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Cosmic rays variations in solar activity minimum of the 24th cycle

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The observed weakening of the global magnetic field of the Sun, which began at the end of the 22nd cycle of solar activity (SA) raises the question of the response of this phenomenon in cosmic rays (CR). Weak modulation in the 23rd and 24th cycles of SA is the result of the trend of the solar magnetic field in the last cycles. The work was carried out on the material of continuous CR observations by a network of neutron monitors, telescopes, and stratospheric balloon probes. The spectrum of CR variations in the minimum SA cycles was determined using the global spectrographic method developed by us. The spectral characteristics of the variations of the anomalous 24th SA cycle are compared with the corresponding characteristics of the previous SA cycles (22-23) (base 1987). At an SA minimum of 24/25, a flat (confirming the drift modulation theory for qA=1) maximum of the CR flow is observed from 2017 to the present time. At the same time, the amplitude of variations for low-energy particles (observed in the stratosphere) exceeds the value of the base period variations by ~8% and is 0.8% of the amplitude of the CR variations at the minimum of 23/24 in 2009. Max particle flow medium and high energies observed in neutron monitors and telescopes are 1-2% lower than that of 23/24.Here you can write the abstract for your paper.

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1. Introduction

The role of the magnetic field in the dynamics of processes occurring on the Sun is the key to all active phenomena occurring on the Sun, in the solar atmosphere, and in the heliosphere. CR variations observed on Earth using a worldwide network of detectors (neutron monitors, muon telescopes, and sounding balloons) are an indispensable tool for studying the dynamics of the heliosphere on a long-term scale. SA cycles are clearly visible inhomogeneous long-term data series of ground-based detectors, and, if there were no observations of the Sun, solar cyclicity and its main periods would have been known from observations of CR variations.. A significant trend of the solar magnetic field, which began at the end of the 22nd SA cycle and continues to this day, gives us an opportunity to observe and study the features of long-term CR modulation in the last two SA cycles with the opposite direction of the global magnetic field (GMF) of the Sun. The anomalously weak long-term CR modulation in the 23rd and 24th SA cycles is the result of the trend of the GMF in cycles with different polarities (qA=±1). At the same time, in the minimum in 2009, which was in the lowest SA cycle in the epoch of regular ground-based CR observations since 1951, an unusually high, restored CR flux was observed (sharp CR maximum for qA<0), which exceeded the maxima of CR fluxes with a similar direction qA at previous cycles [1]. As we approach the next SA minimum of the 24/25 SA cycle, starting from 2017 to the present, a flat (for qA> 0) maximum of CR variations is observed. The height of the CR flux maximum for particles of different energies during this period requires special attention and research. To understand the relationship between processes on the Sun and CR modulation during their propagation in the heliosphere, leading to a change in the rigidity dependence of the spectrum of 22-year CR variations in cycles with different signs of the GMF of the Sun, it is necessary to turn to the results of a detailed analysis of the time course of long-term CR variations and their relationship with solar and heliospheric characteristics. This analysis is carried out for the spectrum of long-term variations in CR, calculated by the method [2], obtained for particles with a rigidity $R \leq 100$ GV. The main attention in this work is paid to the determination of the spectral characteristics of CRs at the minima of cycles and to the features of CR modulation in cycles with different signs of the GMF of the Sun. For this, a model description of long-term CR variations (according to [3]) was carried out using regression equations using various SA indices. The recently observed trend of the main parameter modulating CR - the GMF of the Sun, its significant and long-term weakening is manifested in the features of the correlation between SA and CR in the analyzed period 1991-2020, which includes two periods with the direction of the GMF of the Sun qA> 0 and a period with qA <0. The role of solar-heliospheric characteristics in the creation of a contribution to the general modulation from the cyclical changes of each index in the periods under consideration with a certain qA sign is determined.

1.1Data and method

The global spectrographic method (GSM) which was developed to determine the spectrum of long-term CR variations taking into account the rigidity dependence of variations was proposed in [3] based on all available information about CR intensity which was obtained during CR registration by a ground-based network of detectors and detectors probing the stratosphere. The analysis of the energy and temporal changes of the spectrum of CR variations was carried out for the period 1957-2020 when there were observational data of neutron monitors (~ 40 stations of the world network), stratospheric balloon-probes (3 points) [4] and a telescope (Nagoya, [5]). When using the GSM, the network of the listed detectors is considered as a single multidirectional detector equipped with high-precision standard instruments. The characteristics of the rigidity spectrum which is given in the form δ (R) = a / (1 + bR^{γ}) are obtained in zero harmonic approximation. The analysis of spectrum characteristics (a is the amplitude of variations, γ is the spectrum index) was carried out for galactic CRs with rigidity R =5, 10, 20 GV. Monthly mean CR variations were determined in % relative to the 1987 baseline. The choice of this base was made on purpose: 1987 is not very far from the time of the studied period, but the CR flux at this year differs significantly from the maximum fluxes in 23/24 cycles, and this makes it possible to determine the rigidity spectrum of CR variations in SA minimum. In this work, we will consider and compare the CR modulation in three periods: 1991-1999 (qA>0), 2000-2010 (qA<0) and 2014-2020 (qA>0). To study the relationship between CR modulation and SA for each period and for different CR rigidities, the CR behavior will be modelled using multivariable regression. The models include 5 indices of SA: first of all, these are indices reflecting the strength and structure of the GMF of the Sun: the value of the average field strength on the Sun B_{ss} [6] and the slope η of the heliospheric current sheet [7]. The influence of the quasi-twenty-two-year magnetic cycle includes in the models mainly through the magnitude of polar magnetic field H_{pol} [7]. The models also take into account smaller-scale and sporadic solar phenomena through the CMEi index [8] and the areas of low-latitude coronal holes *Al* [9]. The selection and analysis of solar-heliospheric characteristics for the empirical description of CR modulation in SA cycles were performed in [1].

1.1.1 About CR variations at SA minimum

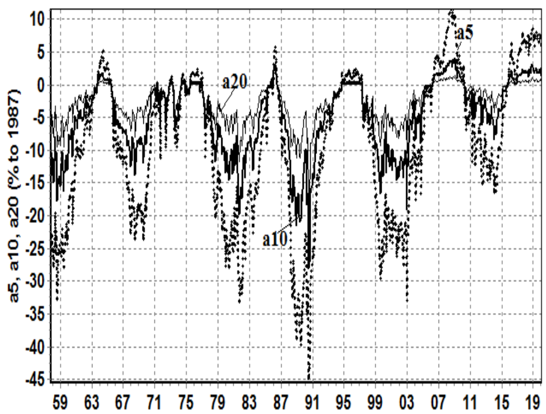

Figure 1. CR variations a5, a10, a20 (%. 1987), obtained on the basis of the complex of detectors: a5 (dashed line), a10 (bold), a20 (thin).

Figures 1 and 2 show the changes of the parameters a and γ obtained by using the GSM and a three-parameter model of rigidity dependence of CR variations. The excess of the CR variations (both for particles with R=5 GV and for R=10, 20 GV) is observed in the minimum in 2009 in comparison with preceding minimums, and in the next minimum in 2019, variations for particles with R = 5, 10. 20 GV is slightly less. The values of the amplitudes in the last two minimums show an anomalously large increase of CR fluxes as a response of CR to the trend of magnetic field Sun. The greatest increase is observed for low energies. In the last SA minimum (2019), the CR variations have a soft spectrum compared to previous minimums. This is evidenced by the fact that the variation for 5 GV is more than an order of magnitude greater than the variation for 20 GV. The analysis of obtained the amplitudes of CR variations a5, 10, 20, using a set of instruments and GSM carried out for periods of a relatively quiet heliosphere.

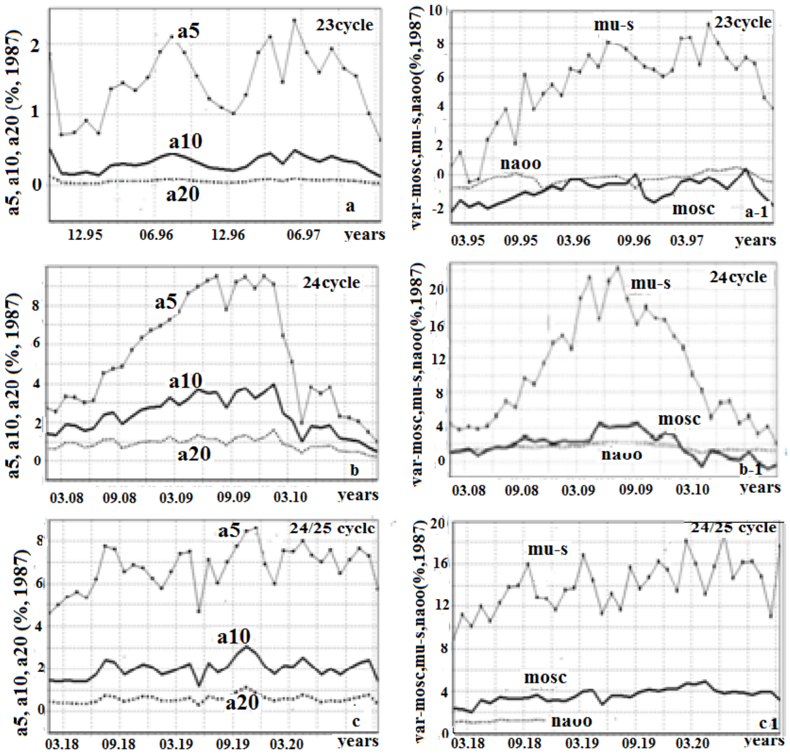

Figure 2. Amplitudes of CR variations in periods near SA minima in 23-24 cycles (a-c): a5-thin curves (with dots), a10-thick solid curves, a20-dashed curves; (a1-c1)-CR variations at the stations: mu-s (strat., Apatity), mosc (NM, Moscow), naoo-telescope (Nagoya).

When studying CR modulation, the data of separate stations are often used as data on CR intensity. Therefore, CR modulation, the data of separate stations are often used as data on CR intensity. Therefore, in order to compare the characteristics of the density of restored CR fluxes for the same periods of SA minima, CR variations were determined for individual stations and observation points of CRs for different geomagnetic cutoff rigidity. The analyzed CR variations in the periods close to the minimums of 20-24 SA cycles are divided by shape into two types of 11-year SA cycles: with a sharp maximum of the CR flux (1965, 19/20), (1987, 21/22), (2009, 23 / 24) and flat maximums (1977, 20/21), (1997, 22/23), (2019, 24/25) depending on the direction of GMF of the Sun. The reconstructed particle maximum for the 5, 10, 20 GV rigidities in the case of a peak-like maximum, the change (in% of 1987) in altitude occurs as follows: (monthly averaged amplitudes) for R = 5 GV - 5.0, 5.7, 9.5; for R = 10 GV - 1.7, 3.2, 3.8; for R = 20 GV- 0.6, 1.7, 1.6, indicating a decrease in the recovered fluxes of high-energy particles (R = 20 GV) in 2009, this anomaly is observed during the period when low- and medium-energy particles grow. The polarity of GMF of the Sun qA <0 and the magnetic configuration of the heliosphere in these periods (1965, 1987, 2009) were the same. This situation with a decrease of high-energy particles requires additional explanation. As for the time of reaching the maximum CR flux at the minimum in 1965 and in 1987, it reached by particles of different rigidity almost simultaneously (for R = 5 GV in 05.1965 and R = 10-20 GV in 04.1965; for R = 5 - 10 GV in 03.1987 and R = 20GV in 02.1987), i.e. with a slight advance, the maximum is reached by particles with high rigidity. The complex nature of modulation of particles of different energies is evidenced by reaching of the CR maximum in 2009. Usually, when particles of different energies from one source arrive at the observation point, dispersion by energy and by diffusion rates leads to an earlier growth of variations of harder particles. But here the situation is different. The CR maximum is reached when the recovery process, which is characteristic of the SA minimum, is interrupted, and this occurs with the beginning of a new solar cycle. The new cycle of solar CR modulation manifests itself earlier on particles of comparatively low energy.

The obtained features of reaching the maximum of the reconstructed CR flux using the example of SA minima in 1965 and 1987 by particles of different energies can also be explained by the beginning of a new cycle in CR, but it occurs almost simultaneously for all considered rigidities. Considering the behavior of the time variation of flat CR variations in SA minima in cycles with the direction of the solar polar field qA> 0, the first thing to note is some ambiguity in determining the CR maximum. The magnitudes of the amplitudes at the maxima of the reconstructed fluxes for different rigidities in cycles 21 and 23 do not exceed 2% and their values are close in different months. For a minimum of 24/25, the variations of low-energy particles differ significantly from variations in other cycles with the same direction of the GMF: the a5 amplitude reaches 8.5% at the end of 2019. The height of the restored CR fluxes is 24/25 for medium- and high-energy particles exceeds the modulation in cycles with a similar direction of the magnetic field, but insignificantly (a10 = 3.1%, a20 = 1.1% in 10.2019). This circumstance may indicate a softening of the spectrum at a minimum of 24/25; confirmation of this is the result of determining spectrum index γ (Figure 3), given with standard statistical error for 1976-2020. Comparison of the γ spectrum index for the minimums of the three cycles(22/23, 23/24 and 24/25) shows that the softening began in 24/25 already from 2017 ($\gamma = 2$), for 23/24 - $\gamma = 1.8$, for 22/23- $\gamma = 0.9$.

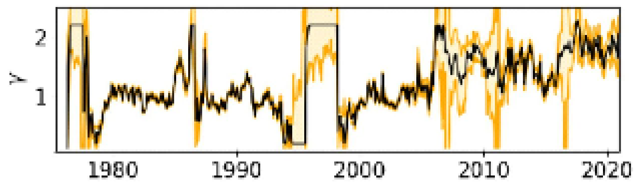

Figure 3.Temporal changes of spectrum index γ.

The soft spectrum of long-term CR variations obtained by us in a minimum of 24/25 is confirmed by the results [10], obtained with the use of ACE CRIS and NM data.

The above discussion of variations calculated using a set of instruments for R=5, 10, 20 GV does not contradict the variations obtained for individual detectors (Figure 2. a1-c1) in general, but data the separate monitor sometimes does not allow making a correct conclusion about modulation. If, when obtaining the variations for R=5, 10, 20 GV, the accuracy is determined by the adequacy of the CR variation model used, then for many operating stations CRs the accuracy is characterized by sporadic changes in efficiency and drift of the data CR registration. The issue of long-term stability of detectors is described in detail in [11], the conclusions of which indicate the advantages of using the model approach to determine the spectral characteristics.

2. Results of the description of long-term CR variations

To simulate CR modulation by electromagnetic fields of the heliosphere, we have proposed a semiempirical multiparameter model [3, 8], in which the long-term modulation of CR is described by the above-mentioned characteristics η, B_{ss}, H_{pol}, CME*i* and *Al* with a detailed justification of their choice. For these indices and amplitudes of the isotropic part of CR variations with rigidity 5, 10, 20 GV (*a5, a10, a20*,% to 1987), a multivariable regression analysis was performed taking into account the delay for each modulation parameter and the role of each of them in CR modulation was revealed in 1991-1999, 2000-2013 and 2014-2020. It should be noted that: 1. the effect of the 22-year cycle of solar polar field H_{pol} on the CR density was taken into account by introducing a correction to the amplitudes of variations in a_{Hpol}. For the corrected variations in a_{Hpol}, a multiparametric linear approximation of CR variations was performed; 2. as a modulation characteristic of heliospheric field in the model instead of IMF (B_{imf}), the field on the surface of the solar wind source B_{ss} is used. It was shown in the work [12] that replacing module B_{imf} by the mean magnetic field on the surface of the solar wind source B_{ss} in the empirical model is not only possible but even improves the quality of the model. The modulation in the minimum of the 24/25 cycle is compared with the modulation of the previous cycles 22/23 and 23/24, in order to compare the dependence of the modulation of particles of different rigidity from the direction of the GMF. As a result of the model description of CR variations, which was carried out separately for the amplitudes a5, a10, and a20 for three periods, the following values were obtained:1) the correlation coefficient ρ =0.96-0.98, the standard deviation of the model σ ~0.34% - 2.43%. 2) below, we consider the possible reasons for CR modulation with quantitative estimates of the contribution of various characteristics of SA to the observed CR modulation in the period 2014-2020. (qA> 0) and comparison with contributions in 1991-1999 (qA> 0) and 2000-2013 (q <0) was carried out.

2. Discussion

Observed and expected CR variations in the periods 1991-1999, 2000-2013. 2014-2020 in SA cycles with a certain polarity of the GMF of the Sun and contributions to the modulation model from changes in solar-heliospheric characteristics are shown in Figure 4. Analyzing the obtained model results, we can note: 1. In the period 1991-1997 qA> 0 for R = 5 GV, the decisive role at creating of modulation in terms of the contribution (11.7%) belongs to the current sheet slope η. Attention pays to the decrease of the influence of the slope angle η on the CR modulation and to the decrease in the effectiveness of its influence during the period of weak CR modulation, but the noted decrease of the η effect was related to particles with R = 10 GV and to the period when q <0. Here, the efficiency could change for two reasons: the direction of the Sun field qA> 0 and the low energy of the particles; 2. For R = 10 GV and R = 20 GV for the period 1991-1997, the contributions to modulation from the action of η and *Bss* differ insignificantly; 3. for the period 2000-2013 q <0, CR modulation is mainly determined by changing of B_{ss} characteristic for the entire rigidity interval; 4. For the period 2014-2020 qA> 0, the main role in creating CR modulation for R = 5 GV is played by the mean magnetic field B_{ss} (6.4,%) and the current sheet slope η (5.3,%) with ~ the same contribution. For particles with rigidity 10 and 20 GV, with general small amplitude of variations in this period, the contribution from the influence of the CMEi on modulation is slightly higher (an increase of the CMEi at the end of 2014). Weak CR modulation in the 24th and in the beginning of the 25th SA cycles, the lowest ones during the CR observation, can be explained by the different impacts on CRs of specific physical processes (drift, diffusion, convection, and adiabatic energy changes) which creating modulation. About the interaction of the main modulation mechanisms and the role of modulation characteristics in creating general modulation changes with solar cycles is stated in [13,14]. The current sheet is the largest magnetic inhomogeneity in the heliosphere with which CR interacts; it is the place of the most effective drift. Comparing the modulation of particles of different energies during periods with the same direction of the GMF, we note that at the SA minimum, the η values fall, which can be reflected in the drift effect during propagation CR. In the presented modulation model, the contribution to the overall modulation from the effect of CR drift in the 24th cycle is lower, a significantly smaller value of the drift effect in the incipient minimum (2017-2018) 24/25, obtain in [15]. In the modulation model for the period 2000-2013 qA <0, the predominance of the contribution from the impact on CRs of a large-scale magnetic field on the Sun, expressed in the value of the B_{ss} index, may indicate an increase in the role of CR diffusion during propagation in the heliosphere with reduced IMF [16]. The predominance of the diffusion process in CR modulation at qA <0 (in our analysis, the period 2000-2013) is also confirmed by the results of [15].

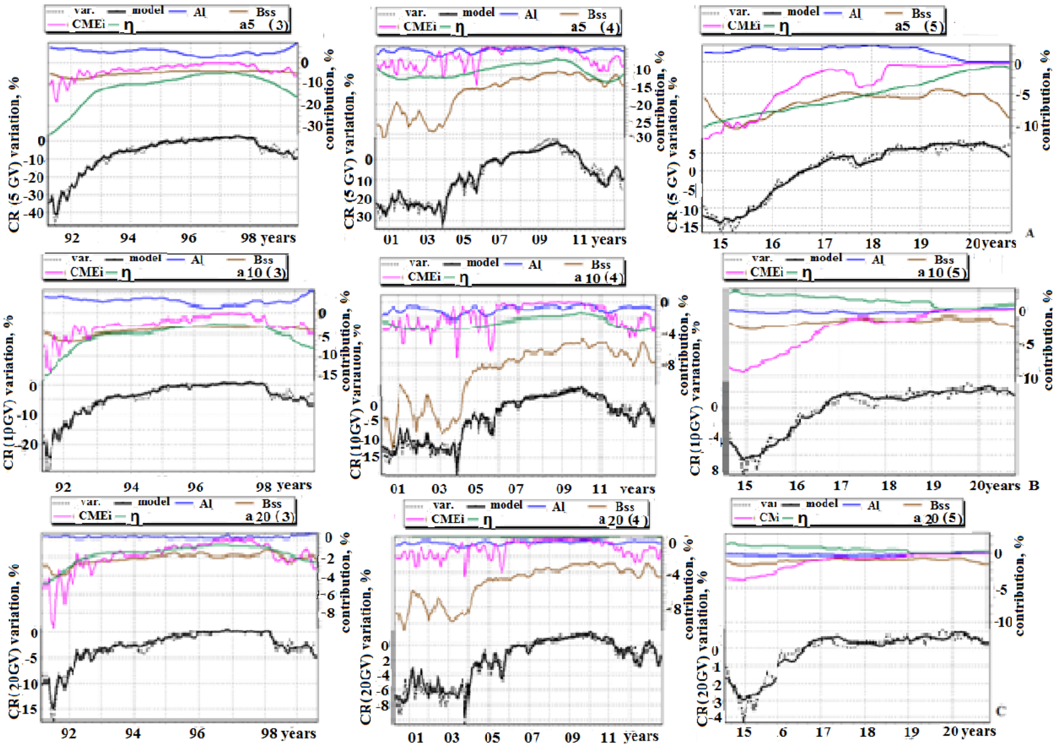

Figure 4: A- a5, B- a10, C- a20 (%,1987) – CR variations (dashed line in the lower part) and the result of their modeling (solid black); upper part-contribution from: η (green), B_{ss} (brown), CME*i* (pink) and *Al* (blue): (3) - 1991-1999, (4) 2000-2013 and (5) -2014-2020.

3. Conclusion

1.The amplitudes of long-term CR variations in the minimums and near the SA minimums give an idea about the complex nature of modulation of particles of different energies in periods with different directions of the solar GMF. The recovered particle fluxes during periods of low SA differ in height and time to reach a maximum for the analyzed rigidities of 5, 10, 20 GV. For a minimum of 24/25, the variations of low-energy particles differ significantly from variations in other cycles with the same direction of the solar polar field qA> 0, the value of a5 reaches

8.5% (in cycles 21 and 23, it does not exceed 2%). The height of the reconstructed CR fluxes of 24/25 for medium- and high-energy particles exceed the modulation in cycles with a similar magnetic field direction, but insignificantly (a10 = 3.1%, a20 = 1.1%). This circumstance indicates a softening of the spectrum at a minimum of 24/25; which is confirmed by the result of determining the index γ. Mitigation began on 24/25 from 2017 (γ = 2), for 23/24 - γ = 1.8, for 22/23 - γ =0.9. 2. The conducted study says about the advantages of using the GSM and the model approach in the study of long-term variations, rather than the CR registration data at individual stations. 3. The restored CR flux at the 24/25 minimum is lower than in the anomalous 23/24, and the dependence of recovery level from the particle energy is observed. For the period 2014-2020 qA> 0, the main role of creating CR modulation for R = 5 GV is played by the mean magnetic field B_{ss} and the current sheet slope η with ~ the same contribution. For particles with R=10 and 20 GV, with a general small amplitude of variations in this period, the contribution from the influence on the modulation of the CMEi index slightly exceeds the corresponding contribution in other periods. 4. At a minimum of 24/25, a decrease of the influence η on the CR modulation was revealed. The change in its value occurs within the same limits as in other cycles, but the effectiveness of the effect on modulation is greatly reduced. In the 24th and the beginning of the 25th SA cycle, the impact on CR of a large-scale magnetic field on the Sun, expressed in the B_{ss} index, prevails in the general CR modulation, despite a decrease in the B_{ss} value itself.

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