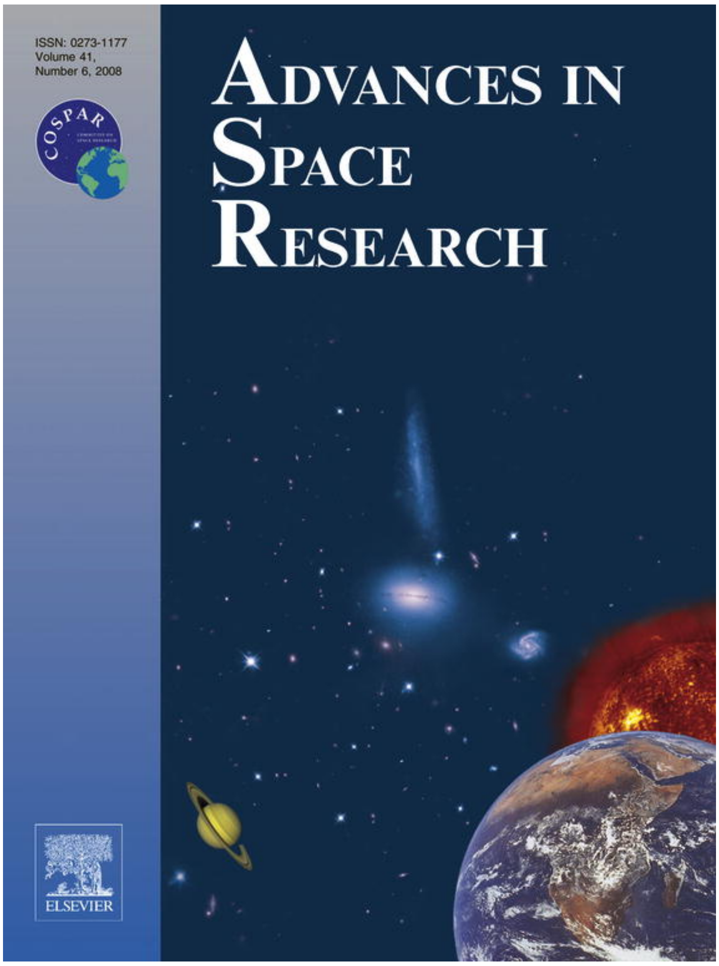
ISSN: 0273-1177
Volume 41,
Number 6, 2008
COSPAR
ADVANCES IN SPACE RESEARCH
ELSEVIER

Available online at www.sciencedirect.com
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Advances in Space Research 41 (2008) 955–961
ADVANCES IN SPACE RESEARCH (a COSPAR publication)
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Fluctuations of cosmic rays and IMF in the vicinity of interplanetary shocks

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Received 7 November 2006; received in revised form 5 April 2007; accepted 12 April 2007

Abstract

Fluctuations of cosmic rays and interplanetary magnetic field upstream of interplanetary shocks are studied using data of ground-based polar neutron monitors as well as measurements of energetic particles and solar wind plasma parameters aboard the ACE spacecraft. It is shown that coherent cosmic ray fluctuations in the energy range from 10 keV to 1 GeV are often observed at the Earth's orbit before the arrival of interplanetary shocks. This corresponds to an increase of solar wind turbulence level by more than the order of magnitude upstream of the shock. We suggest a scenario where the cosmic ray fluctuation spectrum is modulated by fast magnetosonic waves generated by flux of low-energy cosmic rays which are reflected and/or accelerated by an interplanetary shock.

Keywords: Cosmic rays; Solar energetic particles; Interplanetary shock; Turbulence

1. Introduction

Cosmic ray (CR) intensity is measured for decades both at the ground (energy of cosmic rays above 500 MeV) and in space (usually lower energies – from keV up to 100 MeV). The measured intensity varies on different time scales from minutes up to decades and more. These variations of CR intensity can be divided in stationary and non-stationary. The former are determined by cyclic processes such as the solar cycle (11- and 22-year cycles), solar rotation (27 days), Earth's rotation period (diurnal). The later include Forbush decreases, solar energetic particle, energetic storm particle events as well as short-time variations with the time scale from minutes to few hours, called also rapid CR fluctuations (RCRF). While mid- and long-term variations have been intensively studied and are well understood now, RCRF are least studied. They have been discovered about 40 years ago (Dhanju and Sarabhai, 1967), but their source was not clearly defined (Dorman and Libin, 1985).

The RCRF in space (using direct in situ observations) are poorly studied. Most of the results have been obtained 20–30 years ago and can be summarized as follows. Simultaneous measurements of CR and IMF spectra have been studied for a number of strong solar disturbances to show that RCRF spectra are in agreement with IMF spectra, and their temporal variations agree within a few minutes. This led to a conclusion that RCRF originate from IMF fluctuations (the nature of IMF fluctuations is not known though). For low-energy (<100 MeV) CR, a basic theoretical consideration was presented by Dorman et al. (1977) for fluctuations of the CR distribution function in a strong regular magnetic field with random irregularities (Larmor radius smaller than the correlation length of magnetic field irregularities). Unfortunately, that work was not finished so that it is hardly possible to compare experimental and theoretical estimates of the RCRF spectrum.

The phenomenon of RCRF has been studied systematically by means of ground observations (e.g., Kozlov et al.,

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doi:10.1016/j.asr.2007.04.044

2003; Starodubtsev et al., 2004; Starodubtsev et al., 2006 and references therein), including solid evidence of their interplanetary origin. The following points can be summarized from earlier studies (e.g., Owens, 1974; Dorman and Libin, 1985; Toptygin, 1985; Berezhko et al., 1987; Berezhko and Starodubtsev, 1988; Kozlov et al., 2003):

- Fluctuations of CR with high energy (above 500 MeV) have amplitude of ~1%.
- RCRF have extraterrestrial origin. They are observed at both high-latitude CR stations with narrow acceptance cones and mid-latitude stations with wide acceptance cones, with the decreasing magnitude of fluctuations. The combined effect of atmospheric and magnetospheric variations does not exceed 0.01%.
- Significant dynamic changes of RCRF occur before and during large-scale disturbances of solar wind (SW).
- Spectra of RCRF are closely related to the power spectrum of IMF fluctuations.
- RCRF may be used for diagnostics of the interplanetary medium and the space weather forecasts.

On the other hand, physical mechanisms responsible for RCRF still remain elusive. The main possible mechanisms of RCRF generation are related to the modulation of cosmic ray flux by MHD-waves, either Alfvén or fast magnetosonic waves, during large-scale disturbances in SW (Owens, 1974; Berezhko and Starodubtsev, 1988). However, a question on how does such a modulation depend on the turbulence level of the interplanetary medium is still open. In order to resolve this problem we perform a simultaneous study of both RCRF in a wide-energy range and SW plasma parameters in the vicinity of interplanetary shock waves, caused by flare and coronal activity of the Sun.

2. Data and methods

In this work, we analyze RCRF and IMF parameters observed in the vicinity of 177 interplanetary shock fronts during 1998–2003. The data have been obtained by the instruments onboard the ACE spacecraft, which is located in the Lagrangian point L1. Here we analyze 5-min data on the cosmic ray fluxes (J) measured by the EPAM/LEMS30 instrument, which detects protons in eight differential channels (see Table 1). For monitoring of the IMF plasma parameters we use 4-min and 64-s data on the IMF modulus (B), as well as 64-s data on the density (n) and velocity (U) of the SW plasma. In addition we make use of 5-min data of (pressure corrected) count rates (N) of high-latitude neutron monitors Tixie Bay, Apatity and Oulu with the geomagnetic cutoff rigidities of 0.53, 0.65 and 0.81 GV, respectively.

Since the amplitude of fluctuations is very small for all the analyzed variables, we studied them by means of spectral analysis methods. In order to avoid problems related to inhomogeneous data series, we have normalized all CR data, which may vary by orders of magnitude, to the mean level within each 24-h interval. Data on IMF and SW plasma have been off-set by subtracting the mean value for each 24-h interval. After normalization, detrending and off-setting, the series have been high-pass filtered in the frequency band from 10^{-4} to $\approx 2\times10^{-3}$ Hz and processed by the Blackman–Tuckey method (Blackman and Tukey, 1958).

The lower frequency limit (10^{-4}) roughly corresponds to the boundary between energetic and inertial parts of the turbulence spectrum with different properties. The higher frequency bound is defined by the Nyquist frequency. Next, using standard methods, we have computed the spectral power density (P) and the coherence function Γ (defined as a positive square root of the coherence spectrum (Paschmann et al., 2000)) for different variables. The latter is similar to the correlation coefficient but in the frequency domain. Note that the correlation between the fluctuating magnetic, $\delta\mathbf{B}$, and velocity, $\delta\mathbf{U}$, fields suggests that the fluctuations correspond to pure Alfvén waves (Belcher and Davis, 1971; Unti and Neugebauer, 1968), while the correlation between B and n implies the presence of fast magnetosonic waves (Luttrell and Richter, 1987).

3. Theoretical background

First theoretical studies of the distribution function of CR fluctuations have been considered by Shishov (1966). Full theoretical consideration of high-energy (above 1 GeV) cosmic rays has been developed by Owens (1974), that establishes a link between fluctuation spectra of CR and IMF. Basing on the kinematic equation, Owens studied behaviour of charged particles in stochastic IMF with non-zero mean field, considering also resonance interactions between particles and the magnetic field as well as anisotropy of CR flux. The following equation relates spectra of fluctuations for CR, P_{CR}, and IMF, $P_{\mathrm{B}\perp}$,

$$\frac{P_{\mathrm{CR}}(v,\mu,V)}{j_{\mathrm{o}}^2} = C(v,\mu,V)\frac{P_{\mathrm{B}\perp}(v)}{B_{\mathrm{o}}^2}\delta_{\parallel}^2, \tag{1}$$

where B_{o} is the mean IMF strength, j_{o} CR flux, V and μ are the particle's velocity and pitch angle cosine, $\delta_{\parallel}$ CR flux anisotropy, and $C(v,\mu,V)\sim 1$ is a parameter accounting for the nonlinear interaction in the vicinity of resonance frequencies. This formula is in good agreement with the ob-

Table 1
Energy channels of the EPAM/LEMS30 experiment onboard ACE spacecraft

Channel	$P1$	$P2$	$P3$	$P4$	$P5$	$P6$	$P7$	$P8$
Energy (MeV)	0.047– 0.065	0.065–0.112	0.112–0.187	0.187–0.31	0.31–0.58	0.58–1.06	1.06–1.91	1.91–4.75

served spectra of RCRF for low frequencies $\nu < 10^{-4}$ (Owens, 1974). For higher frequencies, power of the observed spectrum is much higher than predicted by the theory, which may be caused by the low anisotropy at high energies. Note that the power of high-energy CR fluctuations is proportional to the squared anisotropy $\delta_{\|}$ (see Eq. (1)), whose pessimistic estimate (for relativistic particles) is $\delta_{\|} \sim U/c \sim 10^{-3}$. Thus, the existence of a small factor ($\sim 10^{-6}$) in Eq. (1) can explain the disagreement between theoretical and observed spectra in the high frequency range.

Stronger effects in the CR intensity are expected in the presence of magentosonic turbulence, because magenotosomic waves modulate not only the tiny anisotropic but also the main isotropic component of CR intensity. The level of magnetosonic waves is low in the undisturbed SW since they damp quickly when moving off the Sun (Toptygin, 1985). On the other hand, they can be effectively excited locally by fluxes of super-thermal particles (Berezhko, 1986, 1990). Therefore, one may expect that CR fluctuation spectra can be significantly modulated with the arrival of energetic particles 10 keV–10 MeV (of solar origin or accelerated in the shock) (Berezhko, 1986). The effect of magnetosonic wave on the CR intensity can be described by the transport equation for CR distribution function:

$$\frac{\delta f}{\delta t} = \nabla_i \kappa_{ij} \nabla_j f - \mathbf{U}\nabla f + \frac{\nabla \mathbf{U}}{3} p \frac{\delta f}{\delta p}, \tag{2}$$

where κ_{ij} is the CR diffusion tensor, and p impulse. According to this equation, a flat magnetosonic wave of small amplitude $\delta u \ll u$ causes periodic variations of the CR distribution function with the amplitude:

$$\delta f = \frac{i\delta\mathbf{U}\nabla f - \frac{\mathbf{k}\delta\mathbf{U}}{3}\frac{\delta f}{\delta p} - i\nabla_i\kappa_{ij}\nabla_j f}{\omega - \mathbf{kU} - i\kappa_\perp \mathbf{k}_\perp^2 - i\kappa_\| \mathbf{k}_\|^2}, \tag{3}$$

where ω and $\mathbf{k}$ are the frequency and wave vector of the wave, $\kappa_\perp$ and $\kappa_\|$ coefficients of perpendicular and parallel diffusion of CR with respect to IMF. The value of $\omega - \mathbf{kU} = C_w k$ is the wave frequency in the co-moving frame, and C_w is the wave velocity. For the energy above $\approx$1 GeV $\kappa > 10^{20}$ cm^2 s^{-1}, and the term $C_w k$ in the denominator can be neglected in the considered frequency range $\nu > 10^{-4}(\nu = \omega/2\pi)$. Moreover, taking into account that $k^{-1} > 1$AU and $|\delta f/\delta r|/f \approx 3\%/$AU in the interplanetary medium, one can neglect also terms containing gradient of the CR distribution function (Toptygin, 1985). Then assuming, for $E > 1$ GeV, a power law form for the CR intensity $I \sim p^2 f \sim p^{-\gamma}$, one can obtain that

$$\frac{\delta f}{f} = \mathrm{i}\frac{\gamma+2}{3} \cdot \frac{\delta\mathbf{Uk}}{\kappa_\perp \mathbf{k}_\perp^2 + \kappa_\| \mathbf{k}_\|^2}, \tag{4}$$

Anisotropic fluxes of super-thermal particles most effectively excite fast magnetosonic waves perpendicular to IMF (Berezhko, 1986). Therefore, the term $\kappa_\| \mathbf{k}_\|^2$ can be neglected in comparison with $\kappa_\perp \mathbf{k}_\perp^2$. Then taking into account that $\mathbf{k} \perp \mathbf{B}$, $C_\mathrm{w} = \sqrt{C_\mathrm{a}^2 + C_\mathrm{s}^2}$ and $C_\mathrm{a} \sim C_\mathrm{s}$ in the solar wind, the amplitude of velocity can be expressed via the magnetic field amplitude as $\delta\mathbf{U}\mathbf{k} = \sqrt{2}(\delta B/B)kC_\mathrm{a}$. Note that $C_\mathrm{a} = B_\mathrm{o}/\sqrt{4\pi\rho}$ is the Alfvén velocity and $C_\mathrm{s} = \sqrt{\gamma_\mathrm{g} P/\rho}$ is the magnetosonic velocity, where B_o is the mean IMF magnitude, $\rho = m_\mathrm{p} n$ the SW density, m_p proton's mass, n proton concentration in SW, $\gamma_\mathrm{g} = 5/3$ corresponds to the fully ionized gas, $P = nkT$ is the pressure. This leads to the expected relation between power spectra of CR and IMF:

$$\frac{P_\mathrm{CR}(\nu)}{f_\mathrm{o}^2} = \left(\frac{\gamma+2}{3\pi} \cdot \frac{C_\mathrm{a}(C_\mathrm{w} + U\sin\phi)}{\sqrt{2}\kappa_\perp \nu}\right)^2 \frac{P_\mathrm{B}(\nu)}{B_\mathrm{o}^2}, \tag{5}$$

where ϕ is the angle between SW velocity and the mean IMF directions.

For relativistic electrons, the term in parentheses in Eq. (5) is $7.1 \times 10^{-8}(\sin\phi + 0.\ \ 16)^2/\nu^2$, assuming $\gamma = 2.7$, $C_a \approx 43$ km s^{-1}, $U \approx 400$ km s^{-1}, $\kappa_\perp = (\rho c/3)\ (\rho/\lambda_\|)$, gyroradius $\rho = E/(300B)$, scattering path length $\lambda_\| \sim 1$ AU (Toptygin, 1985). For the frequency range $\nu > 10^{-4}$, this term is about $10^{-2} \div 1$, which is by several orders of magnitude larger than in a case when the turbulence is presented only by Alfvén waves (See Eq. (1)).

Therefore, an assumption on modulation of the CR intensity by fast magnetosonic waves (through fluctuations of the SW density) leads to agreement between observed and theoretically expected spectra in the frequency range $\nu > 10^{-4}$ Hz. The above consideration is valid only for high-energy particles, and has been verified by data from ground-based measurements (Berezhko and Starodubtsev, 1988; Starodubtsev et al., 1996).

Unfortunately, analytical relations between CR and IMF fluctuation spectra have not been so far derived for lower energy particles, which makes it difficult to extend the theory into the energy range covered by space-borne observations.

4. Results and discussions

One can roughly split the CR flux in the vicinity of the Earth in two main populations of different origin. One compounds high-energy CR (above 100 MeV) originating mostly from the galaxy. The other includes CR of lower energy, which have solar/heliospheric origin. Cosmic rays of different populations interact with interplanetary shocks in different ways and thus have different dynamics on different time scales. We note that the majority (more than 75%) of all events with interplanetary shock (IPS) studied here were accompanied by significant increases of lower energy CR fluxes. Those were either solar energetic particles (SEP) or particles related to the shock front – accelerated and/or reflected by the front – the so-called energetic storm particles (ESP).

A typical example of such IPS and its effects in CR is shown in Fig. 1. This IPS was related to a X1/2B solar flare

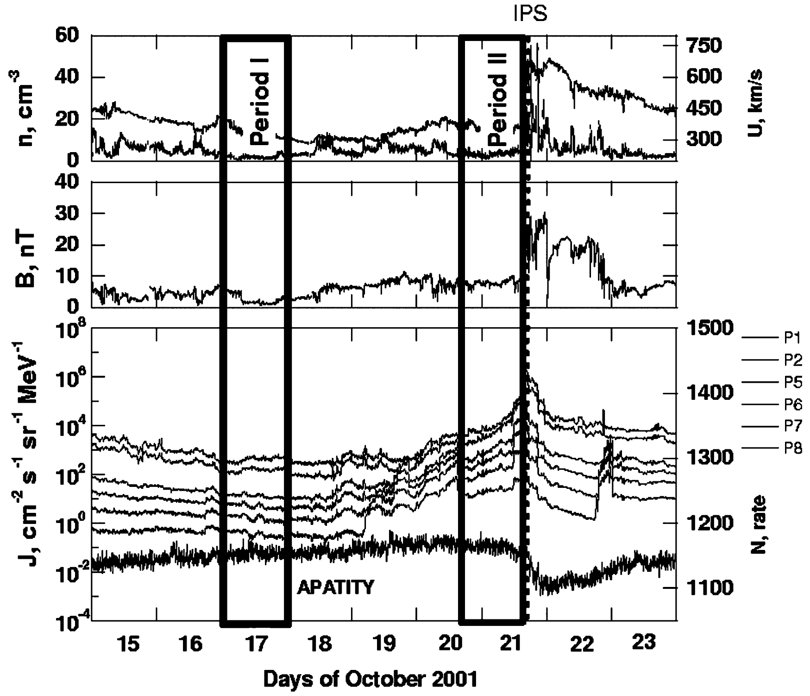

Fig. 1. Variations of the parameters of solar wind plasma (upper panel), IMF strength (middle panel) and cosmic ray intensities in different channels of ACE and Apatity NM (lower panel) for the event of 21 October 2001. Vertical grey bars denote two periods selected for further analysis: quiet conditions 00-24 UT 17 October 2001 (period I); and period before IPS 16 UT 20 October 2001–16 UT 21 October 2001 (period II). The dotted line denotes the interplanetary shock front.

occurred at 16:30 UT on 19 October 2001 in the active region 9661 located at the helio-coordinates N15W29 on the solar disc. After the flare, a halo-type coronal mass ejection has been registered. An associated increase of SEP with energy above 10 MeV has been detected at the Earth's orbit at 22:25 UT (http://umbra.nascom.nasa.gov/SEP/seps.html). Components of the vector, defining the shock normal in the RTN-coordinate frame, were $n = (0.8790;\ 0.0701;\ -0.4716)$ (http://www.ssg.sr.unh.edu/mag/ace/ACElists/obs_list.html), implying that the shock was propagating almost towards the Earth. One can see from Fig. 1 that a significant increase of ESP was observed at the ACE spacecraft about 2 days before the arrival of the shock. A spike was observed during the passage of IPS through the ACE at 16:12 UT 21 October 2001. Typical pre-decrease and pre-increase of the CR intensity, associated with the shock front passage, were detected at the Earth. After the passage, a significant decrease of CR intensity was observed in all energy ranges both at the spacecraft location and at Earth. A reverse shock from the same source has been detected at 00:13 UT 22 October 2001. We note that the parameters of IMF and SW plasma corresponded to undisturbed conditions during several days before the event. Changes in the RCRF spectra associated with the passage of an IPS are illustrated in Fig. 2c,d. In quiet conditions (period I in Fig. 1), spectra corresponding to CR with energy between 10 keV to few GeV are characterized by chaotic statistically significant fluctuations at different frequencies (Fig. 2c). The fluctuations are not coherent – the coherence function Γ_{P1P6} between $P1$ and $P6$ energy channels takes values between 0.2 and 0.4 (see Fig. 2e). Immediately before the arrival of the bulk of storm particles (period II in Fig. 1), RCRF spectra are qualitatively modified and depict dominant fluctuations around 10^{-3} Hz in all energy ranges (Fig. 2d). The fluctuations are coherent for all energies, with Γ_{P1P6} reaching nearly 1 (Fig. 2f). Similarly high coherence is observed also for the ground-based NM stations. On this basis we believe that contribution of fast magnetosonic waves into the observed MHD-turbulence spectrum is significant in the vicinity of the shock front. More detailed spectral analysis of the IMF strength shows that the energy density of MHD-waves in the studied frequency range increases gradually during this event along with the increase of the ESP flux. The power spectrum of IMF fluctuations is also significantly changed when the IPS passes the spacecraft, as shown in Fig. 2a,b: the overall power increases by an order of magnitude and the spectrum becomes harder. The energy density increases by orders of magnitude from 3×10^{-13} ergs cm^{-3} to the maximum of 4×10^{-11} ergs cm^{-3} in the considered frequency band, just behind the front. In order to estimate the contribution of MHD-waves of different types into the observed IMF spectrum one needs direct measurements of the SW plasma parameters. Alfvén waves characterize high correlation between the IMF strength and SW velocity, while fast magnetosonic waves – between the IMF modulus and SW density (Toptygin, 1985; Luttrell and Richter, 1987). Here we study the coherence which is an analogue of the correlation function but in the frequency domain. Fig. 3 depicts the

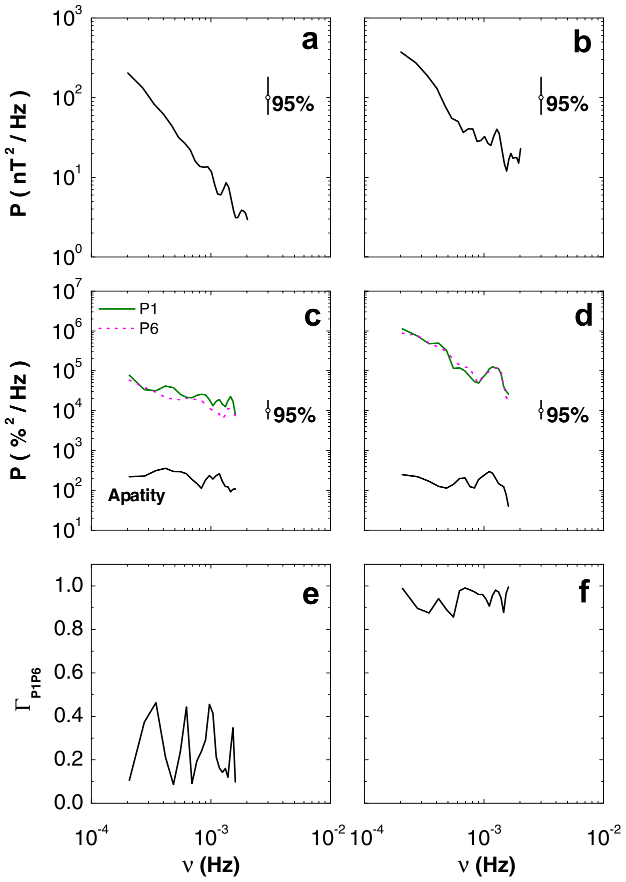

Fig. 2. Power spectrum of IMF fluctuations (upper panels); Cosmic ray fluctuation spectrum for channels $P1$ and $P6$ from the ACE spacecraft as well as for the Apatity NM (middle panels); Coherence function of CR fluctuations for the data from ACE $P1$ and $P6$ channels (bottom panels). Left-hand and right-hand panels correspond to the periods I and II in Fig. 1, respectively. 95% confidence intervals are denoted.

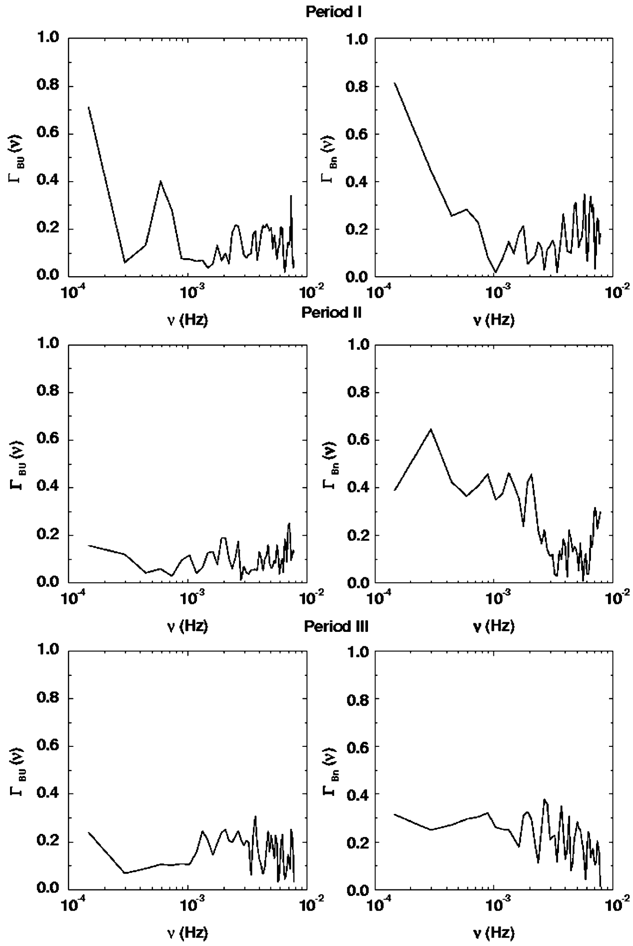

Fig. 3. Coherence function of SW and IMF fluctuations for the data from ACE correspond to the periods I, II and III, respectively.

coherence function for three time intervals marked by rectangles in Figs. 1 and 4. One can see that the type of coherence is different for the different intervals. Estimates of the coherence function Γ_{Bn} between the density and strength of IMF show that the contribution of magnetosonic waves into the turbulence spectrum (in the frequency range around 10^{-3} Hz) increases up to 40%, while the fraction of Alfvén (estimated as Γ_{BU}) drops to 10%, upstream of IPS (Fig. 3). Note that this is dramatically different from the quiet conditions, when Alfvén waves dominate (up to 80%) in the turbulence spectrum, while the contribution of magnetosonic waves is small. Thus, an analysis of the data on direct measurements of the parameters of IMF and SW plasma supports the conclusion about generation of fast magnetosonic waves in the upstream region of an interplanetary shock, obtained from the study of CR fluctuations.

Note also the effect of isotropization of fluctuations of high energetic CR during a passage of IPS (Starodubtsev et al., 1999). We interpret this as a result of the presence of magnetosonic waves in the foreshock region of IPS.

The picture discussed above is typical for all events analyzed here, where an IPS was accompanied by strong fluxes of SEP or ESP.

Qualitatively different event with IPS of 13 January 1999 is shown in Fig. 4. The shock normal RTN-coordinates for this IPS were $n = (0.3777; 0.7294; 0.5704)$, implying that it crossed the Earth by its west wing. Accordingly, it was not spectacular in observed CR flux, neither at Earth nor at the ACE location, in contrast to the central IPS analyzed above. Fig. 5a shows spectra of CR fluctuations in channels $P1$ and $P6$ of ACE as well as Oulu neutron monitor. Fig. 5b shows coherence between $P1$ and $P6$ ACE channels in the upstream region (grey bar in Fig. 4). One can see that the spectra and coherence are qualitatively similar, in this case without strong SEP fluxes, from those shown in Fig. 2c,e to undisturbed SW conditions (period I in Fig. 1).

The general picture of generation of RCRF upstream of an interplanetary shock can be interpreted as follows. It is known that CR are effectively accelerated on quasi-parallel regions of the shock front and may escape ahead. In such conditions, flux of lower energy (10 keV–10 MeV) solar or storm particles may excite MHD-waves, both Alfvén and magetosonic (Berezhko, 1986; Reames, 1989; Ber-

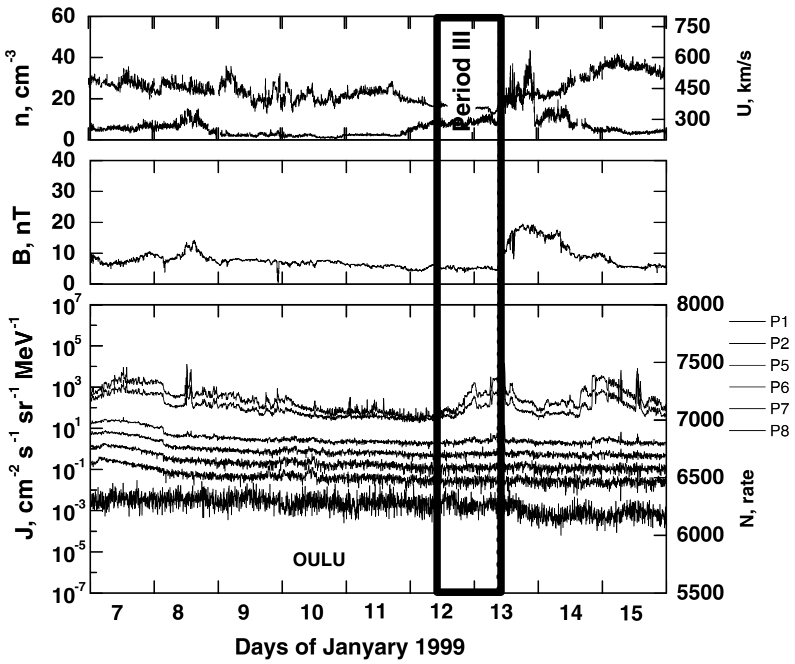

Fig. 4. The same as in Fig. 1 but for the event of 13 January 1999. The vertical bar denotes the period selected for further analysis: before IPS.

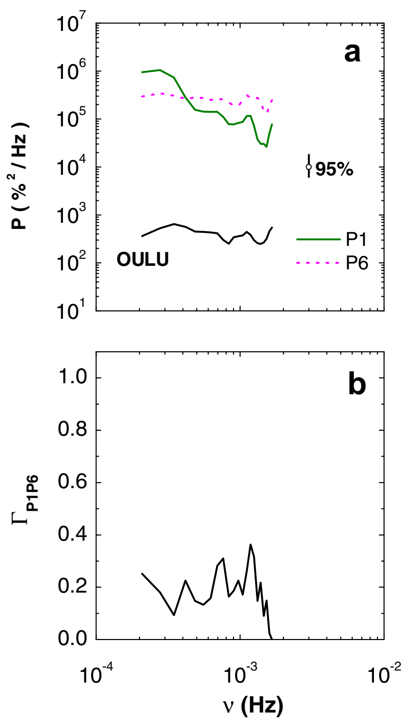

Fig. 5. Cosmic ray fluctuation spectrum for channels $P1$ and $P6$ from the ACE spacecraft for the period marked in Fig. 4 (a); Coherence coefficient of CR fluctuations for the data from ACE $P1$ and $P6$ channels (b). 95% confidence intervals are denoted.

ezhko, 1990; Vainio, 2003). The efficiency of wave generation depends mainly on the magnitude of gradient and flux of CR. It is important that the resonance frequency of CR interaction with IMF inhomogenities, in case of CR flux modulation by Alfvén waves depends on the energy of CR (see Fig. 6). On the other hand, such a frequency-vs-energy dependence is not expected in case of CR modulation by fast magnetosonic waves. Since CR particles move preferably along the IMF field lines frozen in the SW plasma, all variations of the SW density should be reflected in the CR flux changes, irrespectively of the particle's energy. Therefore, the fact that CR fluctuations are coherent in a wide-energy range (from 10 keV up to few GeV) favors our interpretation that CR flux is modulated by magnetosonic waves in the considered frequency band.

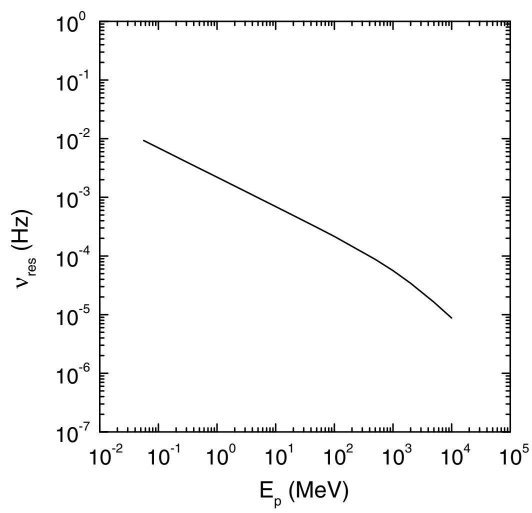

Fig. 6. Frequency ν_{res} of resonance interaction between a proton with energy E_p and Alfvén wave in the quiet solar wind ($B_o = 5$ nT, $U = 400$ km s^{-1}).

5. Conclusions

We have analyzed a large number (177) of events with interplanetary shocks and their effect on cosmic rays and interplanetary plasma parameters. From the analysis we can draw the following conclusions.

- Coherent cosmic ray fluctuations in a wide-energy range (from 10 keV up to few GeV) often occur in the pre-front region of an interplanetary shock.
- A necessary condition for the occurrence of such fluctuations is the presence of lower energy cosmic rays (from 10 keV to 10 MeV) with large magnitudes of flux and gradient in the pre-front region.
- We suggest that these coherent fluctuations occur due to modulation of CR flux by fast magnetosonic waves.

Acknowledgements

The financial support by the Academy of Finland, the Program of the RAS Presidium No.16, part 3, project 14.2, Complex Integration Project of SB RAS-2006 No.3.10 and the RFBR Grant 06-02-96008-r-East is gratefully acknowledged. We thank the ACE EPAM instrument team and the ACE Science Center and Apatity Cosmic Ray Station for providing the data online.

References

Belcher, J.W., Davis, L. Large-amplitude Alfvén waves in the interplanetary medium, 2. J. Geophys. Res. 76, 3534–3563, 1971.

Berezhko, E.G. Instability in a shock propagating through gas with a cosmic-ray component. Sov. Astr. Lett. 12, 352–354, 1986.

Berezhko, E.G. Generation of magnetohydrodynamic waves in interplanetary plasma by streams of solar cosmic-rays. Sov. Astr. Lett. 16, 483–487, 1990.

Berezhko, E.G., Starodubtsev, S.A. Nature of dynamics of a spectrum of cosmic-ray fluctuation. Izv. Akad. Nauk SSSR, Ser. Fiz. 52, 2361–2363, In Russian, 1988.

Berezhko, E.G., Kozlov, V.I., Kuzmin, A.I., Tugolukov, N.N. Cosmic ray intensity micropulsations associated with disturbances of electromagnetic conditions in heliosphere. Proc. 20th Internat. Cosmic Ray Conf., Moscow. 4, 99–102, 1987.

Blackman, R.B., Tukey, J.W. The Measurement of Power Spectra from the Point of View of Communications Engineering. Dover, New York, p. 120, 1958.

Dhanju, M.S., Sarabhai, V.A. Short-period variations of cosmic-ray intensity. Phys. Rev. Lett. 5, 252–254, 1967.

Dorman, L.I., Libin, I.Ya Short-period variations in cosmic-ray intensity. Sov. Phys. Uspekhi 28, 233–256, 1985.

Dorman, L.I., Katz, M.E., Steglik, M. On the Kinetic Theory of Cosmic Ray Fluctuations, 15th Internat. Cosmic Ray Conf., v.3., 76–79, Budapest, 1977.

Kozlov, V.I., Markov, V.V., Starodubtsev, S.A., et al. Ground-based monitoring of cosmic rays and space weather forecast for geoeffective decay phase of the 23rd solar activity cycle. Bull. Russ. Acad. Sci. Phys. 67, 572–574, 2003.

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

Owens, A.J. Cosmic-ray scintillations. 2. general theory of interplanetary scintillations. J. Geophys. Res. 79, 895–906, 1974.

Paschmann, G., Daly, P.W. (Eds.). Analysis Methods for Multi-Spacecraft Data. ISSI Scientific Report, ESA Publications Division, Noordwijk, The Netherlands, 2000.

Reames, D.V. Wave generation in the transport of particles from large solar flares. Astrophys. J. 342, L51–L53, 1989.

Shishov, V.I. Propagation of highly energetic solar protons in the interplanetary magnetic field (High energy solar proton propagation in interplanetary magnetic field by Fokker–Planck equation). Geomagnet. Aeronom. 6, 174–180, 1966.

Starodubtsev, S.A., Transkii, I.A., Verigin, M.I., Kotova, G.A. Intensity fluctuations of cosmic rays and of the interplanetary magnetic field in the region of interaction of solar-wind streams with different velocities. Geomagnet. Aeronom. 36, 241–245, 1996.

Starodubtsev, S.A., Kozlov, V.I., Kudela, K. Effect of isotropization of galactic cosmic ray fluctuations during large-scale solar-wind disturbances. Geomagnet. Aeronom. 39, 499–502, 1999.

Starodubtsev, S.A., Usoskin, I.G., Mursula, K. Papid cosmic ray fluctuations: evidence for cyclic behaviour. Solar Phys. 224, 335–343, 2004.

Starodubtsev, S.A., Usoskin, I.G., Grigoryev, A.V., Mursula, K. Long-term modulation of the cosmic ray fluctuation spectrum. Ann. Geophys. 24, 779–783, 2006.

Toptygin, I.N. Cosmic Rays I Interplanetary Magnetic Fields. D. Reidel Publishing Co., Dordrecht, p. 387, 1985.

Unti, T.W., Neugebauer, M. Alfvén waves in the solar wind. Phys. Fluids 11, 563, 1968.

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