Solar cycle variation of rapid fluctuations of energetic particles at the geostationary orbit

Sergey Starodubtsev*, **Ilya Usoskin**† **and Kalevi Mursula**‡

*Yu.G. Shafer Institute of Cosmophysical Research and Aeronomy of SB RAS, 31 Lenin Ave., 677980 Yakutsk, Russia
† Sodankylä Geophysical Observatory (Oulu unit), P.O. Box 3000, FIN-90014, University of Oulu, Finland
‡Department of Physical Sciences, P.O. Box 3000, FIN-90014, University of Oulu, Finland

Abstract**. We study the level of rapid fluctuations in the frequency range of $10^{-4} - 1.67 \cdot 10^{-3}$ Hz (periods between 3 hours and 10 minutes) of energetic particles in the roughly 1-500 MeV energy range observed inside the magnetosphere using measurements onboard the GOES satellites in 1986–2007. Earlier observations of rapid fluctuations of energetic particles outside the magnetosphere have shown that these fluctuations vary over the solar cycle: Fluctuations of particles of higher energies above 100 MeV (low energy range of galactic cosmic rays) are in phase with the solar cycle, while lower energy particles (energy less then 100 MeV) of solar and/or heliospheric origin depict fluctuation levels varying in anti-phase with the solar cycle. Here we find that the solar cycle variation of rapid fluctuations of energetic particles observed in the magnetosphere is very different than outside the magnetosphere and depends on energy. This differs from all other particles, including heliospheric particles of the same energy, and shows that the high speed streams have a controlling role on magnetospheric particles of this energy range. The results provide evidence that the magnetospheric dynamics have a dramatic effect on the short-term (rapid) fluctuations of energetic particles up to several MeV, and a notable effect even at energies above 100 MeV.**

Keywords**: cosmic rays, solar cycle, geostationary orbit**

I. INTRODUCTION

The most energetic particles of the near-Earth space, typically above a few hundred MeV, are galactic cosmic rays (GCR). They have been observed continuously by ground-based neutron monitors (NMs) since 1951. Energetic particles in the low part of the GCR energy range and below it have been measured by space-borne instruments since 1970s both in the heliosphere and inside the magnetosphere. The flux of energetic particles depicts systematic variations at different time scales, from minutes to decades and even beyond. Recently, increasing interest has been devoted to the short-term fluctuations of energetic particles in the period range from minutes to several hours, now commonly called the rapid CR fluctuations (RF) ([1] – [6]). Here, as in our earlier papers, the RF frequency range is defined to be more specifically between 10^{-4} Hz and $1.67 \cdot 10^{-3}$ Hz, i.e., covering periods from 10 minutes to about 3 hours.

Most studies of rapid fluctuations have concentrated on energetic particles in the GCR energy range, using ground-based NM data. Only recently, systematic studies of rapid fluctuations have been made using energetic particles observed in the interplanetary space by satellite instruments [6], [7]. The results from these earlier studies can be briefly summarized as follows:

- Rapid fluctuations have been observed both in the GCR fluxes observed by ground-based NMs, as well as in the energetic particles observed in the interplanetary space.
- RF spectra are related to the spectra of interplanetary magnetic field turbulence [12], [13], [14]. Significant dynamical changes in RF spectra are often observed about one day before and during large-scale solar wind disturbances.
- RF spectra are modulated in the course of the solar cycle [5], [6]. While the RF power of ground-based neutron monitor data changes in phase with the sunspot cycle, the RF power of energetic particles with energy below 100 MeV measured in the interplanetary space varies in the opposite phase. Thus, in either case, the RF level varies over the solar cycle (SC) oppositely to the flux of the respective particles.
  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 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.

In this paper we study rapid fluctuations of energetic particles in the energy range of $\sim 1 < E < 500$ MeV observed inside the magnetosphere at the geostationary orbit. This study continues our earlier work on rapid fluctuations of GCR and solar/heliospheric particles with the aim to examine the rapid fluctuations of energetic particles observed inside the magnetosphere

TABLE I
ENERGY CHANNELS OF THE GOES SATELLITES EPS/HEPAD EXPERIMENTS.

Satellite	Energy channel, MeV							Operation
	P1	P2	P3	P4	P5	P6	P7	period
GOES-5	0.6–4.2	4.2–8.7	8.7–14.5	15–44	39 – 82	84 – 200	110 – 500	01/01/1986 – 31/03/1987
GOES-6	0.6–4.2	4.2–8.7	8.7–14.5	15–44	39 – 82	84 – 200	110 – 500	01/01/1986 – 31/12/1994
GOES-7	0.6–4.2	4.2–8.7	8.7–14.5	15–44	39 – 82	84 – 200	110 – 500	01/03/1987 – 31/08/1996
GOES-8	0.8–4.0	4–9	9–15	15–40	40 – 80	80 – 165	165 – 500	01/03/1995 – 16/06/2003
GOES-9	0.8–4.0	4–9	9–15	15–40	40 – 80	80 – 165	165 – 500	01/04/1996 – 31/08/1998
GOES-10	0.8–4.0	4–9	9–15	15–40	40 – 80	80 – 165	165 – 500	01/07/1998 – 31/12/2007
GOES-11	0.8–4.0	4–9	9–15	15–40	40 – 80	80 – 165	165 – 500	01/07/2000 – 30/09/2001
								18/06/2003 – 31/12/2007

and, thereby, the possible effect of the magnetosphere on these fluctuations.

II. DATA AND METHODS

Energetic particles in the Earth's magnetosphere are continuously recorded over a wide energy range, typically from tens of keV up to hundreds of MeV, by several satellites. Since we are interested in the long-term behavior of the rapid fluctuations, we require a reliable, homogeneous and sufficiently long record of energetic particle measurements in different energy ranges. The GOES satellite series offers the most suitable data for this purpose. The geostationary GOES satellites (at L = 6.6) provide a stable, calibrated series of proton fluxes in different energy bands measured by the Energetic Particles Sensor (EPS/HEPAD) instrument. We use here the 5-min resolution data from the seven EPS channels called P1 to P7 which cover the energy range from 0.6 MeV to 500 MeV. The energy ranges of the 7 EPS proton channels and the operation periods of the GOES-5 to GOES-11 satellites are given in Table I. Note that the energetic particle data from the GOES series exist from 1986 till present, covering the last two solar cycles.

The EPS measurement technique was slightly changed between GOES-7 and GOES-8 satellites, leading to slightly different energy boundaries of the channels. However, since the differences are small, we can regard the entire GOES EPS proton data as a homogeneous series covering 22 years (1986–2007). Note that EPS detectors of the first type onboard GOES-5 to GOES-7 cover roughly the solar cycle 22, while the newer of detectors onboard GOES-8 to GOES-11 cover the ending solar cycle 23. Accordingly, possible inhomogeneities due to the small detector differences do not affect the solar cycle variation which is the main topic in this paper, but rather the relative level between the two successive solar cycles.

The (corrected) 5-min data of proton fluxes from the GOES EPS instrument are avaiiable at http://goes.ngdc.noaa.gov/data/avg. We included only those days where data gaps or apparent errors did not exceed 8 hours. The 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 then subtracted from I every 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 is the Nyquist frequency of the 5-min data. Significant dynamical changes occur in this frequency range corresponding to the rapid fluctuations. We have calculated the daily power spectral density (PSD) of rapid fluctuations in this frequency range using the standard Blackman-Tukey algorithm [8] with the Tukey window. The average daily value over this frequency range is called the daily P-value of the RF level.

Most of the time there were two or more GOES satellites simultaneously in operation. Since the EPS data from the different GOES satellites are inter-calibrated, we have averaged the P-values of all satellites that were operating on a given day. The spectra in each satellite pair are quite similar to each other, that allows their averaging in order to reduce statistical errors. Averaging also reduces the possible small systematic differences between the two types of EPS instruments, thus leading to a more homogeneous overall series of rapid fluctuations.

In addition to the GOES EPS data we also use here, for comparison, the 5-min data of the Oulu neutron monitor (http://cosmicrays.oulu.fi) and the 5.5-min data of proton fluxes by the CPME instrument [9] onboard the IMP-8 spacecraft (http://sd-www.jhuapl.edu/IMP/imp_index.html). (The Nyquist frequency for the IMP-8 data is slightly lower, $\nu_2 = 1.52 \cdot 10^{-3}$ Hz). We use here only one low energy proton channel, $P2_{\mathrm{IMP}} = 0.5 - 0.96$ MeV and one high energy channel, $P11_{\mathrm{IMP}} = 145 - 440$ MeV of IMP-8 since the mid-energy channels suffered a normalization error in August 1989, which makes it difficult to use them after 1989. Note that the change of the background level was due to the failure of the anti-coincidence scintillator of the instrument that had eliminated the cosmic rays penetrating from off-axis directions. But the intensities at the peak of the solar energetic particle (SEP) events are not affected by the change of background [10]. Since the original data have been reduced to the percentage with respect to an average level, such calibration errors do not affect the definition of RCRF. As earlier [6], we have excluded periods when the IMP-8 satellite was within the Earth's bow shock in order to avoid the magnetospheric effect in the IMP-8 data. The CPME instruments operated until the IMP-8 operations were terminated at the end of October 2001.

Thus we have the daily P-values depicting the RF power from the following particle channels: $P1_{\mathrm{GOES}}$, $P7_{\mathrm{GOES}}$, $P2_{\mathrm{IMP}}$, $P11_{\mathrm{IMP}}$ and P_{NM}. These daily P-values were further smoothed by a 27-day running mean filter.

III. RESULTS AND DISCUSSION

Fig. 1 shows the temporal profiles of the sunspot number R_z (a) and the P-values of RF level (b and c) in channels P7 and P1 calculated by data of the GOES satellites. One can see that the level of high-energy RF (Fig. 1b) generally follows variations of solar activity (Fig. 1a). On the other hand, the level of low-energy particle fluctuations (Fig. 1c) does not depict apparent 11-yr cyclic variations. Taking into account some earlier results [5], [6] one can suppose that this discrepancy is associated with strong influence of the Earth's magnetosphere on the fluctuations of low-energy CR fluxes. It is important that the source of protons in this energy range lies in heliosphere and magnetosphere. Thus one would expect that fluctuations of these energetic particle fluxes could reflect the corresponding fluctuations of the geomagnetic field. On the other hand, the results show that it is not so at the geostationary orbit. One can see from Fig. 2 that the level of the total magnetic field fluctuations at $L = 6.6$ has a pronounced dependence on the solar activity cycle. However, strong (semi)annual variations of the field are observed, which are absent in CR fluctuations. Accordingly and taking into account that the radiation belt of low-energetic protons extends up to the shell $L \sim 7-8$, one can suppose that the level of CR fluctuations at the geostationary orbit is related to dynamics of the radiation belt. This dynamics is caused by the degree of interplanetary medium disturbances. It is important that, in this case, high-speed solar wind streams are quite often observed even around the solar activity minimum. Such streams deform the Earth's magnetosphere leading to dynamical changes of the radiation belts and to various geophysical disturbances. This assumption is also based on the fact that proton fluxes themselves, as measured at $L = 6.6$, correlate with both solar CR and the solar wind speed. The last circumstances can essentially disturb the dependence expected of the level of low-energy CR fluctuations on the 11-year cycle. However, further systematic studies including greater number of magnetosphere parameters are necessary for understanding of the specific mechanism of the magnetosphere's influence on CR fluctuations.

We have also studied in details spectra of CR at different energies and their evolution in time using measurements both ground-based and onboard the spacecraft in the solar wind. We used the data of neutron monitors with the geomagnetic rigidity cutoff between $R_C = 0.45$ and 6.32 GV. Based on a study of the level of CR fluctuations we have concluded the effect found in [5] is a real phenomenon. It appears that the amplitude of the 11-year modulation of RCRF changes by a factor of 5 decreasing with increasing geomagnetic cutoff. It

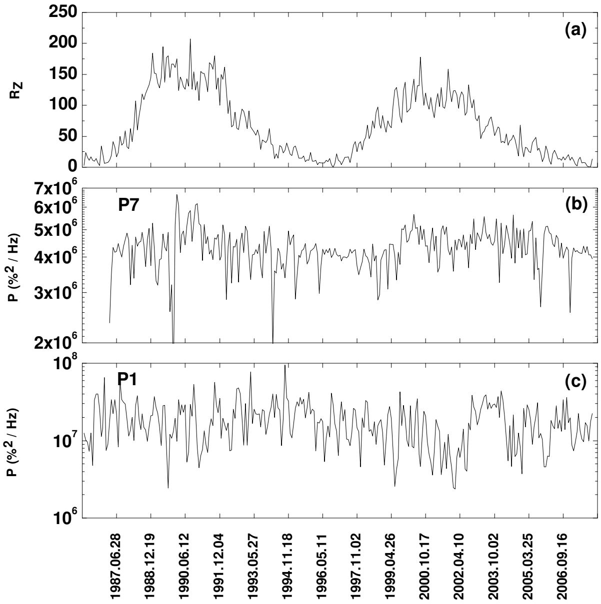

Fig. 1. Time profiles of the sunspot numbers R_z (a) together with the P-values of $P7_{\mathrm{GOES}}$ (b) and $P1_{\mathrm{GOES}}$ (c).

was therefore concluded that a possible influence of the Earth's magnetosphere on the fluctuations of GCR with energy $E > 0.5$ GeV can be neglected.

Here we used data of proton flux observed at ACE and IMP-8 spacecrafts in-situ in the solar wind. The results obtained have led us to a conclusion that the level of energetic particle fluctuations of various origin behave differently in the solar cycle (Fig. 3). The behavior of GCR ($E > 100$ MeV) fluctuations in the solar wind correspond to the pattern obtained for ground-based data (Fig. 3a and b) — they correlates the phase with solar activity. Evolution of the inertial part of IMF fluctuation spectrum is similar as observed in an experiment [11]. On the other hand, fluctuations of low-energy CR ($E < 100$ MeV) of the heliospheric origin, measured onboard both spacecrafts, demonstrate the opposite behavior (Fig. 3c). In this case proton fluxes with significant gradients are connected with large-scale SW disturbances, which vary in phase with the solar activity phase. Considering some theoretical results [12], [13] we conclude that, during times with significant fluxes of energetic particles with energy ($E \sim 0.01-10$) MeV, transfer of the energy of these particle to MHD-waves of Alfv́en type with a scale 10^{10}–10^{12} cm may take place owing to the development of hydrodynamics instabilities in the SW plasma. Furthermore, due to conversion during their propagation in SW they can generate fast magnetosonic waves. Experimental data suggests that such waves can indeed modulate the CR flux in a wide energy range at the same frequencies causing the appearance of fluctuations [7]. In this case the magnitude of the level of CR fluctuations increases considerably for high energy CR, but decreases for low-energy CR, compared to the non-disturbed background

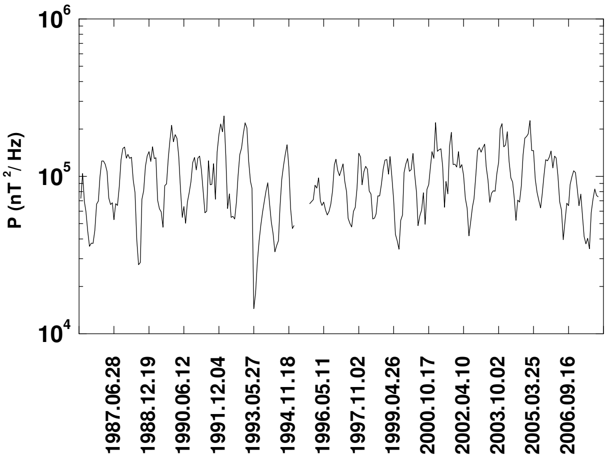

Fig. 2. Time profiles of the P-values of total magnetic field by GOES data.

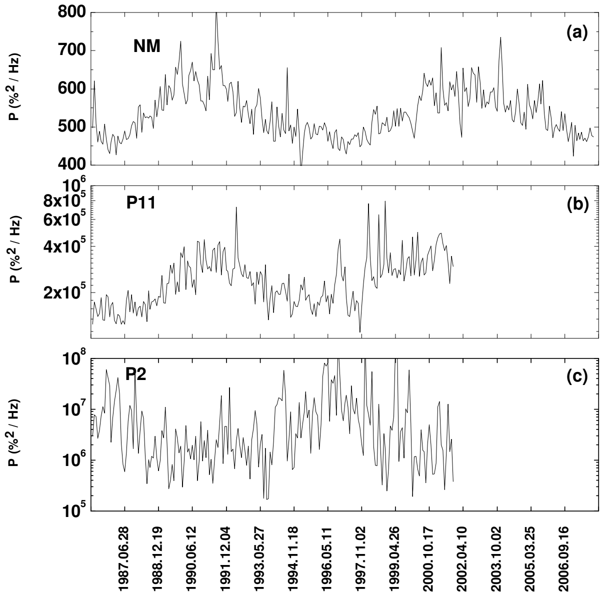

Fig. 3. Time profiles of the P-values of P_{NM} (a), $P11_{\mathrm{IMP}}$ (b), $P2_{\mathrm{IMP}}$ (c) in the solar cycl.

level.

Since temporal changes of solar/heliospheric energetic particles is directly connected with the behavior of coronal and flare solar activity, it explains the observed pattern, described above, of the evolution of the CR fluctuation level in a wide energy range from a few keV up to tens of GeV.

IV. Conclusions

Thus, a new earlier unknown phenomenon in CR behavior has been established. It is related to the confirmed existence of regular 11-year cyclic modulation of the fluctuation spectrum of cosmic rays of heliospheric and galactic origin. In this case, a considerable influence of the Earth's magnetosphere on the long-term modulation of the fluctuation spectrum of lower energy CR with $E < 100$ MeV has been founded.

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