+Q_{xy}^2(\nu)}, \quad (2)$$

where the one-sided cospectral density of the power spectrum is

$$C_{xy}(\nu)=2\int_0^m w(\tau)R_{xy}(\tau)\cos(2\pi\nu\tau)\,d\tau, \quad (3)$$

and the one-sided quadrature power spectral density is

$$Q_{xy}(\nu)=2\int_0^m w(\tau)R_{xy}(\tau)\sin(2\pi\nu\tau)\,d\tau. \quad (4)$$

The coherence coefficient $\Gamma_{xy}(\nu)$ is defined as the positive square root of coherence function $\Gamma_{xy}^2(\nu)=\left|P_{xy}^2(\nu)\right|/\left(P_{xx}(\nu)P_{yy}(\nu)\right)$:

$$\Gamma_{xy}(\nu)=+\sqrt{\Gamma_{xy}^2(\nu)}. \quad (5)$$

The coherence coefficient Γ is a generalization of the correlation function to the frequency domain and, by definition, takes values $0\le\Gamma\le1$. If preliminary filtering of the data was not carried out, $\Gamma_{xy}(\nu)\equiv1$ [Kanasevich, 1985]. Note that the coherence coefficient plays an important role in analyzing data. It is used both to estimate the percentage of each MHD wave type in the total observed spectrum of IMF modulus fluctuations [Luttrell, Richter, 1987; Berezhko, Starodubtsev, 1988] and to adequately determine the plane of polarization of these waves [Transkii, Starodubtsev, 1991].

If there are no measurements of SW plasma parameters but there are only measurements of IMF components, we adopt the method of determining the polarization parameters of MHD waves from spectral matrices, which is described in [Kanasevich, 1985; Transkii, Starodubtsev, 1991]. For Alfvén waves, the plane of oscillations of the magnetic field strength vector $\vec{B}$ is perpendicular to the plane containing the regular field $\vec{B}_0$ and the wave vector $\vec{k}$; for magnetosonic waves these planes are parallel [Kulikovskii, Liubimov, 1962]. It is necessary to rotate the spectral matrix to transform from the reference coordinate system GSE to a new reference system GSE′ whose axes are further designated by primed letters. Only then can we adequately identify the polarization parameters of MHD waves and conclude that their certain type prevails in the observed power spectrum of the IMF modulus.

Figure 1, for the general case of the presence of a harmonic signal, shows a polarization ellipse in the reference coordinate system XOY and in the new coordinate system X′OY′, coincident with its main axes (the origin of

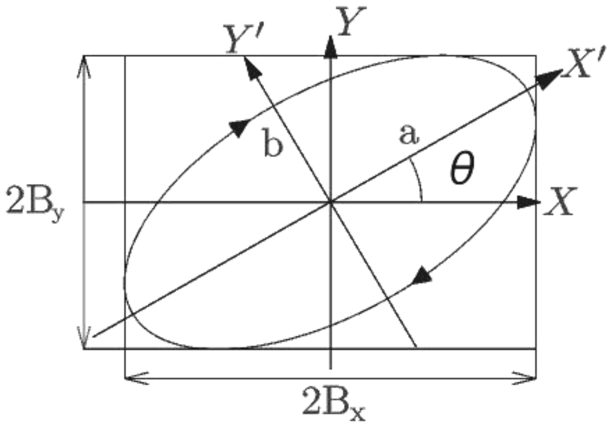

Figure 1. Polarization ellipse in the reference coordinate system XOY and in the X′OY′ coordinate system coincident with the main axes. X, Y and X′, Y′ are the axes of the reference and new coordinate systems; *a* and *b* are the major and minor semi-axes of the ellipse; θ is the polarizing angle; B_x and B_y are IMF components. Arrows on the ellipse indicate the polarization direction

coordinates — point O — is omitted in Figure 1). Using spectral matrices for the IMF vector components in the new coordinate system X′OY′, the polarization parameters can be written as follows.

Degree of polarization:

$$R(\nu)=\sqrt{\left(1-\frac{4\,|P_{xy}(\nu)|}{P_{xx}(\nu)+P_{xy}(\nu)}\right)},\ 0\le R(\nu)\le 1. \qquad (6)$$

Here and below in the formulas, the indices *x* and *y* are the two orthogonal IMF components selected for the analysis from three ones after transforming to the GSE′ coordinate system. Note that the coherence coefficient plays an important role in the polarization analysis since the equality $R(\nu)=\Gamma(\nu)$, must hold between the IMF components X and Y if this plane is the plane of polarization. However, in practice, due to the unavoidable presence of noise in data and a mixture of different waves and fluctuations, their approximate equality holds.

Ellipticity: $\varepsilon(\nu)=\tan\chi(\nu)$,

$$\sin 2\chi(\nu)=\frac{2Q_{xy}(\nu)}{\sqrt{(C_{xx}(\nu)+C_{yy}(\nu))^2-4\,|P_{xy}(\nu)|}}. \qquad (7)$$

If $0\le\chi(\nu)\le\pi/4$, the wave corresponding to the frequency *v* is right-hand polarized (clockwise rotation); if $-\pi/4\le\chi(\nu)<0$, the wave is left-hand polarized (counterclockwise rotation).

The polarizing angle, which is formed by the major semi-axis of the ellipse and the X-axis:

$$\tan 2\theta(\nu)=\frac{2C_{xy}(\nu)}{P_{xx}(\nu)-P_{yy}(\nu)}. \qquad (8)$$

It is important that the direction cosine technique allows using spectral estimates to determine wave propagation directions in the reference coordinate system depending on the frequency *v* for all three components of $\vec{k}$:

$$K_x(\nu)=\frac{Q_{yz}(\nu)}{\sqrt{Q_{xy}^2(\nu)+Q_{xz}^2(\nu)+Q_{yz}^2(\nu)}},$$
$$K_y(\nu)=\frac{Q_{xz}(\nu)}{\sqrt{Q_{xy}^2(\nu)+Q_{xz}^2(\nu)+Q_{yz}^2(\nu)}}, \qquad (9)$$
$$K_z(\nu)=\frac{Q_{xy}(\nu)}{\sqrt{Q_{xy}^2(\nu)+Q_{xz}^2(\nu)+Q_{yz}^2(\nu)}}.$$

At the same time, the condition $K(\nu)=\sqrt{K_x^2(\nu)+K_y^2(\nu)+K_z^2(\nu)}\equiv 1$ must always be fulfilled which is also a validation of determining the MHD wave propagation direction. This approach to determining $\vec{k}$ is valid because the realization length is quite considerable, and the spacecraft velocity is by an order of magnitude lower than the MHD wave propagation velocity, so they can be considered stationary relative to SW. Note that in collisionless SW plasma there are always various kinds of static oscillations and discontinuities frozen in it and carried along with it, which cannot be distinguished from waves on time plots (therefore they are often confused), but they, unlike the latter, have no preferential propagation direction. Note also that the approach we use can be applied to plane waves.

2. RESULTS AND DISCUSSION

We present the results of the analysis of CR and MHD wave fluctuations in SW for two different events. The first event covers the period from 10:04 UT on March 12, 2022 to 10:04 UT on March 13, 2022; and the second, 00:00–23:59 UT on October 18, 2009. These two time periods feature completely different electromagnetic and radiation conditions in Earth's orbit (Figure 2).

In the former case, at 10:05 UT on March 13, 2022, the WIND spacecraft registered a quasi-parallel interplanetary shock wave (ISW) with an angle between the mean IMF direction $\vec{B}_0$ and the normal $\vec{n}$ to the front θ_{Bn}=43.2° and the components of the normal in the GSE coordinate system n_x=–0.586; n_y=0.648; n_z=–0.01 [https://lweb.cfa.harvard.edu/shocks] (see Figure 2, *a*–*c*). It was accompanied by accelerated particle fluxes detected by the ACE spacecraft [https://izw1.caltech.edu/ACE/ASC/index.html], which could generate fast magnetosonic waves (FMSW) in the vicinity of the pre-front [Berezhko, Starodubtsev, 1988]. The latter event (October 18, 2009) corresponds to a quiet period of time: it occurred on the fourth day after a weak SW stream arrived in Earth on October 15 with a low, below 440 km/s, maximum speed (see Figure 2, *d*–*f*).

Let us take a closer look at the March 12–13, 2022 event.

Figure 3, *a* shows the coherence coefficient of CR fluctuations, determined from measurements made by neutron monitors of Tixie Bay and Yakutsk stations. A pronounced peak is seen at *v*=2.41·10^{-3} Hz. The previously identified nature of CR fluctuations [Berezhko, Starodubtsev, 1988; Transkii, Starodubtsev, 1991; Starodubtsev et al., 1996] allows us to assume that there were FMSWs in SW during that time period. To test this

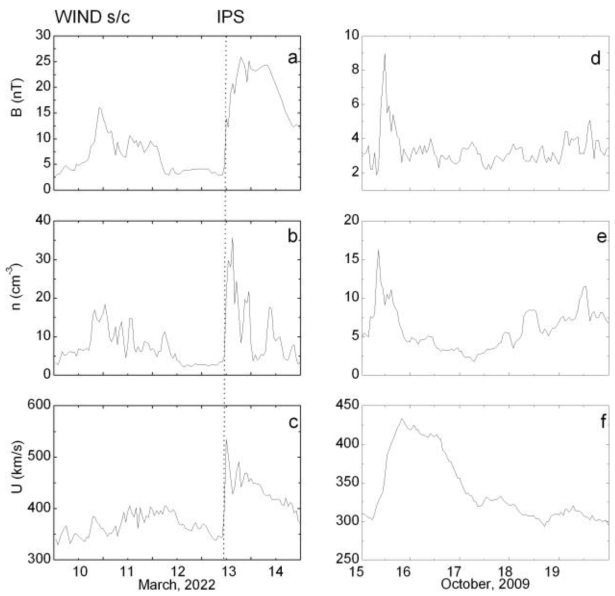

Figure 2. Time dependence of IMF modulus (*a*, *d*), SW density (*b*, *e*) and velocity (*c*, *f*) as measured by the WIND spacecraft for the events of interest in March 2022 and October 2009 respectively. The vertical dotted line marks the time of ISW detection

assumption, we turn to the determination of properties of these waves by analyzing direct measurements of IMF and SW parameters.

Figure 3, *b* depicts power spectra of fluctuations of IMF modulus and components. Powers of the IMF components and modulus are seen to be approximately equal in the frequency range $\nu>10^{-3}$ Hz. This suggests that not only the IMF direction, but also its strength contributes to the observed spectra, which is characteristic of magnetosonic waves [Kovalenko, 1983]. Analysis of the measurement data on IMF, SW parameters, and the coherence coefficient Γ_{Bn} (Figure 3, *c*) leads to the conclusion that in this frequency range the FMSW contribution to the observed power spectrum of IMF modulus fluctuations is ~30 %. Multiplying the above-defined values of the power spectra of the IMF modulus $P_{|B|}$ and the coherence coefficient Γ_{Bn}, we obtain the FMSW power spectrum (Figure 3, *d*).

As is known, MHD waves, unlike discontinuities and static oscillations frozen in SW plasma, are polarized; it is therefore important to determine their characteristics when identifying the type of waves.

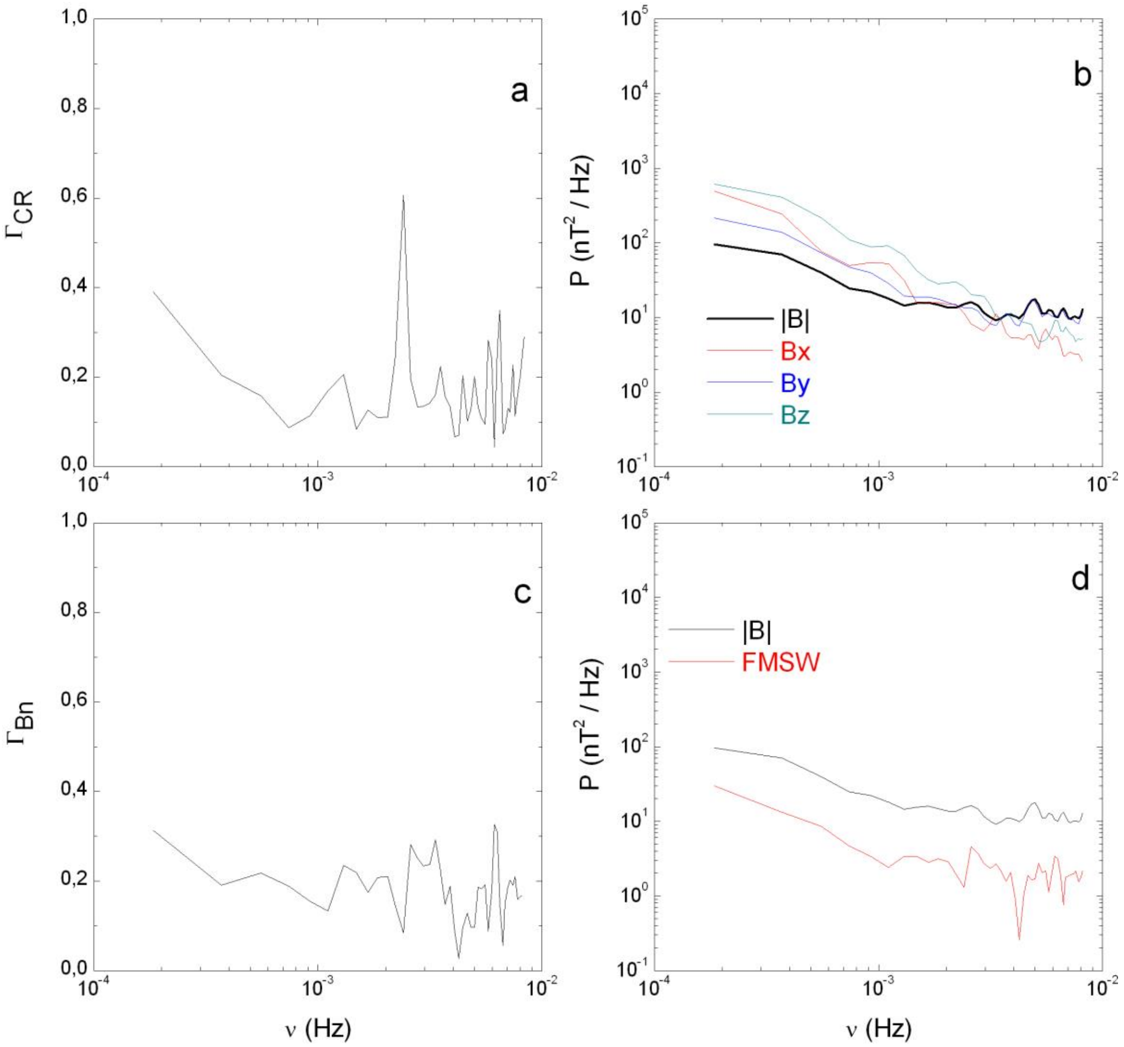

Figure 3. Coherence coefficient of CR fluctuations Γ (*a*); power spectra of fluctuations of IMF modulus and components (*b*); coherence coefficient of IMF modulus *B* and SW density *n* (*c*); power spectra of IMF modulus and FMSW fluctuations (*d*) as a function of frequency ν for the March 12–13, 2022 event

For the event of interest, Figure 4, *a–e* shows the polarization parameters we have determined. Given that the relation $R \approx \Gamma$ must be fulfilled in the plane of polarization, it follows from Figure 4, *a–c* that in the case under study for a wave with $\nu = 2.41 \cdot 10^{-3}$ Hz the plane of polarization is X′Y′ parallel to the plane containing the regular field $\vec{B}_0$ and the wave vector $\vec{k}$. Note that the plane X′Z′ is also parallel to this plane, but it is not a plane of polarization since the condition $R \approx \Gamma$ is not satisfied for it. This also applies to the Y′Z′ plane.

We can conclude that it is X′Y′ that is the plane of polarization, and the MHD wave at $\nu = 2.41 \cdot 10^{-3}$ Hz is magnetosonic. The degree of its polarization $R \approx 0.56$ (Figure 4, *a*), the ellipticity $\varepsilon \approx 0.46$ (Figure 4, *d*), its corresponding angle $\chi \approx 24.7°$, i.e. the wave is right-hand polarized, and the polarizing angle $\theta \approx 176°$ (Figure 4, *e*). The $\vec{k}$ components at $\nu = 2.41 \cdot 10^{-3}$ Hz in the reference coordinate system GSE $k_x \approx -0.38$, $k_y \approx -0.83$, $k_z \approx -0.41$ (Figure 4, *f*).

Let us analyze the October 18, 2009 event. In Figure 5 is the same information for this event as in Figure 3 for the March 12–13, 2022 event. The coherence coefficient of CR fluctuations at $\nu \approx 10^{-3}$ Hz is seen to have a small peak $\Gamma_{CR} \approx 0.4$, which can be taken as a marker of the presence of FMSW in SW (Figure 5, *a*). However, in the observed spectrum of fluctuations of IMF components and modulus (Figure 5, *b*), the IMF modulus power is much lower than the power of its components. Thus, field direction variations, rather than its strength, mainly contribute to the spectrum of fluctuations. This in turn indicates the presence of a considerable number of Alfvén waves (AW) in SW. The field coherence coefficient *B* and the SW velocity *U* are shown in Figure 5, *c*. Referring to the Figure, the AW contribution to the observed IMF spectrum varies from a few to 50 % at different frequencies. The relationship between the observed spectrum of IMF modulus fluctuations and the AW spectrum is illustrated in Figure 5, *d*.

The results of the polarization analysis confirm our conclusion that Alfvén MHD waves predominate in this event. Figure 6, *a* shows that the IMF vector fluctuations occur in the Y′Z′ plane perpendicular to the plane containing the regular field $\vec{B}_0$ and the wave vector $\vec{k}$, thereby indicating the presence of AW. In Figure 6, *b–c* are polarization parameters: ellipticity, direction of rotation, and polarizing angle at each frequency characteristic of the entire AW ensemble. Figure 6, *d* sheds light on the AW propagation direction in SW.

Numerous measurements and analysis of the MHD wave properties suggest that Alfvén waves are present in SW in at least 80 % of cases [Neugebauer et al., 1978; Toptygin, 1983; Kovalenko, 1983]. It is also known that due to the small damping decrement they propagate from the place of their generation in a source on the Sun or in interplanetary space far beyond Earth's orbit, and also that whenever they are detected we should not expect the occurrence of significant CR intensity fluctuations.

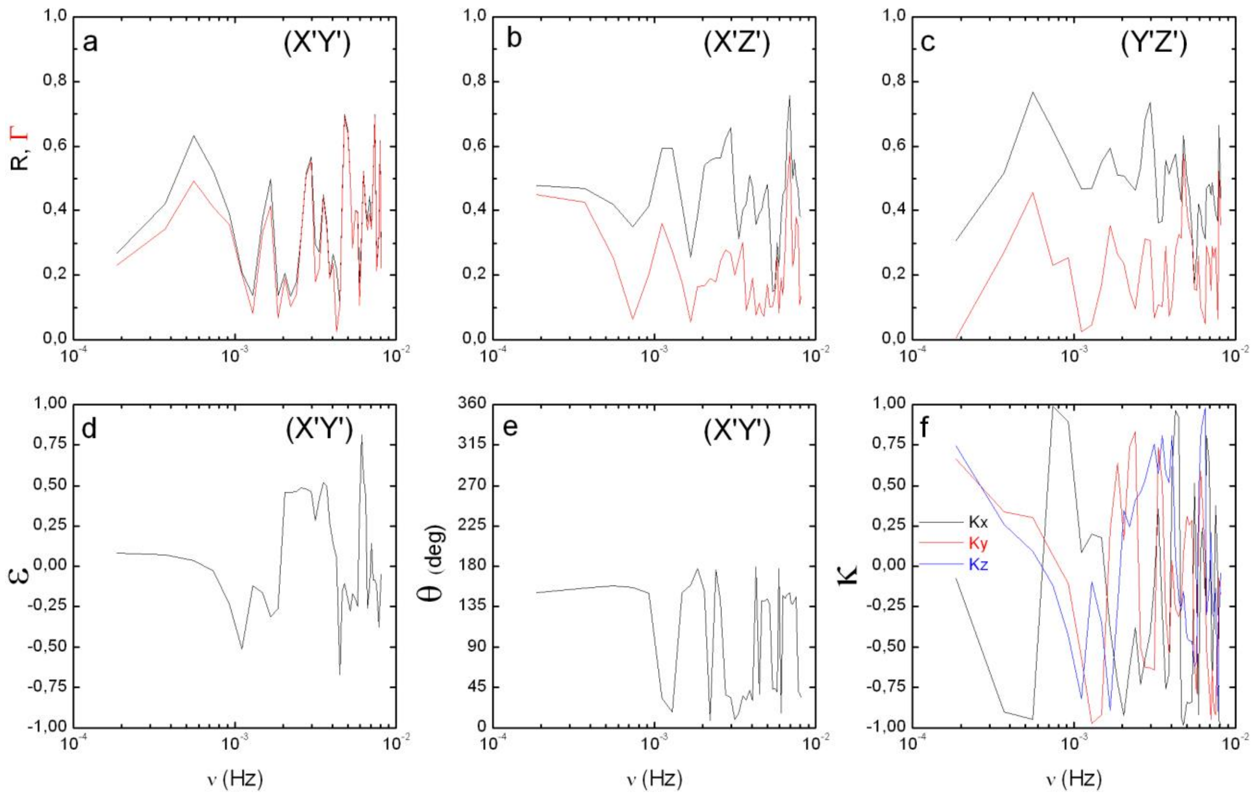

Figure 4. Polarization parameters after transforming to a new coordinate system for the March 12–13, 2022 event: degree of polarization *R* and coherence coefficient Γ of the IMF components B'_x and B'_y (*a*), B'_y and B'_z (*b*), B'_y and B'_z (*c*) in the planes X′Y′, X′Z′, and Y′Z′ respectively; ellipticity ε (*d*); polarizing angle θ (*e*) in the plane X′Y′; components of MHD wave propagation direction vector $\vec{k}$ (*f*) as a function of frequency *ν*

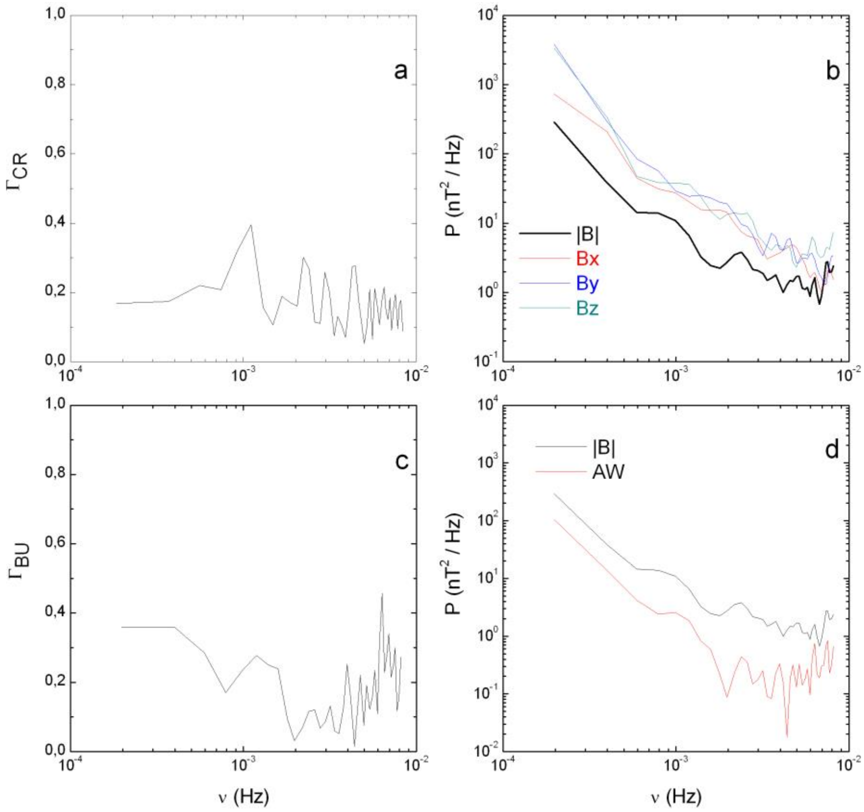

Figure 5. Coherence coefficient of CR fluctuations Γ (*a*); power spectra of fluctuations of IMF modulus and components (*b*); coherence coefficient of IMF modulus *B* and SW velocity *U* (*c*); power spectra of fluctuations of IMF modulus and Alfvén waves (*d*) as a function of frequency *v* for the October 18, 2009 event

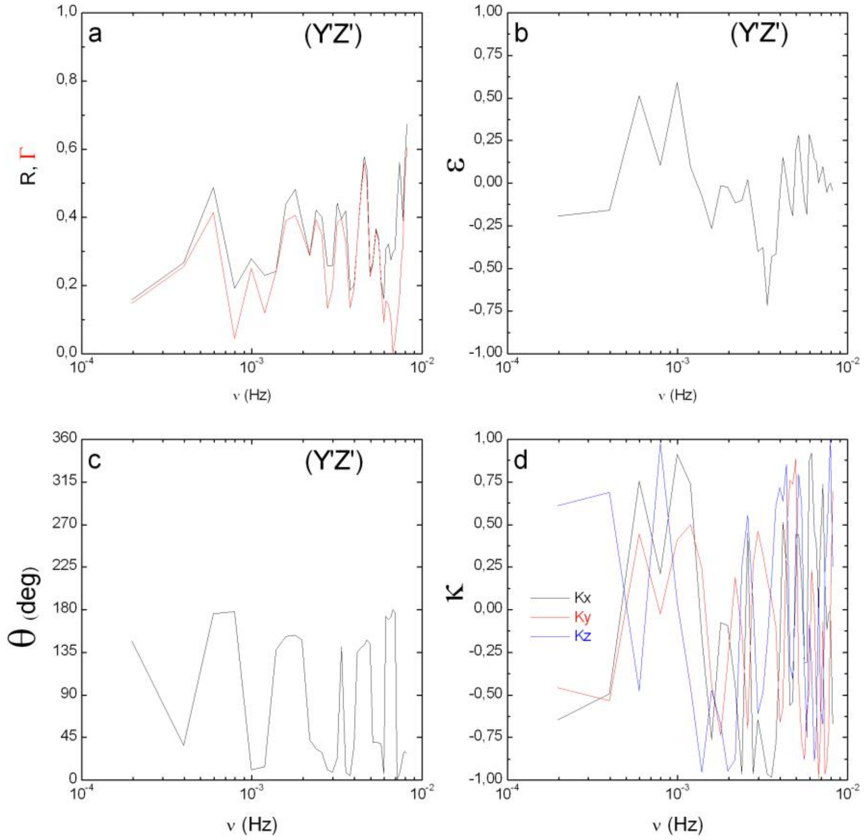

Figure 6. Polarization parameters after transforming to a new coordinate system for the October 18, 2009 event: degree of polarization *R* and coherence coefficient Γ of the IMF components B'_y and B'_z (*a*); ellipticity ε (*b*) and polarizing angle θ (*c*) in the X′Z′ plane; components of the MHD wave propagation direction vector $\vec{k}$ (*d*) as a function of frequency *v*

The results we have received show that when spectra of MHD waves of the three types are adequately identified their sum, within the limits of error, are in fairly good agreement with the observed IMF modulus spectra. The observed small difference can be attributed to static oscillations frozen in plasma and to various discontinuities that are always present in SW. This is confirmed by our calculations of MHD wave spectra for many thousands of realizations of measurement data on IMF and SW parameters from different spacecraft at different levels of solar activity. Figure 7 displays the power spectra of AW, FMSW, and slow magnetosonic wave (SMSW) fluctuations we obtained, their sum, as well as the observed IMF modulus spectrum. Figure 7 demonstrates that within the 95 % confidence interval the sum of the spectra of MHD waves of all three types agrees well with the observed IMF modulus spectrum. This once again confirms the validity of the methods we use to identify MHD waves in collisionless SW plasma.

CONCLUSIONS

The analysis we have carried out allows the following conclusions to be drawn:

1. The appearance of pronounced peaks in variations of the coherence coefficient of CR intensity fluctuations corresponding to the SW turbulence spectrum inertial region indicates the presence of FMSW in the interplanetary medium.

2. We have demonstrated that it is possible to determine the contribution of all three branches of MHD waves in SW (Alfvén, fast and slow magnetosonic) to the observed power spectra of IMF modulus fluctuations in the SW turbulence spectrum inertial region ($10^{-4}<\nu<10^{-1}$ Hz), using spectral analysis methods based on direct measurements of IMF and SW parameters.

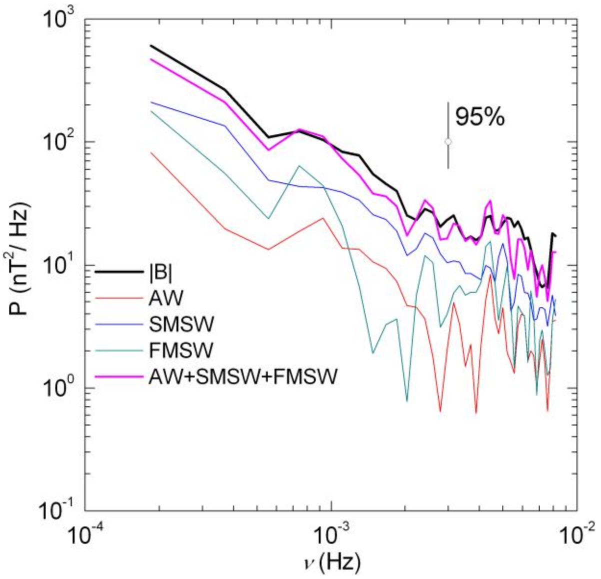

Figure 7. Observed power spectrum of |*B*| fluctuations; obtained power spectra of Alfvén (AW), fast (FMSW), and slow (SMSW) magnetosonic waves, as well as their sum (AW+SMSW+FMSW) for March 21, 2021. The confidence interval is 95 %. WIND spacecraft one-minute measurements of IMF and SW parameters are used

3. We have shown that it is possible to determine the polarization characteristics (plane of polarization, ellipticity, direction of rotation, and polarizing angle) and propagation direction of MHD waves of magnetosonic and Alfvén types from direct measurements of IMF.

4. We have found out that when the spectra of MHD waves of the three types are adequately determined, their sum, within limits of error, agrees fairly well with the observed IMF modulus spectra, and a small difference between them can be attributed to static inhomogeneities and oscillations frozen in SW plasma, as well as to discontinuities of various types, which are always present in the interplanetary medium.

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