On the description of the 11- and 22-year cycles in the GCR intensity

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Abstract. The time profiles of the galactic cosmic ray intensity near the Earth are considered. We try to reproduce the main features of these profiles by solving the usual boundary–value problem with the transport equation and rather simple models of its coefficients. Only the "normal" 22-year cycle consisting of the pair of the successive 11-year cycles in the GCR intensity (1980-2000) is discussed. Besides, we suggest the method to decompose the intensity into the partial "intensities" connected with the main physical processes.

1. Introduction
The GCR intensity near the Earth has been measured by different methods for more than 70 years. The main features of its time behavior, both similar for the successive cycles characterized by different polarity $A$ of the heliospheric magnetic field (HMF) (11y cycle) and the different for them (22y cycle), are well–known. We call two successive cycles the "normal" pair if the solar and heliospheric characteristics are typical and similar in both cycles (except for $A$). In the accompanying paper [1] the model is formulated and the observations of the GCR intensity during the normal pair of the successive minima between the solar cycles (SC) 21/22 (1987, $A < 0$) and 22/23 (1997, $A > 0$) are approximated by solving the GCR modulation boundary–value problem. In this paper using the same model we try to reproduce the main features of time profile of the GCR intensity in 1980–2000. Besides we suggest a simple method to decompose the calculated intensity into the parts (we call them the partial "intensities") connected with the main physical processes.

2. Time profiles of the GCR intensity in 1980–2000
The sets of the parameters of the transport equation coefficient models used for approximating the observed distribution of the GCR intensity in the normal pair of solar minima 21/22 and 22/23 are described in [1]. To imitate the time dependence of the intensity near the Earth we used the same sets making some of the parameters constant, while the other, the radial component of the regular HMF near the Earth $B_{r,E}$, the tilt $\alpha_t$ of the heliospheric current sheet (HCS), the parallel diffusion coefficient (for $B_{hmf} = 5$ nT and $R = 1$ GV, see [1]) $K_0^\parallel$, and the solar wind velocity $V_{sw}$ changed in very simple way during two solar cycles: the first three parameters varied harmonically between their values in maxima and minima of the cycles and the solar wind velocity latitude profiles were determined by the tilt with the same $V_{sw,eq}$ and $V_{sw,pol}$ as in [1]. The time behavior of the postulated $B_{r,E}, K_0^\parallel, \alpha_t$ and the calculated proton
intensity at \( r = 1 \) AU, \( \vartheta = 86 \) deg and \( T = 200 \) MeV are shown by the solid red curves in the panels (a–d) of Fig. 1. The solid black line in the panel (d) shows the calculated intensity with \( A = 0 \) (the sunspot component of the intensity, \( J_{\text{ss}}^\text{calc} \), see [1]).

It can be seen that even such simple imitation of the time dependence of the GCR intensity reproduces by and large the main feature of the observed 11y and 22y variations: the different forms of the intensity time profile for \( A > 0 \) and \( A < 0 \) sunspot minima. Note that the other important features, the variation of the maximum intensity from one minimum to another and change of the sense of this variation at the ”crossover” energy \( R_{\text{obs}}^{\text{co}} \approx 10 \) GV, were ensured by the sets of parameters chosen for the solar minima [1]. The main cause of the sensitivity of the form of the time profile of the GCR intensity to the polarity \( A \) of HMF is the different direction of the magnetic drift velocity along HCS for \( A > 0 \) and \( A < 0 \). It should be expected from the sets of parameters chosen in [1] for approximating the GCR distributions in the solar minima as the main feature of both sets is that some of the characteristics (the relative perpendicular diffusion coefficient in the latitudinal direction \( \alpha_{\vartheta} \) and the parameter \( \delta_{JK} \), modifying the Parker HMF) are large in the high–latitude (\( \vartheta < 45 \) deg) heliosphere and much smaller at lower latitudes. The reasons why we made this choice is that the propagation of the particles should be more diffusive in the polar region but at low latitudes the magnetic drift should play important role in order to allow for the sensitivity of the form of the intensity time profiles to tilt as in initial works on this effect [5, 6].

Beside the main run (solid red and black curves), when \( K_0^\parallel \) and \( V_{\text{sw}} \) changed in the described way, two more cases were calculated: 1) \( V_{\text{sw}} \) varied as before but \( K_0^\parallel \) did not varied from one

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**Figure 1.** 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 ([2], blue) and that used in calculations (red); (b) the parallel diffusion coefficient \( K_0^\parallel \) at \( B_{\text{hm}} = 5 \) nT and \( R = 1 \) GV (see [1]) used in different runs of calculations (see text); (c) the observed ([3], classic, blue) and used for calculations (red) tilt of HCS; (d) the observed near the Earth ([4], blue) and the calculated in different runs (see text) proton intensities (\( T \approx 200 \) MeV) with the real \( A \) (red) and with \( A = 0 \) (black).
Figure 2. The energy dependence of the intensity gradients and terms of eq. (2) in the minima of solar cycle. The red solid lines are for \((A > 0)\)– and the blue dashed lines for the \((A < 0)\)– minima while the black dotted curves show the quantities calculated for \(A = 0\). The panels (a) and (b) show the radial and colatitudinal gradients of the intensity, while in the panels (c), (d), and (e) the diffusion, drift and convection terms of eq. (2) are shown, respectively.

Figure 3. The energy dependence of the partial “intensities” in the minima of solar cycle with \(A > 0\) (panel (a), red lines) and \(A < 0\) (panel (b), blue lines) near the Earth. The black dashed curves are for the unmodulated spectra and the black solid ones are for the initially calculated \(J(\vec{r}_0, T)\) for both polarity. The dotted color lines are for diffusion partial “intensity”, while the dashed and dash–dotted ones show the drift and convection partial “intensities” (both multiplied by 5). The dash–dot–dot–dotted curves are for the adiabatic–loss partial “intensity”.

solar maximum to the next and at maximum changed abruptly to its level corresponding to the next solar minimum (the dotted red and black lines in the panels (b) and (d) of Fig. 1); and 2) the latitudinal dependence \(V_{sw}\) also did not changed and all the time was corresponding to the solar minimum (the dashed red and black lines in the panel (d)). It can be seen that switching off the change of \(K^0_{\parallel}\) and \(V_{sw}\) with the solar cycle makes the forms of the time profiles of the GCR intensity around \(A > 0\) and \(A < 0\) solar minima more similar (i. e., less corresponding to
One can also see that during almost all the time the black curves in Fig. 1 (d) lie much lower than the red ones. It means that in the framework of the models used for calculations the magnetic component of the intensity $J_{m}^{\text{calc}}$ is greater than its sunspot component $J_{ss}^{\text{calc}}$ not only in minima of solar cycle [1] but during almost all solar cycle (except for 2–3 years around maxima).

3. Partial GCR intensities relevant to different physical processes

Like in [1] in the process of solving boundary problem we tried to make use of the intermediate results. Here we used the "zero–test", when after each step in energy we recalculated each term of the transport equation to be sure that their sum is small (see [7]). We memorized the terms at some space location ($\vec{r}_0$) for each step in energy and then reconsidered the usual partial transport equation (1) as the ordinary equation (2) for $U_{dcd}$, the sum of the partial distribution functions in $\vec{r}_0$ connected with the diffusion, convection, and drift, with the "initial" condition (3):

$$0 = \nabla (K \nabla U) + \nabla \mathbf{v} \cdot \nabla \nabla U + \nabla \mathbf{V} \cdot \nabla U - \frac{\nabla \mathbf{V} \cdot \nabla U}{3} \rho \frac{\partial U}{\partial \rho}$$  \hspace{1cm} (1)

$$\frac{dU_{dcd}(\vec{r}_0, \tau)}{d\tau} = T_{\text{diff}}(\vec{r}_0, \tau) + T_{\text{conv}}(\vec{r}_0, \tau) + T_{\text{drift}}(\vec{r}_0, \tau), \hspace{1cm} \tau = \ln \frac{p_{\text{max}}}{p}$$  \hspace{1cm} (2)

$$U_{dcd}(\vec{r}_0, \tau)|_{\tau=0} = U_{\text{um}}(p_{\text{max}})$$  \hspace{1cm} (3)

$$J_{dcd}(\vec{r}_0, \tau) = J_{p}^{\text{diff}} + J_{p}^{\text{conv}} + J_{p}^{\text{drift}} + J_{\text{um}}(p_{\text{max}})$$  \hspace{1cm} (4)

Then integrating (2–3) and converting from the distribution functions to the intensities we get $J_{dcd}(\vec{r}_0, \tau)$ (4) and adding to it the partial "intensity" connected with the adiabatic loss, $J_{p}^{\text{adiab}} = J_{\text{calc}} - J_{dcd}$, we have the decomposition of the calculated intensity into the partial "intensities" pertaining to the main physical processes: $J = J_{p}^{\text{diff}} + J_{p}^{\text{conv}} + J_{p}^{\text{drift}} + J_{p}^{\text{adiab}}$. The Figs. 2 and 3 illustrate the energy dependence, respectively, of the gradients and different terms of (2) and of the partial "intensities" near the Earth ($r=1$ AU, $\vartheta=86$ deg) in the minima of solar cycle. Of course, one can further decompose the diffusion partial "intensity" into those connected with the diffusion parallel and perpendicular (in both directions) to the regular HMF and the same can be done with the drift "intensity". Moreover, it can be easily done for each phase of the solar cycle. We believe that this method can help in understanding the behavior of the GCR intensity in the heliosphere.

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