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About long term modulation of cosmic rays in the 23-24 solar activity cycles

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Abstract
Recently, there has been a significant trend in magnetic fields on the Sun. The total magnetic field of the Sun from the end of the 22nd cycle of solar activity (SA) has more than halved and this decrease continues. Changes in the magnetic field are the key to all the active phenomena occurring on the Sun and in the heliosphere and, accordingly, to processes in cosmic rays. In long-term CR variations in 23-24 cycles of SA the attenuation of the solar magnetic field is displayed and these variations turned out to be the smallest for the entire time of CR observations. Model calculations of CR modulation for 21-22 and 23-24 cycles of SA showed: with a slight difference in the regression characteristics obtained, the distribution of contributions to the generated CR modulation from the effects of various SA indices is strongly varies in the analyzed periods. Possible reasons for the features of the last two SA cycles are discussed.

1. Introduction

The sun is a magnetically active star. The role of the magnetic field in the dynamics of the processes occurring on the Sun is decisive and its variations are the key to all active phenomena occurring on the Sun, in the solar atmosphere and heliosphere. The solar cycle is the result of cyclical changes of the magnetic field that occur in the solar interior. The connection between the CR variations observed on Earth and the cyclic SA has been established long ago, and the variety of manifestations of which provides constant interest in solar CR modulation. Long-term changes of the characteristics of the global magnetic field of the Sun and sporadic SA indicate a decrease of SA observed more than twenty years, which starting from the end of the 22nd SA cycle. During the transition from the 22nd cycle to the 23rd, the activity of the Sun decreased quite sharply, and in the 24th cycle this decrease continued. For the entire time of observations of the Sun, there was nothing like this. This change of SA is especially manifested as a weakening of the solar magnetic field, which spreads to the solar wind and the heliosphere (Livingston et al. 2012; Ishkov 2013; Sun et al. 2015). As a result of the process of restructuring the general magnetic field of the Sun, there is a trend towards a decrease of magnetic fields of all structures on the Sun. The rate of development and the level of flare activity in the 24th cycle is significantly lower than observed in previous cycles, and there were no very large and extreme flare events at all.

The observed weakening of the global magnetic field of the Sun and the corresponding trend of heliospheric characteristics in 23-24 SA cycles (1996-2019) raises the question of the response of this phenomenon to long-term CR modulation in these cycles. This can be clarified most clearly

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when comparing the observed CR variations in cycles 23-24 (1996-2019) with variations in the previous 21-22 SA cycles (1976-1996). In this work, the study of long-term CR variations is based on the construction of a CR modulation model, combining several solar indices. As the main modulating characteristics of the global magnetic field of the Sun, the model proposes: the polar magnetic field of the Sun, coronal holes, characteristics of large-scale fields - the average magnetic field on the surface of the solar wind source and the field of the Sun as a star, as well as the slope of the heliospheric current sheet (corresponding justification for the choice of characteristics given in Belov et al. 2002; Gushchina et al. 2008, and links to them). The sporadic SA in the model is described using the CME index (Belov & Gushchina 2018). In the modulation model developed by us, the characteristics of the magnetic field on the surface of the solar wind source are calculated based on observations that began in 05.1976 (the beginning of the 21st cycle) at the observatory Wilcox (WSO, http://wso.stanford.edu/, last accessed April 6, 2021). The analysis of the CR modulation features in 21-24 cycles was carried out on the basis of long-term observations of the above mentioned SA characteristics and of the data of continuous CR monitoring on the world network of cosmic ray stations. The density of CR continuous ground observations of which on the world network of cosmic ray stations have been carried out using neutron monitors since 1957, in the last two cycles (23rd and 24th) is very different from what we saw in previous cycles. Firstly, the low SA minimum at the end of 2009 (minimum SA 23/24 cycle) caused a record increase in the CR density and a comparable minimum 24/25 cycle (in August 2019, according to preliminary data) is distinguished by a continuing increase of CR intensity until the end of 2019. For more than sixty years of continuous CR observations, previously ground-based observations did not achieve such CR density values which exceed the previous four CR maxima (in cycles 19-22) the value of which may approach the extraheliospheric level. Secondly, the unusually weak CR modulation in the 23rd and 24th SA cycles is surprising. The purpose of this work is to analyze the features of CR modulation in 23-24 cycles (1996-2019) and compare the results obtained with CR modulation in 21-22 cycles (1976-1996).

2. Data of CR and characteristics of SA peculiarities of time variations CR and SA indices

Here, continuing the study of long-term CR modulation those begun in a previous works (for example, Belov et al. 2002, 2005; Gushchina et al. 2008), we describe the process of long-term CR modulation separately for two periods 05.1976-10.1996 and 11.1996-12.2019 to consider the role of weakening of the solar magnetic field in CR modulation. The observed trend of the solar magnetic field to cosmic radiation is considered for the 23rd and 24th cycles of «lowered» SA and is compared with CR modulation in the 22nd cycle of the «transient» SA and in the 21st cycle of the «increased» SA (https://www.izmiran.ru/library/pushkov2019/pushkov2019abs.pdf, last accessed April 6, 2021).

The initial data for modeling CR variations are observations of the CR intensity and of a number of SA characteristics which reflect changes in the solar wind structures observed during the development of SA cycles and contribute to modulation. Long-term variations of galactic CRs in 21-24 SA cycles were obtained by global survey method based on data from the global network of ground-based detectors (~ 40 neutron monitors), data from a multi-directional telescope (Nagoya station), and the results of stratospheric sounding at three different points (Stozhkov et al. 2007). The spectrum of long-term CR variations for 1976-2019 calculated by the method (Belov, Gushchina, Sirotina 1993), further analysis was carried out using the monthly mean values of CR variations with 10 GV rigidity *(a10* is the value of long-term variations in galactic CRs). In this work, the spectrum of long-term variations was determined relative to the SA minimum in the 23rd cycle (2009).

The contribution to modulation is largely determined by the temporal changes of the solar magnetic fields of different scales (global and local) during their interaction. Since CR are charged particles, their behavior is determined by IMF and can be seen in observed variations of cosmic

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radiation. The effect of SA on the observed CR modulation is described through the following chain: the magnetic field of the Sun (the dipole component of the solar magnetic field *Hpol*, which changes its sign at the maximum of the local fields cycle) - the surface of the solar wind source (the average magnetic field *Bss* - the integral energy characteristic of the SA, defined as the square of the radial component of the magnetic field, and the structural characteristic - the slope of the current sheet *hcst*), the average field of the Sun as a star *Bmf* - heliosphere (characteristic of the solar wind - interplanetary magnetic field *Bimf*) - cosmic rays (in work - the amplitude of CR variations with a rigidity of 10GV - *a10*). The time changes of the parts of this interconnected chain, which are important for CR modulation, namely, the characteristics of the global magnetic field of the Sun (according to the results of daily observations of the Sun's field on magnetographs (http://wso.stanford.edu/) and the heliospheric characteristic - the interplanetary magnetic field (https://omniweb.gsfc.nasa.gov/, last accessed April 6, 2021) associated with the solar field is shown in figure 1 (a-h), where, in addition to the above modulating CR characteristics, the characteristics of the coronal holes area effect to modulation (Gushchina et al. 2016) and sporadic solar activity (using the introduced CME index). The decrease trend in the 23-24 SA cycles (1996-2019) of the indicators of global processes on the Sun and in the heliosphere is clearly visible. A particularly significant decrease occurs in the solar magnetic field (figure 1a-e) at the boundary of the solar wind and extends to the characteristics of heliomagnetosphere, primarily by the IMF value (figure 1b), together with a change in the density and speed of the solar wind (Belov et al. 2001). Accordingly, a decrease in the SA and IMF levels leads to a change (increase) in the CR intensity observed on Earth and in near-Earth space (figure 1f). A twofold decrease of average field on the source surface *Bss* has occurred, as is clearly seen in figure 1a, in the last more than 20 years. As for the magnetic fields in the solar wind above the poles, heliophysicists have established (Ishkov 2013) that, in general, over the past 30 years, they have decreased by about three times.

3. Choice of the indices for a modulation model

Long-term CR modulation was described using a multiparameter model in which the SA parameters are linearly related to the amplitude of CR variations. When constructing the model, a combination of modulating parameters is used; the corresponding justification for the choice of which is given in (Belov et al. 2002, 2005; Gushchina et al. 2008). Figure 1 (a-h) shows the time course of the characteristics for several cycles; below (figure 2 a-c,e,f) will be presented the temporal changes of the characteristics which used to build the modulation model in the 21-22nd and 23-24th cycles to compare the CR variations (figure 2d) in them. The trend of the main parameter modulating CR - the global magnetic field of the Sun-is its significant and prolonged decreasing, ultimately leads to a trend in the characteristics of the SA and the heliospheric field. Below is a summary of the temporal changes in each index. The *hcst* (figure 1d) correlates best with CR variations and is the main parameter in the CR modulation model, the modulation depth depends on it, the current sheet is the largest magnetic inhomogeneity in the heliosphere with which CRs interact; it is the place of the most effective drift. In the last activity minima, the *hcst* values increase (from 9.3° at the 22/23 minimum to 16.6° in the period close to the 24/25 minimum). Increase of this structural characteristic at the SA minima was noted in (Gushchina et al. 2012) with the assumption of the role of the drift effect in its creation.

The square of the radial component of the magnetic field averaged over the surface of the solar source the wind *Bss* (figure 1a) has been decreasing since the end of the 22nd cycle, at the 23/24 minimum unprecedentedly low values were recorded. When using IMF data *Bimf* (figure 1b) in modeling, there is always a doubt: can the measurements of the IMF near the Earth sufficiently well characterize changes in magnetic fields in the entire heliosphere, where CR modulation occurs.

Therefore, there is a desire to find another parameter that also well complements the hcst, but, in contrast to the IMF intensity, is more global. Probably it is better idea to search for this parameter

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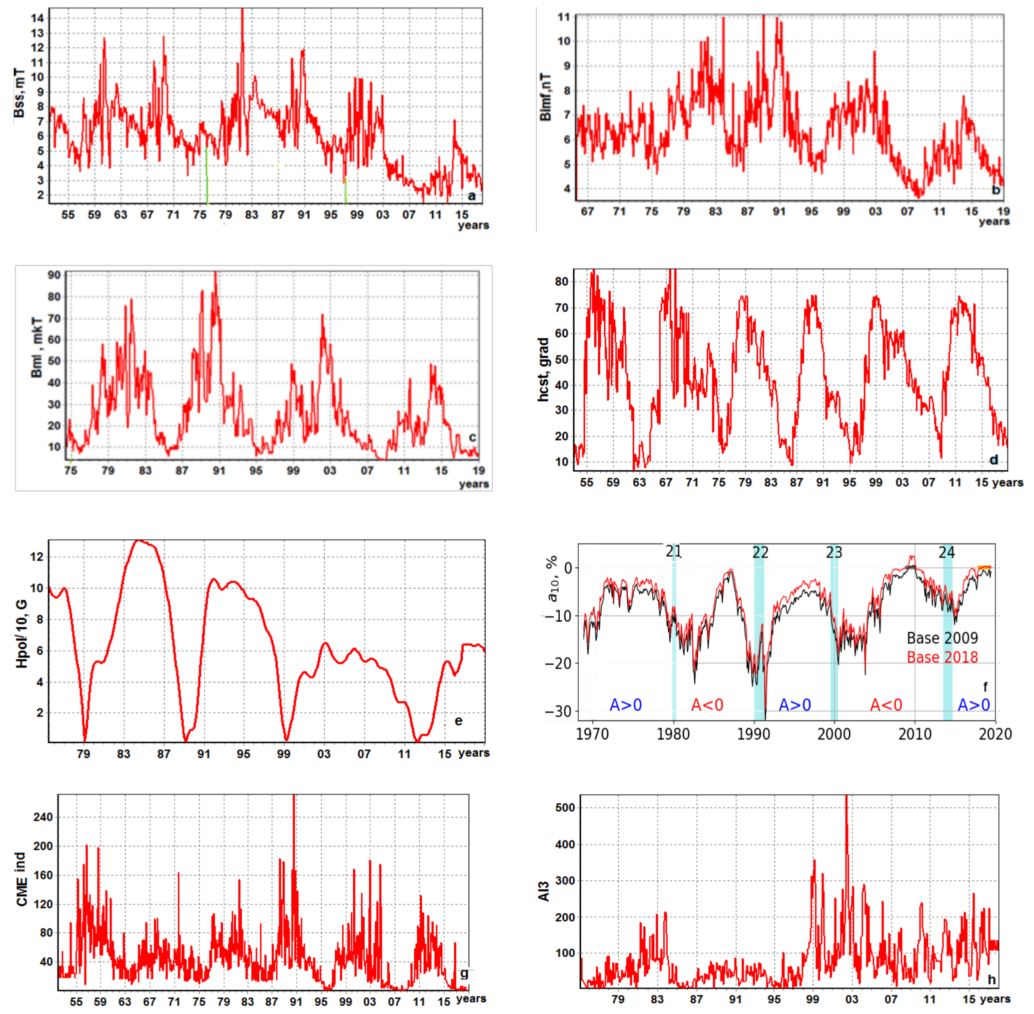

Figure 1: Cyclic variations of: a) - mean magnetic field of the Sun (*Bss*) (Obridko & Shelting 1999) b) magnetic induction of the interplanetary magnetic field near the Earth (*Bimf*); c-magnetic field of the Sun as Bmf stars); d) - the slope of the heliospheric current sheet (hcst);e) polar field of the Sun (*Hpol*) f) -variations of CR density with a rigidity of 10 GV (a10,% -); g) -CME index (Belov & Gushchina 2018); h) -area of low-latitude coronal holes (AL3) (Gushchina et al. 2016).

on the surface of the source, where the hcst is determined. The relationship between *Bss* and the modulus of the heliospheric field *Bimf*, measured near the Earth, is quite close. So interchangeability of *Bimf* and *Bss* in modulation models is revealed. It is shown at (Belov et al. 1999, 2002), that replacing the heliospheric field module *Bimf* in the empirical model by the average magnetic field *Bss* is not only possible, but even improves the quality of the model. *Hpol* (figure 1e) - the polar magnetic field of the Sun - is taken into account in the model by magnitude and by sign; in the last two cycles it has a smaller, than before, and decreasing with time amplitude; CME-index (figure 1g) - takes into account the effect of sporadic SA on CR modulation; it decreases, especially in the 24th cycle. AL3 (figure 1h) – the area of low-latitude coronal holes, the choice was justified in (Gushchina et al. 2016); it increases modulation in contrast to high-latitude coronal holes. The effect of low-latitude holes occurs in antiphase with other modulating indices. Note that in solar cycles the indices listed below behave differently, this allows us to hope that we can get a complete picture of modulation when constructing a model with complementary indices.

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4. Describing long-term CR variations using a model based on solar characteristics

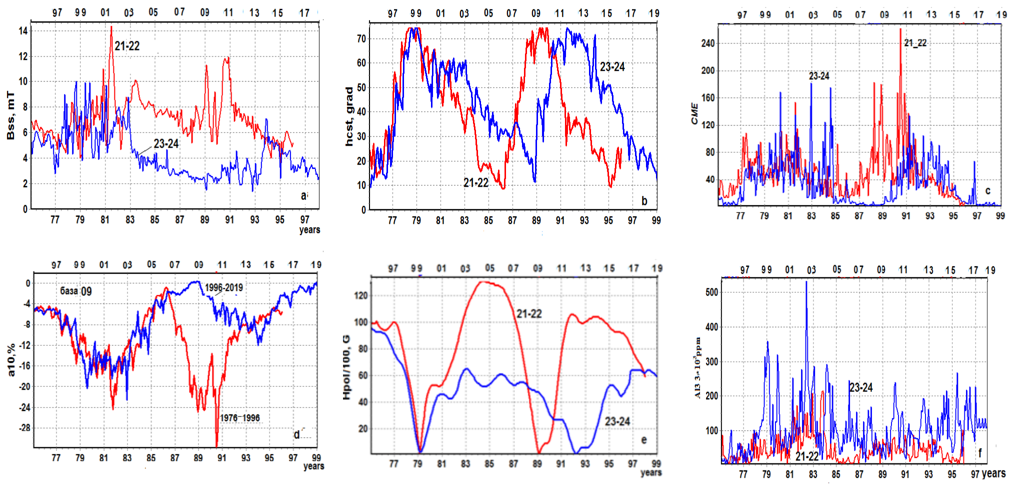

Figure: 2 (a-f) Changes of indices (red curves - 21-22 cycles; blue ones - 23-24 cycles; a, b, c-are determined on the source surface: a) - mean magnetic field of the Sun (*Bss*); b) is the slope of the heliospheric current sheet (hcst); c) -CME index; d) - variations in CR density with a rigidity of 10 GV (a10,% to 2009); e) - solar polar field (*Hpol*); f) - area of low-latitude coronal holes (AL3).

An understanding of the process of modulation of galactic CRs by the heliosphere electromagnetic fields is facilitated by modeling CR variations. Our group has proposed a semi-empirical multivariate model (Belov et al. 2002, 2018; Gushchina et al. 2008, 2016; Yanke et al. 2019), in which the long-term CR modulation is described by the mentioned above characteristics with a detailed justification for their choice. For these indices and the amplitude of CR variations with a rigidity of 10 GV *a10,%* to 2009, a multivariable regression analysis was performed taking into account the delay for each parameter and the role of each of them in CR modulation was revealed. The set of the above indices reproduces well the observed variations when describing modulation. The CR level has been growing at the last two cycles, while the 11-year cyclicity has been preserved, but the amplitude of variations has decreased. As a result of the model description of CR variations, carried out separately for 21-22 and 23-24 cycles, we obtained: correlation coefficient (r), standard deviation of the model (δ), regression characteristics (k), and delay times of CR variations relative to the SA indices (t_{delay}) (table 1).

cycles	r	δ	k_{hcst}	k_{Bss}	k_{CME}	k_{Al3}
21-22 (1976.08-6.10)	0.97	1.59	-0.19	-0.76	-0.05	0.009
t_{delay}			14	5	1	8
23-24 (1996.11-9.12)	0.96	1.60	-0.10	-1.90	0.038	0.009
t_{delay}			25	4	1	8

Table 1: Results of multivariable regression analysis for 21-22 and 23-24 cycles.

5. Discussion and conclusion

The observed and expected CR variations in 21-22 and 23-24 cycles and the contributions to the modulation model from changes in solar heliospheric characteristics are shown in figure 3. The main role in

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modulation in 21-22 cycles belongs to the slope of current sheet (*hcst*), and in 23-24 cycles belongs to *Bss*. (figure 3a, b). Regression coefficient for *hcst* in 23-24 cycle model is - 0.1%/°. This is ~ 2 times less than in 21-22 cycles (-0.19%/°). The regression coefficient for *Bss* in 23-24 cycles is -1.9% / μT, and in 21-22 cycles is-0.76% / μT. The CR modulation in these SA cycles is much weaker than the modulation in 21-22 cycles. The reason is anomalies which appears on the Sun and in the heliosphere during last two cycles due to the weakening of the solar magnetic field and the state of the heliosphere.

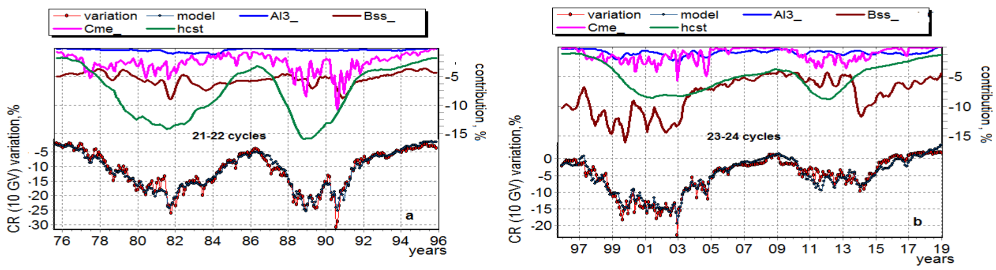

Figure 3: - a10 (% to 2009) - variations of the density of CRs with a rigidity of 10 GV (red curve with dots in the lower part of the figure) and the result of their simulation (solid black curve); upper part of the figure - the contribution from changes: the slope hcst (green curve), the mean magnetic field of the Sun *Bss* (brown), the CME index (pink) and the area of coronal holes AL3 (blue): (a) - 21-22 and (b) -23-24 cycles.

The analysis of the 23rd cycle with weak CR modulation and the 24th cycle, the lowest during the CR observation time, can be explained by the different (in comparison with other cycles) impact on CR of specific physical processes (drift, diffusion, convection, and adiabatic energy changes) which create modulation. The interaction of the main modulation mechanisms and the role of modulation characteristics in generating overall modulation changes with solar cycles (Potgieter 2013; Belov et al. 2017, Kalinin et al. 2017). In the presented modulation model, the contribution to the overall modulation from the CR drift effect in the 24th cycle is lower. In the modulation model for cycles 23-24, the aforementioned predominance of the contribution from the action of a large-scale magnetic field on the Sun on CR, expressed in the value of the *Bss* index (taking into account the relationship between *Bimf* and *Bss*), may indicate an increase in the role of CR diffusion during propagation in the heliosphere with a low IMF (Kalinin et al. 2017). In the 23-24th cycles, a decrease of the influence of the current sheet tilt angle 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 (requires additional explanation!). In the 23-24th SA cycles, the general CR modulation is dominated by the effect of a large-scale magnetic field on the Sun on CR, expressed in the *Bss* index, despite a decrease in the *Bss* value itself.

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