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Fluctuations of Energetic Particle Flux during Solar Cycle Based on Measurements in the Solar Wind, in the Magnetosphere, and at Earth

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Abstract—We present the results of our studies of the cosmic-ray fluctuations in the frequency range 10^{-4}-1.67×10^{-3} Hz based on energetic particle flux measurements on spacecraft in the solar wind, in the magnetosphere, and at Earth in the 11-year solar cycle. The cosmic-ray fluctuation spectrum is shown to have an 11-year modulation related to the solar cycle. A different behavior of the level of energetic particle fluctuations measured in different regions of space is observed for cosmic rays of different origins. We conclude that the new, previously unknown phenomenon of 11-year modulation of the cosmic-ray fluctuation spectrum has been established. A possible explanation of this phenomenon is given.

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INTRODUCTION

Continuous measurements of energetic particle intensity variations covering a wide energy range, from several keV to tens of GeV, have been carried out on various spacecraft and at ground-based cosmic-ray (CR) stations for several decades. The studies of various authors show that the temporal CR intensity variations occur on time scales from minutes to decades and longer. As a rule, preference is given to the study of variations with periods from 1 day. In many respects, this is because the physics of the CR variations in this range of periods is known fairly well; various kinds of models and theories describing these phenomena have been developed. It has been established that the observed CR flux can be divided into two populations: Galactic and heliospheric (e.g., solar or those accelerated at interplanetary shock fronts) CRs. The boundary between them is rather arbitrary and is near an energy $E \sim 100$ MeV. It has also been established that the intensities of CRs of different origins behave differently in the 11-year solar cycle. The former anticorrelate and the latter, on the contrary, correlate with the cycle phase.

The situation with the faster CR variations, with periods from several minutes to several hours (the corresponding frequency range is above 10^{-4} Hz), which were called CR fluctuations, is quite different. Although their origin has not been completely established, the studies conducted since the early 1970s have revealed several facts: (1) the CR fluctuation amplitudes are low ($A < 1\%$ of the noise level); (2) the CR fluctuations are heliospheric in origin (Kozlov et al. 1973), but the possible influence of the magnetosphere is not completely ruled out (Dorman and Libin 1985); (3) they result from the presence of large-scale solar wind (SW) disturbances in the interplanetary medium, in particular, solar CRs and interplanetary shocks (Sakai 1986; Kudela et al. 1996; Starodubtsev et al. 2004); (4) the CR fluctuation spectra are closely related to the SW turbulence spectra (Owens 1974; Berezhko and Starodubtsev 1988).

Therefore, studying the behavior of the CR fluctuation power in the solar cycle and comparing it with the well-known behavior of the intensity of CRs of various origins are of considerable interest.

Since the frequency of the large-scale SW disturbances varies in the 11-year solar cycle in a known way, Berezhko et al. (1993) suggested that the fluctuation spectrum of Galactic CRs ($E > 1$ GeV) should also undergo similar variations with the cycle phase. Our first studies using independent ground-based

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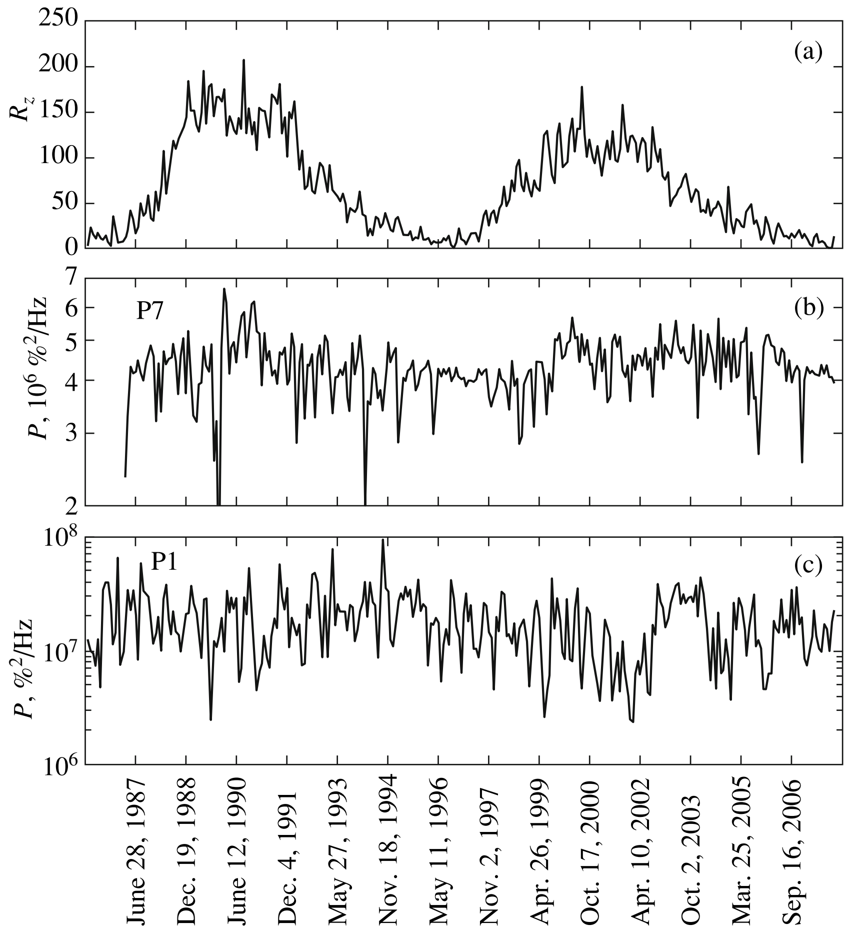

Fig. 1. Time dependence of the sunspot number (a) and the CR fluctuation level in the differential energy channels P7 (165–600 MeV) (b) and P1 (0.6–4.2 MeV) (c) from GOES measurements.

measurements at two different stations showed that this is actually the case (Berezhko et al. 1993; Starodubtsev and Usoskin 2003). However, the questions about the influence of the Earth's magnetosphere on the fluctuations of CRs with different energies in the solar cycle and about the nature of this phenomenon still remain open.

DATA AND THE METHOD

To answer the first question, we studied the dynamics of the CR fluctuations based on data from geostationary spacecraft that were always above the equator at an altitude corresponding to the magnetic shell $L \sim 6.6$. For this purpose, we used 5-min corrected data on the proton fluxes in the energy range 0.6 MeV $< E <$ 500 MeV recorded on GOES 5–11. The measurements in seven differential energy channels in the EPS/HEPAD experiment, the longitude distribution, and the operating time of each spacecraft are accessible at http://spidr.ngdc.noaa.gov/spidr/index.jsp. Although each spacecraft operated only for a few years, our analysis spans the 22-year time interval (from January 1, 1986, to December 31, 2007), covering the solar cycles 22 and 23 almost completely. Simultaneous energetic particle flux measurements on two or three spacecraft were almost always available at that time. Using the fact that the particle detectors were well calibrated between themselves, we suggested that we would be able to study the behavior of the energetic particle fluctuation level in the entire period.

In our calculations, we used the following technique. For each spacecraft, we calculated the daily CR fluctuation spectra in the frequency range 10^{-4}–1.67×10^{-3} Hz for all of the differential channels P1–P7 with energies 0.6–4.2, 4.2–8.7, 8.7–14.5, 15–44, 39–83, 84–165, and 165–500 MeV, respectively. Next, we averaged the calculated spectra for each day for the spacecraft that carried out measurements at this time. This allowed us to obtain the spectral estimates characterizing the CR fluctuations for the measurements in the magnetosphere as a whole, irrespective of the longitude at which the

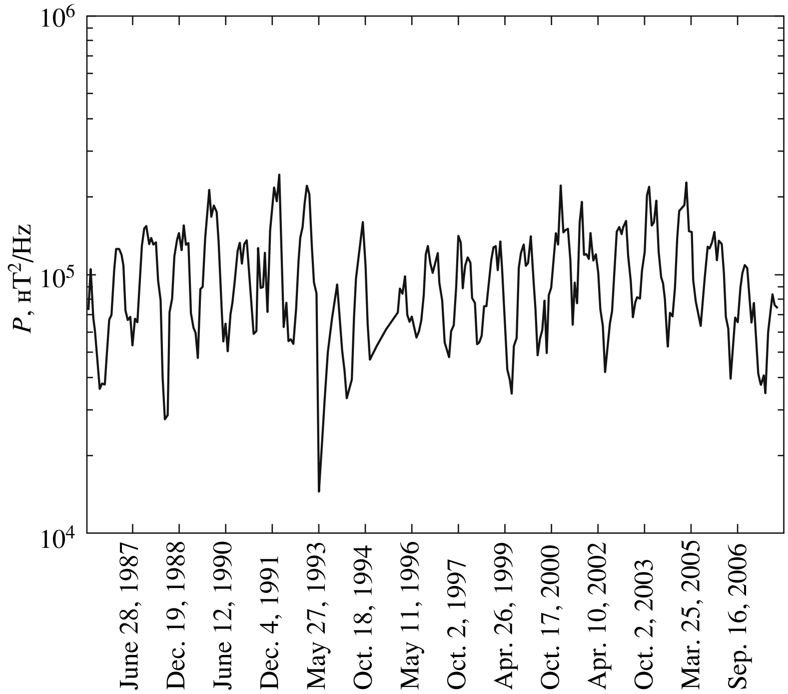

Fig. 2. Time dependence of the level of fluctuations in the total magnetic field vector from GOES measurements.

individual spacecraft was located. Subsequently, to eliminate the possible influence of the solar rotation effects, we performed another averaging over the 27-day Bartels rotations. Finally, for each spectrum obtained in this way, we calculated the mean power of the CR fluctuations in the entire frequency range studied. We took the quantity obtained as the level of CR fluctuations whose dynamics was studied for each solar cycle. Similarly, also based on the 5-min data, we calculated the level of fluctuations in the total magnetic field vector measured on the same spacecraft. For the comparison with other parameters, we also used the 27-day sunspot numbers (http://omniweb.gsfc.nasa.gov/ow.html), the CR fluctuation level calculated from the CR measurements at the Oulu Station, Finland (http://cosmicrays.oulu.fi), and the proton fluxes in two differential channels, P2 and P11, with energies $E = 0.50{-}0.96$ and $E = 145{-}440$ MeV, respectively, recorded on the IMP-8 spacecraft in the CPME experiment (http:// hurlbut.jhuapl.edu/IMP/data/imp8/cpme).

RESULTS AND DISCUSSION

Figure 1 shows the time profiles of the sunspot number R_z and the CR fluctuation levels P in channels P7 and P1 calculated from GOES data. We see from this figure that the fluctuation level of energetic CR in channel P7 (Fig. 1b), generally reflects the variations in the level of solar activity (Fig. 1a) and varies in phase with it. At the same time, however, the fluctuation level of low-energy particles in channel P1 (Fig. 1c), does not show such a clear dependence on the cycle. Given the previous results (Berezhko et al. 1993; Starodubtsev and Usoskin 2003), it can be assumed that this discrepancy is related to the strong influence of the Earth's magnetosphere on the low-energy CR flux fluctuations. It is important to note that the sources of protons in this case are CRs of both heliospheric and magnetospheric origins.

From the previously established facts, one would expect the fluctuations in the fluxes of energetic charged particles to reflect the corresponding variations in magnetic field fluctuations. However, our calculations show that this is not the case at a geostationary orbit. It follows from Fig. 2 that the level of fluctuations in the total magnetic field on the shell $L \sim 6.6$ has a clear dependence on the solar cycle, but, at the same time, large annual field variations are observed, which are completely absent in the CR fluctuations.

Then, given that the belt of low-energy protons extends to the shell $L \sim 7{-}8$ (Panasyuk and Novikov 2007), it can be assumed that the CR fluctuation level in channel P1 varies in accordance with the dynamics of the belt itself, which is determined by the degree of disturbance of the interplanetary medium. In this case, we should take into account the fact that high-velocity SW streams of various kinds that deform the Earth's magnetosphere, affecting the dynamics of the radiation belts and producing various geophysical disturbances, are often recorded even at the minimum of solar activity. This assumption is also justified by the fact that the proton fluxes themselves on $L \sim 6.6$ correlate not only with the solar CRs but also with the SW velocity (Panasyuk and Novikov 2007). The latter can violate considerably the expected dependence of the low-energy CR fluctuation level on the 11-year cycle. However, to understand the specific mechanism of the magnetospheric influence on the CR fluctuations, further systematic studies using data on a large number of magnetospheric parameters are needed.

To answer the second question, about the nature of the observed 11-year variations in the level of energetic particle fluctuations, we studied in detail the frequency spectra of CRs with various energies and their evolution with time based on measurements at Earth and on spacecraft located in the SW (Starodubtsev et al. 2007; Grigoryev et al. 2008). We used data from eight neutron monitors at CR stations with geomagnetic rigidity cutoffs from $R_c = 0.45$ to 6.32 GV (Starodubtsev et al. 2006). Our study of the behavior of the CR fluctuation level led us to conclude that the effect first detected by Berezhko et al. (1993) actually exists. It turned out that the 11-year modulation amplitude changes by a factor of almost 5, decreasing with increasing geomagnetic cutoff of the observing site. This serves as a basis for the assertion that the possible influence of the Earth's magnetosphere on the fluctuations of Galactic CRs with $E > 0.5$ GeV is negligible.

In studying the proton flux fluctuations directly in the SW, we used data in eight differential energy channels on ACE (0.047–4.75 MeV) and in eleven channels on IMP-8 (0.29–440 MeV) (Starodubtsev et al. 2006). The results obtained (Fig. 3) led us to conclude that the fluctuation levels of energetic particles of different origins behave differently in the solar cycle. The behavior of the Galactic CR ($E >$ 100 MeV) fluctuations in the SW closely corresponds to the observed picture from the the measurements at Earth (Figs. 3a and 3b): their level follows the phase of the solar cycle. However, the fluctuations of lower-energy ($E < 100$ MeV) heliospheric CRs on both spacecraft, while changing in the 11-year cycle, show a behavior opposite to that of the sunspot number (Fig. 3c). In this case, however, it is well known that the proton fluxes with considerable gradients are related to large-scale SW disturbances and solar flares and vary with the phase of solar activity.

Since the properties of the CR fluctuations are determined by those of the interplanetary magnetic field (IMF) fluctuations, it is necessary to establish their nature (Alfvénic or magnetosonic) and to study their behavior in the solar cycle. Our studies showed that, in the latter case, there is also a regular 11-year evolution of the experimentally observed inertial part of the IMF fluctuation spectrum (Starodubtsev 1999).

In contrast, in establishing the nature of the IMF fluctuations responsible for the formation of CR fluctuations, we should take into account the fact that Alfvén waves of both solar and heliospheric origins are often recorded at the Earth's orbit owing to their low damping rate (Toptygin 1983). On the other hand, because of the high damping rate, the MHD waves of the magnetosonic branch of the SW turbulence spectrum observed in experiments on spacecraft (Luttrell and Richter 1987) must be generated locally, near the Earth's orbit. It is well known that compressed fluctuation modes like fast magnetosonic waves can be generated in interplanetary space in various ways. In particular, they can develop in the region of interaction between corotating fast and slow SW streams (Kennel and Sagdeev 1967) and can be produced by energetic particle fluxes of a solar or interplanetary origin (Berezhko 1986, 1990; Reames 1989; Vainio 2003). Taking into account the results of these theoretical works and analyzing our results, we concluded that in periods when significant fluxes of energetic particles with $E \sim 0.01$–10 MeV are recorded, the energy of these particles is transferred to Alfvén-type MHD waves with a characteristic scale of 10^{10}–10^{12} cm through the development of hydrodynamic instabilities in the SW plasma. Subsequently, fast magnetosonic waves are generated through conversion as they propagate in the SW. The experiment shows that precisely these waves modulate the CR flux at the same frequencies (above 10^{-4} Hz) in a wide energy range (from $\sim$10 keV to $\sim$10 GeV), giving rise to CR fluctuations (Grigoryev et al. 2008). Prominent peaks are observed at the same frequencies in the fluctuation spectra of CRs and the IMF magnitude. The fluctuation amplitude of the high-energy CRs increases considerably, while that of the low-energy ones decreases relative to the unperturbed noise level.

Note that at present a quantitative theory describing the relationship between the CR and IMF fluctuation spectra has been developed only for Galactic CRs with energies above 1 GeV. Owens (1974) and Berezhko and Starodubtsev (1988) established the relationship of the CR fluctuation spectrum to the Alfvén-type turbulence spectrum and to fast magnetosonic turbulence, respectively. The results of both works show that at frequencies above 10^{-4} Hz, there is a significant discrepancy between theory and experiment for Alfvén waves, while for fast magnetosonic waves this does not take place. This once again convinces us that precisely the magnetosonic

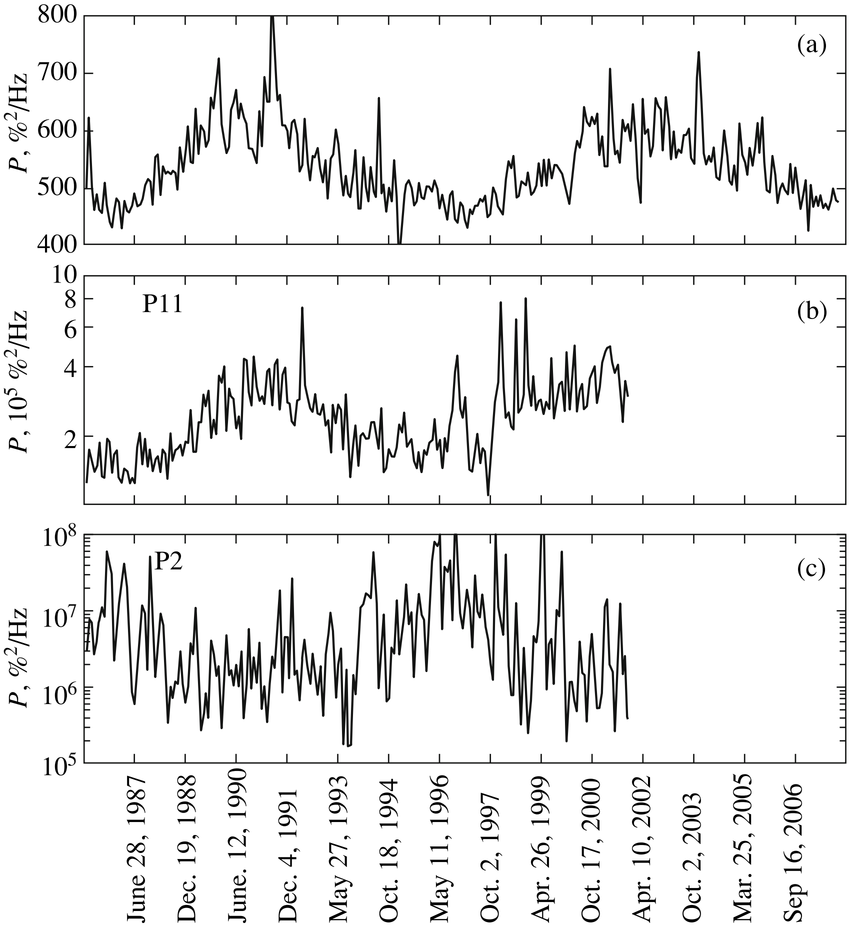

Fig. 3. Time profiles of the CR fluctuation level based on data from the Oulu station (a) and IMP-8 in the differential energy channels P11 (145-440 MeV) (b) and P2 (500–960 keV) (c).

branch of the SW turbulence spectrum is responsible for the formation of CR fluctuations.

Since the time distribution of low-energy heliospheric particles is directly related to the manifestation of solar coronal and flare activity, it becomes clear why the picture of evolution of the CR fluctuation level described above is observed in a wide energy range, from several keV to tens of GeV.

CONCLUSIONS

We established a new, previously unknown phenomenon in CRs, a regular modulation of the fluctuation spectrum of heliospheric and Galactic CRs in the 11-year solar cycle. A significant influence of the Earth's magnetosphere on the long-term modulation of the fluctuation spectrum of CRs with energies $E <$ 100 MeV was detected.

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