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The role of cyclic solar magnetic field variations in the long-term cosmic ray modulation

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Abstract

Updating the semi-empirical model of cosmic rays (CR) modulation proposed in our previous work has been discussed. In order to provide a description of long-term variations, in which the CR modulation would adequately reflect the complex interaction of global and local solar magnetic fields, we have supplemented the model with the following characteristics: the solar magnetic field polarity, the integral index, the partial indices, the tilt of the current sheet, and the index characterizing the X-ray flares. The role of each index in the CR modulation has been determined. In the multi-parameter description of long-term CR variations using the integral index or one of four partial indices, the best fit for the period 1977–1999 has been obtained for the integral index and the sector-odd index characterizing the inclined dipole. The discrepancy between the model and observations increases from the beginning of 2000. Therefore, the problematic features in the behavior and modeling of CR during cycle 23 have been discussed. It is suggested that the cycle-to-cycle decrease of the CR density in the minimum epochs of the past solar activity (SA) cycles could be explained by the decrease of the zone-odd index.

Keywords: Long-term cosmic rays variations; Solar magnetic field; Model of CR modulation; Indices of the global magnetic field

1. Introduction

The solar wind modulates CR in the heliosphere, thus providing a relation between the CR density and solar magnetic fields. The CR density reflects various solar cyclic variations. In order to understand these processes the CR modulation by electromagnetic fields in the heliosphere is modeled. It has been supposed by Wang et al. (2006) that the CR modulation during the solar activity (SA) cycle is determined by changing of solar non-axisymmetric (longitudinally averaged) component of open magnetic flux (Φ_{nax}), which is created in active regions. This conclusion is based on studies of the empirical connection between CR and the solar open magnetic flux as well as correlations with sunspot numbers, tilt of the heliospheric current sheet, CME rate and value of the equatorial dipole. Wang et al. (2006) considered a set of simple models with single modulating index without accounting of CR delay relatively to manifestations of the solar activity. In this work, the long-term modulation for 21–23 cycles and separately for the 23rd cycle additionally accounting a CME rate has been studied, since the correlation between Φ_{nax} and CR falls for the last cycle.

The present study of galactic CR modulation in the heliosphere through the 21–23 cycles continues our previous works (Belov et al., 2001, 2002, 2005, 2006, 2007) and is based on the long-term distribution of CR obtained by the neutron monitor network. We discuss the improving of our semi-empirical model of CR modulation proposed previously. This model shows that the long-term CR modulation depends on cyclic changes of the total energetic characteristic B_{ss}, which provides the information on the total magnetic flux passing across the solar wind source surface, a 'gofferness' of the current sheet in the

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interplanetary space (i.e. from the tilt η of the heliospheric current sheet) and changes of the polar magnetic field H_{pol}.

For more complete account of complex interaction between global and local solar magnetic fields for the CR modulation during solar cycle development it has been proposed to introduce into the model a new index of X-ray flares and characteristics of the solar magnetic field. A role of each index in the CR modulation is determined with detailed justification of such a choice and accounting the delay time. Our modeling shows that a discrepancy between the model and observations increases beginning from the year of 2000. Thus, we discuss possible problems of CR behavior and its modeling during the 23rd cycle.

2. Long-term behavior of the CR and parameters of the modulation

Initial data for modeling of CR variations are results of long-term CR observations, characteristics of the solar global magnetic field and solar X-ray flares (importance $\geqslant$ M1). The rigidity spectrum of CR variations for each month was obtained using data of the neutron monitor global network and data of the stratospheric sounding for 1976–2006 (by the method described in Belov et al., 1998). We study amplitude variations of CR with 10 GV rigidity, excluding variations associated with ground level enhancements of solar CR (Belov et al., 2007). Note that for some events a value of the last effect is greater than 3% even for values of monthly averaged amplitude and some particular CR stations used in our analysis. Thus, eliminating the effect of solar CR, amplitude of long term CR variations with 10 GV rigidity obtained by using the method of global survey becomes a value of pure galactic cosmic ray (GCR) origin. Calculations of CR modulation have shown that using amplitude of GCR origin the proposed modulation model is improved.

The structural and quantitative characteristics of the solar global magnetic field as: a heliospheric current sheet tilt η, the solar polar field H_{pol} and the average magnetic field intensity B_{ss} are calculated on the surface of solar wind source. Along with using of the average B_{ss} index of solar magnetic field, the partial indexes have been determined from data of the Wilcox solar observatory (WSO) for 5.1976–12.2006 (zone-even, ZE; zone-odd, ZO; sector-even, SE; and sector-odd, SO). Here we used data of measurements of the large-scale photosphere magnetic field with magnetometer resolution of (3′) performed in WSO (http://quake.stanford.edu/~wso) and processed by the original method described in Obridko and Shelting (1999). 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. The question do various observations of large-scale magnetic fields fit each other in a various degree of conformity year from a year occasionally or they are governed by some real physical mechanism (solar or instrumental) is still unresolved yet (Demidov and Golubeva, 2007).

In order to understand a modulating influence of local solar activity on CR it is proposed to use F_x, a specially calculated index of solar flares F_x, empirically determined by Belov et al. (2007). The flare index depends on maximum X-ray intensity (events of $\geqslant M1$ have been selected) during the flare and its longitudinal location relatively to the Earth

$$F_x = \left[1 + \alpha \ln\left(\frac{I_x}{I_c}\right)\right] \exp\left(-\left(\frac{\varphi - \varphi_0}{\sigma_\varphi}\right)^2\right), \quad (1)$$

where $F_x = 0$, if $I_X < I_C$ (I_X – the maximum flux of X-ray event, $I_C = 10^{-5}$ W/m^2), $\sigma_\varphi = \sigma_E$ for $\varphi < \varphi_0$; $\sigma_\varphi = \sigma_W$ for $\varphi > \varphi_0$. It is supposed $\sigma_W = \sigma_E/2$. The evaluation of F_x is performed accounting the previous results (Belov et al., 2007), but for other parameters, in particular, for longitudes $\varphi_0 = -18°, -14°, -10°, -6°, -2°$ and $\sigma_\varphi = 55°, 60°, 65°, 70°, 75°$. In this work given values of the α parameter are $\alpha = 65; 70; 75; 80; 85; 90$.

Fig. 1 shows a behavior of the modulating characteristics in 1976–2006. In the phase of SA minimum all indices of the global field fluctuate nearly zero excepting the quasi-dipole ZO, which has a maximum value. Belov et al. (2007) examined features of the F_x variations during the whole interval under investigation and the decay phase of the 23rd solar cycle. The magnetic field indexes were introduced by Obridko and Shelting (1992) for the potential magnetic field model with the source surface.

Further we use an expansion of the observed magnetic field into the spherical functions (Legendre polynomials) with the coefficients for the expansion of the photosphere magnetic field g_{lm} and h_{lm} with indexes l and m. The coefficients g_{lm} and h_{lm} were calculated according to the WSO data. The partial index ZO ($m = 0$, $l = 2k + 1$) partially accounts a magnetic field with odd zone symmetry (analogue of the vertical dipole). The zonal-even index ZE ($m = 0$, $l = 2k$) is small as a result of the Hale law, being by a special case an action of the polarities generalized rule of solar magnetic fields (Obridko and Shelting, 2007). The sector-odd index SO ($m = l = 2k + 1$) characterizes the tilted structure similar to dipole and reflects an influence of the SA at low and middle latitudes. The sector-even index SE ($m = l = 2k$) is usually manifested in the four-sector field structure.

In order to obtain a clear picture of time changes of SA and CR during different epoch of the solar cycle variations of the CR (10 GV) intensity and chosen indexes of SA with directions of the global solar magnetic field are shown in Fig. 2. The CR variations (% to 1976) and solar characteristics are obtained using the method of epoch superposition (the years of SA minimum 1976, 1986, 1996 are accepted as zero years) are presented in Fig. 2(a)–(f). The 22 year variations of H_{pol} are calculated by the method of superposition epoch relative to the SA maximum (when the field changes a sign) are shown in Fig. 2(g); temporal changes of the polar magnetic field module $|H_{pol}|$ and the index ZO are presented in Fig. 2(h). Let us underline now some crucial results:

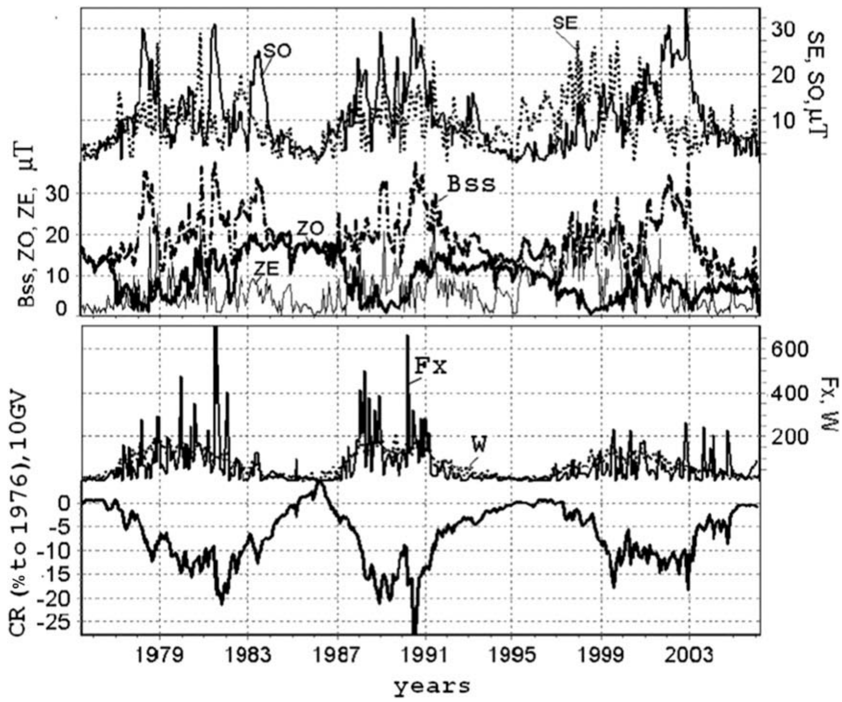

Fig. 1. Temporal changes of CR intensity (% to 1976), flare index F_x, sunspot numbers W, average values of solar magnetic field strength – index B_{ss} and partial indexes ZO, ZE, SO, and SE (μT).

- Variations of indexes and CR from cycle to cycle are small and similar to each other during the SA increasing phase.
- Time profiles of all indexes are essentially different for periods of decreasing SA in cycles with different direction of the global Sun field. This is especially important for the current sheet tilt η, the zone-odd index ZO and the solar polar field H_{pol}. The current sheet tilt remains abnormally large during the decay phase of 23rd solar cycle in comparison with other cycles. The η parameter has varied from 60° to 50° during 5,5 years till the middle of 2004. Even in the deep SA minimum of 2007 the tilt η remains large (~30°) and this certainly should be reflected in the CR modulation. The tendency of zone-odd index ZO and polar field $|H_{pol}|$ to decrease from cycle to cycle is clear, especially during the 23rd cycle. The sector-odd index SO significantly increases both during the decay and rise phases of SA, behaviour of the average solar magnetic field B_{ss} shows the same tendency.

Basing on observations of large-scale magnetic fields it is shown, that the largest scale of a magnetic field is connected with dipole component – the global dipole. The full magnetic moment of the dipole and its vertical and horizontal components cyclically vary and never vanish completely (Livshits and Obridko, 2006). The calculations performed on the basis of solar supervisions for last three cycles (1976–2005) shows that the magnetic dipole is strictly vertical at the cycle minimum, so the horizontal dipole vanishes during this epoch and the latitude of the dipole axis becomes close to 90°. Approaching the cycle maximum, the total magnetic moment strongly decreases at some time moments but never vanish. From figures presenting in the paper by Livshits and Obridko (2006) it is clear that the vertical components of a magnetic dipole reduces in SA minima from a cycle to a cycle, the same tendency is appreciable for behaviour of the total magnetic moment. This temporal behaviour is similar to changes of the indexes ZO and B_{ss}, which we use for modeling of the CR modulation. The horizontal component appears in each cycle during periods of the high solar activity, but its values are large sometimes in comparison with vertical component and are characterized by a fairly large scatter close to the epochs of polarity reversals. Temporal behaviour of variations of the sector-odd index SO has a similar tendency. During epoch of the cycle minimum namely the polar region govern the interplanetary magnetic field parameters down to the ecliptic plane. Undoubtedly, this circumstance will effect on the integral heliospheric index such as the CR intensity (observed near Earth and at the Earth) by contribution of the H_{pol} and ZO characteristics in the proposed modulation model.

Values of all solar indexes and CR intensity differ larger between cycles than do the sunspot number of different solar cycles. These differences have a specific character for each index. So, some features of the 23rd cycle are precisely visible in cyclic changes of η; ZO changes show its reduction from cycle to cycle and the short-term increases of B_{ss} and SO are reflected in their cyclic variations during

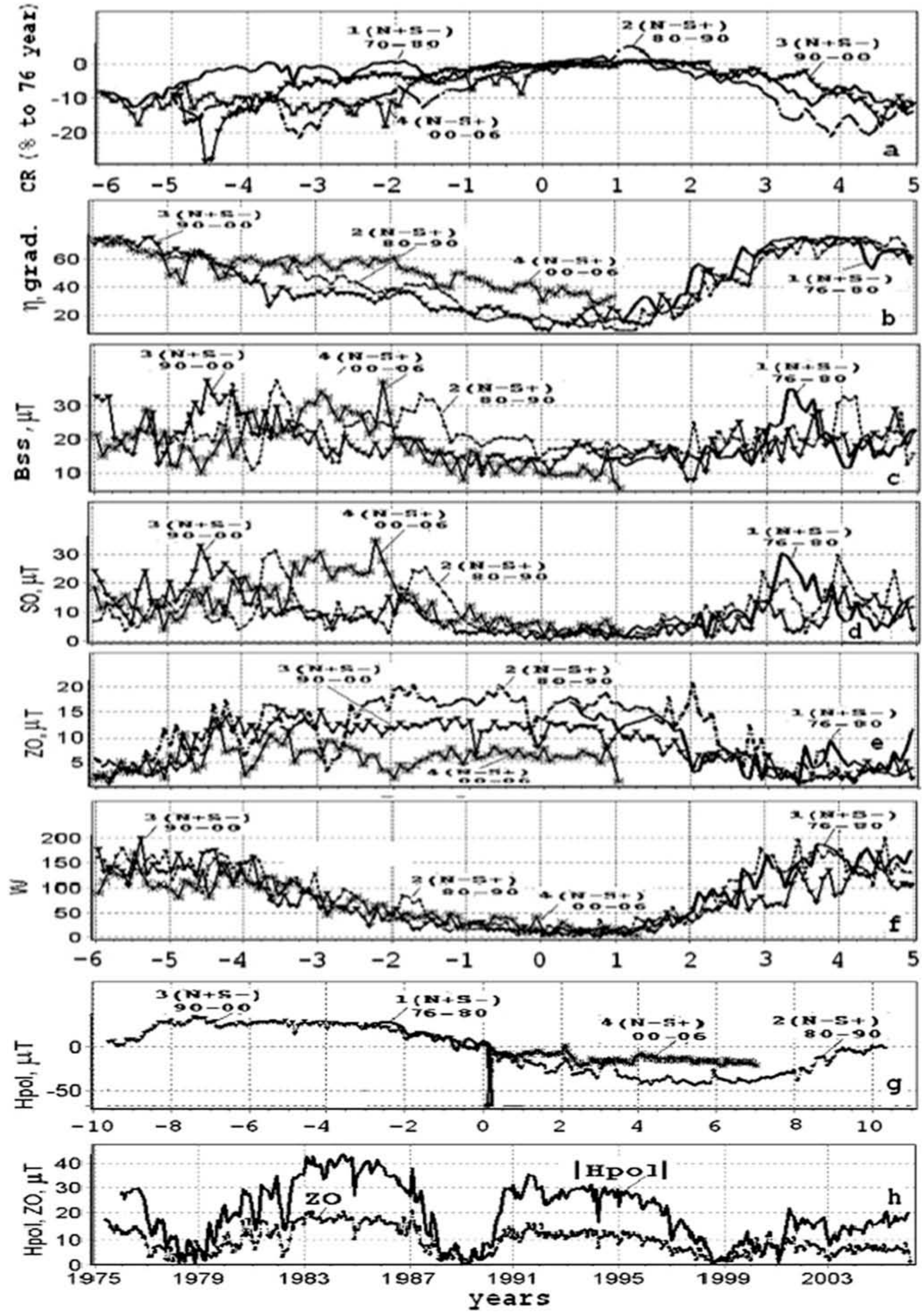

Fig. 2. (a)–(f) 11-years variations received by the superposition epoch method relative to minimum SA: (a) – CR% to 1976, rigidity $R = 10$ GV; (b) – current sheet tilt η (grad.); (c–e) – indexes B_{ss}, SO, ZO (μT); (f) – sunspot numbers W. (g) and (h) 22 years variations H_{pol} obtained by the superposition epoch method relative to maximum SA – (g); temporal changes of $|H_{pol}|$ and index ZO (μT) – (h).

the increased periods of SA. We may say that the sunspot number is a rather ‘‘rough” characteristic of SA and other solar indexes should be added for better accuracy.

3. Discussion – results of CR modulation

The model is further improved for reliable representation in CR modulation of short-period variations by introducing the index of X-ray flares. The modified model of CR modulation with account of the partial indexes of solar magnetic field listed above was used to answer the question about influence of various modes of the global Sun field on the long-term CR variations. A joint consideration of following modulating parameters: above-mentioned η, B_{ss} (or one of the partial indices), H_{pol} as well the F_x index of X-ray flares is necessary for model description of CR according to the multi-parametric regression analysis. Including an influence of solar flares for description of CR variations provides a better representation of observed CR variations for effective range of longitudinal distribution σ_φ = 55–75° for all parameters φ_0 and $\alpha > 65$. Introducing of F_x allows improving representation of observed CR variations. For the period of 1.1977–12.1999 the correlation coefficient increases up to $\rho = 0.96$ in a case of the four-parametric model. The performed modeling allows estimating a relative impact of temporal changes of each parameter with its own time delay to the total modulation. The time delay of CR modulation relative to the flare activity obtained in our model of long-term modulation shows that the flare influence is rather prolonged in the heliosphere. It is shown that for the long-term CR modulation of the longitudinal dependence of the flare index is not so important, but there is a strong dependence on flare intensity. However, description of short-term CR phenomena (like Forbush-decreases (FD)) includes the longitudinal dependence. Amplitude and other characteristics of FD's strongly depend on flare intensity and longitude of the solar source of interplanetary disturbance.

The multiparameter model of CR modulation, which additionally accounts the index F_x improves the description of observed variations, but once again only up to the year of 2000 only. After the year of 2000 a discrepancy between expected and observed variations increases. It is very difficult to describe the period of 12.1999–12.2006 (and accordingly investigated period 5.1976–12.2006) within the proposed model with a high accuracy (Mavromichalaki et al., 2007).

The description of long-term variations CR was performed with consecutive inclusion into the CR modulation model of the integral index B_{ss} and above-mentioned partial indexes in various combinations with other SA parameters for finding a reason of the specified discrepancy. Calculations show 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. For the whole period of 1976–2006 the model description of CR variations is presented, which accounts all parameters listed. During this period we have $\rho = 0.93$ and $\sigma = 2.05\%$. Fig. 3 shows an impact of different index changes to the CR modulation. The behavior of the parameters ZE and SE in cycle 23 is anomalous. A contribution of cyclical variations of these indexes may increase by two reasons. They are either strongly depend on sector structure or there is an error in the WSO data. A contribution of the ZO index decreases from cycle to cycle during last three SA cycles considered.

One of the model results is presented on Fig. 4. It is the variant of the description of long-term CR modulation with account of the most effective combination for modulation: current sheet tilt η, the solar polar field H_{pol}, index F_x considering X-ray flares together with sector-odd index SO. For the multiparameter description of long-term CR variations by using the average of solar magnetic field or one of four partial indexes during the period of 1.1977–12.1999 the best fit is obtained for the average of solar magnetic field B_{ss} and the sector-odd index SO, the correlation coefficient $\rho = 0.96$, the minimum value of the rms deviation is $\sigma = 1.73\%$ ($\sigma = 1.80$–1.86% for others indexes). The cyclic variations of SO index are well reflected in the CR modulation, especially clearly in the maximum of cycles and during the active periods on the Sun. So the contribution to modulation from changes SO in 2003 ($\approx -6.5\%$) exceeds the contribution from changes η, then a sharp drop of SO followed and consequently a decrease of contribution to the CR modulation. Cyclical variations of ZO index are in the phase with CR variations. It is

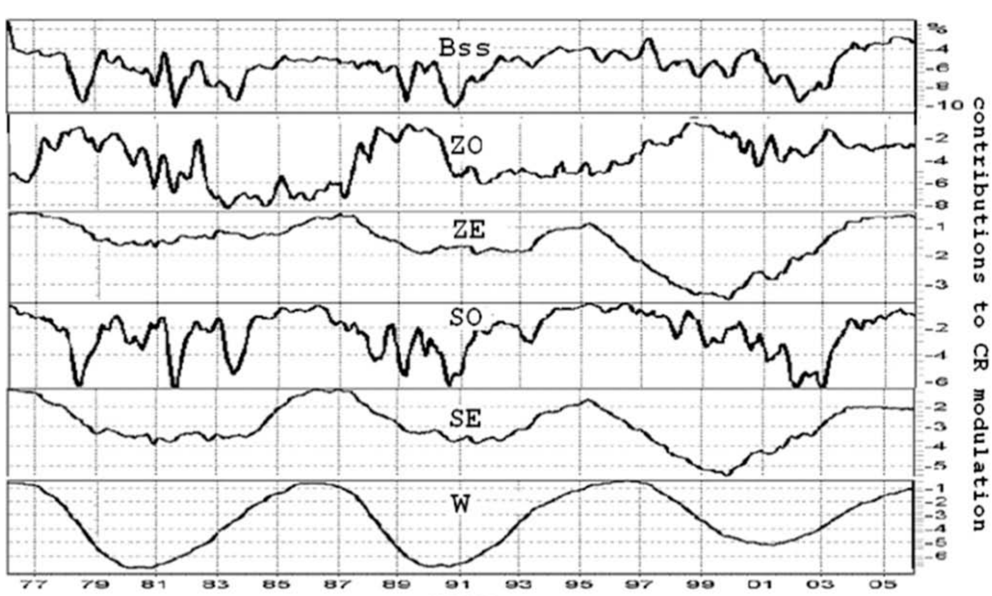

Fig. 3. A contribution (%) of B_{SS}, ZO, ZE, SO, SE, and W indexes to simulated CR variations.

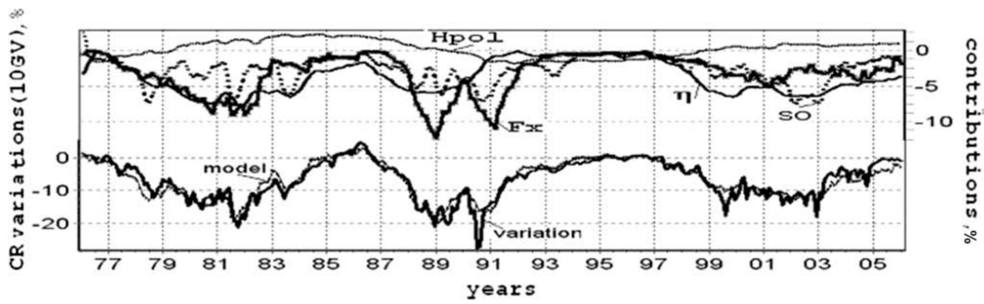

Fig. 4. Monthly CR variations (%) observed and simulated by the multiparameter model for F_x, H_{pol}, SO, and η indexes.

noteworthy that contribution to the modulation from this parameter goes down from cycle to cycle and reduction of the contribution after the maximum of cycle 23 is clearly visible. This impact is much less as compared with the other cycles.

We propose that a negative trend of the CR intensity, which is widely discussed now by space physics community (for example, Stozhkov and Svirzhevsky, 2006), could be related with significant decrease of the zone-odd (ZO) index maximum values and similar decrease of the vertical component of the dipole magnetic moment recently found (Livshits and Obridko, 2006). As a result it is possible to tell, that average of solar magnetic field B_{ss} and index ZO play the main role in creation of the long-term CR modulation observed in the heliosphere. The cyclical variation of the total solar magnetic field is defined by variations of the local fields, which provide a large contribution into the average of solar magnetic field B_{ss} (also in index SO) and by the global field, which appreciably defines itself ZO, especially on the source surface. We shall note, that a model description of modulation by means of the indices ZO and SO together with F_x and η gives not worse result than modeling with the average of solar magnetic field B_{ss} index and the value of polar magnetic field H_{pol}.

It is necessary to tell, that further improvements of the considered model are possible. In particular, not all possible modulating parameters are considered yet by the model, for example, some additional characteristics of coronal holes and coronal mass ejections might be introduced (in the present model they are described by the F_x index). The specified solar phenomena undoubtedly participate in formation of solar wind irregularities and creation of the observed CR modulation.

4. Conclusion

1. The multiparameter model of CR modulation with the additionally included index F_x characterizing X-ray flares allows an improved description of the observed variations. The longitudinal dependence of the F_x index is not important to the long-term CR modulation, however, there is a strong dependence on the flare intensity, which is characteristic of this type of variations.
2. It is possible to use the partial indices in the CR modulation model along with the mean solar magnetic field.
3. The behavior of the proposed indices of the solar magnetic field and their contribution to the CR modulation are described and analyzed. During the period 1977–1999, the best fit is obtained for the mean solar magnetic field or (with a very small difference as to the quality of the description) the sector-odd index together with the current sheet tilt, F_x index and polar field.
4. The model for all indices under examination shows a large discrepancy with observations at the beginning of 2000. This is, probably, connected with the anomalous behaviour of the parameters ZE and SE and a significant decrease of ZO in cycle 23. On the basis of the model description of long-term CR variations, it is suggested that the cycle-to-cycle decrease of CR at the minima of the SA cycles be described by the corresponding decrease of the zone-odd ZO index.

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References

Belov, A.V., Gushchina, R.T., Yanke, V.G. Long-term cosmic ray variations: rigidity spectrum. Geomagn. Aeron. 38 (N4), 131–134, 1998.

Belov, A.V., Gushchina, R.T., Kharshiladze, A.F., et al. Global magnetic field of the sun and long-term variations of galactic cosmic rays. J. Atmos. Terr. Phys. 63 (N18), 1923–1929, 2001.

Belov, A.V., Gushchina, R.T., Obridko, V.N., et al. Relation of the long-term modulation of cosmic rays to the characteristics of the global solar magnetic field. Geomagn. Aeron. 42 (N 6), 693–700, 2002.

Belov, A.V., Gushchina, R.T., Obridko, V.N. et al. The relation of the global magnetic solar field indices and the solar wind characteristics with the long-term variations of galactic cosmic rays. In: Proc. 29th ICRC (Pune), vol. 2, 239–243, 2005.

Belov, A.V., Gushchina, R.T., Obridko, V.N., et al. Long term variations of galactic cosmic rays in the past and future from observations of various solar activity characteristics. J. Atmos. Terr. Phys 68 (N 11), 1161–1166, 2006.

Belov, A.V., Gushchina, R.T., Obridko, V.N., et al. Simulation of the modulation of galactic cosmic rays during solar activity cycles 21–23. Bull. Russ. Acad. Sci. Phys. 71 (7), 974–976, 2007.

Demidov M.L., Golubeva E.A. Time changes research of difference parameters of large-scale solar magnetic fields on various series of supervision. In: Proc. of Conf.: ‘‘Sun: active and variable” (Crimean Astrophysical Observatory 2007) http://quake.stanford.edu/~wso.

Livshits, I.M., Obridko, V.N. Variations of the dipole magnetic moment of the Sun during the solar activity cycle. Astron. Rep. 50 (N11), 926–935, 2006.

Mavromichalaki, H., Paouris, V., Karalidi, T. Cosmic ray modulation: An empirical relation with solar and heliospheric parameters. Solar Phy. 245, 369–390, 2007.

Obridko, V.N., Shelting, B.D. Cyclic variation of the global magnetic field indices. Solar Phys. 137, 167–177, 1992.

Obridko, V.N., Shelting, B.D. Structure of the heliospheric current sheet as considered over a long time interval (1915-1996). Solar Phys. 184, 187–200, 1999.

Obridko, V.N., Shel'ting, B.D. A Generalized polarity rule for solar magnetic fields. Astron. J. 51 (N4), 339–343, 2007.

Stozhkov, Y.I., Svirzhevsky, N.S. Cosmic ray fluxes from stratospheric measurements. In: Proc. 20th ECRS, Lisbon, http://www.lip.pt/events/2006/ecrs/proc/ecrs06-s0-131.pdf, 2006.

Wang, Y.-M., Sheeley, N.R., Hulburt Jr., E.O. Role of the sun's nonaxisymmetric open flux in cosmic-ray modulation. Astrophys. J. 644, 638–645, 2006.