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Global magnetic field of the Sun and long-term variations of galactic cosmic rays

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Abstract

The paper deals with the relation of long-term variations of 10 GV galactic cosmic rays (GCR) to the global solar magnetic field and solar wind parameters. This study continues previous works, where the tilt of the heliospheric current sheet (HCS) and other solar-heliospheric parameters are successfully used to describe long-term variations of cosmic rays in the past two solar cycles. The novelty of the present work is the use of the HCS tilt and other parameters reconstructed from Hα observations of filaments for the period when direct global solar magnetic field observations were unavailable. Thus, we could extend the GCR simulation interval back to 1953. The analysis of data for 1953–1999 revealed a good correlation (the correlation coefficient > 0.88) between the solar-heliospheric parameters and GCR in different cycles of solar activity. Moreover, the approach applied makes it possible to describe the behavior of cosmic rays in the epochs of solar maxima, which could not be done before. This indicates both the adequacy of the model and the reliability of the reconstructed global solar magnetic field parameters. © 2001 Elsevier Science Ltd. All rights reserved.

Keywords: Solar activity; Solar cycle; Long-term variation of cosmic rays

1. Introduction

Long-term variations of galactic cosmic rays were compared with the behavior of various solar-activity indices and heliospheric parameters many times by different authors. In doing so, special importance was attached to the solar magnetic field calculated on the solar wind source surface (Hoeksema and Scherrer, 1986). The coronal magnetic field is calculated from photospheric field observations under potential approximation, i.e., in terms of a source surface (SSMF) model. Under this assumption and within the Parker model, the field is radial at some height above the photosphere. This sphere is called the source surface and, for better agreement with real measurements near the Earth, is placed at a distance of 2.5 solar radii (see, for example, Hoeksema and Scherrer, 1986). The complex field structure in the photosphere simplifies with increasing height in the corona until a single line is left separating the two polarities at about 2.5 solar radii.

SSMF determines the structure and properties of the solar magnetosphere; therefore, it is likely to bear a closer relationship to cosmic ray modulation than other solar parameters, such as the sunspot numbers or coronal emission intensity. It is no surprise that the amplitudes of the global solar magnetic field spherical harmonics were successfully used by Mikhajlutsa (1990) and Nagashima et al. (1991) to simulate long-term modulation of cosmic rays. The basic equation of galactic cosmic rays (GCR) modulation describes (Parker, 1963) the diffusion, convection and drift processes. Although drift effects were formally included in

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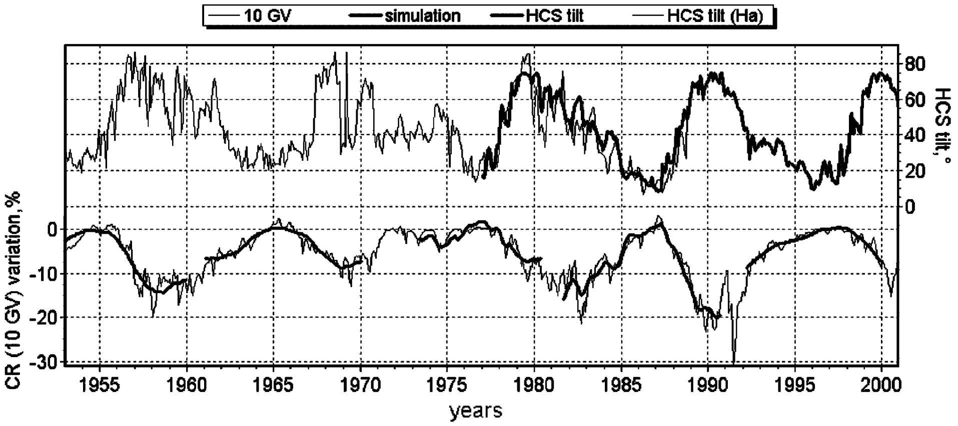

Fig. 1. HCS tilt (monthly mean data) as inferred from magnetic measurements (thick curve) and Hα optical observations (thin curve) — top panel. Variations of 10 GV cosmic rays (thin curve) and their model representation (thick curves) based HCS tilt variations.

this transport equation, only in the past two decades the importance of GCR drift due to the gradients and curvatures of the interplanetary magnetic field (IMF) as well as along the wavy HCS was proved. The current sheet separating the heliomagnetosphere into the northern and southern parts must favor the transport of CR in the radial and, at a significant tilt, in the latitudinal directions. It should be noted that the HCS tilt also determines the size of the low-latitude region of reduced mean solar wind speed and intensified interaction of the wind streams of different velocity. This region seems to have a strong modifying effect on cosmic rays. Finally, it is important that CME events originate mainly in the vicinity of the current sheet.

A close relation of the HCS to the behavior of GCR was substantiated theoretically (Jokipii and Thomas, 1981; Kota and Jokipii, 1983). It was proved experimentally in numerous investigations (Smith and Thomas, 1986; Saito and Swinson, 1986; Webber and Lockwood, 1988; Smith, 1990; Webber et al., 1990; Belov et al., 1995, 1997; Bazilevskaya and Svirzhevskaya, 1998; Belov et al., 1999a, b).

At present, it is clear that the details of GCR modulation could not be explained unless we invoke the HCS tilt and other magnetic field parameters on the source surface. However, the uniform series of SSMF parameters are only available since 1976, and all studies referred to above are confined to a few latest solar cycles alone. Recent work appears to have removed these time limitations (Wang, 1993; Obridko and Shelting, 1999).

Direct measurements of the magnetic field in the photosphere are only available since 1976 (WSO data). There are also earlier data obtained at Mt-Wilson and Kitt Peak observatories from 1965 up to 1984, which were reduced to the Stanford system by Obridko and Shelting (1999). The problem is that this set of data is not uniform. Direct magnetic field measurements for earlier periods do not exist. Obridko and Shelting (1999) used the data on the polarity of large-scale magnetic fields obtained by systematic Hα observations of solar filaments. A special calibration method was developed to calculate the field at the source surface in the Stanford system of units (see Obridko and Shelting, 1999). The SSMF parameters can be determined in that way for a long time interval covering the entire series of CR observations.

In an earlier work (Belov et al., 1997), the modulation of cosmic rays was studied using an alternative method of reconstructing HCS tilt from geomagnetic data (Vanyarkha, 1995). The disadvantage of this method is its being inapplicable under high solar activity.

The aim of the present study is to simulate long-term modulations of cosmic rays over a longer time interval than using the source surface magnetic field parameters and to check the reliability of the SSMF parameters inferred from indirect optical observations.

2. Cosmic ray data

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 by the method proposed by Belov and co-authors from the world-wide neutron monitor data, stratospheric sounding data, and IMP-8 observations of CR with energies > 106 MeV (see Belov et al., 1993 and references therein). These results until 1998 inclusive were published earlier. Now, the results for the 1950s and 1990s have been essentially improved, and the results for 1999 have been obtained for the first time. The latter should be considered preliminary, since the neutron monitor data are incomplete.

Table 1
Regression coupling parameters δ and η for Eq. (1)

Period	a (%)	b (%/°)	τ_u (months)	ρ	σ (%)
53.07–59.06	2.7 ± 0.2	-0.24 ± 0.01	26	0.93	2.26
61.02–70.01	2.2 ± 0.1	-0.16 ± 0.01	23	0.92	1.32
73.05–80.05	4.3 ± 0.2	-0.15 ± 0.02	4	0.88	1.51
81.09–91.09	4.6 ± 0.2	-0.33 ± 0.01	5	0.95	2.23
92.03–99.12	4.0 ± 0.1	-0.20 ± 0.01	25	0.93	1.04

3. CR modulation and HCS tilt

In Fig. 1, the HCS tilt η_m, obtained from magnetic observations (Hoeksema, 2000) is combined with the tilt $\eta_{H\alpha}$ calculated from optical data (Obridko and Shelting, 1999). One can readily see a good agreement between η_m and $\eta_{H\alpha}$ during 1976–1989, where the series overlap (the correlation coefficient is 0.89).

A close relationship between the HCS tilt and long-term behavior of cosmic rays in the periods of the same polarity of the global solar magnetic field was revealed in earlier work (e.g., Belov et al., 1995, 1999a, b; Belov, 2000). To find out whether such a relationship exists at longer time scales, we have taken a combined data series η, which comprises $\eta_{H\alpha}$ up to April 1976 and η_m since May 1976. Using linear regression analysis, we isolated the intervals approximately coinciding with the periods of equal heliomagnetospheric polarity, when CR variations were described reasonably well by the expression

$$\delta(t) = a + \frac{b}{\tau_u + 1} \sum_{\tau=0}^{\tau_u} \eta(t - \tau), \qquad (1)$$

τ being the delay between solar indices and cosmic rays. Here, we take into account that CR modulation is controlled by the solar events both in the current month ($\tau = 0$) and in the nearest past beginning with moment $t - \tau_u$. Three parameters (a, b, and the maximum delay τ_u) were determined for each period by the least square method. The obtained values are tabulated together with the correlation coefficient ρ and the standard r.m.s. deviation σ in Table 1. Cosmic ray variations in the time intervals under consideration derived from Eq. (1) are represented in Fig. 1.

The values of η_m alone were used for the last two periods, and the values of $\eta_{H\alpha}$, for the first two ones. In the third period (1971–1981), various data were combined. The relationship between CR variations and the HCS tilt was often analyzed in the 1980s. Recently, this analysis has been extended to cover 5 half-periods of the solar magnetic cycle (i.e., the total of 47 years).

One can see that the current sheet and cosmic rays usually behave in a similar way, except for relatively short periods during and immediately after the field reversal. In all selected periods, the correlation coefficient proved to range from 0.88 to 0.95, and the r.m.s. deviation was $< 2.3\%$. Such correlation can be considered quite satisfactory, taking into account that a simplified model (1), based on a single solar-heliospheric parameter, was used. Thus, the HCS tilt derived from indirect optical data correlates with CR variations well enough and can, obviously, be used instead of the traditional tilt values obtained from magnetic measurements. To what degree is such substitution justified? The results for the last two periods look more convincing than the others, and it is, most probably, no mere chance. Separately, we analyzed in the same way the period of 1981.04–1989.12, when the HCS tilt data obtained by different methods overlapped. The correlation with CR variations proved to be definitely higher for η_m than for $\eta_{H\alpha}$, though the latter also provided quite a satisfactory result ($\rho = 0.93$ at $\sigma = 2.37$ and $\rho = 0.89$ at $\sigma = 2.93$, respectively). The results obtained above imply that optical observations can be an adequate and well-justified substitute for HCS tilt data and can be successfully used in analyzing CR modulation in the periods when direct magnetic observations are unavailable.

Our analysis corroborates a good correlation between the long-term behavior of cosmic rays and the HCS tilt both under negative (1960s and 1980s) and positive polarity of the global solar magnetic field (Belov et al., 1995).

4. Multi-parameter model and CR modulation under high solar activity

Our description of actual cosmic ray variations is rather approximate, and it could not be otherwise. CR modulation is a complex phenomenon, which occurs all over the heliosphere and depends on many factors. No single solar index, however, sophisticated, can account for CR variations. Belov et al. (1999b) proposed a multi-parametric description of long-term CR variations, based on a joint use of the HCS tilt and intensity variations of the IMF. The effect of IMF intensity variations on cosmic ray modulation is even easier to substantiate theoretically than the effect of the HCS tilt. The main determining parameter of particle transport—gyroradius—is inversely proportional to IMF module (H). According to theoretical reasons (e.g. Parker, 1963) an increase of H should lead to a decrease of transport path and the diffusion coefficient and, consequently, to an increase of the CR modulation. The relationship between the IMF modulus and long-period variations of CR was corroborated experimentally (Cane et al., 1998; Belov et al.,

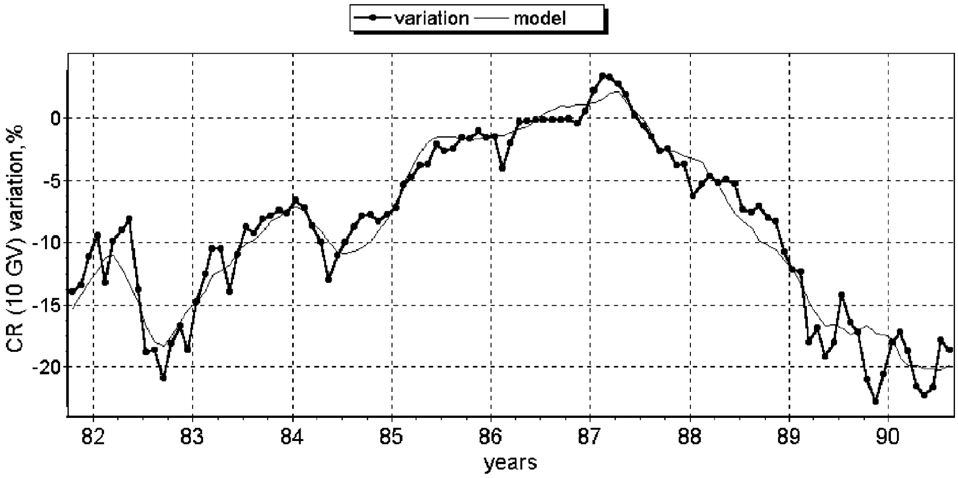

Fig. 2. Observed variations of 10 GV cosmic rays during 1981.10–1990.08 (thick curve) and their model representation (thin curve) based on description (2).

1998) when long data series of solar wind measurements were built up. Indeed, these parameters—the HCS tilt and the IMF intensity—successfully supplement each other. The point is that the HCS tilt manifests the structure of the heliosphere, while the IMF intensity characterizes quantitatively its effect on cosmic rays.

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 more global. Such solar index might be the magnetic field of the Sun as a star or, more logically, it should be sought at the source surface, where the HCS is determined.

We tried to combine various SSMF parameters with the HCS tilt, and, at last, we decided in favor of intensity of the magnetic field radial component B_r averaged over the entire source surface: $B_\mathrm{ss} = \sqrt{\langle B_\mathrm{r}^2 \rangle}$. Since the SSMF 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 SSMF 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, b).

Now, let us modify Eq. (1) as follows:

$$\delta(t) = a + \frac{b_\eta}{\tau_{\mathrm{u}\eta}+1}\sum_{\tau=0}^{\tau_{\mathrm{u}\eta}} \eta(t-\tau) + \frac{b_\mathrm{B}}{\tau_{\mathrm{u}B}+1}\sum_{\tau=0}^{\tau_{\mathrm{u}B}} B_\mathrm{ss}(t-\tau). \tag{2}$$

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: $a = 7.9 \pm 1.5$, $b_\eta = -0.35 \pm 0.01\%/^\circ$, $b_\mathrm{B} = -1.3 \pm 0.2\%/\mathrm{nT}$, $\tau_{\mathrm{u}\eta} = 4$ months $\tau_\mathrm{uB} = 11$ months. These parameters ensure a very good agreement (correlation coefficient equal to 0.97) between the observed and calculated CR variations (Fig. 2). Such agreement cannot be any longer regarded as "rough". 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 cosmic rays 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 is ill-correlated with cosmic rays in itself, 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 a leading role, at least in the 1980s.

Model (2) was successfully applied to other periods, too. This prompts us to try and describe the entire period of 1977.01–1999.10, for which a uniform series of SSMF parameters is available. We leave out 1976 because of the lag, which must be taken into account. Since two field reversals occurred during the period under examination, the model must include index p, which characterizes polarity variations of the global solar magnetic field. Polarity of the global magnetic field is determined as function $p(\tau)$, which can only adopt three values: ± 1 in the periods of positive and negative polarity and 0 in the field reversal periods. Following Belov et al. (1999b), we take into account both the direct effect of polarity on CR variations and its effect on CR modulation as the HCS tilt changes. The corresponding

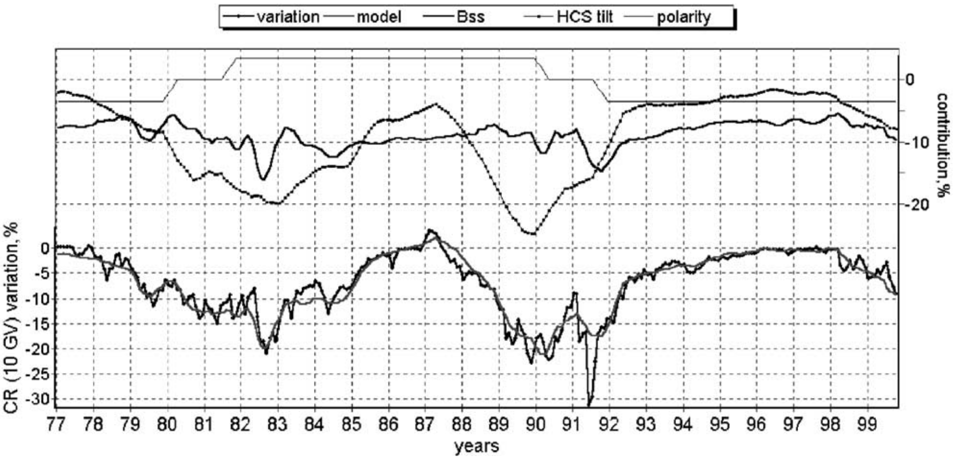

Fig. 3. Monthly CR variations observed and simulated by the multi-parametric model (3) for 1977–1999 years (lower part). A contribution of mean source surface magnetic field intensity B_{SS}, HCS tilt and heliomagnetic polarity changes p to simulated variations (upper part).

supplemented model has the form

$$\delta(t) = a + \frac{b_\eta}{\tau_{\mathrm{u}\eta}+1}\sum_{\tau=0}^{\tau_{\mathrm{u}\eta}}(1 + b_{\eta\mathrm{p}}\,p(t-\tau))\eta(t-\tau) + \frac{b_{\mathrm{B}}}{\tau_{\mathrm{uB}}+1}\sum_{\tau=0}^{\tau_{\mathrm{uB}}}B_{\mathrm{ss}}(t-\tau) + \frac{b_{\mathrm{p}}}{\tau_{\mathrm{up}}+1}\sum_{\tau=0}^{\tau_{\mathrm{up}}}p(t-\tau). \tag{3}$$

This description differs from the model proposed by Belov et al. (1999b) by the absence of the solar wind velocity parameter and by using B_{SS} instead of the IMF intensity.

Fig. 3 illustrates a good agreement (correlation coefficient 0.945) 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: $a = 7.7 \pm 0.7$, $b_\eta = -0.242 \pm 0.007\%/^\circ$, $b_{\eta\mathrm{p}} = -0.52$, $b_{\mathrm{B}} = -1.25 \pm 0.10\%/\mathrm{nT}$, $b_{\mathrm{p}} = -3.5 \pm 0.2\%$, $\tau_{\mathrm{u}\eta} = 9$ months, and $\tau_{\mathrm{uB}} = \tau_{\mathrm{up}} = 4$ months. A comparison with the earlier results (Belov et al., 1999a) 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 modulus measured near the Earth (Fig. 4) is not as close (correlation coefficient for the period of 1976.05–1999.10 is 0.52). Therefore, the revealed interchangeability of B_{IMF} and B_{SS} in the modulation models is not a trivial fact.

One can readily see that two SSMF 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 a leading role in the periods of low and moderate solar activity, yielding to B_{SS} in the vicinity of the cycle maxima.

The effect of polarity is, on the contrary, very important. In the periods of negative polarity (qA < 0), the CR density increases by $\sim 3\%$ 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). An alternative mechanism of influence of the GMF polarity on CR modulation was suggested by Burger et al. (1997). Theoretical estimates given in that work qualitatively agree with our results.

At present, it is commonly believed (McDonald, 1998) that CR modulation under high solar activity is mainly determined by expanding magnetic shells in the solar wind (the global merged interaction regions—GMIRs (Burlaga et al., 1993). We do not think that the close correlation between the source surface magnetic field and cosmic ray modulation, revealed above, contradicts the traditional concept. The coupling of solar and interplanetary fields, including major solar wind disturbances, is still poorly investigated; the clue to its understanding is, obviously, to be sought for at the source surface.

We have made an attempt to apply the same approach to an earlier period, using $(B_{\mathrm{SS}})_{\mathrm{H}\alpha}$—the magnetic field inferred from indirect optical data and averaged over the source surface. However, no explicit relationship between this parameter and CR modulation was revealed. The fact is that $(B_{\mathrm{SS}})_{\mathrm{m}}$ and $(B_{\mathrm{SS}})_{\mathrm{H}\alpha}$ (Fig. 4) differ substantially in the physical sense. The local components and sector structure of the solar magnetic field contribute significantly to $(B_{\mathrm{SS}})_{\mathrm{m}}$, whereas $(B_{\mathrm{SS}})_{\mathrm{H}\alpha}$ describes mainly the global field and its zonal components (Obridko and Shelting, 1999). Fig. 4 shows that the long-term behavior of $(B_{\mathrm{SS}})_{\mathrm{m}}$ and $(B_{\mathrm{SS}})_{\mathrm{H}\alpha}$, coinciding in some features (e.g., in 1982), differs

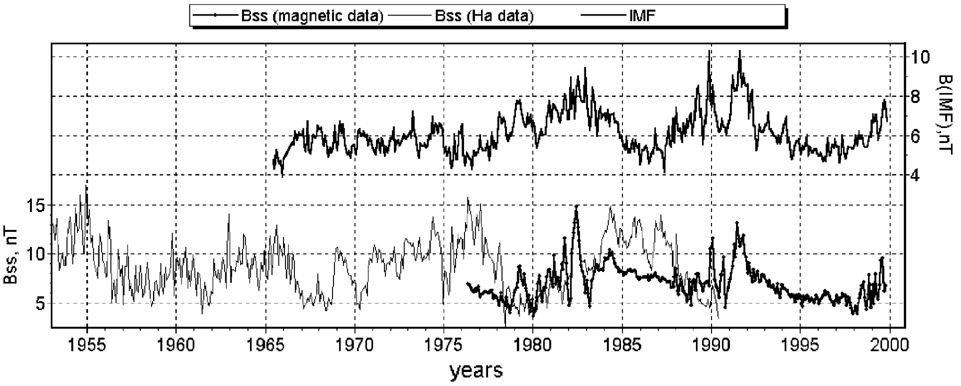

Fig. 4. Long-period variations of the mean source surface magnetic field as inferred from magnetic measurements of $(B_{SS})_{m}$ (thick curve) and optical Hα observations of $(B_{SS})_{H\alpha}$ (thin curve). Variations of the monthly mean IMF intensity near the Earth (OMNI Data) are given at the top.

essentially. The obtained negative result is likely to suggest an important conclusion: The formation of the heliomagnetosphere is controlled not only by global magnetic field but by local solar magnetic fields, too. It means that local fields also play an important part in long-term modulation of cosmic rays.

5. Basic conclusions

(1) The HCS tilt derived from optical data can be used, with some reservations, to study the modulation of cosmic rays.
(2) A good agreement between long-term cosmic ray variations and the tilt of the heliospheric current sheet exists in all periods of the same heliomagnetospheric polarity, since 1953 (i.e. during the whole history of ground-based CR observations with neutron monitors).
(3) 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 semi-empirical models of CR long-term variations, particularly, in the periods of high solar activity.
(4) The local components and sector structure of the solar magnetic field take part in the formation of the heliomagnetosphere and play an important role in CR modulation.

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