The reflection in the long-term cosmic ray modulation of the cyclic variations of integral and partial indices of the solar magnetic field

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Abstract— **The following solar activity (SA) characteristics as modulating parameters have been considered in the modelling description of the long-term cosmic ray (CR) variations at 19-23 cycles: the magnitude and polarity of solar magnetic field, the integral and partial indexes (the mean intensity of the field on the surface solar wind source) as well the tilt of the current sheet and the index considering of x-ray flare properties. The features behavior of proposed indices of solar magnetic field and their contribution in the cosmic rays modulation are shown and analyzed. The role of each indexes (and their combinations) in the cosmic rays modulation is determined in the different phases of solar activity cycles and in cycles with different direction of the sun global field. The discrepancy between the model and observations increases beginning from the beginning of 2000 therefore the problematic features of SA and CR behavior and modeling during the 23rd cycle up to the end 2007 are discussed.**

1. INTRODUCTION

The density of CR is modulated in the heliosphere by the solar wind thus providing a relation to the solar magnetic activity. The density of CR reflects the various solar cyclic variations. The modeling of the CR long-term variation by electromagnetic fields in the heliosphere is carried to understand the processes creating modulation.

Synoptic Hα maps give the chance to receive the data on the latitude-temporal distribution of unipolar regions of large-scale solar magnetic field. In turn, the magnetic Hα maps were tested via comparisons with various solar and geophysical data and variations of galactic cosmic rays [1-3].

The present study of galactic CR modulation in the heliosphere through the 19-23 cycles is a continuation of our previous works [1, 2, 4, 5] and is based on the long-term distribution of CR obtained by the neutron monitor network.

In order to describe the long-term variations with more complete reflection in the CR modulation of the complex interaction of global and local solar magnetic fields it has been proposed to introduce into the model the next characteristics: the magnitude and sign of the polar magnetic field, the integral index, the partial indexes as well the tilt of the current sheet and the index considering x-ray flares. It is as a result received, that the mentioned characteristics are necessary for the description of long-term CR modulation. The role of each index in the CR modulation is determined with detailed justification of such a choice and also the contribution to created CR modulation is estimated from changes of each index.

The discrepancy between the model and observations increases beginning from the beginning of 2000. The purpose of this work to consider problem features of CR behavior and according to feature of its modeling during the 23rd cycle, especially on decreasing phase of SA and in the beginning minimum of 24th cycle proceeding till now.

2. 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 ≥ *M1*).

*A. Cosmic rays data***:** The rigidity spectrum of CR variations for each month was obtained from the data of neutron monitors of the entire global network of CR stations and stratospheric sounding data for 1976–2007. It is supposed that the CR differential density is more convenient for modulation studies than the data from individual detectors.

We are using CR variations, obtained on neutron monitors (NM) data (about 40 NM, with a tentative estimation of long-term stability 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. Thus, in this case amplitude of long-term CR variations with 10 GV rigidity obtained by using the method of global survey becomes a value of pure galactic origin and free from influence of solar particles.

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Calculations of CR modulation have shown that such amplitude improves the proposed modulation model.

B. Solar-heliospheric parameters: In order to describe the long-term variations with more complete reflection in the CR modulation of the complex interaction of global and local solar magnetic fields it has been proposed to introduce into the model the solar magnetic field characteristics as well the index considering x-ray flares. The structural and quantitative characteristics of the solar global magnetic field as: heliospheric current sheet tilt η, the solar polar field H_{POL}, the average magnetic field intensity B_{SS} and the partial indexes (zone-even ZE, zone-odd ZO, sector-even SE and sector-odd SO) are calculated on the surface of solar wind source. The average magnetic field intensity B_{SS} full integral index of SA, such as the squared radial component of the magnetic field averaged over a sphere of fixed radius, gives the information on all magnetic stream which is passing through the source solar wind surface. The partial indexes: zone-odd *ZO* (m=0, l=2k+1) - the part of the magnetic field with the odd zonal symmetry (analogy of the vertical dipole); zone-even *ZE* (m=0, l=2k) is small as a result of the Hale law; sector-odd *SO* (m=l=2k+1) - the tilted dipole and manifests itself in the 2- and 4-sector structure sector-even *SE* (m=l=2k) is usually manifested in the 4-sector structure. The choice of such a set of solar activity indexes and methods of their evaluation were described in details previously in [1, 2, 4, 5]. We used data of measurements of the large - scale photosphere magnetic field with magnetometer resolution of (3′) scale performed in the Wilcox solar observatory (WSO) in 1976 – 2007 [6] and processed by the original method described in [7]. There is a problem of the magnetometer sensitivity in results of solar field observations in 2000-2002 and, possibly, after recalibration the data set is not uniform. Heliophysicists still do not know whether the observations of large-scale magnetic fields at different observatories are in random different correspondence from year to year or this correspondence is caused by real physical processes (of solar or instrumental nature) [8].

In order to understand a modulating influence of local solar activity on CR it is proposed to use *Fx*, a specially calculated index of solar flares, empirically determined in [9]. The flare index depends on maximum x-ray intensity (events of $\geq M1$ have been selected) during the flare and its longitudinal location relatively to the Earth. Improving of the modulation model, caused by a necessity to represent adequately a role of variations with the shortest period and the modulation during the declining phase of the 23rd solar cycle and the beginning minimum of 24th cycle in the global picture of CR modulation, is a purpose inclusion of this parameter to the model.

3. THE TEMPORAL CHANGES OF THE DIFFERENT MODEL PARAMETERS

The time changes of the modulating characteristics and variations of the CR (10 GV) intensity during 1976-2007 are shown in fig.1 (a-d).

All indices of the global field in the phase of SA minimum fluctuate nearly to zero except of quasi-dipole *ZO,* which has a maximum value. The time behavior of all indexes is essentially different for decreasing period of SA, especially for *η, Bss, ZO* and *Hpol.*

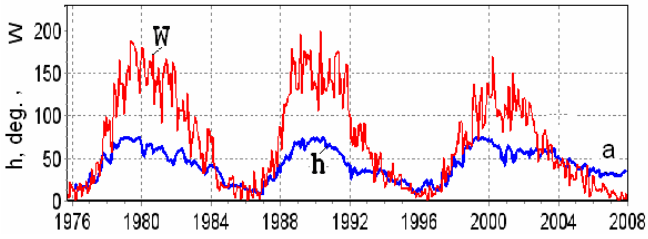

Fig.1(a). Temporal changes of the heliospheric current sheet tilt *η (deg.)* and sunspot numbers *W*.

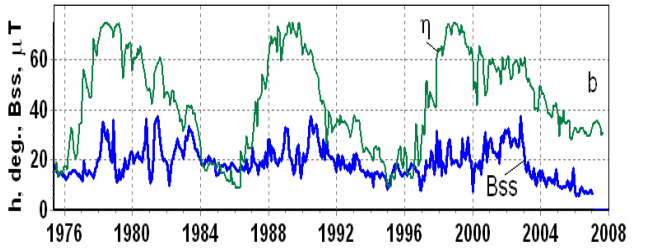

Fig.1(b). Temporal changes of the mean source surface magnetic field B_{SS} (μT) and the heliospheric current sheet tilt *η (deg.)*

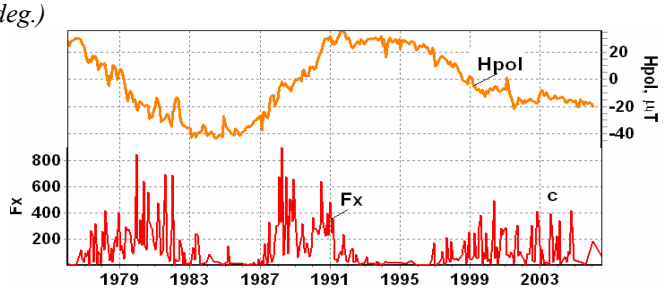

Fig. 1(c). Temporal changes of the polar magnetic field H_{POL} (μT) and the index considering of x-ray flare *Fx*

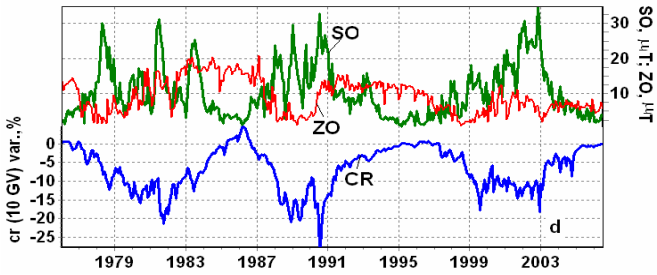

Fig.1(d). Temporal changes of the partial indexes: sector-odd *SO* (μT) and zone-odd *ZO* (μT); CR variations (%) for 1976-2007 years (lower part).

During the decline phase in cycle 23, the current sheet tilt (*η*) remains anomalously large as compared to other cycles. Tilt remained large (31.3 deg.) even in 2007 at a deep SA minimum, which is certainly shown in CR modulation. Probably the unusual behavior of the structural characteristic η exists not to itself in 23rd cycle. It is connected with

changes of the quantitative characteristics. In the behavior of the *ZO*, B_{SS} indices and polar solar field $|H_{POL}|$ from cycle to cycle during the last three considered SA cycles the tendency toward a decrease is especially pronounced in cycle 23. The heliospheric current sheet tilt η remains to be anomalously large in 23 cycles, which has to be reflected in CR modulation. From cycle to cycle one can see a phenomenon of decreasing H_{POL} and index *ZO* in a maximum of cycles. Considerable increases during the phases of SA decline and growth (which are also shown in the energetic index B_{SS}) are observed in the sector-odd index *SO*. The cycle of the large-scale magnetic fields H_{POL} of the Sun proceeds by 5.5 years the sunspot cycles *W* and are with them in anti-phase.

High values η (observed recently in 2007 and in the beginning 2008) are compensated by abnormal low values B_{SS}, *ZO* and H_{POL} in the model description of CR variations.

The behavior of the parameters *ZE* and *SE* in cycle 23 is anomalous. The increase a contribution from cyclical variations of these indices may be related with two reasons. They are either strongly developed from sector structure or an error in the WSO data.

The features Fx variations during the decay phase of 23 solar cycle are considered in [9], where it is shown that the decay phase of the 23rd solar cycle is the most disturbed (remember events of autumns 2003 and 2004) during the whole period solar-terrestrial studies. This period is outstanding by large input of solar matter and energy into the heliosphere, moreover, not only the equatorial region was active, but the magnetic flux from polar regions was enlarge, that might be associated with increase of the dipole component in the solar field structure [3] and all together are related to the integral heliosphere index as CR intensity.

4. DISCUSSION RESULTS OF CR MODULATION

The multiparametric regression analysis has shown that model description of CR needs a joint consideration of following modulating parameters: above-mentioned η, *Bss*, (or one of the partial indexes) H_{POL} as well the flare index *Fx*.

The performed modeling allows estimating a relative impact of temporal changes of each parameter with its own time delay τ to the total modulation. Fitting of the CR modulation becomes much more accurate, if it is performed for cycles of the same polarity.

The account of the current sheet tilt η, defined on distances r_0=2.5 and 3.25 (r_0 is Sun radius), is not reflected on the modeling result, except for received other times of delay.

The model description of CR variations was provided for the whole period of 05.1976 - 12.2007 for all listed parameters (fig. 2a). We have the correlation coefficient ρ = 0.94 and rms deviation σ = 2.11 % during this period. The model provides the result for 4-parameter case with the correlation coefficient. ρ = 0.96, σ = 1.75 % in the period 1.1977-12.1999. The features of modulation behavior during the declining phase of the 23rd cycle are revealed. These characterize variations of SA indexes are problematic for the considered model description of CR modulation. The discrepancy between expected and observed CR variations increases after the year of 2000 (for 1.2000г. – 12. 2006).

The calculation has shown that such a picture of modulation (with worsening of CR description from the beginning of 2000) is observed for all partial indices under their use in turns as the forth modulation parameter.

But the quality of the modelling was restored and comes nearer to results for 1977-1999 after addition of the data 2007 years, i.e. for the period 2000-2007 (fig. 2b). We believe that high quality of model was restored because year of deep SA minimum has been added (not simply one more year).

The observation results and regression analysis have shown for all investigated period that CR modulation in 23rd cycle (4.1996 – 12.2007) has certain distinctive features (Fig.2b). It is necessary to address to the changes of the modulating characteristics *Bss, η, Hpol* and *ZO* and to the corresponding impacts of these indexes to the CR modulation. The anomalies of indexes behaviors especially are appreciable on decreasing phase of the 23rd cycle and in minimum of 24th cycle proceeding now.

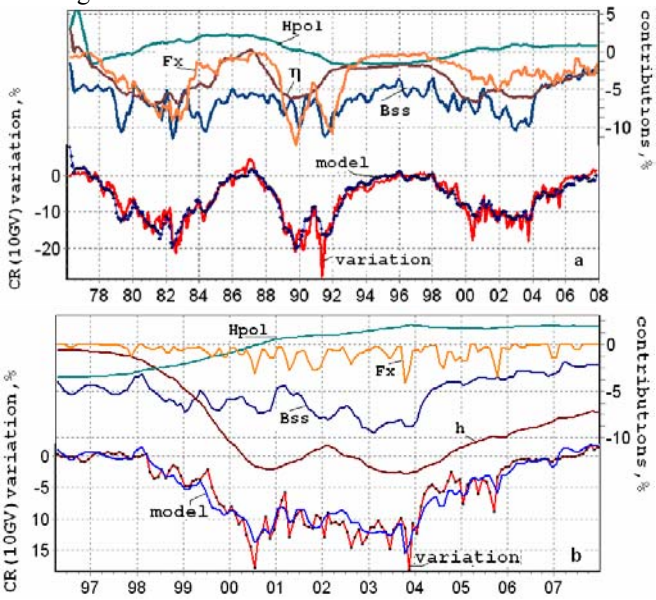

Fig.2 (a, b). Monthly CR variations (% to 1976) observed and simulated by the multiparameter model (bottom); impact (%) of H_{POL}, B_{SS}, η and F_X changes to simulated CR variations (top): a) for 1976 – 2007; b) for 1997 – 2007

The evident picture of the contribution changes to CR modulation in SA minimum from various modulating characteristics is shown on fig 3(a, b). It is visible as the behavior modulation parameters are reflected in CR modulation on an example of the tilt η. The neutral current sheet plays an important role in the CR modulation by intensification of their radial and latitudinal (for large tilt values) transport. Index η is one of the main things for modulation. It follows from the impact value from η changes and the CR recovery, especially evident after a maximum of 23rd cycle. The contribution from changes η remains big at modeling of CR modulation separately for 23rd cycle that is

completely not peculiar for the epoch of deep SA minimum (on sunspot numbers) in which we are now (fig.3a).

The analysis of data for 1976–2007 has revealed a good correlation between the multi-parameter model and galactic CR (10GV) during long period, spanning several SA cycles. The model description of CR variations was provided for the whole period of 1976-2007 years for all parameters and separately for periods of the same direction of the polar field (qA>0 and qA<0). It seems that the model description provides, however, different pictures of the process: for qA>0 the main role play the flare index *Fx* and the value B_{SS} on the source surface. The current sheet η plays this role for qA<0 (07.2000-12.2007), according to the drift theory in a such field configuration a drift of particles occurs along the current sheet and its structure is important for the modulation. These results confirm conclusions of work [10].

Polar regions define parameters of the interplanetary magnetic field up to ecliptic plane during of the SA minimum epoch. [11]. Doubtless this circumstance will be to influence on 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 size of the contribution to modulation from changes of characteristics Bss, Hpol and ZO in the considered description of CR variations.

The big contribution from the heliospheric current sheet tilt η is compensated by low values of the impacts B_{SS}, *ZO* and H_{POL} in the description of CR variations for the termination of 23rd and the beginnings of 24th cycle (fig3a, b).

It is noteworthy that contribution to the modulation from the *ZO* index goes down from cycle to cycle during the last three considered SA cycles and reduction of the contribution after the maximum of cycle 23 is clearly visible (fig.3b). This impact is much less as compared with the other cycles. Cyclical variations of *ZO* index are in the phase with 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 maximal 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]. Based on the observations of the large-scale magnetic fields, it was indicated [13] that the largest scale of the vertical component of the magnetic dipole decreases at SA minimums from cycle to cycle. The same tendency is observed in the behavior of the total dipole magnetic moment. Such time variations are similar to changes in the *ZO* and *Bss* (as full integral index of SA, which gives the information on all magnetic stream which is passing through the source solar wind surface) indices, used by us to model CR modulation. The reduced contributions from changes *Bss*, *ZO* and *Hpol* indexes is compensated by the increased contribution from the current sheet tilt η during the decreasing phase of the 23 cycle SA and in minimum of 24th cycle proceeding now.

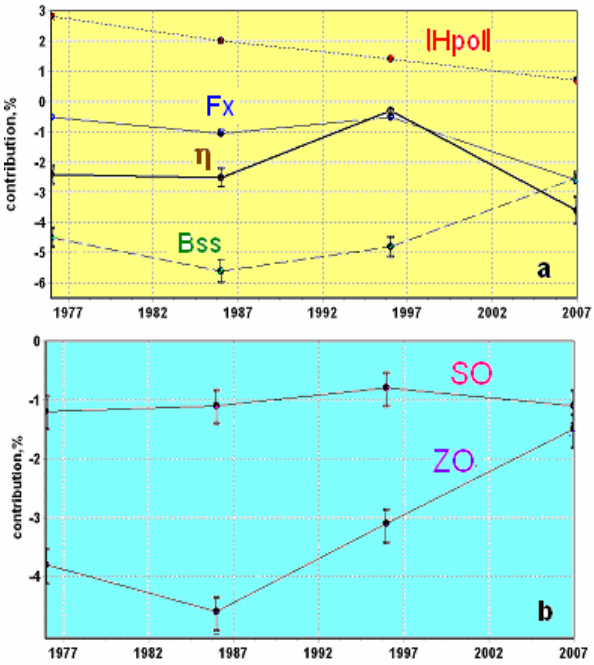

Fig.3. (a, b). The contributions (%) of the different indexes to the CR modulation during the minimum phase of the cycles SA (1976, 1987, 1997 and 2007) a) | H_{POL}|, F_X, η, *Bss*; b) *ZO*, *SO*.

Partial index SO gives information about the tilted dipole and reflects influence of low- and middle latitude regions of SA. The cyclic *SO* variations are adequately represented in CR variations, and this representation is especially distinct at maximums and during active periods on the Sun. The contribution to the CR modulation from the cyclic changes of SO index remains small and almost invariable from cycle to cycle during the considered minimum SA cycles (fig.3b).

The horizontal component of the magnetic dipole manifests itself in each cycle during the periods of high activity close to the epochs of repolarization [13]. This component sometimes becomes larger than the vertical component of the magnetic dipole and is characterized by widely variable values. A similar pattern is observed in the variations in the *SO* index.

We can state that the average magnetic field *Bss*, η and the *ZO* index play the main role in the creation of long -term CR modulation observed in the heliosphere. The cyclic variation in the total magnetic field depends on the cyclic variation in the local fields, which considerably contribute to the total *Bss* index and global field, which is largely responsible for *ZO*, especially on the source surface. We note that the proposed model description with the help of the *ZO* and *SO* indices together with *Fx* and η is at least not worse than the model description using the average field index *Bss* and the characteristics of the polar magnetic field *Hpol*.

5. CONCLUSION

It is possible to use the partial indexes along with the average of solar magnetic field in the model of CR modulation. The features behaviour of proposed indices of

solar magnetic field and their contribution in the CR modulation are shown and analysed.

The propose is made on the basis of model description of long term CR variations that the CR decreasing in minima of SA cycles (from cycle to cycle) could be described by corresponding decreasing of the zone-odd *ZO* index.

The contribution to CR modulation from changes B_{SS}, *ZO* and H_{POL} is less during the decay phase of the 23rd cycle and minimum of 24th cycle, than in corresponding periods of the previous 20-22 cycles. But the used CR modulation model manages 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 current sheet tilt η.

We cannot approve yet (in 2008) that CR were completely restored, as occurs usually in SA minima. It is not excluded that the current sheet tilt can decrease up to usual for an epoch of a minimum of sizes. In this case probably further increase in CR density.

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