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Long-term variations of galactic cosmic rays and their relation to the solar magnetic field parameters

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Abstract. The paper deals with the relation of long-term variations of galactic cosmic rays (CR) to the global solar magnetic field (GMF) and solar wind (SW) parameters. This study continues the series of work, where the tilt of the heliospheric current sheet (HCS) and other solar-heliospheric parameters are successfully used to describe long-term variations of CR in the solar cycles. The novelty of the present work is the combined use of the source surface magnetic field characteristics, including HCS inclination, mean intensity of magnetic field and polarity of the global magnetic field. We take into account both the direct effect of polarity on CR variations and its effect on CR modulation related to the HCS tilt changes. The combined use of different solar parameters allows us to improve the model of long-term CR variations. The analysis of data for 1976–2000 has revealed a good correlation (the correlation coefficient 0.95) between the multi-parameter model and 10 GV galactic cosmic ray behavior during long period, spanning several cycles of solar activity.

1 Introduction

CR modulation is a complex phenomenon, which occurs all over the heliosphere and depends on many factors. No single solar index, however sophisticated, can be responsible for CR variations. We have to take into account many parameters with the special attention to the magnetic field characteristics, calculated on the solar wind source surface (Hoeksema and Scherrer, 1986). The source surface magnetic field determines the structure and properties of the solar magnetosphere. The amplitudes of the spherical harmonics of the source surface magnetic field were successfully used by Mikhailutsa (1990) and Nagashima et al. (1991) to simulate long-term modulation of CR. The tilt η of the HCS, extremely important to CR modulation, is also determined on the source surface. A close relationship between the HCS tilt and long-term behavior of CR in the periods of the same polarity of the GMF was revealed in earlier work (Belov, 2000 and references therein).

Belov et al. (1999) succeeded in combining the HCS tilt with interplanetary magnetic field (IMF) intensity and solar magnetic field polarity determined from photospheric observations. However, at least one doubt is always present when IMF data are used. It is whether the IMF parameters measured in the Earth's environment are able to fully characterize the magnetic fields all over the heliosphere, which are responsible for CR modulation. This urges us to search for a different parameter, which would supplement the HCS tilt well enough, but unlike the IMF intensity, would be global. Such solar index should be most logically sought for at the source surface where the HCS is determined. And wouldn't it also be reasonable to use the source surface magnetic field calculations to determine the polarity?

The aim of this work is to construct a semi-empirical model of CR long-period variations based on the source surface magnetic field characteristics.

2 Data and method

We have used as CR characteristic the amplitude δ of density variations of 10 GV particles. (the lower curve in Fig. 1). The rigidity spectra of CR variations for every month were obtained from the world-wide neutron monitor data, stratospheric sounding data, and IMP-8 observations of CR with energies >106 MeV (Belov et al., 1993 and references there in). These results until 1998 inclusive were published earlier. Now, the results for the 1990s have been essentially improved, and the results for 1999–2000 have been obtained for the first time. The source surface magnetic field parameters η and B_{SS} are used to describe long-term variations of CR. The novelty of the present

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Correspondence to:R. Gushchina (rgus@izmiran.troitsk.ru) work is the use of the HCS tilt reconstructed from H_α observations of filaments for the period of 1950-1976 when direct observations of GMF were unavailable. In Fig. 1, the HCS tilt η_m obtained from magnetic observations (Hoeksema, 2000) is combined with the tilt $\eta_{\text{H á}}$ calculated from optical data (Obridko and Shelting, 1999). One can readily see a good agreement between η_m and $\eta_{\text{Há}}$ in 1976-1989, where the series overlap (the correlation coefficient is 0.90). Belov et al. (2001) have shown that the HCS tilt determined from optical data correlates well enough with CR variations and can be used to study the CR modulation.

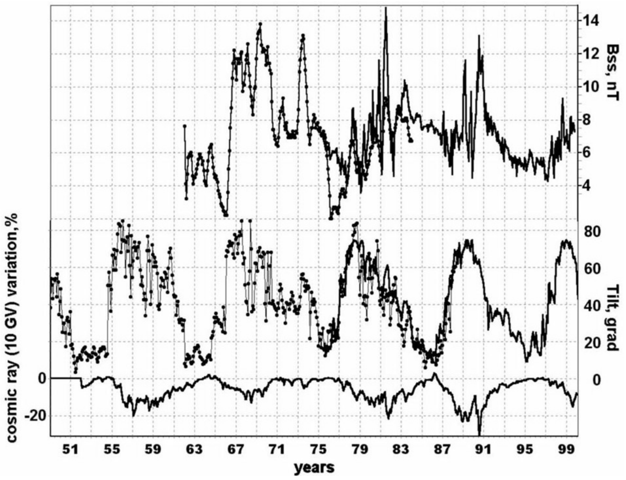

Fig. 1. **C**alculated long-period variations of the mean source surface magnetic field B_{SS} (monthly mean data) as inferred from magnetic measurements in Stanford (Hoeksema, 2000) - thick curve and combined Kitt-Peak and Mt.Wilson (calculated by Obridko and Shelting, 1999) - thin curve at the top part. HCS tilt as inferred from magnetic measurements of η_m (Hoeksema, 2000) - thick curve and optical H_α observations of $\eta_{H\alpha}$ (calculated by Obridko and Shelting, 1999) - thin curve at the mean part. Variations of 10 GV cosmic rays – bottom part.

We tried to combine the HCS tilt with various the source surface magnetic field parameters and, at last, we decided in favor of intensity of the magnetic field radial component B_r averaged over the entire source surface: $B_{ss} = \sqrt{\langle B_r^2 \rangle}$. Since the source surface magnetic field is primarily determined by the dipole component of the solar magnetic field, this parameter must behave virtually in the same way as the dipole moment in the source surface magnetic field expansion. Calculated long-period variations of the mean source-surface magnetic field as inferred from magnetic measurements of B_{SS} for the period 1963–2000 are shown in Fig. 1. The data were obtained by GMF observations at Mt. Wilson, Kitt-Peak and Stanford and processed by the method similar to (Hoeksema and Sherrer, 1986) The calculation method is described in (Obridko and Sheting, 1999 and references there in)

We constructed a multi-parameter model of CR modulation for a long time interval from the minimum of cycle 21 in July 1976 up to the August 2000. Two sign reversals of GMF occurred during that period. The effect of changes of heliomagnetic polarity on CR was taken into account in the model by using the function $p_S(\tau)$, which assumes values ±1 in the periods of positive and negative polarity and is 0 during the sign reversals. The periods of inversion of the solar magnetic field were determined on the source surface from optical observations (Obridko and Shelting, 2001). Besides, the model takes into account that the effect of HCS tilt on CR changes depending on GMF polarity. For this purpose, we used the same field reversal periods (as the function $p_F(\tau)$ further) based on photospheric observations as in our previous work (Belov et. al., 1999).

Long-term variations of the solar wind parameters were taken into account by using the product of velocity V_{SW} by the field intensity $|B_{IMF}|$ (Belov et. al., 2001). The SW parameters were inferred from satellite observations near the Earth (OMNI Data).

Thus, we propose a multi-parametric description of long-term CR variations based on a joint use of solar magnetic field characteristics on the source surface and solar wind parameters.

3 Results and Discussion

At first we consider the model accounting for the intensity of the magnetic field B_{SS} and the HCS tilt η, in which:

$$\delta(t) = a + \frac{b_\eta}{\tau_{u\eta}+1}\sum_{\tau=0}^{\tau_{u\eta}} \eta(t-\tau) + \frac{b_B}{\tau_{uB}+1}\sum_{\tau=0}^{\tau_{uB\,ss}} B_{ss}(t-\tau) \qquad (1)$$

We take into account that CR modulation is controlled by the solar events both in the current month (τ=0) and in the nearest past beginning with moment t-τ_u, where τ_u is the maximum delay. The following parameters were obtained by the least square method for the period of 1981.10-1990.08, approximately coinciding with negative polarity of the global solar magnetic field: a=8.1±1.4, b_η=-0.33±0.01%/°, b_B=-1.1±0.2%/nT, $\tau_{\upsilon\eta}$=4 months, τ_{uB}=8 months. These parameters ensure a very good agreement (correlation coefficient equal to 0.96) between the observed and calculated CR variations (Fig. 2). One can see that the model adequately represents CR variations not only in general, but also in many details. The agreement is amazing for such a simplified model. It describes the behavior of CR in the complex period under consideration better than other models based on a greater number of parameters (Belov et al., 1999; Nagashima et al., 1991). It is to be noted that B_{SS} variation in itself is ill correlated with cosmic rays, but changes its capabilities drastically when combined with the

HCS tilt. This index is not merely involved in determining CR variations together with η, but plays the leading role, at least in the 1980s. Model (1) was successfully applied to other periods, too. This prompts us to try and describe the long period of 1976.07-2000.8 (from 21 cycle beginning up to now), for which the series of source surface parameters from magnetic and optical observations is available. The corresponding multi-parametric model has the form:

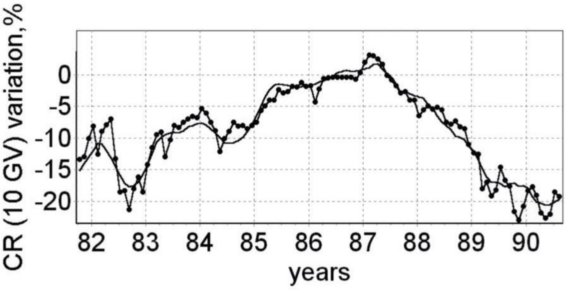

Fig. 2. Observed variations of 10 GV cosmic rays during 1981.10-1990.08 (thick curve) and their model representation (thin curve) based on description (1).

$$\delta(t) = a + \frac{b_{\eta}}{\tau_{u\eta}+1}\sum_{\tau=0}^{\tau_{u\eta}}(1+b_{\eta p}p_F(t-\tau))\eta(t-\tau) + $$

$$+\frac{b_B}{\tau_{uB}+1}\sum_{\tau=0}^{\tau_{uB}}B_{ss}(t-\tau)+\frac{b_p}{\tau_{up}+1}\sum_{\tau=0}^{\tau_{up}}p_S(t-\tau)+ \tag{2}$$

$$+\frac{b_{VB}}{\tau_{uVB}+1}\sum_{\tau=0}^{\tau_{uVB}}(VB)(t-\tau)$$

Figure 3 illustrates a good agreement (correlation coefficient 0.952) of the observed and calculated variations both in general and in many details. The calculations were performed for the following values of the parameters involved: $a=14.9\pm0.1$, $b_{\eta}=-0.224\pm0.009$ %/º, $b_{\eta p}=-0.49\pm0.05$, $b_B=-1.27\pm0.15$ %/nT, $b_p=-3.2\pm0.6$ %, $\tau_{u\eta}= \tau_{uB} = 7$ months, $\tau_{up}= 2$ months, $\tau_{uVB}=0$. One can readily see that two the source surface magnetic field characteristics – the structural (HCS tilt) and quantitative (mean field B_{SS}) ones – well supplement each other in describing CR variations. The changing HCS tilt controls long-term variations (11-year cycles and their basic features), while B_{SS} is responsible for shorter period variations. Correspondingly, the HCS tilt plays the leading part in the periods of low and moderate solar activity, yielding to B_{SS} in the vicinity of the cycle maxima.

A comparison with the earlier results (Belov et al., 1999) shows that substitution of the IMF intensity by B_{SS} is quite justified, and it even improves the model as far as the periods of high solar activity are concerned. From general reasons, it is obvious that IMF must be related to the source surface field. In reality, however, the coupling between B_{SS} and the IMF intensity measured near the Earth is not as close. Therefore, the revealed interchangeability of B_{IMF} and B_{SS} in the modulation models is not a trivial fact. Since the source surface magnetic field is primarily determined by the dipole component of the solar magnetic field, this parameter must behave virtually in the same way as the dipole moment in the source surface magnetic field expansion. It is appropriate to recall here the work by Bazilevskaya et al., (1990) and Nagashima et al. (1991), where the solar dipole was invoked to account for the CR variation anomalies in 1982. On the other hand, the behavior of B_{SS} must resemble the magnetic flux variations, whose importance is the main inference from Cane et al. (1999a, 1999b). The solar wind characteristics obtained at the Earth (VB-parameter) contribute to the shortest period part of CR modulation. It is, probably, due to the local effect of interplanetary disturbances as implied by the zero delay of modulation. The effect of local SW parameters on CR modulation is of secondary importance in this model.

The effect of polarity is, on the contrary, very important. In the periods of negative polarity (qA<0), the CR density increases by ~3% and at (qA>0), decreases by the same value. This effect corresponds by its sign to the drift model and by its value, to the difference of potentials between the low-latitude and polar parts of the heliomagnetosphere (e.g., Jokipii and Levy, 1979). At present, the periods of field reversal are determined from various solar observations, and they differ essentially. Calculations performed by Obridko and Shelting (2001) show that the magnetic field at the source surface changes its sign much earlier than in the photosphere. We successively included in the model several versions of the reversal periods to find out that the behavior of CR correlated with the polarity changes at the source surface much better than in the photosphere. The best agreement was obtained when we used the reversal periods at the source surface reconstructed from $H_{á}$ observations of filaments (Obridko and Shelting, 1999). The time boundaries in the photosphere and at the source surface were determined using both the line-of-sight observations of the polar field and the field calculated in radial direction. As shown by the correlation analysis, the CR behavior is most closely related to the sign of magnetic fields obtained from H_{α} observations for the solar wind source surface- $p_{H\alpha ss}$. The obtained boundaries are as follows: 09.1979–03.1981, 10.1989–03.1991, and 04.1999.

The increase of the HCS tilt results in enhancement of CR modulation both at the negative and positive polarity, but at qA<0 this effect is much stronger (Belov et.al., 1997), which is taken into account in the first term of equation (1). Here, as before, we used the GMF inversion boundaries derived from generalized photospheric data of various authors. The attempt to use the source surface polarity in this place leads to obviously deteriorated result. We interpret it as manifestation of small-scale solar structures and nonstationary phenomena, which are not reflected in the calculated source-surface field, but participate in CR modulation.

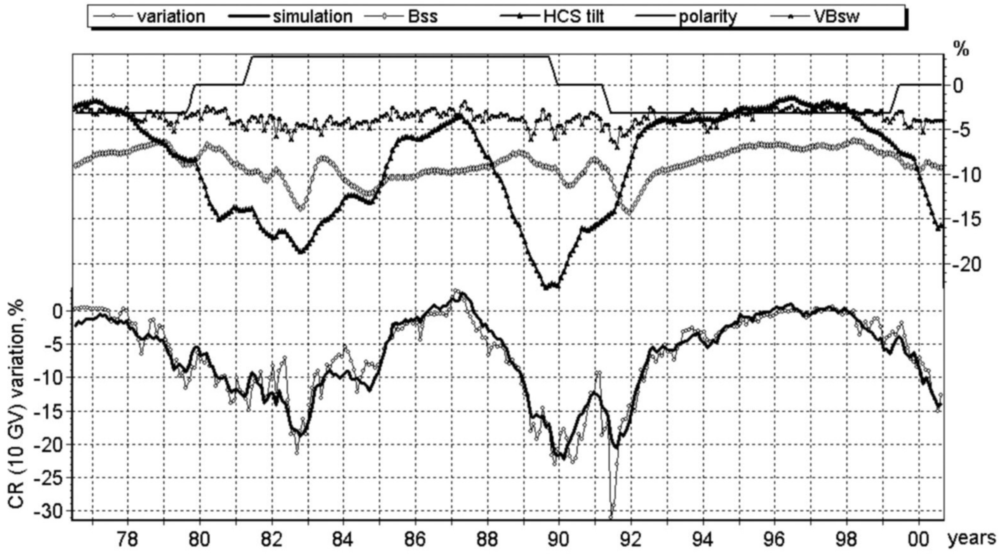

Fig. 3. Monthly CR variations observed and simulated by the multi-paramer model (2) for 1976 – 2000 years (lower part). A contribution of mean source surface magnetic field intensity B_{SS}, HCS tilt, heliomagnetic polarity changes, and solar wind characteristics (product V_{SW} $|B_{IMF}|$) to simulated variations (upper part).

4 Conclusion

The parameters of the solar magnetic field calculated at the solar wind source surface can be used to construct a semi-empirical model, which adequately describes the behavior of density of 10 GV cosmic rays during the last three cycles of solar activity.

The HCS tilt and B_{SS} mean intensity successfully supplement each other, providing the structural and quantitative characteristic of the source surface magnetic field. Therefore, the combined use of these parameters in describing CR modulation allows us to improve simulation of CR long-term variations. It concerns, first of all, the periods of high solar activity, though the model needs further improvement in those periods.

The behavior of cosmic rays is more closely related to the reversals of magnetic field at the solar wind source surface than on the photosphere. However, the local components and sector structure of the solar magnetic field (observed in the photosphere) are involved in formation of the heliomagnetosphere and play an important part in CR modulation.

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