The observed spectrum of long-term cosmic ray variations in minimum solar activity 2009

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Abstract. The method for determination of the long-term rigidity spectrum of the cosmic ray (CR) variations within the range R=1-50 GV was presented in our previous works on the base of CR observations with the different detectors. In this paper meson telescope data (Nagoya) are added. The monthly averages of the CR intensity during 1974-2011 are used to investigate rigidity spectrum of the CR maximum in 24th cycle and compare with other cycles. The main focus is specific features of CR modulation at a prolonged minimum of solar cycle 24, when maximum CR intensity was higher than it was during the other maxima. It has been found the best fitting for rigidity dependence of CR variations. The main results are: a) the power of the 11-yr cycle is different from one cycle to next; b) the maximum 24th cycle (2009) exceeds the previously established maximum flux of CR; c) the spectral index, obtained from different sets of CR detectors, shows that resulting spectrum becomes steeper with increasing of CR energy

1. Introduction
Cosmic rays (CR) in the energy interval 1-100 GV are subject to solar modulation in the heliosphere. On its way to Earth the flow of galactic CR passes through the atmosphere and the magnetosphere, where the intensity of CR is divided and is filtered by energy under the influence of these natural detectors. Knowledge of the spectrum is of utmost importance when constructing a model of CR modulation. At present the method of global survey and its variants are used to define the spectrum of long-term modulation, for example, the spectrographic method and the method of differential coupling coefficients [1]. The global-spectrographic method was developed [2] in order to determine the spectrum of long-term CR variations. Rigidity dependency of the variations proposed in [3] on the basis of all available information on the intensity of CR, obtained by registering it using an Earth-based network of neutron monitors (NM) [4] and by probing the stratosphere [5]. Here we are going to add the results of CR registration using a meson telescope (T) in Nagoya [6]. Most attention will be devoted to the period of SA decline in the 23rd cycle (2006-2008) and the minimum in the 24th cycle (2009). This period is remarkable due the value of the recovering of CR density, exceeding the value of all previous CR maxims. The anomalous CR maximum under consideration includes features, the reason for which is connected with the unusual behavior of the SA characteristics responsible for CR modulation [7 and references to it]. Our aim here is to analyze the energy spectrum of long-term CR variations in the minimum SA in 2006-2009, obtained from the above-mentioned detectors and compare it with the spectrum of 1986-1987 (during a minimum SA 22 years before).
2. Method and data

The analysis of energy and temporal changes in the spectrum of CR variations performed by several researchers, using data from the network of NM, the results of stratosphere observations, latitudinal measurements of CR. Hypotheses have been made concerning the complex nature of the energy spectrum of long-term CR variations. The determination of the spectrum of long-term CR variations in this paper has been conducted for the period when observation data was available from all instruments (1974-2011) for the rigidity \( R < 25 \) GV. Data from the NM have been corrected for instrumental variations and muon data has been corrected for temperature [8]. In our previous papers [3, 9] we explained the method of determining the isotropic component of the spectrum of long-term CR variations. We obtained the characteristics of the rigidity spectrum in the form \( \delta(R) = \frac{a}{(1 + bR^\gamma)} \). In this case the variations \( \delta(\gamma, b) = ac_i 00, \) where \( c_{i00} \) are the coupling coefficients for the given station, determined by the primary CR spectrum and the response function. Analysis of the characteristics of the spectrum (\( a \)- amplitude of variations, \( \gamma \) - index of the spectrum) has been carried out for galactic CR with \( R = 5, 10, 20 \) GV. The monthly average variations (in \%) have been determined relative to 1997 using the method of global survey. We used a multi-parameter model of the spectrum because the model of a simple power law spectrum was insufficient for a detailed description of these variations. In this way, using the results of continual observation of CR (figure 1 variations of CR for all the detectors and for T in Nagoya), the method of global survey and proposed three-parameter rigidity model of the spectrum, enables us to continually determine the spectral characteristics of long-term CR variations in different SA cycles on a wide energy interval. This makes it possible to detect the peculiarities of the large-scale effects in CR modulation, namely the presence of 22-variations together with the 11-year cycles. In figure 1 we clearly see the alternation of flat and peak maximums of CR in the SA minimums of 1976 and 1996, 1987 and the largest variation of CR in the minimum 2009 (both for \( R = 10 \) GV and 20 GV). The aim of this paper is to analyze the changes of the spectral

![Figure 1](image1.png)  
Figure 1. Long-term variations of CR (% to 1997) for \( R = 10 \) GV (a nm T) using data from the NM network, using data from the stratosphere and meson telescope Nagoya for \( R = 20 \) GV (aT_20).

![Figure 2](image2.png)  
Figure 2. Variations of CR – maximum CR (10.2009) and CR minimums (06.1991 and 11.2003) for data of the telescope (Nagoya), the NM network and the stratosphere as functions of the coupling coefficients \( c_{i0} \).

characteristics of long-term CR variations in the minimum SA 2009 and compare them with the changes in the CR spectrum in the previous minimum of the 22-year SA cycle (1987). In order to determine whether our proposed three-parameter rigidity model of the spectrum corresponds to the observed CR variations, we drew correlation curves (figure 2) which reflect the link between the experimental data and the parameters of the model (with the coupling coefficients \( c_{i0}(\gamma, b) \)). This figure shows CR variations for the SA minimum (10.2009) and for 2 periods of high SA (06.1991 and 11.2003). We can conclude that the data from all the detectors for all periods of SA correspond to the proposed description of the energetic dependence of the spectrum of CR variations.
3. The spectrum of long-term CR variations in SA minimums

The CR flow established in the CA minimum in 2009 in a period of quiet heliosphere is the largest in all the period of CR monitoring and shows dependency on rigidity (figures 1, 2). The parameters of the rigidity spectra of CR variations $a$ and $\gamma$ have been determined for 2 adjacent maximums of 22-year periodicity in CR (in 1987 and 2009) and for the same base (1997) in order to carry out comparative analysis. For the 2009 maximum, apart from the amplitude of CR variations for the whole set of detectors, separate amplitudes were obtained for the NM network and for the multi-direction T (17 directions, Nagoya), which are set out in figures 3a,b,c (for R=5, 10, 20 GV respectively).

![Figure 3](image1.png)  
Figure 3 Temporary changes CR variations with R=5, 10, 20 GV (a,b,c), on the basis of data from detectors: balloon-probes at the Moscow station (a_strat.Mo_s), of neutron monitors together with the telescope (a_nmT), separate from the monitor network (a_nm) and for the telescope (a_T).

![Figure 4](image2.png)  
Figure 4 Variations of the CR amplitude (% 1997) obtained during minimum CR in 1987-1988 from observations in the stratosphere, on NM and T.

The CR variations (figure 3a) according to these measurements in the stratosphere (a_strat.Mo_s) are close to the variations received for particles with a rigidity 5 GV registered by all Earth detectors (a_nm+T) and to the variations for the NM network (maximum $a \approx 12\%$). Thus they confirm accuracy of the proposed model for determining the spectrum parameters. Analogous time dependency (figures 3b, c) is shown for R=10 and 20 GV. The progression in time of the amplitude of CR modulation represents the complex character of the modulation of different energies in 2009. In picture we see the modulation of softer energy in the period of CR recovery (figure 3b), rather than the other way round. CR with R=10 GV reaches a maximum with restored intensity (a_nm+T, figure 3b) two months after (09.2009) the CR recovery (07.2009) with R=5 GV, registered by NM and in the stratosphere.

4. Discussion of the results

Outstripping the maximum of high energy CR in the ~ 08-09.2009. confirmed by the results presented in Figure 3c: CR variations at R = 20 GV, according to data obtained by the telescope, peaking in August 2009., and the maximum of the same variations, calculated from the data of neutron monitors observed later - in January 2010. The observed effect of the differing maximums of restored CR flows needs to be explained. Usually, when the observation point particles of different energies come from the same source, the dispersion of the energy and velocity diffusion leads to the earlier development of the variations of more hard particles. But here the situation is different. CR maximum is achieved
when the recovery process is interrupted, characteristic of low solar activity, and this is the beginning of a new solar cycle. A new cycle of solar CR modulation before seen on the particles is relatively low energy. For a detailed understanding of the CR modulation in the minima SA and a comparison of the two peaks of 2009 and 1987 identify differences CR variations in the two considered minimums CA. The difference is not only in the maximum value of CR variations, but in the different dependence of modulation for particles of different energies. At the maximum of 1987 all detectors detect particles of different energies at almost the same time (2.1987-3.1987), with little difference in magnitude. Amplitude variations (a ~ 2.5%). 03.1987- the maximum in the form of a sharp peak and the beginning of new cycle occurs simultaneously for CR of all energies. The difference in the beginning of the 22nd (simultaneous start for different energies) and the 24th (the start of the dependence on the energy) cycle is not easily explained, since the polarity of the general solar magnetic field and the magnetic configuration of the heliosphere in these periods were presumably the same. The slope of the spectrum γ, obtained by the ratio of the amplitudes for the energy 5-10 GV in the period 2007-2011 when registering CR with all the used detectors becomes very hard abruptly and remains so for several years. During the previous maximum with the same polarity of the solar field in 1987 in the same rigidity interval the same thing happened to the spectrum of CR variations, but the period of the hard spectrum was significantly shorter, only 5 months.

The existence and size of the 22-year CR wave in SA minimums and the reasons for its existence discussed in [10], where it is concluded that the amplitude of the 22-year CR wave increases from cycle to cycle, reaching its maximum in 2009. Changes in the structural characteristics of the large-scale solar field (determined by the tilt of the current sheet α) play a role in the creation of the 22-year periodicity in CR minimums. So do the variations in quantity characteristics (determined by the size of the average intensity of the solar field – integral index Bss, and also by the changes in size and polarity of the polar fields Hpol). For the minimum of 1987 the tilt increases sharply from 9° in 01-04 1987 to 24° in 05.1987. For the minimum in 2009 the tilt remains anomalously large from 2006 to 07.2009 and rises sharply from 12°in 09.2009 to 25° in 11.2009. As we already mentioned above, the noted time can be connected to the beginning of a new CR cycle. The other parameters are observed in a much smaller quantity in the 2009 minimum than in other SA minimums. The tilt of the current sheet plays the main role in modulation for direction qA<0 and this is emphasized in [11]. In the minimum 2009, in contrast to other cycles, the influence of changes in the tilt on the general CR modulation remains anomalously large for a long period, beginning in 2006 until the end of 2009 resulting in a radical CR modulation and confirming conclusion concerning the decisive role of the tilt for the modulation in periods of SA minimum.

5. Conclusion

1. The rigidity spectrum of long-term variations for energy 1-25GV makes it possible to describe the observed CR modulations based on monitoring data of CR from the Earth network of NM, observations of the meson telescope and results of measurement of CR in the stratosphere from 1974-2011. 2. The special characteristics of the achievement of a maximum of the restored CR flow using the example of SA minimum in 1987 and 2009 with particles of different energy can be explained by the beginning of a new CR cycle. This conclusion is confirmed by the dramatic changes in the slope of the current sheet, the main SA modulation parameter in relatively quiet periods. Additionally the average size of the field on the Sun and the size of the polar field can be regarded as characteristics of SA leading to the extraordinary high density of CR in 2009. Their joint influence resulted in the restored CR flow in 2009, which exceeded all previous observations.

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