ISSN 1062-8738, Bulletin of the Russian Academy of Sciences: Physics, 2007, Vol. 71, No. 7, pp. 991–993. © Allerton Press, Inc., 2007.
Original Russian Text © S.A. Starodubtsev, A.V. Grigor'ev, V.G. Grigor'ev, I.G. Usoskin, K. Mursula, 2007, published in Izvestiya Rossiiskoi Akademii Nauk. Seriya Fizicheskaya, 2007, Vol. 71, No. 7, pp. 1022–1024.

Fluctuations of Cosmic Rays and Interplanetary Magnetic Field in the Vicinity of Interplanetary Shock Fronts

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Abstract—The spectral characteristic of fluctuations of cosmic rays (CRs) and the interplanetary magnetic field in the prefront region of interplanetary shock waves, where coherent CR fluctuations with energies from ~ 10 keV to ~1 GeV are often observed, have been studied. It is concluded that the spectrum of CR fluctuations is subjected to modulation by fast magnetosonic waves generated by low-energy CRs reflected and/or accelerated at the shock fronts.

DOI: 10.3103/S1062873807070295

Long-term observations show that the intensity of cosmic rays (CRs) detected on the Earth and in space changes on time scales from several minutes to several decades or even longer periods. CR-intensity fluctuations (or short-period, from several minutes to several hours, variations) belong to the least studied type of CR variations, although they were revealed almost 40 years ago in ground-based observations [1]. Now there are no reasons to doubt their interplanetary origin [2]. Currently, a large amount of data on their properties has been accumulated; however, to understand more completely the phenomenon of CR fluctuations, it is necessary to establish their physical nature. This problem can be solved to a great extent by simultaneous study of the fluctuation phenomena in CRs of different energies and in the parameters of the solar wind plasma in the vicinity of interplanetary shock waves (that are the most pronounced manifestation of the flare and coronal activity of the Sun).

In this paper, we report the results of studying CR fluctuations and the interplanetary magnetic field in the vicinity of 177 fronts of interplanetary shock waves detected by the ACE spacecraft from 1998 to 2003. The analysis was performed using the 5-min data on the CR proton fluxes J obtained by the EPAM/LEMS30 instrument on ACE board in eight differential channels in the following energy ranges: ($P1$) 0.047–0.065, ($P2$) 0.065–0.112, ($P3$) 0.112–0.187, ($P4$) 0.187–0.310, ($P5$) 0.310–0.580, ($P6$) 0.580–1.060, ($P7$) 1.060–1.910, and ($P8$) 1.910–4.750 MeV. We used also the 4-min data on the magnitude B of the interplanetary magnetic field and the density n and velocity U of the solar wind plasma. In addition, we used 5-min pressure-corrected data (N) of the neutron monitors located at high-latitude CR stations at Tixie Bay, Apatity, and Oulu, with geomagnetic cutoffs of 0.53, 0.65, and 0.81 GV, respectively.

Since the fluctuation amplitudes in the frequency range from $\sim 10^{-4}$ to 1.67×10^{-3} Hz of all studied physical quantities are small, methods of spectral analysis were used for their selection. As a result, the densities P of the power spectra and the coherence coefficients γ between different physical quantities were calculated according to the standard technique [3]. Note that the coherence coefficients should be considered as correlation coefficients generalized to the frequency range.

The CR flux measured at the Earth's surface and in the interplanetary space can be arbitrarily divided into two populations of different nature: high-energy CRs (~100 MeV and higher), which are mainly of galactic origin, and lower energy CRs, produced in the heliosphere. It is known that they differently interact with interplanetary shock waves, a fact that manifests itself in their variations on different time scales. More than 75% studied here events of passage of interplanetary shock waves were accompanied by significant increases of the low-energy CR fluxes. These are either solar CRs or the CRs related to the shock front, accelerated and/or reflected from it. Figure 1 shows a typical example of detection of such an interplanetary shock wave and the effects induced by it in the CR fluxes at the Earth and in space. This shock wave was due to the solar flare of magnitude $X1/2B$ that occurred on October 19, 2001 at 16.30 UT in the active region 9661 with the coordinates 15° N, 29° W. After this flare, a coronal mass ejection of halo type was detected on the Sun at 16.50 UT. At 22.25 UT, a flare of solar CRs with $E_p > 10$ MeV was observed on the Earth's orbit (http://umbra.nascom.nasa.gov/SEP/seps.html). Figure 1 indicates that a significant increase in the low-energy particle fluxes J was observed 2 days before the arrival of the interplanetary shock wave at the spacecraft. During the shock wave arrival on October 21, 2001 at 16.12 UT, a flare was detected by the spacecraft, and classical predecrease and preincrease in the CR intensity were observed on the Earth simultaneously with this flare. After the passage of the shock front, a decrease in the CR intensity at all energies was observed both at the spacecraft and on the Earth. A reverse interplanetary shock wave from this source was detected on October 22, 2001 at 00.13 UT. Note that several days before the shock wave passage, the parameters of the interplanetary magnetic field and the solar wind plasma corresponded to the undisturbed conditions.

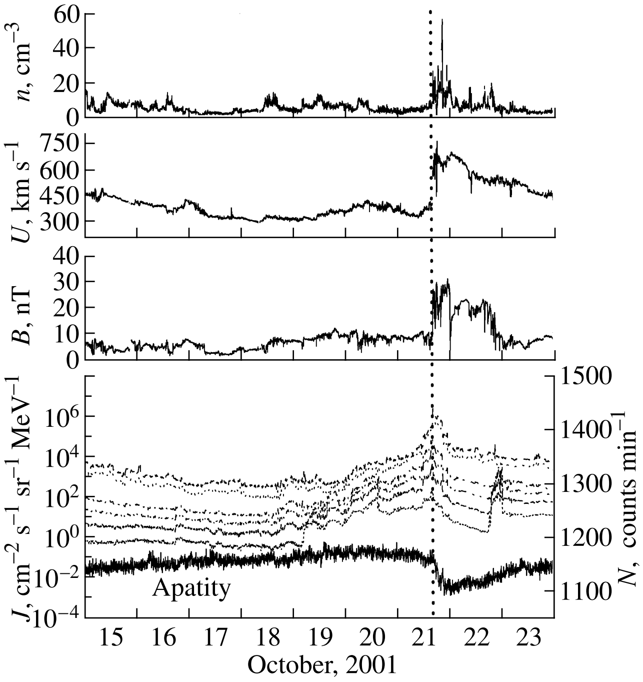

Fig. 1. Variations in the solar-wind plasma parameters n and U; magnitude of the interplanetary magnetic field B; and CR fluxes measured at the ACE spacecraft and the Apatity CR station (J and N, respectively) during the event of October 21, 2001. The dotted lines show the front of the interplanetary shock wave.

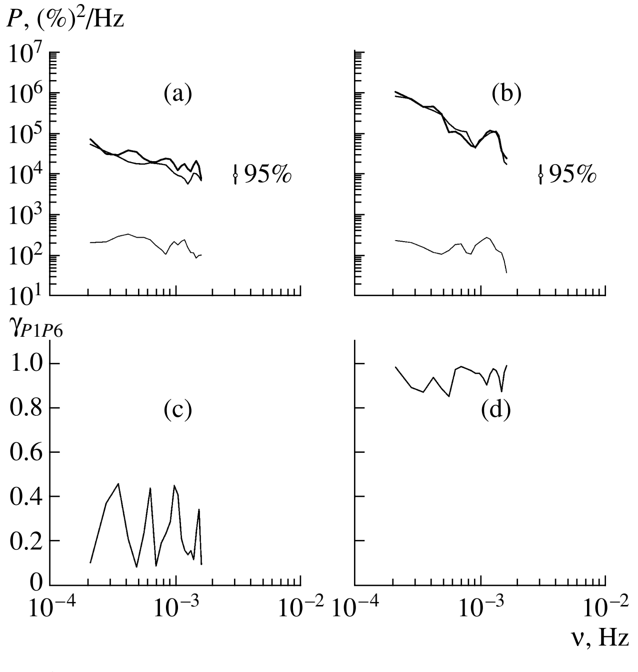

Fig. 2. (a, b) Spectra of CR fluctuations observed at (upper curves) the ACE spacecraft (channels $P1$ and $P6$, thin and bold lines, respectively) and (lower curves) Apatity station for (a) the quiet-Sun period (October 17, 00.00–23.55 UT) and (b) in the shock prefront region (16.05–16.00 UT, October 20–21). (c, d) Coherence coefficients γ of CR fluctuations for channels $P1$ and $P6$, corresponding to the spectra in panels a and b.

The changes occurring in the spectra of CR fluctuations before the shock wave arrival are shown in Fig. 2. It can be seen that before the onset of the increase in the low-energy CR flux J, the spectra of CR fluctuations in the energy range from several tens of kiloelectronvolts to several gigoelectronvolts show the presence of chaotic fluctuations at different frequencies. Immediately with the observed onset of the increase in the flux of low-energy particles in the prefront region, the spectra of CR fluctuations are significantly transformed and show the presence of coherent fluctuations at frequencies in the vicinity of 10^{-3} Hz, independent on the particle energy. In this case, the calculated coherence coefficients $P1$ and $P6$ between the energy channels $P1$ and $P6$ increase almost to unity. The coherence coefficients γ_{P1P6} for the data of the ground-based CR stations behave in the same way. Since the spectrum of CR fluctuations is closely related to the spectrum of fluctuations of the interplanetary magnetic field, this circumstance directly indicates that the contribution of fast magnetosonic waves to the observed spectrum of solar wind turbulence significantly increases in the vicinity of the shock prefront. Spectral analysis of the magnitude of the interplanetary magnetic field shows that during this event, also simultaneously with the onset of the increase in the flux of storm particles, the energy density of magnetohydrodynamic waves gradually increases in the above-mentioned frequency range. Specifically, it increases by an order of magnitude from 3×10^{-13} to 3×10^{-12} erg cm^{-3}, reaching a maximum (4×10^{-11} erg cm^{-3}) directly behind the shock front.

Detailed study of all 177 events of detection of interplanetary shock waves showed that the increase in the level of solar wind turbulence before the shock wave arrival was observed in 121 cases; significant fluxes of low-energy particles, related to the shock front, were observed in 116 cases. Estimation of the turbulence level shows that the energy density of magnetohydrodynamic waves increases from the undisturbed background level by one to three orders of magnitudes (from $\sim 10^{-13}$ to $\sim 10^{-10}$ erg cm^{-3}) during 6–18 h before the shock front arrival. In some cases, it is comparable with the energy density of the undisturbed large-scale interplanetary magnetic field B_0: $E_0 = B_0^2(8\pi)^{-1}$. The maximum turbulence level (up to ~10^{-10} erg cm^{-3}) is observed directly behind the shock front. The analysis performed suggests that the general pattern of distribution of the magnetohydrodynamic turbulence in the vicinity of shock fronts is as follows. The quasi-parallel portions of the shock front exhibit a region (in the form of a tongue with a size of ~0.1 au) of enhanced magnetohydrodynamic turbulence; its existence is in agreement with the conclusions of [4]. This region can be formed as a result of generation of magnetohydrodynamic waves by low-energy (0.01–1.00 MeV) CR fluxes J [5–9], which can be either of solar origin or effectively accelerated in these shock front portions. There is good reason to believe that in this case, along with Alfven waves, fast magnetosonic waves also make a significant contribution to the observed spectrum of solar wind turbulence [5, 7, 9]. Some delay from the onset of increase in the CR flux to the onset of the increase in the turbulence level can be explained by the difference of the velocities of energetic particles and magnetohydrodynamic waves in the solar wind. Since interplanetary shock waves propagate at supersonic velocities, the CR-generated turbulence should drift beyond the shock front; a situation observed in the form of a sharp jump in the energy density of magnetohydrodynamic waves.

To understand the general pattern of occurrence of CR fluctuations in the shock prefront region, it is necessary to take into account the known properties of magnetohydrodynamic waves. Alfven waves are transverse, and scattering of charged CR particles on them is characterized by a resonant frequency related to the CR Larmor radius (or energy). Magnetosonic waves, vice versa, are longitudinal. Their frequency is determined by the oscillation frequency of the density of the solar wind plasma, into which the interplanetary magnetic field is frozen. Hence, CRs, propagating predominantly along the magnetic field lines, undergo oscillations with the oscillation frequency of the solar wind plasma, independent of the Larmor radius (or energy). Therefore, the high coherence for particles with significantly different energies directly indicates that specifically fast magnetosonic waves modulate the CR flux in a wide energy range in the entire frequency range under consideration and are responsible for the occurrence of CR fluctuations.

Thus, on the basis of the investigation performed, we can conclude the following.

(i) It is shown that the presence of low-energy (10 keV–10 MeV) CRs with large gradients before the fronts of interplanetary shock waves and fluxes in the prefront region in a wide range of energies (from several tens of kiloelectronvolts to several gigoelectronvolts) leads to the occurrence of CR fluctuations in the frequency range from ~10^{-4} to 1.67×10^{-3} Hz.

(ii) There is good reason to believe that the occurrence of CR fluctuations in the prefront region is due to the CR flux modulation by fast magnetosonic waves.

(iii) In many cases, a significant increase in the level of solar-wind magnetohydrodynamic turbulence is observed from 6 to 18 h before the shock wave arrival, and the wave energy density increases from ~10^{-13} to ~10^{-10} erg cm^{-3}. The region of quasi-parallel front portions exhibits a characteristic distribution of the enhanced magnetohydrodynamic turbulence (formation of a tongue with a size of ~0.1 au).

ACKNOWLEDGMENTS

This study was supported by the Russian Foundation for Basic Research, project nos. 05-02-16954 and 06-02-96008-r_vostok; the complex integration project SD RAS-2006, no. 3.10; RAS Presidium program no. 16, part 3 (project 14.2); and the Finnish Academy of Sciences. We are grateful to the teams of the ACE Science Center and Apatity CR station (Dr. Sci. (Phys.–Math.) Vashenyuk) for supplying measurement data.

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