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Spectral index of the recurrent variation of the galactic cosmic rays during the solar cycles 23/24.

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We study temporal changes of the power-law rigidity spectrum $\delta D(R)/D(R)$ ($\delta D(R)/D(R) \propto R^{-\gamma}$) of the first three harmonics of the 27-day variation of the galactic cosmic rays (GCR) intensity during the solar cycle (SC) no. 24 and compare with other 11-year cycles of solar activity. We show that our recent finding - a hard spectrum of the amplitudes of the 27-day variation of the GCR intensity in maximum epochs and soft one in the minimum epochs during solar cycles (SCs) no. 20 - no. 23 is kept, with some peculiarity in SC no. 24. Particularly, while the rigidity spectrum of amplitudes of the first harmonic of the 27-day variation of the GCR intensity practically behaves as for previous periods, the rigidity spectrum of the amplitudes of the second and the third harmonics demonstrate a valuable softening.

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1.Introduction

Galactic cosmic rays are highly energetic nuclei of extra solar source. When they are propagating through the heliosphere (being a region totally driven by the Sun's magnetic activity), they are partially modulated by the solar wind and heliospheric magnetic field (HMF). Moreover, heliosphere changes in time, and those influence on the GCR stream in different time scales (e.g., [1]).

The 27-day variation of the galactic cosmic rays intensity was described for the first time in the thirties of the XX century [2] and still is in an interest. Among recent publications devoted to this issue one can mention [3, 4]. However, changes of the amplitudes of the 27-day variation of the GCR intensity versus the rigidity R were studied only by Alania and co-authors [5-7]. There was demonstrated [6, 7] that the rigidity spectrum of the 27-day variation of the GCR intensity is hard in the maximum epochs, and soft in the minimum epochs of solar activity (SA). We explained this phenomenon due to the fluctuation of the sizes of the modulation areas of the recurrent variation of the GCR intensity in different epochs of SA. The size of the modulation region of the GCR recurrence is smaller in the minimum epochs than in the maximum epochs.

Because the maximum epoch of the lasting SC no. 24 was about 50% weaker than previous four SCs [8, 9] it is important to check thus the power of the solar activity cycle influenced the spectrum of the recurrence of the GCR intensity. Thus, the main aim of this paper is to study the behaviour of the rigidity spectrum and its spectral index of the recurrent variation of the galactic cosmic rays during the solar cycle no. 24.

2.Data and methods

In our paper we present the computed rigidity spectrum of the amplitudes of the first three harmonics of the recurrent variation of the GCR intensity during the ongoing SC no. 24. For this purpose we have collected daily data from eight neutron monitors with different cut off rigidities in the period of 01.01.2000-31.12.2014. Details of the stations used for this calculation presents Table 1.

Table 1 Details of neutron monitors used in order to compute the rigidity spectrum of the first three harmonics of the recurrence of the GCR intensity

	Station	Effective vertical cutoff rigidity [GV]	Geographical	
			latitude	longitude
1	Apatity	0.65	67.57° N	33.4° E
2	Fort Smith	0.3	60.02° N	111.93° W
3	Jungfraujoch	4.5	46.55° N	7.98° E
4	Kiel	2.36	54.34° N	10.12° E
5	Moscow	2.43	55.47° N	37.32° E
6	Oulu	0.8	65.05°N	25.47°E
7	Potchefstroom	6.94	26.42°S	27.05°E
8	Rome	6.27	41.86° N	12.47° E

Using harmonic analysis (e.g., [10]) we computed the amplitudes of the first three harmonics of the 27-day variation of the GCR intensity by means of daily data from all NMs for each

consecutive solar rotation during the considered period. For this purpose we used formula:

$$x(k\Delta t) = \frac{a_0}{2} + \sum_{n=1}^{K/2}\left[a_n \cos\left(\frac{2\pi}{T} nk\Delta t\right) + b_n \sin\left(\frac{2\pi}{T} nk\Delta t\right)\right],$$

where $a_n = \frac{2}{K}\sum_{k=1}^{K} x(k\Delta t)\cos\frac{2\pi kn}{K}$, $b_n = \frac{2}{K}\sum_{k=1}^{K} x(k\Delta t)\sin\frac{2\pi kn}{K}$, K=27 days and $A = \sqrt{a_j^2 + b_j^2}$, $j \in \{1,2,3\}$, is the amplitude of the j-th harmonic of the 27-day variation of the GCR intensity.

Variability of the primary spectrum of the GCR flux in the heliosphere can be defined as (e.g., [11]): $\left[\frac{\delta D(R)}{D(R)}\right]_i = \frac{D_i(R) - D_0(R)}{D_0(R)}$, where $D_i(R)$ means the primary spectrum of GCR during the i-th rotation and $D_0(R)$ the primary spectrum for the considered period. A typical procedure of reconstructing the primary cosmic rays characteristics from NMs measurements is by the usage of the neutron monitor yield function Y(R,h) (in units of m^2 sr) dependent on the primary particle rigidity/energy and observational level h (e.g., [12-14]): $N(R_c,h,t) = \int_{R_c}^{\infty} Y(R,h)D(R,t)dR$, where N means count rates of concrete NM, D(R,t) primary spectrum (in units of particles/(m^2 sr s GeV/nucleon)) of GCR at the orbit of the Earth depending on rigidity and time. Thus, the amplitudes of the recurrence of the GCR intensity for the k-th neutron monitor with characteristic cutoff rigidity R_{ck} can be calculated by the formula (e.g., [11]): $I_{ik} = \frac{N_{ik} - N_{k0}}{N_{k0}} = \int_{R_{ck}}^{R_{max}} \left[\frac{\delta D(R)}{D(R)}\right]_i \frac{D_0(R)Y(R,h_k)}{N_{k0}} dR$, where $[\delta D(R)/D(R)]_i$ means the rigidity spectrum for the i-th rotation. By the aid of the broadly used approximation, we defined the rigidity spectrum of the 27-day variation of the GCR intensity as (e.g., [12, 15]):

$$\frac{\delta D(R)}{D(R)} = \begin{cases} a R^{-\gamma} \; for \quad R \le R_{max} \\ 0 \quad for \quad R > R_{max} \end{cases}$$

where R_{max} is a maximal rigidity of an existence of the recurrent variation, in our paper R_{max}=200GV, a is a constant, for R_0 being equal $\delta D(R)/D(R)$, and γ is the spectral index of the harmonics of the 27-day variation of the GCR intensity. Detailed description of the method of calculating exact values of γ can be found in [16].

To compare a behaviour of the spectral index γ of the 27-day variation of the GCR intensity during the ongoing SC no. 24 with its behaviour during four previous SCs no. 20-23 we need to have a continuous values of γ for a long period. For this purpose essential are neutron monitors with substantially different cut off rigidity, with well established, continuous measurements during the long period. This request is reasonably fulfilled by Kiel and Rome NMs.

Using those NMs by the aid of the above described method we computed values of the spectral index γ of the first three harmonics of the recurrent variation of the GCR intensity for the period of 01.01.1964-31.12.2014.

3. Behaviour of the rigidity spectrum of the 27-day variation of the GCR intensity during the solar cycles 23/24

To study precisely the behaviour of the rigidity spectrum of the recurrent variation of the galactic cosmic ray intensity during the lasting solar cycle no. 24 we used eight various neutron

monitors with considerably different cut off rigidity during the period of 01.01.2000-31.12.2014. Fig. 1 a-c presents results of our calculations.

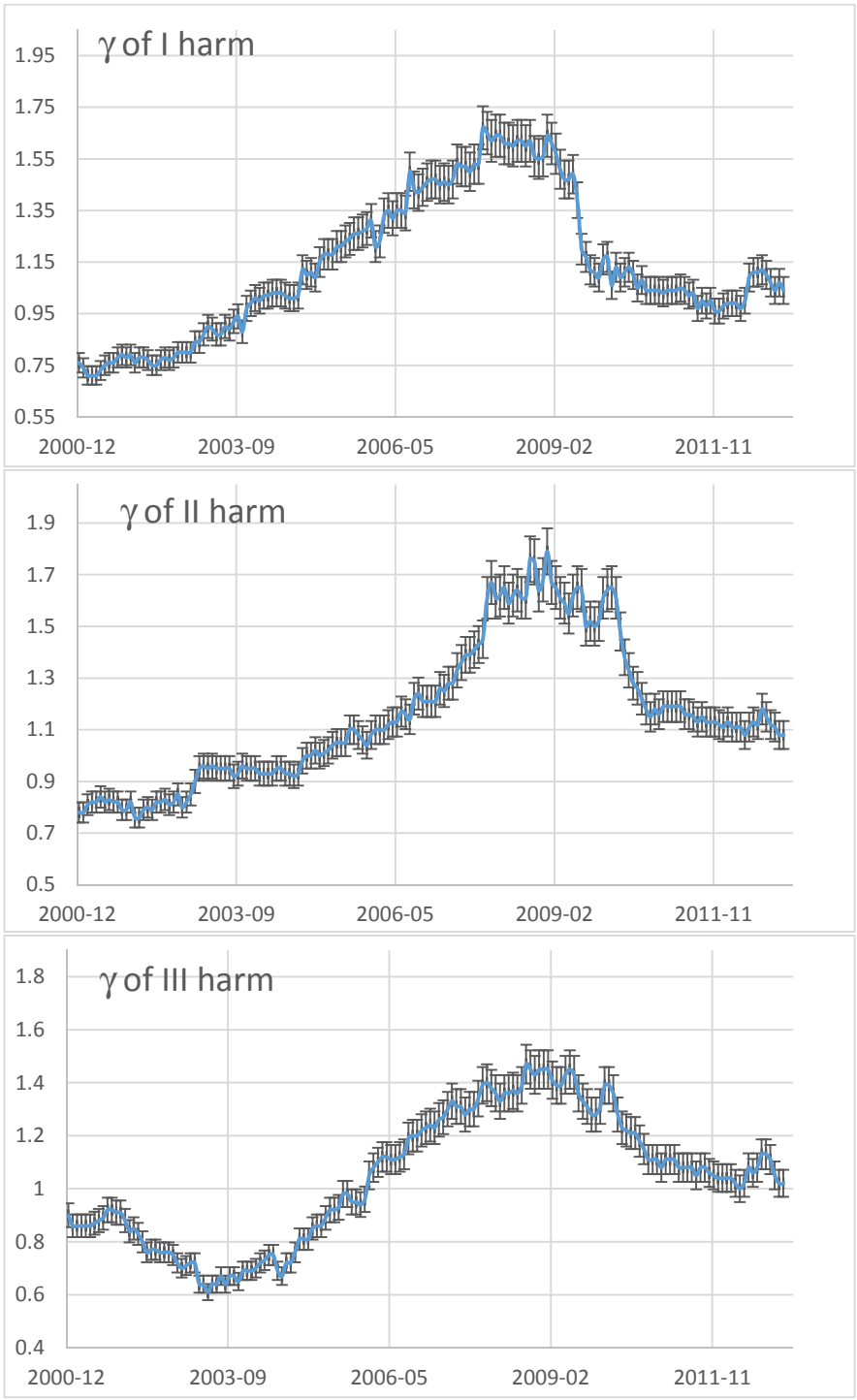

Fig. 1a-c Changes of the spectral index γ of the first three harmonics of the 27-days variation of the GCR intensity calculated using 8 neutron monitors (details in Table 1) with different cut-off rigidity during the period of 01.01.2000-31.12.2014, smoothed over 39 solar rotations.

Fig. 1a displays that during the recent, unusual minimum epoch between SCs no. 23 and 24 a value of the spectral index γ of the first harmonic of the 27-day variation of the GCR intensity was the highest, being equal 1.67±0.08. Moreover, the lowest value of γ during the recent

maximum was 0.96±0.05, being 35% higher in comparison with the value of γ during the maximum epoch of SC no. 23. Fig. 1b shows that the rigidity spectrum of the amplitudes of the second harmonic of the recurrence of the GCR intensity was extremely soft, with the highest γ≈1.79±0.09, being even larger than γ of the first harmonic. Fig. 1c illustrates that the lowest value of γ for the third harmonics during the recent maximum was 1.02±0.05, being almost 60% higher in comparison with γ during the maximum of SC no. 23. Fig. 1c presents that the rigidity spectrum of the amplitudes of the third harmonic of this variability of the GCR intensity during the recent minimum was soft, with the highest γ≈1.43±0.07. It could be caused by the fact that during the recent minimum epoch, at the end of SC no. 23, the second and the third harmonics of this variability were really enhanced (Fig. 2a), as well as in the solar wind and solar activity parameters (Fig. 2b).

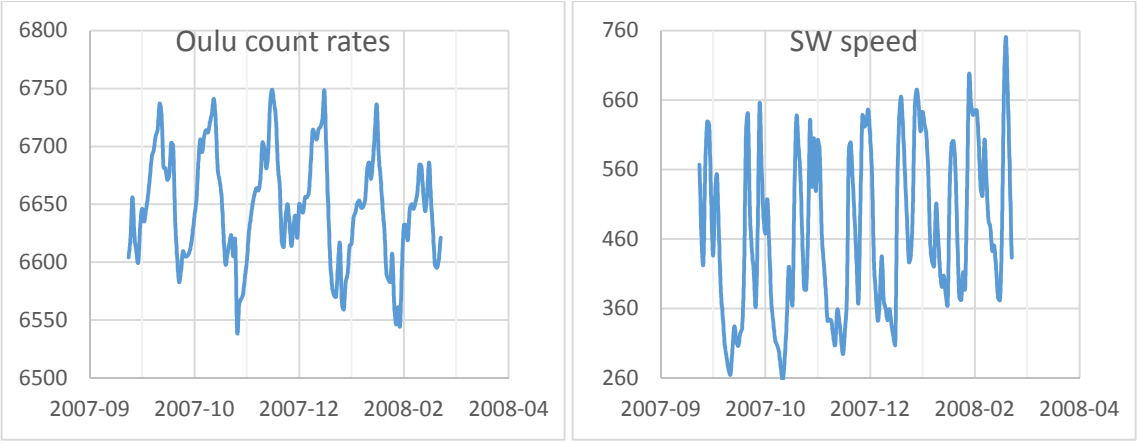

Fig. 2a-b Daily changes of the Oulu NM count rates (a) and solar wind speed (b) at the end of the SC no. 23.

In order of comparison the rigidity spectrum, δD(R)/D(R), of the first three harmonics of the 27-day variation of the GCR intensity during the ongoing SC no. 24 with previous SCs, we have calculated value of the spectral index γ of the first three harmonics of the recurrent variation of the GCR intensity for the period of 01.01.1964-31.12.2014 by the aid of the methods described above, using Kiel and Rome NMs. Fig. 3a-c shows that the rigidity spectrum of those harmonics is, indeed, hard in the maximum and soft in the minimum epochs of solar activity, as it was found in [6, 7]. To emphasise the properties of the long-term changes of the rigidity spectra we smoothed values of the spectral index γ with running average over 39 solar rotations. Fig. 3 confirms that during the SC no. 24 the rule concerning the hardening of the rigidity spectrum of the 27-day variation of the GCR intensity during the solar maximum epochs, is kept. Furthermore, Fig. 3 endorses that during the ongoing SC no. 24 values of the spectral index γ for the first harmonic of this variability of the GCR intensity (Fig. 3a) were at the comparable level as during previous SCs no. 20-23, but values of γ for the second (Fig. 3b) and the third (Fig. 3c) harmonics were much higher, from a few up to several dozen percent, than during the previous four solar activity cycles. We do not understand this phenomenon well yet, but it can be related to the temporal changes of the structure of coronal holes, which we do not consider in this paper.

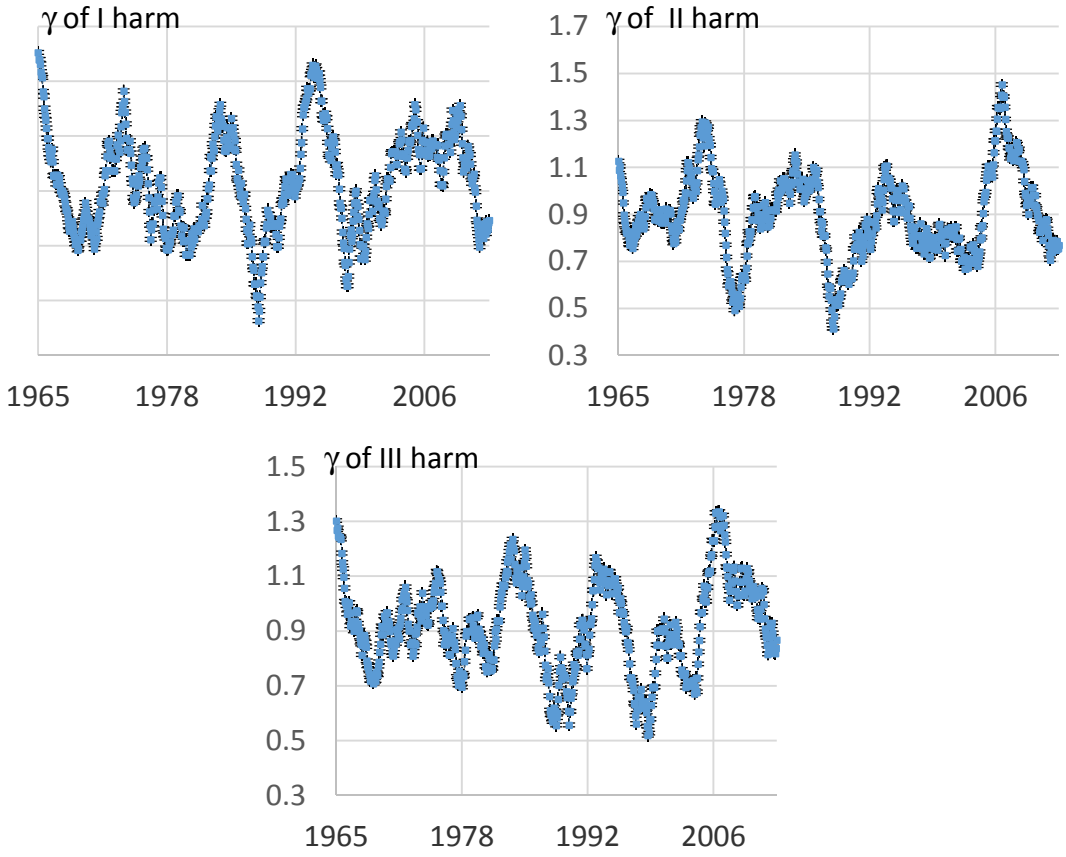

Fig. 3a-c Changes of the spectral index γ of the first three harmonics of the 27-days variation of the GCR intensity calculated for the period of 01.01.1964-31.12.2014, smoothed over 39 solar rotations.

4.Summary

The rigidity spectrum of the amplitudes of the first three harmonics of the 27-day variation of the galactic cosmic rays intensity was hard during the maximum epoch of the lasting solar cycle no. 24 and soft during the recent, unusually prolonged, minimum epoch between SCs no. 23 and 24. Moreover, the rigidity spectrum of the second and third harmonics of this recurrence of the GCR intensity was extremely soft during the last solar minimum. We do not know the reasons of this phenomenon well yet, but it can be related to the temporal changes of the structure of coronal holes.

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