The formation of the sunspot and magnetic cycles in the GCR intensity in the heliosphere

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Abstract. We compare the different approaches (observational and theoretical) to the definition and separation of the GCR intensity variations due to the changing number and area of sunspots (the sunspot cycle) and the changing polarity of the high-latitude solar magnetic fields (the magnetic cycle). Using the theoretical approach we can consider how both types of the GCR intensity variations change with energy in different parts of the heliosphere during the minima of the sunspot cycle and their relative weights in the calculated intensity.

1. Introduction
When we discuss the long-term variations in the galactic cosmic ray (GCR) intensity in this paper we use terms sunspot and magnetic cycles as referring to the causes on the variations due to the changing sunspot area and the polarity of the high-latitude solar magnetic field, respectively. Usually these variations are called 11–year and 22–year variations, but here we are interested not in the time behavior of the GCR intensity but in its change with the position and energy in the minima of solar cycle (SC). The GCR intensity time behavior is considered in the accompanying paper [1]. In [2] we discussed how two type of the GCR intensity variations can be isolated using the observations and calculations, then tried to describe the observations during two normal consecutive minima of solar activity and studied the space and energy distributions of the intensity. By a normal pair of the sunspot minima we mean the minima of two successive cycles when the Sun and the heliosphere behaved typically and similarly in different characteristics and differed mainly by the polarity \( A \) of the heliospheric magnetic field (HMF). In the first approximation we can consider the minima between SC 21/22 (\( A < 0 \)) and 22/23 (\( A > 0 \)) as such a pair for the second half of the 20–th century. In this paper we discuss the same questions as in [2] but using much better description of the GCR observations during normal solar minima.

2. Observations of the sunspot and magnetic cycles in the GCR intensity
It is well–known that the sunspot cycle manifests itself, beside the active regions, in the strength of the HMF, the width of its sector zone and also in many parameters of the solar wind, so that it also can be called the "energetic" cycle. The magnetic cycle shows itself only in the change of the mean polarity \( A \) of the HMF and of its helicity [3]. In the inner heliosphere the GCR intensity shows both the sunspot cycle (the general change in the opposite phase with the sunspot area) and the magnetic cycle (the different forms of the time profiles and the levels of the maximum intensity during successive solar minima, and the different latitudinal gradients
of the intensity). In the intermediate and outer heliosphere the radial gradient of the GCR intensity during minima of the solar cycle also demonstrates the magnetic cycle. It is usually believed that the more powerful solar sunspot cycle produces the greater part of change in the GCR intensity while the magnetic cycle causes only small variation of the intensity. Then one can estimate the maximum intensity due to the sunspot cycle as $J_{ss}^{obs} = (J_+ + J_-)/2$ and the magnetic cycle in the GCR intensity as $J_{m}^{obs} = (J_+ - J_-)/2$, where $J_+$ and $J_-$ are the maximum GCR intensities during the A–positive and A–negative minima of solar activity, respectively. Then the relative contribution of the magnetic cycle can be estimated as $\delta_m^{obs} = J_m^{obs} / J_{ss}^{obs} * 100\%$ and at the Earth’s orbit $\delta_m^{obs} \approx 3 – 30\%$, the amplitude and phase of the magnetic cycle being dependent on the charge’s sign and energy of the particle (for protons the ”crossover” rigidity where the phase of the magnetic cycle changes to opposite, $R_{co}^{obs} \approx 7 – 10$ GV), while in the outer heliosphere $\delta_m^{obs} \approx 30 – 50\%$ [4, 5].

The drawbacks of such a definition of the sunspot and magnetic cycles in the GCR intensity are evident: 1) it is impossible to estimate the amplitude of the particular sunspot cycle in the GCR intensity as it is necessary to know also the maximum intensity during the previous or following solar minimum (which can be anomalous as the minimum between SC 23/24 [6]); 2) the observations cover only small part of the heliosphere and not the whole range of the GCR energy; and the main drawback of such a definition is that 3) it is based on the strong assumption that the main part of the change in the GCR intensity is due to the solar sunspot cycle and the direct contribution of the latter is unobservable as in nature it is impossible to switch off the HMF mean polarity. However, it is possible to do so as well as to calculate the GCR intensity in the whole heliosphere and for all energies in calculations of the intensity. What one needs are the reliable theory and the reliable model of the heliosphere.

3. Description of the observed GCR intensity in the normal solar minima

Now the observed GCR intensity $J(\vec{r}, T, t)$ in steady case is usually described using the differential boundary–value problem for the distribution function $U(\vec{r}, p, t) = J(\vec{r}, T, t)/p^2$, formulated mainly in [7, 8, 9]:

$$-\frac{\partial U}{\partial t} = -\nabla(K \nabla U) + \vec{V}_{sw} \nabla U - \frac{\nabla \vec{V}_{sw}}{3} \frac{\partial U}{\partial p} + \vec{V}_{dr} \nabla U = 0$$ (1)

with the usual boundary conditions and the ”initial” condition $U|_{p=p_{max}} = U_{um}(p_{max})$ where $p$ and $T$ are the momentum and kinetic energy of the particles; $p_{max} \approx 100$ GeV/c and $U_{um}$ is the distribution function of the unmodulated GCRs; $\vec{V}_{sw}$ and $\vec{V}_{dr}$ are the solar wind and drift velocities, respectively; and $K$ is the diffusion tensor with components along the regular HMF, $K_\parallel$, and across it in the radial, $K_{\perp r}$, and latitudinal, $K_{\perp \vartheta}$, directions. From these coefficients only $\vec{V}_{dr}$ and $K_\parallel$ directly depend on the HMF polarity $A$. Beside finding the solution $J_{+/-}(\vec{r}, T)$ of the boundary–value problem (1), reflecting the real situation in some phase of solar cycle (i. e. with given solar wind velocity, HMF with preferred polarity $A = +1/-1$ etc.), one can also solve the problem with the same heliospheric characteristics but with $A = 0$. We suggest that the latter solution $J_0(\vec{r}, T)$ can be considered for this phase as the (unobservable in reality) intensity component $J_{ss}^{calc}$ due to the solar sunspot cycle. Then we can consider $J_{m}^{calc} = J_{+/-}(\vec{r}, T, t) - J_{ss}^{calc}$ as the GCR intensity component due to the solar magnetic cycle and $\delta_m^{calc} = J_{m}^{calc} / J_{ss}^{calc} * 100\%$.

As here we are interested in the GCR intensity components during the normal minima of solar cycle SC 21/22 (1987, $A < 0$) and SC 22/23 (1997, $A > 0$), to use the above method we should describe the GCR observations for these periods, then calculate $J_0(\vec{r}, T)$ and form the sunspot and magnetic components of the intensity. In Fig. 1 the distributions of both observed...
and calculated GCR protons are shown for the above solar minima. It can be seen that the calculated intensities rather closely describe the observed ones.

**Figure 1.** The observed and calculated distributions of the GCR protons during solar minima 21/22 and 22/23. The red squares and dotted curves are for the observed [10] and calculated intensity for \( A > 0 \), while the blue triangles and dot-dashed curves are for \( A < 0 \). The black solid curves show the calculated intensity for \( A = 0 \). In the panels: (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 are shown. The energy spectra are divided into two panels: (c) for \( T < 1000 \) MeV and (d) for \( T > 1000 \) MeV to show in greater details the spectra around crossover \( T_{co} \approx 9900 \) MeV (shown by the star in (d)). The black dashed lines are for the unmodulated spectrum.

In the calculations we used the following parameters: the parallel diffusion coefficient (at \( B_{hm\parallel f} = 5 \) nT and \( R = 1 \) GV), \( K^0_0 \), was equal to 4, 16, and 10 for \( A > 0 \), \( A < 0 \), and \( A = 0 \) cases, respectively, and \( K_{\perp R} = 0.005 K_0 \parallel \) (all in \( 10^{21} \) cm\(^2\)/s). The general expression for the parallel diffusion coefficient was used, \( K_\parallel = K^0_0 \\cdot \frac{5}{B_{hm\parallel f} \cdot f(R)} \), with simple \( f(R) \) as in [11]. Besides, \( K_{\perp \vartheta} = \alpha_{\perp \vartheta} \cdot K_\parallel \) near the Earth \( B_{r,E}(\vartheta) = 3.5 \) nT and the form of the HMF lines corresponded to Parker HMF \( B_P \), but \( B_{hm\parallel f} \) was modified according to [12], \( B_{hm\parallel f} = B_P \cdot (1 + r^2 \cos^2 \vartheta \cdot \delta_{JK})^{0.5} \), and both \( \alpha_{\perp \vartheta} \) and \( \delta_{JK} \) were made high at \( \vartheta < 45 \) deg (\( \alpha_{\perp \vartheta} = 0.29 \) and \( \delta_{JK} = 0.12 \)) and small at lower latitudes (\( \alpha_{\perp \vartheta} = 0.03 \) and \( \delta_{JK} = 0 \)) using the hyperbolic tangent latitude dependence as in [13]. The solar wind velocity \( V_{sw} \) also depended on \( \vartheta \) in the same way, changing from \( V_{sw, eq} = 450 \) km/s at low latitudes to \( V_{sw, pol} = 800 \) km/s for \( \vartheta < 90 - \alpha_t \), where \( \alpha_t = 10 \) deg is the tilt angle. The simple model for the regular and current sheet drift velocities (as in [14]) was used.

4. Distribution of the GCR components for the solar sunspot minima

In the process of solving boundary–value problem (1) one can consider the space distribution of the intensity for each step in energy and study how this distribution changes the energy. In Fig. 2 \( \delta_m^{calc} \) is shown as function of \( r, \vartheta \) in the whole heliosphere in the solar minima with \( A > 0 \) and \( A < 0 \) for the protons with \( T \approx 200 \) MeV. At the highest energy studied, \( T \approx 100 \) GeV, the intensity for \( A > 0 \) is by a fraction of percent lower and for \( A < 0 \) higher than for \( A = 0 \) in accordance with the different \( K^0_0 \). However, as the energy decreases the contribution of the magnetic component grows for both polarities and near the Earth for the neutron monitor energies (\( T \approx 15 \) GeV) \( \delta^{calc}_m \approx 25 \% \) for \( A > 0 \) and \( \delta^{calc}_m \approx 20 \% \) for \( A < 0 \) (not shown). As can be seen in Fig. 2 for the energies typical for the spacecraft (\( T \approx 200 \) MeV) \( \delta^{calc}_m \approx 300 \% \) for \( A > 0 \) and \( \delta^{calc}_m \approx 200 \% \) for \( A < 0 \) and it is positive almost in the whole heliosphere except near the outer boundary. It means that in the framework of the model used the above assumption that the main part of the change in the GCR intensity is due to the solar sunspot cycle is wrong.
and near the Earth the much greater part of the calculated intensity is due to the magnetic cycle.

![Figure 2](image.png)

**Figure 2.** The distribution in the heliosphere of the relative contribution of the magnetic component of the GCR intensity $\delta_{\text{calc}}$ for the solar minimum with $A > 0$ (the left square panel) and $A < 0$ (the right square panel) for $T \approx 200$ MeV. The correspondence between the color and the value and sign of $\delta_{\text{calc}}$ is indicated in the narrow right panel.

As to the understanding of the above features, it is essential that when the sunspot cycle in the GCR intensity is being formed, its space and energy distribution is formed as the result of the balance between the divergences of the diffusion and energy–loss fluxes, while turning–on the magnetic drift changes the above balance, so that the gradients of the intensity significantly change and this change is different in different parts of the heliosphere. In the inner part of the heliosphere these changes increase the intensity for both HMF polarities, and the effect accumulates as the energy decreases.

So if one defines the magnetic component in the GCR intensity as the difference between the full intensity and that formed by only the sunspot activity, then in the framework of the heliospheric model used the magnetic cycle in the GCR intensity for the low energy GCR in the inner heliosphere is the most powerful large–scale variation. Then the evident opposite behavior of the sunspot area and the GCR intensity is in the large measure the result of the drifts and not only of the diffusion, convection and adiabatic energy loss.

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