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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: