On the status of the sunspot and magnetic cycles in the galactic cosmic ray intensity

M B Krainev\textsuperscript{1}, G A Bazilevskaya\textsuperscript{1}, S K Gerasimova\textsuperscript{2}, P A Krivoshapkin\textsuperscript{2}, G F Krymsky\textsuperscript{2}, S A Starodubtsev\textsuperscript{2}, Yu I Stozhkov\textsuperscript{1} and N S Svirzhevsky\textsuperscript{1}

\textsuperscript{1}Lebedev Physical Institute, Russian Academy of Sciences, Moscow, Russia
\textsuperscript{2}Yu.G. Shafer Institute of Cosmophysical Research and Aeronomy, Siberian branch of Russian Academy of Sciences, Yakutsk, Russia

E-mail: mkrainev46@mail.ru

Abstract. The views of two research groups are presented on the progress achieved in understanding one specific class of the long-term variations of the galactic cosmic ray intensity, the variations due to the sunspot and magnetic cycles in the solar activity. The main observational features of both cycles and how they can be described and understood are discussed for the two-decade period (1980–2000) that we consider as normal for the development of both cycles for the second half of the 20-th century. The unusual features in the cosmic ray behavior observed during the long and deep minimum between solar cycles 23 and 24 (2008–2010) are also discussed.

1. Introduction

The sunspot (or 11-year) cycle in the galactic cosmic ray (GCR) intensity, that is its variation in the opposite phase with the number of the sunspots, was discovered in the 1950s and was described and understood to some extend (see the review [1]) in the framework of the transport equation [2, 3] and the tacitly adopted ”orange” model of the heliospheric magnetic field (HMF) as consisting of the unipolar magnetic segments divided by the meridional current sheets. The magnetic cycle in the GCR intensity is its change with 22-year period in phase with the polarity of the high-latitude solar magnetic field. The potential importance of the magnetic drifts for the GCR intensity was proposed [4] soon after the birth of the HMF model of two unipolar magnetic ”hemispheres” divided by the thin global heliospheric current sheet (HCS) [5]. The first observed effect of the magnetic cycle in the GCR intensity, the variation of the form of its time profile for the successive sunspot cycles, was found in [6] and soon it was demonstrated [7] that this effect could be easily modeled as a consequence of the particle’s magnetic drift along the HCS with the changing waviness (characterized by its latitudinal half-width or tilt). Since then the models including drifts have been widely used in modeling the sunspot and magnetic cycles in the GCR intensity and the progress is impressive [8].

In this paper we present our views on the progress achieved in studying and understanding the variations in the intensity of the GCR nuclei due to the sunspot and magnetic cycles in the solar activity during the two-decade period (1980-2000) that we consider as normal for the second half of the 20-th century. The unusual features in the cosmic ray behavior observed during the long and deep minimum between solar cycles 23 and 24 (2008-2010) are also discussed.
2. Sunspot and magnetic cycles: the main observational features

Fig. 1 illustrates the sunspot and magnetic cycles on the Sun, in the heliosphere and in the GCR intensity. In the medium latitude zone of the Sun the well-known sunspot cycle develops (panel a), the number and area of the powerful active regions strongly changing with time. These phenomena are characterized by the toroidal magnetic fields, changing their polarity (different in the north and south) near the sunspot minima (sunspot or toroidal branch of solar activity). At high latitudes (panel b) the much less energetic but larger scale poloidal magnetic fields with different polarity in the north and south are changing in the opposite phase with the sunspot activity (poloidal branch). Their polarity changes every maximum of the sunspot cycle. So the sunspot and polar solar cycles are two mutually complementary (probably through the dynamo mechanism) variations in whole constituting the 22-year solar cycle, developing in the opposite phase in the toroidal and poloidal branches of solar activity.

Due to their relatively small size the strong sunspot magnetic fields do not leave the thin near-the-Sun region, while the larger scale high-latitude solar magnetic fields are dragged from the Sun by the solar wind keeping the same polarity they have in the source. So in the heliosphere the HMF’s polarity changes (forming the magnetic cycle) in phase with the polar but not sunspot magnetic fields. The periods between the successive sunspot maxima are characterized by the quantity $A$, the sign of the HMF’s radial component in the north hemisphere, and are often called the $A$–negative or $A$–positive periods. The heliospheric magnetic equator or HCS is some
surface waved due to its form near the Sun and the solar rotation. When leaving the Sun the plasma and magnetic fields are greatly affected by the active regions so that, as can be seen from Fig. 1, c–e, both the sunspot cycle (in the tilt, the strength of HMF, the energy density of its fluctuations and the index $\alpha$ of their spectra, $P \propto \nu^{-\alpha}$, $\nu$ being the frequency) and the magnetic cycle (in the HMF’s polarity) develop in the heliospheric characteristics. As the GCRs interact with the electromagnetic fields and this interaction depends on the fields polarity, their intensity (Fig. 1, f) is affected by both cycles, changing as a whole in the opposite phase with the sunspot area while the magnetic cycle manifests itself in some details.

As can be seen from Fig. 1, the activity in the solar cycles 21 and 22 is rather high and similar for both the toroidal and poloidal branches. The tilt, the HMF’s strength and the energy and spectrum of its fluctuations change during these cycles in the similar way. The cosmic ray intensity also varies rather similar and without any outstanding features. So we consider the cosmic ray behavior during the last two decades of the last century as normal for the second half of the century, while the first decade of the current century we call anomalous as both the sunspot and polar solar activities and the HMF’s strength were exceptionally low and the cosmic ray intensity was exceptionally high (see, e. g. [13]–[17]). Of course, this anomalous period can be also normal but for the less active Sun.

Fig. 2 illustrates the sunspot and magnetic cycles in the GCR intensity for 1980–2012. For energies lower than about 200–500 MeV/n (the low energies, panel a) the measurement aboard the spacecraft is the only way to detect the GCR intensity and for energies greater than 10 GeV (the high energies, panel c) the main detectors at the Earth are neutron monitors, then muon telescopes, underground installations etc. For the intermediate energies (few GeV, the medium energies, panel b) the regular balloon monitoring of the Lebedev Physical Institute [18, 12] is up to now the best way to study the related GCR intensity variations.

We begin with the discussion of the 1980–2000 ("normal") period. The first feature that one sees from Fig. 2 is that the overall amplitude of the intensity variation monotonically decreases as the energy increases. Second, for all energies we can see the peak-like time profile for A–negative period and more flat profile for A–positive period [6]. More quantitative way to describe the same effect is to demonstrate the better correlation between the cosmic ray intensity and the tilt for A–negative periods and the better correlation with the sunspot number for A–positive periods [21]. The third feature in the low and medium energy GCRs for the normal period is the higher maximum intensity for A–positive periods than for A–negative ones, the difference being greater for smaller energies. For high energies the phase of the magnetic cycle is opposite, that is the intensity is smaller for A–positive periods [22, 23]. As it follows from balloon and neutron monitor data (Fig. 2, b–c) this change of the phase (or cross-over) occurs at about 8–10 GeV. The fourth feature known for the low energy GCR intensity for the normal period is that in the intermediate heliosphere (10–60 AU) the radial gradient of the intensity is significantly smaller for A–positive than for A–negative periods [19]. Besides, for A-positive normal period (the 1990s) it is known from the Ulysses observations that the latitudinal gradient of both low and medium GCR intensity is rather small [24]. So the main features of the normal sunspot and magnetic cycles in the GCR intensity are known rather well. However, they are observed mainly near the Earth, in the low-latitude inner heliosphere, the very special region in the vicinity of the Sun, where the magnetic field forms something like a hard core for the cosmic rays, and always inside the region with the HCS and the interaction between the fast- and low-speed fluxes of the solar wind.

As to the "anomalous" period of the first decade of the current century, it is highly probable that the main cause of the unusual features in the GCR behavior in the last decade is the very low level of solar activity both in its sunspot (Fig. 1, a) and high-latitude (Fig. 1, b) branches of the solar magnetic field. As a result the strength of the HMF (Fig. 1, d) was exceptionally low during the sunspot minimum between SC 23 and 24. Besides, the fluctuation spectra for
The time profiles of the GCR intensity for 1980–2012. The meaning of the shaded vertical bands, the legends above the panels and the horizontal lines near the time axes is the same as in Fig. 1. The yearly smoothed GCR intensity normalized to 1987: (a) the low energy, IMF8/GME He 28-63 MeV/n [19] (solid line), ACE/SIS He 29-41 MeV/n [20] (dotted line); (b) the medium energy, the count rate in the Pfotzer maximum in atmosphere at the polar (Murmansk, solid line, the effective rigidity $R_{\text{eff}} \approx 5 \, \text{GV}$) and middle latitudes (Moscow, dotted line, $R_{\text{eff}} \approx 7 \, \text{GV}$) [12]; (c) the high energy, the neutron monitor count rate at middle (Moscow, solid line, $R_{\text{eff}} \approx 15 \, \text{GV}$) and low latitudes (Tsumeb, dotted line, $R_{\text{eff}} \approx 25 \, \text{GV}$).

Figure 2. The time profiles of the GCR intensity for 1980–2012. The meaning of the shaded vertical bands, the legends above the panels and the horizontal lines near the time axes is the same as in Fig. 1. The yearly smoothed GCR intensity normalized to 1987: (a) the low energy, IMF8/GME He 28-63 MeV/n [19] (solid line), ACE/SIS He 29-41 MeV/n [20] (dotted line); (b) the medium energy, the count rate in the Pfotzer maximum in atmosphere at the polar (Murmansk, solid line, the effective rigidity $R_{\text{eff}} \approx 5 \, \text{GV}$) and middle latitudes (Moscow, dotted line, $R_{\text{eff}} \approx 7 \, \text{GV}$) [12]; (c) the high energy, the neutron monitor count rate at middle (Moscow, solid line, $R_{\text{eff}} \approx 15 \, \text{GV}$) and low latitudes (Tsumeb, dotted line, $R_{\text{eff}} \approx 25 \, \text{GV}$).

all HMF components became significantly softer since 1996 (Fig. 1, e), while the total energy density of the HMF’s fluctuations did not change its behavior (Fig. 1, d) [25]. The main unusual features in the GCR intensity behavior in the anomalous period are as follows. First, as can be seen from Fig. 2, a–b, the excess of the maximum intensity during 2009-2010 was very energy dependent when compared with the normal A-negative period: it peaked at about 50% for the low energy GCRs, quickly decreased with energy and was about zero for the low-latitude neutron monitor. Second, there are some features in the details of the time profiles which look as if the behavior of the low and medium energy GCRs better corresponded to the changes in the modulating parameters and it is the high energy intensity which growth was somehow blocked [26, 27]. And third, the record-setting excess of the GCR intensity near the Earth during 2009-2010 was accompanied by the relative decrease of the anomalous cosmic rays (ACR) intensity [28].
3. Theory and modeling of the sunspot and magnetic cycles in the GCR intensity

The direct way to understand these cycles is to reproduce their main features using the reliable heliospheric models and the theory of the charged particle interaction with the electromagnetic fields. The distribution of the GCR intensity in the heliosphere is usually described as a solution of the boundary-value problem for the distribution function \( U(\vec{r}, p, t) = J(\vec{r}, T, t)/p^2 \) \((\vec{r}, p, T, t \text{ being the position, momentum, kinetic energy and time, respectively})\). This boundary-value problem includes the transport equation (1) for the steady-state [2, 3, 4], balancing the divergences of the diffusion, convection, drift and energy fluxes:

\[
- \frac{\partial U}{\partial t} = -\nabla \cdot (K \nabla U) + \vec{V}^{sw} \cdot \nabla U + \vec{V}^{dr} \cdot \nabla U - \frac{\nabla \cdot \vec{V}^{sw}}{3} \frac{\partial U}{\partial p} = 0, \tag{1}
\]

the general boundary conditions and the "initial" condition \( U|_{p=p_{\text{max}}} = U_{\text{um}}(p_{\text{max}}) \) with \( U_{\text{um}}(p) \) being the unmodulated distribution function and \( p_{\text{max}} \approx 100 \text{ GeV/c} \). To solve this problem one needs the models for the equation coefficients: the solar wind velocity \( \vec{V}^{sw} \) and the regular \( \vec{B} \) and fluctuating HMF, which determine both the diffusion tensor \( K \) and the magnetic drift velocity \( \vec{V}^{dr} \) of the particles. We shall not dwell on these models in details as they are fully described in the original papers (see the review [8]).

However, it is very important that general conclusion of those who tried to describe the observed features of the GCR intensity solving the transport equation numerically is that it is difficult to do without some restrictions imposed on the equation coefficients:

\[
\vec{B} = \frac{\vec{B}_{r,E}}{r}\left(\frac{r_{E}}{r}\right)^2(\vec{e}_r - \tan \chi \vec{e}_\varphi) \cdot \sqrt{1 + (r \cos \chi \cdot \delta_{JK})^2} \tag{2}
\]

\[
K = K_{||} \cdot \begin{pmatrix} 1 & 0 & 0 \\ 0 & \alpha_{\perp,\varphi} & 0 \\ 0 & 0 & \alpha_{\perp,r} \end{pmatrix}, \quad 1 > \alpha_{\perp,\varphi} \geq \alpha_{\perp,r} \tag{3}
\]

\[
K_{||}^+ < K_{||}^- \tag{4}
\]

The first condition is to modify the usual HMF to make it much stronger in the distant high-latitude heliosphere. Usually it is done by the method suggested in [29] and looking as (2) for the unmodified Parker HMF, where \( B_{r,E} \) is the radial HMF component at \( r = r_E \) and \( \chi \) is the HMF spiral angle. The second condition is to use the very anisotropic diffusion tensor with its perpendicular components being much greater in the latitudinal than in the radial directions (3) [30]. At last the third condition is to use the significantly different parallel diffusion coefficients for the A-positive and A-negative periods (4) [31]. It must be emphasized that there are intrinsic reasons for these features of the models (see the references in [8]) but the methods how it is done now provoke objections (e.g., the HMF modified as in (2) is not divergence-free!).

To illustrate the above questionable features of the equation coefficients we compare the solutions of (1) with and without the above restrictions. In Fig. 3 the solid lines show the description of the GCR intensity (its latitudinal and radial profiles and energy spectra with crossover around 10 GeV) for the normal solar minima, while in Fig. 4 the solid line shows the calculated time profile. This description is achieved in the very simple model [32, 33] using the same questionable features of the general numerical modeling

\[ \left\{ \delta_{JK} = 0.12, \alpha_{pol}^{\perp,\varphi}/\alpha_{pol}^{\perp,r} = 60, K_{||}^-/K_{||}^+ = 4 \right\}, \]

for the details see [32, 33]. Of course, this description of the observed GCR intensity is much worse than in the most sophisticated models such as the compound model of the Potchefstroom group (see [8]). However, the main features of the GCR intensity during 1980–2000 are reproduced by the solid lines in Figs. 3 and 4 adequately. The other lines of different styles show how the calculated intensity changes if we do not impose the above restrictions in turn and simultaneously. One can see that giving up the
Figure 3. The observed and calculated distributions of the GCR proton intensity during solar minima 21/22 and 22/23. The red squares and thicker curves are for the observed [19] and calculated intensity for $A > 0$, while the blue triangles and thinner curves are for $A < 0$. (a) the colatitude profiles for $r = 1$ AU, $T = 200$ MeV; (b) the radial profiles for $\vartheta = 86$ deg, $T = 200$ MeV and (c–d) the energy spectra for $r = 1$ AU, $\vartheta = 86$ deg. The crossover ($T_{co} \approx 9900$ MeV) is shown by the star in (d). The solid curves are for the intensity calculated with all three restrictions (2–4) imposed on the equation coefficients; the dotted curves are for the run without restriction (2), $\delta_{jk} = 0$; the dashed curves are for the run with rather weak restriction (3), $\alpha_{\perp, \vartheta}^{pol}/\alpha_{\perp, r}^{pol} = 6$; the dot-dashed curves are for the run without restriction (4), $K^-/K^+ = 1$; and the three-dots-dashed curves are for the run without all three restrictions.

restrictions (3–4) imposed on the diffusion coefficients one at a time much stronger influences the GCR intensity distributions for $A$–positive (increasing the intensity almost everywhere) than for $A$–negative periods (slightly increasing it at $r > 10$ AU and decreasing in the inner heliosphere). Giving up the restriction (2), on the contrary, much stronger increases the GCR intensity for $A$–negative than for $A$–positive period in the inner heliosphere, this asymmetry being reduced at the greater heliocentric distances. At last the results of giving up all three restrictions (2–4) is similar to giving up only restriction (3), as if the restrictions (2) and (4) compensate each other.

Of course, giving up any restriction (2–4) strongly affects the description of the observations. However, the main qualitative features of the sunspot and magnetic cycles in the GCR intensity are retained: the form of the energy spectra, the dependence of the time profiles of the intensity and of its gradients on the IMF’s polarity. That is why the authors of [32, 33] still hope that the main success in understanding the sunspot and magnetic cycles in the GCR intensity can
Figure 4. The time profiles of some heliospheric characteristics and GCR intensity in 1980–2000. All observed data are monthly or 27d averaged. (a) The strength of the heliospheric magnetic field observed near the Earth ([11], blue line) and that used in calculations (red line); (b) the parallel diffusion coefficient at $B_{hmf} = 5$ nT and $R = 1$ GV (see [32]) used in different runs; (c) the observed ([10], classic model, blue) and used for calculations (red) tilt of HCS; (d) the observed near the Earth ([19], blue) and the calculated in different runs proton intensities ($T \approx 200$ MeV) (red lines). The meaning of the lines of different style is the same as in Fig. 3.

be achieved by improving the HMF model and the models of the interaction between the HMF and charged particles. Besides, they appreciate the potential of the numerical methods for some additional studies such as that of the structure of the calculated intensity, see [32, 33].

So the method of the numerical modeling for the sophisticated models was very successful in describing the observed features of the sunspot and magnetic cycles in the cosmic ray intensity during 1980–2000 although to achieve this aim the questionable general features of the HMF and the diffusion tensor were used which put these results in doubt. Moreover, the very important intrinsic assumption of these models is that the time behavior of the heliospheric characteristics in different parts of the heliosphere is the same as near the Earth, which lies as we already said in the very specific region of the heliosphere.

Under these circumstances it is only natural that the other approaches to model the long-term GCR intensity are being developed. The authors of the base-model [34] constructed it as the most simple scheme aimed at understanding the features of the sunspot and magnetic cycles in the high energy GCR intensity without changing the usual properties of the HMF and diffusion coefficients. First they transform the transport equation (1) for the case of the high energy particles and small solar wind velocity (when compared with the drift velocity of the particles).
Then they change the variables and unknown function (5), introduce some new parameter and constants (6) and under some rather realistic assumptions get the new transport equation (7) with new boundary conditions at the heliospheric boundary and pole (8) taking into account the naturally arising latitude-dependent potential difference (9) between the inner point of the heliosphere and the infinity illustrated in Fig. 5 (see also [35] and references therein):

\[ x = \ln \left( \frac{r_{\text{max}}}{r} \right), \quad \lambda = \frac{\pi}{2} - \vartheta, \quad \Psi(x, \lambda, p, t) = U_{\text{um}}(p) - U(r, \vartheta, p, t) \]  

(5)

\[ \eta = \omega \tau, \quad p_1 = \frac{3\eta^2 + 1}{2} q B_{r,E} E_r, \quad b_1 = \frac{2(\gamma + 2)}{3} V_{SW} p_1 U_{\text{um}} \]  

(6)

\[ \frac{1}{2\eta} \Delta \Psi - \frac{1}{\eta} \frac{\partial \Psi}{\partial x} + \frac{\partial \Psi}{\partial \lambda} = b_1 \cos \lambda \]  

(7)

\[ \Psi|_{x=0} = -b_2 \cdot q \Pi(\lambda), \quad \left. \left( \frac{1}{\eta} \frac{\partial \Psi}{\partial \lambda} + \frac{\partial \Psi}{\partial x} \right) \right|_{\lambda=0} = 0, \quad \Psi|_{\lambda=\frac{\pi}{2}} = b_2 \cdot q \Pi(\frac{\pi}{2}) \]  

(8)

\[ \Pi(\lambda) = -\frac{B_{r,E} E_r \omega_S}{c} \left( \sin \lambda - \frac{1}{2} \right), \]  

(9)

where \( r_{\text{max}}, \omega, \tau, v, q, \gamma, \omega_S, b_2 \) are, respectively, the size of the modulation region, the Larmor frequency, collision time, the particle’s velocity and charge, the spectral index of the unmodulated spectrum, the angular velocity of solar rotation, and one more constant (for details see [34]).

**Figure 5.** The sketch of the solar wind velocity, the heliospheric magnetic and electric fields inside the heliosphere for A–positive solar minimum and the corresponding equipotential surfaces (\( \Pi = \text{const} \), with respect to infinity, solid inside the heliosphere and dashed beyond the modulation region) [34].

As an approximate solution (10) of the equation (7) with the boundary conditions (8) the authors of [34] consider the result of the competition between two channels through which cosmic rays get into the inner heliosphere illustrated in the upper panel of Fig. 6: the radial and latitudinal ones, both determined by the drift of the particles. The solutions of the ordinary
Figure 6. The upper panel: the sketch of the allowed (arrows) and prohibited (Do Not Enter sign) channels through which the GCRs get to the Earth for different HMF’s polarity (the signs above) in [34]. The lower panel: the time profile of the calculated in [34] GCR intensity ($I(t)$) for the idealized sunspot cycle (the sunspot number $W(t)$) and both HMF’s polarity, shown in the upper panel. $T_+, T_-$ are the widths of time profile for corresponding A–polarity.

Differential equations for each channel (11–12) are derived analytically:

$$
\Psi_{approx} = \frac{||\Psi_x|||\Psi_\lambda|}{|\Psi_x| + |\Psi_\lambda|}
$$

$$
\Psi_x = (\gamma + 2)\frac{V_{sw}}{v}qB_{r,E}E U_{nm} \left( -\frac{\lambda}{\eta} - \frac{A}{2} \right)
$$

$$
\Psi_\lambda = A(\gamma + 2)\frac{V_{sw}}{v}qB_{r,E}E U_{nm} \left[ -\frac{4(\eta^2 + 1)}{4\eta^2 + 1} + 1 + \frac{1}{\eta(\eta^2 + 1)}e^{-A\eta\pi} \right]
$$

Using also the simplified model of the solar cycle in the HMF (13) the authors of the base model get the simple description of the intensity depending only on $\eta$ as the relative degree of the regularity of the HMF (14) which in turn depends only on the phase $\phi$ of the solar cycle (15). The only free parameter is the residual degree of the HMF’s regularity $\eta_0$ at solar minimum:

$$
B_{obs} = \sqrt{B_{reg}^2 + B_{turb}^2} \approx \text{Const}(t), \quad B_{turb} = B_{obs}(\phi + \frac{1}{\eta_0})
$$

$$
\eta = \frac{B_{reg}}{B_{turb}} \approx \text{Const}(x, \lambda)
$$

$$
\eta = \frac{\sqrt{1 - \phi^2}}{\phi + \frac{1}{\eta_0}}
$$
So the authors of [34] manage to describe the main feature of the magnetic cycle in the GCR intensity, the dependence of the width of the time profile on the magnetic fields polarity (the lower panel of Fig. 6), even with the flat current sheet, without changing its tilt. The authors of the base model can describe the main features of the time profiles of both the high-energy GRCs and, after some tuning of the model, also the medium-energy GCRs [36] during 1980–2000 with the free parameter $\eta_0 = 5$. Moreover, also changing a little their model they can describe in general the annual wave in the cosmic ray intensity near the Earth as due to the small but permanent shift of the HCS to the south [37]. So the authors of the base model consider their model as the real base which after some adaptation can be used to describe the main effects in the long-term GCR intensity in the heliosphere.

As to the GCR behavior in the anomalous period (2000–2010) during the last few years some works [39, 40, 36] were published on the modeling and understanding this complex phenomenon, but in our opinion this aim has not been achieved yet. So the anomalous behavior of the GCRs and ACRs in the 2000s still poses the challenge to understanding the sunspot and magnetic cycles in their intensity.

![Figure 7](image.jpg)

**Figure 7.** The time profiles of the He intensity, 18–27 MeV/n, measured aboard Voyagers–1, 2, and their coordinates for 1980–2012. Outside the solar maximum this energy range is dominated by the ACR He. The meaning of the shaded vertical bands and the legends above the panels is the same as in Fig. 1. In panel (a) the intensity time profiles are shown for Voyager–1 (red, solid) and Voyager–2 (blue, dotted) [38]; (b) the heliocentric coordinates: radial distance of the Voyager–1 (red, dotted) and Voyager–2 (blue, dashed) and latitude of the Voyager–1 (red, dot–dashed) and Voyager–2 (blue, three–dots–dashed).
Now a few words on the main cause of the decrease in the ACR intensity near the Earth in 2009–2010 when compared with 1987 [28]. Probably, it could be the consequence of the unusually low radial component $B_r$ of the solar and heliospheric magnetic field during the last solar minimum (see Fig. 1, b, d), as the potential difference between the pole and equator (and hence the maximum ACR energy, if they are accelerated as they drift along the termination shock, see [41]) is proportional to $B_r$, similar to (9). Moreover, the intriguing fact of the opposite change in the ACR intensity aboard Voyager–1 (the N–hemisphere) and Voyager–2 (the S–hemisphere) in the heliosheath in 2010–2012 (see Fig. 7) can also bear on the opposite behavior of the solar polar fields in the N– and S–hemispheres in 2009–2012 (see Fig. 1, b) for the same reason. Namely, the fast decrease in the ACR intensity aboard Voyager–1 corresponds to the decrease in the strength of the north polar magnetic field (and its reversal in the middle of 2012), while the steady increase in the ACR intensity aboard Voyager–2 as it progresses through the heliosheath corresponds to the steady strength of the south polar magnetic field.

As to the specific acceleration mechanism for the ACR, one of us, Mikhail Krainev, still believes that the latitude-dependent potential difference (9) between the inner point of the heliosphere and the infinity and the corresponding ”external” modulation of the GCR intensity can also bear on the ACR appearance (see [42, 43]). Note that one of our coauthors, Yury Stozhkov, has his own quite different opinion on the source of the anomalous component [44].

4. Conclusions
1. The main features of the normal sunspot and magnetic cycles in the GCR intensity are known in the first approximation although the time profiles are studied only near the Earth in the inner low-latitude heliosphere, which is rather special region.
2. The detailed models have been developed that describe the main observed long-term GCR intensity variations. However, to achieve this aim the properties of the high-latitude heliospheric magnetic field and field-particle interaction should be rather unusual. Moreover, the time behavior of the heliospheric characteristics in different parts of the heliosphere should follow that near the Earth.
3. In these circumstances the other ways to model and understand the normal sunspot and magnetic cycles in the GCR intensity could be explored (such as the base model of the Yakutsk group).
4. The anomalous behavior of the GCRs and ACRs in the 2000s poses the new challenge to understanding the sunspot and magnetic cycles in their intensity.

Acknowledgments
This work was supported by the Russian Foundation for Basic Research (grants 12-02-1007k, 11-02-00095a, 10-02-00326a, 12-02-00215a, 10-02-00877-a, 12-02-98506-r_est-a, 12-02-98507-r_est-a), the Program ”Fundamental Properties of Matter and Astrophysics” of the Presidium of the Russian Academy of Sciences, the Program No. 10 of the Presidium of the Russian Academy of Sciences, grant No. NSH-1741.2012.2 from the President of Russia for support of leading scientific schools and the Department of Federal Target Programs and Projects (Grant No. 8404).

References
[1] Moraal H 1976 Space Sci. Rev. 19 845–920
[2] Parker E N 1958 Phys. Rev. 110 1445
[3] Krymsky G F 1964 Geomagnetism and Aeronomy 4 977–985 (in Russian)
[4] Jokipii J R, Levy E H and Hubbard W B 1977 Astrophysical Journal 213 861–861
[5] Schulz M 1973 Ap. Space Sci. 24 371
[6] Ahluwalia H S 1979 Proc. 16th ICRC 12 182–186
[7] Jokipii J R and Thomas B 1981 Ap.J. 243 1115–1122
