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Long-term modulation of the cosmic ray fluctuation spectrum

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Abstract. Here we study the power level of rapid cosmic ray fluctuations in the frequency range of 10^{-4}–$1.67 \cdot 10^{-3}$ Hz (periods from 10 min to about 3 h), using measurements by space-borne instruments for the period since 1974. We find that the power level of these fluctuations varies over the solar cycle, but the phase of this variation depends on the energy of cosmic ray particles. While the power level of these fluctuations in the higher energy channels (corresponding to galactic cosmic rays) changes in phase with the solar cycle, the fluctuation level for lower energy channels (predominantly of solar/interplanetary origin) is roughly in an opposite phase with the solar cycle. The results prove conclusively that these fluctuations originate in the near-Earth space, excluding their atmospheric or magnetospheric origin. We present these new results and discuss a possible scenario explaining the observed energy-dependence.

Keywords. Solar physics, astrophysics and astronomy (Energetic plasma; flares and mass ejections) – Space plasma physics (Shock waves)

1 Introduction

The intensity of galactic cosmic rays (GCR) varies at different time scales, from minutes to decades and even beyond. While the variation of CR flux was extensively studied, much less attention has been paid to the power level of short-term fluctuations. Such fluctuations with periods from minutes to several hours are called rapid CR fluctuations (RCRF). Here we study the long-term variation of the RCRF power level defined as the mean power of RCRF in the frequency range between 10^{-4} Hz and $1.67 \cdot 10^{-3}$ Hz (10 min to about 3 h). The rapid CR fluctuations have been studied since the 1970s using data of the ground-based neutron monitor network (Kozlov et al., 1973; Dorman and Libin, 1985; Sakai, 1986; Kudela et al., 1996; Starodubtsev et al., 2004), and the earlier results can be summarized as follows:

- The amplitude of the RCRF power level is small, typically ≤1%, and therefore special methods of spectral analysis should be applied.
- Significant dynamical changes in the spectra of RCRF are often observed about one day before and during large-scale IMF disturbances.
- It was suggested that the RCRF are of extraterrestrial origin but possible atmospheric or magnetospheric effects could not be excluded (Dorman and Libin, 1985).

The power spectrum of RCRF is related to the spectrum of the turbulence of the interplanetary magnetic field (IMF) (Owens, 1974; Berezhko and Starodubtsev, 1988). In particular, the observed RCRF are caused presumably by scattering of CR particles on local magnetic inhomogeneities, which can be related to waves in the vicinity of the Earth (e.g. Berezhko and Starodubtsev, 1988; Starodubtsev et al., 1996).

The power level of RCRF obtained from data of ground-based neutron monitors is known to vary in phase with the solar activity cycle (Starodubtsev et al., 2004, and references therein). Note that neutron monitors measure primaily the flux of GCR. On the other hand, there are indications that this relation may not be valid for lower energy cosmic rays of solar/interplanetary origin (Starodubtsev et al., 2004). Since low energy particles do not reach the ground, data of space-borne measurements should be used to study this phenomenon.

In this paper we present the results of the first thorough analysis of RCRF using data of space-borne energetic particle measurements.

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Table 1. Energy channels of the two selected space-borne energetic particle experiments.

ACE/EPAM	Energy (MeV)	IMP-8/CPME	Energy (MeV)
P1	0.047–0.065	P1	0.29-0.50
P2	0.065–0.112	P2	0.50–0.96
P3	0.112–0.187	P3	0.96–2.00
P4	0.187–0.310	P4	2.0–4.6
P5	0.31–0.58	P5	4.6–15
P6	0.58–1.06	P7	15–25
P7	1.06–1.91	P8	25–48
P8	1.91–4.75	P9	48–96
–	–	P10	96–145
–	–	P11	145–440

2 Data and analysis method

Energetic particles are recorded on board a number of spacecrafts, in a wide energy range, typically from tens of keV up to hundreds of MeV. Here we need a stable, homogeneous and sufficiently long record of these particles measured by the same instrument nearly continuously. The two most suitable satellites for our purpose are IMP-8 and ACE. The EPAM/LEMS30 (Gold et al., 1998) experiment, on board the ACE (Advanced Composition Explorer) spacecraft, located in the 1st Lagrange point L1, provides a stable series of particle fluxes measured in different energy channels at 300-s time resolution since late 1997. (The ACE data were obtained from http://www.srl.caltech.edu/ACE/ASC/level2/lvl2DATA_EPAM.html.) The bulk of ions detected by the EPAM experiment are protons. The experiment CPME/Protons (Armstrong, 1976) on board the geocentric IMP-8 satellite was in operation from 1973 until 2001, providing a stable record of particle fluxes at about 330-s time resolution. (The data were obtained from http://hurlbut.jhuapl.edu/IMP/data/imp8/cpme/cpme_330s/protons.)

Parameters of the energy channels in the selected experiments are given in Table 1. Note that energy channels P5–P8 of ACE are well related to the channels P1–P4 of IMP-8. On the other hand, the more energetic IMP-8 channels extend to much higher energies, also covering the energy range dominated by galactic CR. While low-energy particles are of local heliospheric origin (solar and/or interplanetary), the more energetic particles (above some hundred MeV) are predominately of galactic origin. In the lower energy range, anomalous cosmic rays are also present, whose contribution into the measured proton flux is, however, relatively small. Using the above mentioned two data sets allows one to study CR fluctuations in the wide energy range from tens of keV to hundreds of MeV.

Since the IMP-8 satellite has an elliptic geocentric orbit with a rotation period of about 12.5 days, it spends a part of the time inside the Earth's magnetosphere (about 5 days per revolution, on average). In order to avoid the magnetospheric effect in the analyzed data, we excluded all of those periods when the IMP-8 satellite was inside the magnetosphere. In order to identify these time intervals, we used the orbital information of IMP-8 provided at ftp://nssdcftp.gsfc.nasa.gov/miscellaneous/orbits/imp8) Not all IMP-8 channels were stable in time, and mid-energy channels suffered a normalization error in 1989 (Lario and Simnett, 2004), which makes them difficult to be used after 1989. However, the low (P1–P2) and high (P11) channels were quite stable throughout the whole interval since 1974, and we base our analysis primarily on these channels.

Before the analysis, the raw data of particle fluxes were pre-processed as follows. We considered only those days where gaps or apparent errors did not exceed 2 h. Days with solar particle events were also excluded. Forbush decreases were not excluded, since their rate of change is slow enough to be filtered out. All measured fluxes J were normalized to the percentage from the average daily flux J_0 to form $I{=}(J-J_0)/J_0 \cdot 100\%$. A linear trend was subtracted from I separately for each day. Finally, the data was band-pass filtered with the bandwidth ($\nu_1 {<} \nu {<} \nu_2$), where $\nu_1{=}10^{-4}$ Hz and $\nu_2{=}1.67 \cdot 10^{-3}$ Hz (period T=600 s) is the Nyquist frequency for the ACE data and $\nu_2{=}1.52 \cdot 10^{-3}$ Hz (T=660 s) for the IMP-8 data. Significant dynamical changes occur in this frequency range corresponding to the rapid fluctuations. We have calculated the daily power spectral density (PSD) of RCRF in the frequency range (ν_1, ν_2). The average power in this frequency range is called the daily p-value. The power level P of RCRF is then defined as the 27-day (Bartels rotation) average of the daily p-values, thus avoiding the possible effect of longitudinal inhomogeneities in the solar wind and corona. Similarly, we calculated the 27-day averages of the particle flux in a given energy channel J and of the PSD index α of the RCRF ($P(\nu) \propto \nu^{\alpha}$) in the frequency range (ν_1, ν_2).

3 Results and discussion

It has been shown earlier (Starodubtsev and Usoskin, 2003; Starodubtsev et al., 2004) that the power level of rapid fluctuations of GCR with energy above a few hundred MeV, as measured by ground-based neutron monitors, varies in phase with the solar cycle, opposite to the intensity of GCR. On the other hand, it was suggested (Starodubtsev et al., 2004) that this pattern may not be valid in the energy range below hundred MeV. Cosmic rays with such low energy cannot be measured by ground-based instruments, and the suggestion was based on a relatively short (four years) period of data from the ACE spacecraft. Hence, the question of the persistence of this phenomenon on longer time scales remained open.

In order to study this effect systematically, we analyzed the data on cosmic ray measurements performed on board the IMP-8 spacecraft, which covers almost three solar cycles.

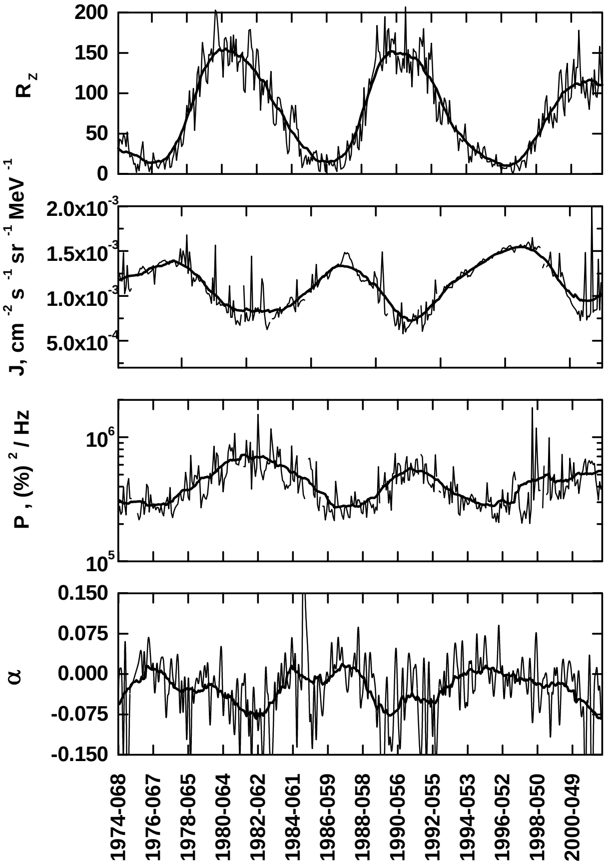

Fig. 1. Time profiles of the sunspot number R_z, particle flux J, CR fluctuation power level P and the PSD spectral index α for IMP-8/CPME (channel P11) data. All data are 27-day averaged. Solid lines depict the corresponding 2-year running means. Time is given in year-DOY.

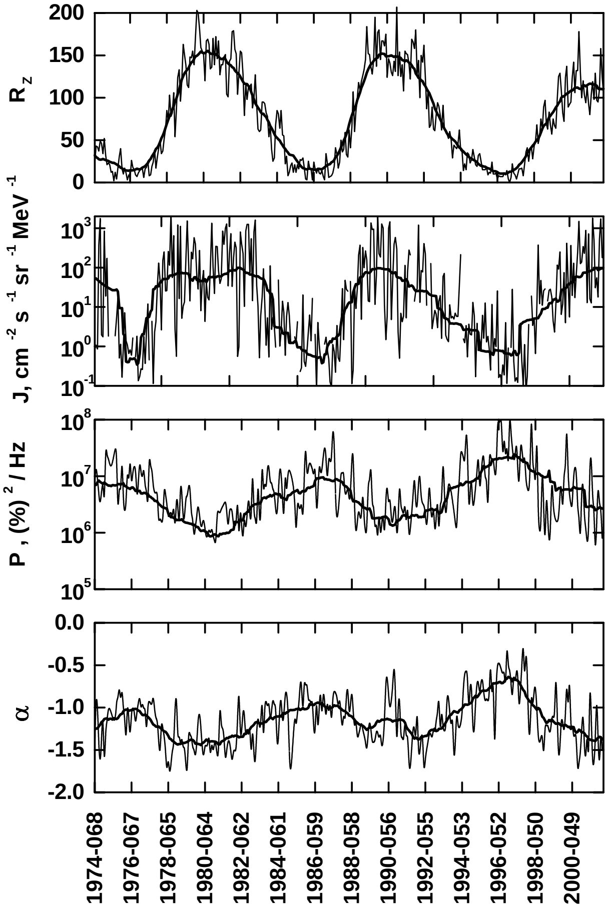

Fig. 2. The same as Fig. 1 but for IMP-8/CPME channel P2 data.

First, we have tested the results for the galactic CR obtained earlier from the ground-based neutron monitor data, which should be comparable with the most energetic P11 (145–440 MeV) channel of IMP-8. Time variations of the indices (flux J, as well as the power level P and the spectral index α of RCRF) are shown in Fig. 1. In the top panel, sunspot numbers are shown to indicate the phase of the solar cycle. One can see that the temporal variations both of the flux J and of the power level P of rapid fluctuations indeed depict the pattern very similar to that inferred from the neutron monitor data: while the flux J varies in the opposite phase with the solar cycle, known as the CR heliospheric modulation (e.g. Potgieter et al., 2001), the power level P of RCRF follows the solar cycle, in agreement with earlier findings; the spectral index α is around zero, indicating a flat shape of the power spectrum of RCRF. It is interesting to note that, while the spectral index α is consistently around zero, it still shows some small variation in anti-phase with the solar cycle. This may be due to some residual contribution of the solar particles. Accordingly, the pattern found for the high-energy (galactic) particles measured by IMP-8 is the same as the one found earlier in neutron monitor data and as expected from the theoretical considerations. This finally confirms the interplanetary origin of the RCRF, since the space-borne data cannot be affected by atmospheric/magnetospheric effects.

Let us now consider the low-energy (IMP-8 P2 channel) particles of solar/interplanetary origin. Their flux, power level of RCRF and the spectral index are depicted in Fig. 2. The particle flux measured by the P2 channel of IMP-8 varies in phase with the solar cycle, in agreement with the solar/interplanetary origin of these particles. However, the power level of RCRF in this energy range changes in anti-phase with the solar cycle, opposite to the galactic particles. The power spectrum is not flat and the spectral index α varies between -0.5 and -1.75 in anti-phase with the solar cycle.

Other energy channels (not depicted) can only be studied during a shorter time period (1974–1989) because of the instrument normalization failure (Lario and Simnett, 2004). Channels P3–P5 (below 15 MeV – see Table 1) reproduce the pattern typical for solar particles depicted by the channel P2

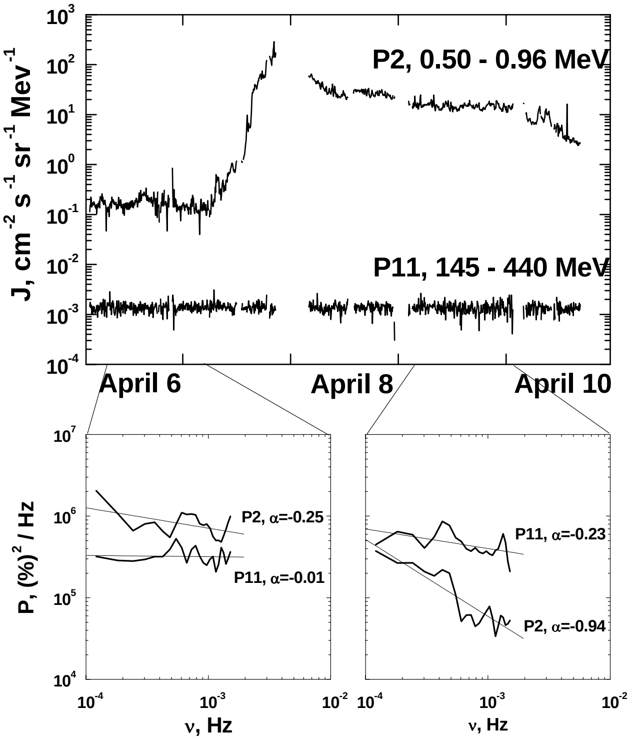

Fig. 3. An example of solar energetic particle event on 6–10 April 1995. Top: time profiles of CR fluxes measured by P2 and P11 channels of IMP-8/CPME. Bottom: Power spectra before (6 April, 04:21–7 April, 04:15 UT) and during the event (9 April, 03:20–10 April, 03:15 UT).

(Fig. 2). Channels P8–P10 (above 25 MeV) are similar to the highest P11 channel (Fig. 1), while the pattern found in channel P7 is a somewhat irregular mixture of the two modes.

These results can be summarized as follows. With increasing solar activity, the flux of solar/interplanetary particles increases and the power spectrum of their fluctuations becomes softer, while the power level of these fluctuations decreases. On the other hand, the flux of galactic particles decreases due to the solar modulation of CR, and the power level of RCRF increases, with increasing solar activity, with the power spectrum remaining nearly flat.

In order to illustrate such a nontrivial behaviour of the power level of rapid fluctuations of solar/interplanetary particles, we discuss the following example of a solar energetic particle event on 6–10 April 1995 (Fig. 3). (Here we only discuss the changes in the RCRF power level without a detailed synoptic analysis of the event.) The upper panel depicts the flux of energetic particles as measured by the IMP-8/CPME experiment in two different channels, P2 (0.5–1 MeV) and P11 (145–440 MeV – see Table 1). One can see that the flux of solar energetic particles increased by more than 2 orders of magnitude during several days of the event, but the flux of galactic particles remained roughly at the same level. The two lower panels show the power spectra of RCRF in the two energy channels for the two periods – a quiet period before, and a disturbed period after the start of the event. The power level of rapid fluctuations of GCR increased by a factor of 2–3 during the event. On the other hand, the spectrum of the low-energy particle fluctuations became significantly softer and its power level strongly decreased with the development of the event, despite the strong increase in the total flux. We note that such a pattern is nontrivial and unexpected. If the RCRF power level was defined by intrinsic turbulence of the solar wind/IMF, one would expect similar changes in the RCRF power level for both solar/interplanetary and galactic particles. On the contrary, the phenomenon discovered here implies a strong interaction between low energy particles and the turbulence level.

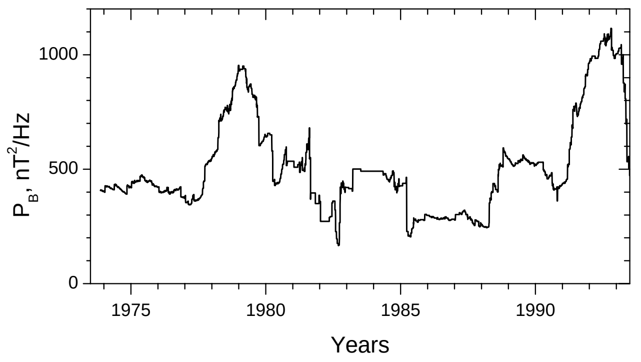

Fig. 4. The 2-year averaged power level of rapid fluctuations of the IMF intensity.

For comparison, we also show the power level of the rapid fluctuations of the interplanetary magnetic field intensity (Fig. 4). It was computed by the same method as described in Sect. 2, using 5-min IMF intensity data measured by IMP-8 (periods when the spacecraft was inside the magnetosphere were excluded). The power level also depicts cyclic variations with maxima around 1978–1980 and 1991, which is in agreement with the rapid fluctuations of GCR (Fig. 1) and in the opposite phase with respect to the rapid fluctuations of solar/inteplanetary particles (Fig. 2). We emphasize, however, that this figure serves only as an illustration, while a further detailed study of the IMF rapid fluctuations/turbulence level is needed.

Here we suggest a possible qualitative scenario as follows. Solar/interplanetary particles with a high flux and strong gradient may generate instabilities in the solar wind plasma (Berezhko, 1986, 1990; Reames, 1989; Vainio, 2003), leading to the generation of Alfvén waves and, by the conversion of Alfvén waves, of magnetosonic waves. Moreover, there are indications that RCRF can be due to fast magnetosonic waves (Berezhko and Starodubtsev, 1988; Starodubtsev et al., 1996). Since magnetosonic waves have a large damping factor, they should be produced locally in the vicinity of the Earth. Thus, the solar/interplanetary particles may generate

MHD-turbulence, losing the power in the studied frequency range, which, in turn, enhances the power level of galactic RCRF. Even though this scenario is only generic and qualitative, it allows for a plausible explanation of the observed behaviour. Further detailed studies are required to fully understand such a nontrivial pattern. Note that we present here a new observational phenomenon, and do not aim for a thorough correlation analysis between CR fluctuations and other solar/heliospheric indices.

4 Conclusions

Using data of space-borne measurements, we have studied, for the first time, the power level of rapid cosmic ray fluctuations in different energy channels for about three solar cycles since 1974. The results prove conclusively that these fluctuations originate in the near-Earth space, thus excluding their atmospheric or magnetospheric origin. Our conclusion is that the long-term variation of rapid fluctuations is different for solar/interplanetary and galactic cosmic rays, contrary to expectations. The flux of galactic particles decreases and the power level of their rapid fluctuations increases with increasing solar activity, the RCRF power spectrum remaining nearly flat. This is in agreement with previous studies based on ground neutron monitor data. On the other hand, while the flux of low energy solar/interplanetary particles increases with increasing solar activity, the power spectrum of their fluctuations becomes softer and the power level of rapid fluctuations decreases.

A possible scenario is suggested to explain such a behaviour. Fluctuations of galactic CR are caused by turbulence in the interplanetary magnetic field which can be affected by the lower energy solar particles through, for example, generation of MHD-waves. In such a way the power of fluctuations of low-energy particles can be transferred to the magnetic turbulence. A more detailed theoretical investigation should be undertaken to quantitatively explain the observed relations.

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