Galactic cosmic ray modulation in the solar activity minima

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***Abstract*. Using long-term observations of galactic cosmic ray (CR) variations in near-earth space and on the Earth we have determined the galactic CR modulation during 19-23 solar activity (SA) cycles in the context of the semi-empirical model. The modulation model relates the CR variations to the solar magnetic field characteristics obtained for the surface of a solar wind source at a distance of 2.5 and 3.25 solar radiuses. Attention has been focused on CR behavior in 19-24 SA cycles minima and features of CR modulation in the lengthy (when compared with the previous cycles) minimum of the 23rd SA cycle. The CR modulation in the SA minima, connected with time change of the dipole component of the Sun field during these epochs of the cycles, is considered. The quality of the long-term variations description has been improved by including in the model the two years (2007 - 2008) of the 23rd cycle with abnormal low SA. An assessment has been made of the role and the contribution to the observed CR modulation from the changes of each index used in the presented CR modulation model.**

***Keywords*: galactic cosmic rays, modulation, cycles**

I. INTRODUCTION

The modeling of the CR long-term variation by electromagnetic fields in the heliosphere has been carried out to understand the processes creating modulation. The model of the CR modulation connecting long-term CR variations with characteristics of the solar magnetic field was developed by us and presented in works (e.g., see [1-4]). The following indices of the magnetic field have been considered as model parameters in order to describe long-term CR variations: the value and sign of the polar solar field Hpol, the average strength of the solar magnetic field (the Bss integral index), partial indices (zone-odd (ZO) and sector-odd (SO) indices), the tilt of the heliospheric current sheet η, and the special index (Fx) taking into account X-ray flares. The various solar cyclic variations are reflected in CR intensity. It is now well-known that an 11-year cycle is the basic cycle for all processes of SA differing in phase and localization on the Sun surface. The cyclic curve varies for indexes SA with increased distance from photosphere. The cyclic changes of indexes on photosphere and at a distance R=1.5Ro (Ro is Sun radius) is similar to the cyclic changes of local magnetic fields. These changes come nearer to the cyclic changes of global fields at R=2.5Ro and 3.25Ro [5]. We have considered the tilt η defined on distances R=2.5Ro and 3.25Ro in the model calculations. Our aim was to discover how the border of change of SA indexes with height can be reflected in model of CR modulation. The purpose of the work is to consider the feature of the behavior and CR modeling at 19-24 cycles (1953-2011). During the period when direct observations of the sun's magnetic field were absent (to 05.1976), the characteristics of this field have been restored from the optical Hα observations. Thus, it was possible to extend the time interval of modeling representation of CR variations right back to 1953. This work also includes the results of the CR variations forecasting for 09.2003-12.2011 presented by us in [6]. The quality of the forecast is discussed within the limits of the developed modulation model, taking into account CR observation between 09.2003 and 12.2008. Most attention is paid to the CR behavior during periods of SA decline and SA minima with the estimation of the contribution to created CR modulation of each SA index used for the description of CR modulation.

II. DATA AND METHOD

Initial data for modeling of CR variations are long-term observations of CR intensity, the characteristics of the solar global magnetic field, and data of solar X-rays flares (importance $\geq M1$). The rigidity spectrum of CR variations for each month was obtained from the data of neutron monitors (NM) of the entire global network of CR stations (1953-2008) and stratospheric sounding data (1957-2008). We are using CR variations, obtained by NM data (about 40 NM, with a tentative estimation of long-term stability of NM) and stratospheric observations (3 points). Here we study amplitude variations of CR with 10 GV rigidity, excluding variations associated with ground level enhancements of solar CR. It has been proposed to introduce into the model the following characteristics: the polar magnetic field Hpol, the integral index Bss, the partial indexes SO and ZO as well the tilt of the current sheet η and the index considering X-ray flares Fx. The choice of such a set of solar activity indexes and methods of their evaluation were described in detail previously in the above-mentioned publications. Since there is no homogeneous, continuous given solar observation data for the construction of CR modulation model for 1953-2008, the modelling has been executed separately for intervals: 1976-2008, 1953-2008 and 1953-2011 (with the addition of results of CR forecasting for 24th cycle). The magnetic field characteristics necessary for the construction of the CR modulation model (η, Bss, ZO, SO,

Hpol)for the period 1976-2008 are defined on the surface of a solar wind source from direct observation of the sun global magnetic field. The contribution to the created CR modulation is estimated from changes of each index. Indexes are defined on two surfaces of a solar wind source (on distances R=2.5Ro and 3.25Ro). We used data of measurements of the large - scale photosphere magnetic field performed in the Wilcox solar observatory (WSO) [7]. The data of direct measurements of solar fields are added by optical observation of magnetic fields in Hα line in 1953-1976 for the second period (1953-2008) [2]. Some features have been revealed recently by the analysis of expected and observable variations for three cycles (21-23) [8]. The modelling has been made for two periods to understand how these features are reflected in the description of long-term CR variations for five cycles (19-23). In particular, attention is focused on the decreasing phase of the 23rd cycle and on the still ongoing minimum preceding the 24th cycle. This approach makes it possible to improve the statistical characteristics of the regression analysis. Besides there is a possibility to check to what extent it is justifiable to use combined number data (direct and indirect observation of solar large-scale fields) for the description of CR modulation for a long period. The quality of the developed model of the CR variations is checked by using the modelling results of CR variations for 2003-2011 and comparing them with already really observable CR variations in 2003-2008. In order to understand the modulating influence of local solar fields on CR it is proposed to use Fx, a specially calculated index of solar flares, empirically determined in [9]. The flare index depends on the maximum X-ray intensity (events of $\geq M1$ have been selected) during the flare and its longitudinal location relative to the Earth. This index is defined for the period 1976-2008. The number of NSSC is used as an index which can display influence of local fields of the Sun for CR modulation calculation in 1953-2008.

III. THE TEMPORAL CHANGES OF THE MODEL PARAMETERS AND RESULTS OF CR MODULATION MODELLING

The features of the model parameters changes: An example of the use of the expanded number of data for definition η is given on fig. 1.

During the decline phase in cycle 23, the current sheet tilt (η) remains anomalously large compared to other cycles during analogical phases. Tilt remained large (31.3; 31.1 deg.) for R=2.5Ro and (14.4; 14.1deg.) for R=3.25Ro correspondingly during 2007 and 2008. We should note that there is a good coincidence of values η, received for R=3.25Ro, and the result of the forecast η in 2004-2008. This could mean that the border of a solar wind source during this period lowered SA and during SA minimum moved away from the Sun. Is this inherent in all minima? It is necessary to mention that it is a period of a deep SA minimum, which is certainly shown

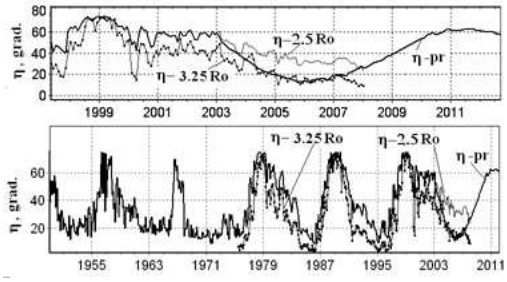

Fig. 1: The bottom part-the tilt η as inferred from WSO measurements in 1976-2008-thin curve for R=2.5Ro and curve with points for R=3.25Ro; optical Hα observations (calculated in [10]in 1950-1976 - mean curve; forecast η (thick curve) is made for 09.2003 - 12.2011.The top part - η in the increased scale for 23rd cycle.

in CR modulation. Along with the unusual behavior of the structural characteristic η in cycle 23, changes of the quantitative characteristics have also been observed. These characteristics (Bss, ZO, SO, Hpol) necessary for the construction of CR modulation model are defined on the source surface from direct observation of the global magnetic field of the Sun for the period 1976-2008. The average magnetic field intensity Bss- full integral index of SA, such as the squared radial component of the magnetic field averaged over a sphere of fixed radius, provides information on all magnetic streams that pass through the solar wind source surface. The maximum of index Bss coincides neither with the maximum, nor with the minimum of local fields as reflect variations of large-scale fields in all solar latitudes. The partial indices: zone-odd ZO - the part of the magnetic field with the odd zonal symmetry (analogy of the vertical dipole). The physical value of ZO is that it describes the basic global field in the best way. The partial index SO (sector-odd) - tilted dipole and manifests itself in the 2- and 4-sector structure and reflects the influence of low- and middle latitude regions of SA. There is data of observation flare activity of the Sun used for calculation of index Fx during the considered period (1976-2008). The pictures of the time changes of the modulating characteristics and variations of the CR (10 GV) intensity in detail are presented in [8].

Model in 1976-2008: The model description of CR variations was provided for joint consideration of the following modulating parameters: η, Bss, (or one of the partial indexes), Hpol as well as the flare index Fx. We have the highest correlation coefficient ρ = 0.95 and rms deviation σ = 1.93 % during this period for the parameters η calculated at R=2.5Ro. The quality of the modeling was improved for 1976-2008 even in comparison with result 1976-2007 (during this period ρ = 0.94, σ = 2.11%). We believe that the high quality of the model was obtained because during this period the year (2008) of deep SA minimum has been added. For the same parameters, but for η fixed at R=3.25Ro was received ρ = 0.95, σ = 1.96 %. The account of the current

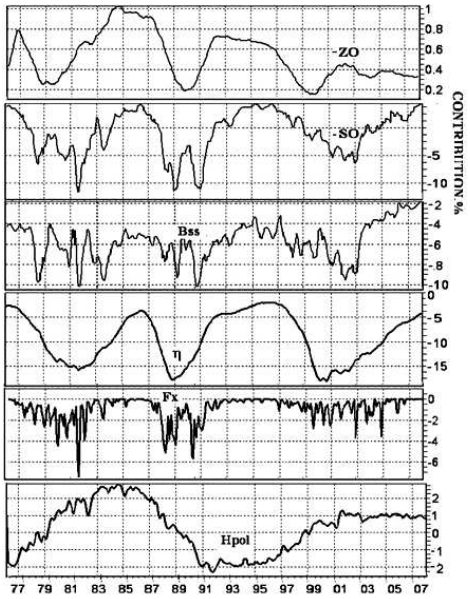

Fig. 2: The contribution (%) to modulation from changes of characteristics of ZO, SO, BSS, η, Fx and Hpol.

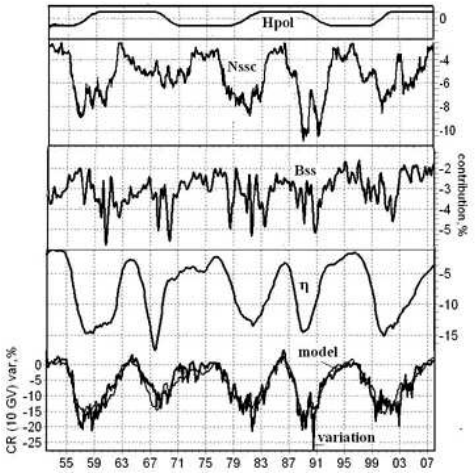

Fig. 3: Monthly CR variations (% to 1976) observed and simulated by the four-parametrical model (bottom); impact (%) of Bss, η, SSC and Hpol changes to simulated CR variations for 1953 - 2008 (top); η and Bss for the period 1976-2008 - from WSO observations and for 1953-1976 - from Hα data.

sheet tilt η, defined on distances R=2.5Ro and R=3.25Ro is not very different in the modeling result in these cases, but the picture of modulation during low SA in 2006-2008 more closely corresponds to changes η on distance R=3.25Ro. From cycle to cycle one can distinguish a phenomenon of decreasing Hpol and index ZO in a maximum of the last three considered SA cycles (fig2). It should not be forgotten that the cycle of the large-scale magnetic fields of the Sun precedes the sunspot cycles by 5.5 years, and is in anti-phase with them. This tendency towards a decrease is especially pronounced in cycle 23. The contribution of high values η to the modulation model are compensated by lower values Bss, ZO and Hpol in the model description of CR variations for the termination of the 23rd and the beginning of the 24th cycle. Considerable increases during the phases of SA decline and growth (which are also shown in the energetic index BSS) are observed in the index SO. Thus the balance of changes of solar characteristics makes it possible to "work" the model of modulation offered by us with sufficient accuracy. Polar regions define parameters of the interplanetary magnetic field up to ecliptic plane during the SA minimum epoch [11]. Doubtless this circumstance will influence the integrated index of the interplanetary environment - CR density, observed on the Earth and in near-earth space. Accordingly this influence will be reflected in the size of the contribution to modulation from changes of characteristics Bss, Hpol and ZO in the considered description of CR variations. It should be noted that the contribution to the modulation from the ZO index decreases from cycle to cycle and the reduction of the contribution after the maximum of cycle 23 is clearly visible. This impact is much less compared with the other cycles. Cyclical variations of ZO index are in phase with the 11-year CR variations. It is assumed that the effect of a decrease in CR from cycle to cycle, currently discussed in space physics [12] is possibly related to the corresponding decrease in the maximum values of the ZO index and to a similar decrease in the vertical component of the dipole magnetic moment, referred to in the work [13]. The same tendency is observed in the behavior of the total dipole magnetic moment. As a result it is possible to state that the main role in the creation of the long-term CR modulation observable in the heliosphere is played by the average of solar magnetic field Bss and index ZO. The cyclical variation of the total solar magnetic field is defined by variations of the local fields, which make an important contribution to the average of solar magnetic field Bss and by the global field, which appreciably defines itself ZO, especially on the source surface. The contribution to the CR modulation from the cyclic changes of SO index remains almost invariable from cycle to cycle during the considered minimum SA cycles. The horizontal component of the magnetic dipole manifests itself in each cycle during the periods of high activity close to the epochs of repolarization. A similar pattern is observed in the variations in the SO index.

Model in 1953-2008 and forecast 2003-2011: The model description of CR variations (fig.3) for the whole period of 1.1953 - 12.2008 for above-mentioned parameters. For the modulation description during several SA cycles, indirect data has been added to the direct data of observation of solar magnetic fields. The structure of the magnetic field was restored by means of Hα observation of filaments for (1953-1976). Number of NSSC is used in the model calculations as an index responsible for the description short-period of variations in 1953-2008, instead of index Fx which was defined only from 1976.

The disturbances of a solar wind extending in the heliosphere are reflected in this characteristic. The analysis of data has revealed a good correlation between the multiparameter model and CR during a long period, spanning several SA cycles. We have the correlation coefficient ρ = 0.91 and rms deviation σ = 2.58 %. It is clearly visible from fig.3 that the contribution to CR modulation from changes η in minima 19-24 cycles has a 22-year wave. The contribution in 20, 22 and 24 cycles (sharper form of the contribution in S minima, qA $<$ 0) exceeds the similar contribution to CR modulation in flat minima (19, 21 and 23 cycles, qA$>$ 0). It is confirmation of the basis of the drift theory [14] once again over an extensive time interval. The model description of CR variations was provided separately for periods of the same direction of the global field (qA$<$ 0 and qA$>$ 0). It is shown that: the main role play the flare index Fx and the value Bss on the source surface for qA$>$ 0. The current sheet η plays this role for qA$<$ 0. The peculiarities of modulation in the periods of different global sun magnetic field polarity can be explained by a changing contribution of cyclic variations in the local and large-scale solar fields to long-term CR variations. These results confirm conclusions of work [15]. Index η is one of most important things for modulation. It follows from the impact value from η changes and the CR recovery, especially evident after the maximum of the 23rd cycle. The contribution from changes η remains significant up to the end 2008. This is not typical for the epoch of deep SA minimum (on sunspot numbers) which we are now experiencing. The model of CR modulation allows us to calculate the observed CR variations with a high accuracy and to make a long-term prediction of these variations (Fig.4). For all period

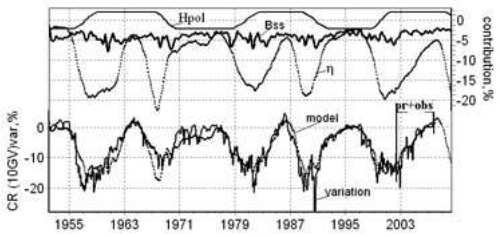

Fig. 4: Monthly CR variations (% to 1976) observed and simulated by the three-parametrical (bottom); impact (%) of Bss, η, and Hpol changes to simulated CR variations for 1953 - 20011 (top); for the period from 09. 2003 to 04.2011 the variation prediction has been made (shaped line); 09.2003-12.2008 - the observed variations and the predicted variations.

1953-2011 it is received ρ = 0.87 and rms deviation σ = 3 %. The forecast the description very well coincides with CR supervision, allowing to draw a conclusion on adequacy of the offered modelling description of CR modulation. The period (09.2003-12.2008) is allocated (fig. 4) for which observable variations and their forecast are available. It is possible to state that the "forecasting" coincides very well with CR observation, making it possible to conclude about the adequacy of the offered modelling description of CR modulation.

IV. Conclusion

The behavioral features of the proposed indices of solar magnetic field and their contribution to the CR modulation are shown and analyzed for the period 1953-2008 including direct observation of characteristics of solar magnetic fields in 1976-2008 and indirect (optical) in 1953-1976. The adequacy of the offered model is confirmed on the basis of a comparison of observable CR variations in 2003-2008 with variations that had been forecast earlier.

The current sheet obtained for the solar wind source surface at a distance of 3.25 solar radiuses makes it possible to present the best picture of CR modulation for the minimum 23rd cycle.

The contribution to CR modulation from changes Bss, ZO and Hpol is less during the minimum phase of the 23rd cycle , than in corresponding periods of the previous cycles. But the CR modulation model used copes successfully with this unusual situation. The small contribution from changes Bss, ZO and Hpol is compensated during this period by the increased contribution from the tilt of current sheet η.

In 2008 (and now, at the beginning 2009) it is still impossible to confirm that CR have been completely restored, as occurs usually in minima . We expect that intensity CR will increase in the near future to abnormal values because of delay CR modulation concerning processes on the Sun. Besides it will increase additionally, if the inclination will decrease to its usual size for an epoch of minimum values.

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