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Manifestation of the solar global field changes in the long-term cosmic rays modulation

R.T. GUSHCHINA[1], A.V. BELOV[1], V.N OBRIDKO[1], B.D SHELTING[1], YU. V. BALABIN[2]
[1]IZMIRAN, 142190 Troitsk, Moscow Region, Russia

[2]PGI, 184209 Apatity, Murmansk Region, Russia
rgus@izmiran.ru

Abstract: We discuss the improving of the semi-empirical model of cosmic ray (CR) modulation proposed by us previously. 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 solar magnetic field polarity, the integral index, the partial indexes as well the tilt of the current sheet and the flare index. The role of each index in the CR modulation is determined. For the multi-parameter description of long-term CR variations by using the integral index or one of four partial indexes the best fit for 1977-1999 periods is obtained for the integral index and the sector-odd index, characterizing an inclined dipole. It is proposed that decreasing of density CR in minima of the last solar activity (SA) cycles (from cycle to cycle) could be explained by decreasing of the zone-odd index. The discrepancy between the model and observations increases beginning from the beginning of 2000 therefore the problematic features of CR behavior and modeling during the 23rd cycle are discussed.

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 modulation by electromagnetic fields in the heliosphere is carried out to understand these processes. The present study of galactic CR modulation in the heliosphere through the 19-23 cycles is a continuation of our previous works [1-4] and is based on the long-term distribution of CR obtained by the neutron monitor network. We discuss the improving of the semi-empirical model of CR modulation proposed by us previously. 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 flare index. The role of each index in the CR modulation is determined with detailed justification of such a choice. The discrepancy between the model and observations increases beginning from the beginning of 2000 therefore the problematic features of CR behavior and modeling during the 23rd cycle are discussed.

Long-term behavior of the CR and modulating parameters

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 of the entire global network of CR stations, stratospheric sounding data for 1976–2006. Here we study amplitude variations of CR with 10 GV rigidity, excluding variations associated with ground level enhancements of solar CR. Note that a value of this effect is greater than 3% even for monthly averaged amplitude values for some events and particular CR stations used in our analysis. 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. Calculations of CR modulation have shown that such amplitude improves the proposed modulation model. 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 of solar magnetic field B_{ss} index, the partial indexes have been determined from data of the Stanford 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 the Wilcox solar observatory (WSO) in 1976 – 2006 [5] and processed by the original method described in [6,7]. 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.

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. The flare index *Fx* empirically determined depends on maximum x-ray intensity (events of ≥ *M*1 have been selected) during the flare and its longitudinal location relatively to the Earth

$$Fx = \left[1 + \alpha \ln\left(\frac{I_X}{I_C}\right)\right] \exp\left(-\left(\frac{\varphi - \varphi_0}{\sigma\varphi}\right)^2\right),$$

where $Fx = 0$, if $I_X < I_C$ (I_X – the maximum flux of x-ray event, $I_C = 10^{-5}$ W/m^2), $\sigma\phi = \sigma_E$ for $\phi < \phi_0$; $\sigma\phi = \sigma_W$ for $\phi > \phi_0$. It is supposed $\sigma_W = \sigma_E/2$. The evaluation of *Fx* is performed for longitudes ϕ_0 = -18, -14, -10, -6, -2° and $\sigma\phi$ = 55, 60, 65, 70, 75°. Given values of the α parameter are $\alpha = 65; 70; 75; 80; 85; 90$. Figure 1 shows the behavior modulating characteristics in 1976-2006. 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 *ZO* cycles are ahead of 11-years of Wolf numbers (*W*) by a half of cycle.

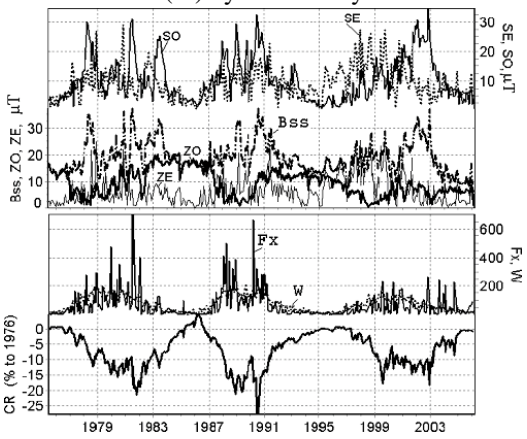

Figure 1: Temporal changes of CR intensity (% to 1976), flare index *Fx*, sunspot numbers *W*, average values of solar magnetic field strength – index B_{ss} and partial indexes *ZO, ZE, SO, SE* (μT)

The index *ZO* accounts for part of the magnetic field with the odd zonal symmetry (analog of the vertical dipole). The index *ZE* is small as a result of the Hale law. The sectorial-odd index *SO* characterizes the tilted dipole and reflects an influence of the SA at low and middle latitudes. The sectorial-even index *SE* is usually manifested in the 4-sector structure. The features *Fx* variations during the decay phase of 23 solar cycles are considered in [4].

Discussion results of CR modulation

Accounting corrected integral indexes of the solar field, which allow describing the long-term CR variations; the model has been tuned for reliable presentation of short - term variations. The multi- parametric regression analysis has shown that model description of CR needs a joint consideration of following modulating parameters: above-mentioned η, B_{ss}, (or one of the partial indexes) H_{pol} as well the flare index *Fx***.** The description of flare influence on CR modulation with the *Fx* index provides the best result for effective range of longitudinal distribution σ_φ=55°-75° for all parameters ϕ_0 and α>65°. The introducing of *Fx* allows improving representation of observed CR variations. In

the period 1.1977-12.1999 the model provides the result for 4-parameter case with the correlation coefficient $\rho = 0.96$. The performed modeling allows estimating a relative impact of temporal changes of each parameter with its own time delay to the total modulation. The delay time of CR modulation relative 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 modulation of CR a longitudinal dependence of the flare index is not so important, but there is a strong dependence from flare intensity, this is characteristic for long- term CR variations. However description of short-term CR phenomena (like Forbush-decreases (FD), includes the longitudinal dependence. The amplitude and other characteristics of FD strongly depend on flare intensity and longitude of the solar source of interplanetary disturbance.

The multiparameter model of CR modulation, which additionally accounts the flare index F_x improves the picture of observed variations, but once again up to the year of 2000 only. After the year of 2000 a discrepancy between calculated and observed variations increases. It is very difficult to describe the separate period of 12.1999-12.2006 within the proposed model with a high accuracy. Such a picture of modulation is observed for all partial indices under their use in turns as the forth modulation parameter. For all listed parameters the model description of CR variations was provided for the whole period of 1976-2006. During this period we have ρ=0.93 and σ = 2.05% and ρ = 0.96 during the period of 1.1977-12.1999. Figure 2 shows the impacts the changes of the different indexes to the CR modulation. The behaviour 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 contribution from *ZO* index decreases during these cycles.

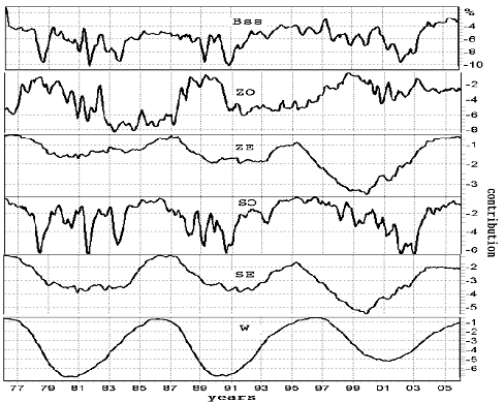

Figure 2: A contribution of B_{SS}, *ZO, ZE, SO, SE, W* indexes to simulated CR variations

The model results represents on the Figure 3a,b. It is shown, that the current sheet tilt and changes of the flare index along with the sector-odd index *SO* are most effective for the modulation (fig.3a).

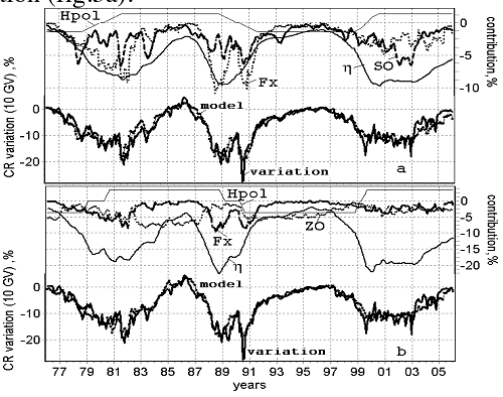

Figure 3a,b: Monthly CR variations observed and simulated by the multiparameter model for a) *Fx, Hpol, SO*, η and b) *Fx, Hpol, ZO*, η

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 minimum value of the rms deviation is σ = 1.73 % (σ = 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. In 2003 they gave the largest contribution over the whole period under consideration, then a sharp drop of *SO* followed and consequently, a decrease of con-

tribution in the CR modulation. Cyclical variations of *ZO* index are in the phase with CR variations. It is noteworthy that contribution in the modulation from this parameter is much less after the maximum of cycle 23 as compared with the other cycles. It is assumed that a phenomenon of CR decreasing in minima of SA cycles (from cycle to cycle) discussed now in space physics could be described by corresponding a significant decrease maximum values of the zone-odd *ZO* index and similar decrease of the vertical component of the dipole magnetic moment recently found [8]. The main role in a definition of the basically points of CR cycles play average of solar magnetic field B_{ss} and index *ZO* because a cyclical variation of the total solar magnetic field is conditioned by a contribution of cyclical variations of the local fields into the average of solar magnetic field B_{ss} and by the global field, which defines *ZO*, especially on the source surface. A model description of modulation by means of the indices *ZO* and *SO* together with *Fx* 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}.

Conclusion

1. The multiparameter model of CR modulation, which additionally accounts the flare index F_x improves the description of the observed variations. It is possible to use the partial indexes along with the average of solar magnetic field in the model of CR modulation. **2.** The features behavior of proposed indices of solar magnetic field and their contribution in the CR modulation are shown and analyzed. During the period of 1977-1999 the best fit is obtained for the average of solar magnetic field and the sector-odd index. The model for all analyzed indexes shows a large discrepancy with observations in the beginning of 2000. It is possible that it connected with the anomalous behaviour of the parameters *ZE* and *SE* and the significant decrease of the ZO in cycle 23. **3.** The longitudinal dependence of the flare index for the long-term modulation of CR is not important, but there is a strong dependence on flare intensity, this is characteristic for this type variation. **4.** 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.

Acknowledgements

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