The features of the rigidity spectrum of the long-period variations of the galactic cosmic ray intensity in descending and ascending epoch of solar activity (2003-2012)

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Abstract:
Data of super neutron monitors have been used to study the features of the temporal changes of the rigidity spectrum of galactic cosmic rays (GCR) intensity long-period variations in descending and ascending epoch of solar activity (2003-2012). They were found the changes of the rigidity spectrum exponent $\gamma$ of GCR intensity variations from 2003 to 2012. We expect that the soft rigidity spectrum ($\gamma$=1.2-1.5) of the GCR intensity variations for the maximum and near maximum epoch and the hard spectrum ($\gamma$=0.4-0.6) for the minimum and near minimum epoch of solar activity is the universal feature of GCR modulation in the energy range of 5-50 GeV to which neutron monitors respond. Thus, the different values of $\gamma$ in above period shows, that during the descending and ascending epoch of solar activity radical changes, of the largescale structure of the interplanetary magnetic field turbulences must take place. We demonstrate that the rigidity spectrum exponent $\gamma$ of the long period variations of the GCR intensity variations should be considered as an important index to study the 11-year variations of the GCR intensity.

Keywords: turbulence of IMF, rigidity spectrum of the GCR, Power Spectrum Density

1 INTRODUCTION
The rigidity R spectrum $\frac{\delta D(R)}{\delta R}$ of the 11-year variations of the GCR intensity has a power law character with the exponent $\gamma$, as in [1]. $\frac{\delta D(R)}{\delta R} = A \cdot R^{-\gamma}$ where A is the power of the rigidity spectrum. In previous papers [2-5] there was shown temporal changes of the power law rigidity spectrum of the long period variations of the galactic cosmic ray (GCR) intensity for long period 1960-2002. It was found that the soft rigidity spectrum ($\gamma$=1.2-1.5) of the galactic cosmic ray intensity variations for the maximum epoch and the hard rigidity spectrum ($\gamma$=0.5-0.7) for the minimum epoch found based on the neutron monitors experimental data (1960-2002) are related with the various dependence of the diffusion coefficient on the GCR particles rigidity for different epoch of solar activity. This dependence is stronger in the maximum epoch than in the minimum epoch of solar activity, and is provided by the essential temporal rearrangements of the structure of the interplanetary magnetic field (IMF) turbulence from the maxima to minima epoch of solar activity. For the diffusion-convection approximation the exponent $\gamma$ of the rigidity R spectrum $\frac{\delta D(R)}{\delta R} \propto R^{-\gamma}$ of the GCR intensity variations generally is determined by the parameter $\alpha$($\alpha \propto \gamma$) [1, 2] showing the character of the dependence of the diffusion coefficient $\chi$ on the rigidity R of GCR particles ($\chi \propto R^{\delta}$) [3, 4]. [5, 6] The parameters $\alpha$ and $\nu$ are related as, $\alpha = 2 - \nu$ ($\nu$ is the exponent of PSD of the IMF turbulence ($PSD = P \cdot f^{-\nu}$, where P is power and $\nu$ is the frequency). A purpose of this paper is continuation of the calculations of the temporal changes of the rigidity spectrum exponent $\gamma$ of the GCR intensity variations using neutron monitors data for the descending and ascending phases of solar activity (2009-2012) and confirmation of the universal character changes in different epoch of solar activity and the role of IMF turbulence in the formation of the 11-year variation of the GCR intensity.

2 EXPERIMENTAL DATA, METHODS AND DISCUSSION
We use the thoroughly selected monthly average data of neutron monitors for descending (2003-2009) and ascending epoch (2009-2012) of solar activity. A criterion for the data selection was continuously function of neutron monitors with different cut off rigidities throughout the period to be analyzed. The magnitudes $J_{i}^{\nu}$ of the monthly average variations of the GCR intensity for $i$ neutron monitor were calculated, as: $J_{i}^{\nu} = \frac{N_{i} - N_{0}}{N_{0}}$; $N_{i}$ is the running monthly average count rate ($k = 1, 2, 3,..., months$) and $N_{0}$ is the monthly average count rate for the year of the maximum intensity (in the minimum epoch of solar activity). The count rate of the maximum intensity is accepted as the 100% level; the year of maximum intensity is called a reference point (RP). The list of neutron monitors used for the calculations (denoted by +) and RP for the period to be analyzed are brought in Table 1. The magnitudes $J_{i}^{\nu}$ of the monthly average variations of the GCR intensity measured by $i$ neutron monitor with the geomagnetic cut off rigidity $R_{i}$ and the average atmospheric depth $h_{i}$ are defined as [11]: $J_{i}^{\nu} = \int \frac{\delta D(R)}{\delta R} k \cdot W(R, h_{i}) dR$, where $(\frac{\delta D(R)}{\delta R})_{k}$ is the rigidity spectrum of the GCR intensity variations for the $k$ month; $W(R, h_{i})$ is the coupling coefficient for the neutron component of GCR [11] and $R_{\text{max}}$ is the upper limiting rigidity beyond which the magnitude of the GCR intensity variation is vanished. For the power law rigidity spectrum $(\frac{\delta D(R)}{\delta R})_{k} = A \cdot R^{-\alpha}$ one can write:
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\[ J_i = A_i^k \int R^{-\gamma} \cdot W_i(R, h_i) dR, \]

where \( J_i \) is the observed magnitude at given month \( k \) and \( A_i^k \) is the magnitude of the GCR intensity variations recalculated to the heliosphere. The values of the \( A_i^k \) are the same (in the scope of the accuracy of the calculations) for any \( i \) neutron monitor when the pairs of the parameters \( \gamma_i \) and \( R_{\text{max}} \) are properly determined. \( A_i^k \) is defined as \( A_i^k = J_i^k \int R^{-\gamma} \cdot W_i(R, h_i) dR \n\). A similarity of the values of the \( A_i^k \) for various neutron monitors is an essential argument to affirm that the data of the particular neutron monitor and the method of the calculations of \( \gamma_i \) are reliable. To find the temporal changes of the rigidity spectrum exponent \( \gamma_k (k = 1, 2, 3, ..., months) \) a minimization of the expression \( \phi = \sum (A_i^k - A_i^k)^2 \) (where \( A_i^k = \frac{1}{n} \sum A_i^k \) and \( n \) is the number of neutron monitors) has been provided [13]. The values of the expression \( \int R^{-\gamma} \cdot W_i(R, h_i) dR \) for the magnitudes of \( R_{\text{max}} \) (from 30GV up to 200GV with the step of 10GV) and \( \gamma \) (from 0 to 2 with the step of 0.05) were found based on the method presented in [11, 12]. The upper limiting rigidity \( R_{\text{max}} \), beyond which the magnitude of the GCR intensity variation is vanished, equals 100GV. This assumption is a reasonable for the 11year variation of the GCR intensity [13]. A minimization of the expression \( \phi \) for the smoothed monthly means (with the interval of 13 months) of the magnitudes of the 11year variation of the GCR intensity has been provided with respect \( \gamma_k \) for given number of neutron monitors (Table 1).

The changes of the for the smoothed monthly means (with the interval of 13 months) magnitudes \( J_i^k \) of the GCR intensity variations of Kiel neutron monitor data normalized with respect maximum intensity of 2009, the sunspot number \( W \) and the rigidity spectrum exponent \( \gamma_k \) are presented in Figure 1abc for the whole period of investigation (2003-2012).

<table>
<thead>
<tr>
<th>No</th>
<th>Station</th>
<th>( R_{\text{GV}} )</th>
<th>2003-2009</th>
<th>2009-2012</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Beijing</td>
<td>9.56</td>
<td>+</td>
<td>-</td>
</tr>
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<td>2</td>
<td>Hermanus</td>
<td>4.90</td>
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<td>+</td>
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<td>+</td>
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<td>+</td>
</tr>
<tr>
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<td>6.32</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>7</td>
<td>Sanae</td>
<td>1.06</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>8</td>
<td>Thule</td>
<td>0.00</td>
<td>+</td>
<td>+</td>
</tr>
</tbody>
</table>

Table 1: List of neutron monitors

On the Fig 1c shows the temporal changes of the rigidity spectrum exponent \( \gamma_k \) from maximum to minimum descending of solar activity 2003-2009) and from minimum to maximum (ascending of solar activity 2009-2012). In 2003-2004 rigidity spectrum is soft (0.92-1.10) then gradually becomes hard (in 20072008; \( \gamma \approx 0.13-0.06 \)). In period 20102012 rigidity spectrum quickly becomes soft (in 2010-12; \( \gamma \approx 1.09-1.50 \)) Very high correlation coefficients for descending (20032009) and ascending (20092012) periods of solar activity between the pairs: sunspot numbers \( W \) and GCR intensity \( J \), (\( W \& J \)), GCR intensity \( J \) and rigidity spectrum exponent \( \gamma \), (\( J \& \gamma \)), and sunspot numbers \( W \) and rigidity spectrum exponent \( \gamma \), (\( W \& \gamma \)) are presented in Table 2.

### 3 SUMMARY

1. We confirm that rigidity spectrum (\( \gamma \approx 1.1-1.5 \)) of the GCR intensity variations for the maximum epochs is soft and for the minimum epochs of solar activity (\( \gamma \approx 0.4-0.6 \)) is hard.

2. We believe that \( \gamma \) is the universal index based on the calculations of the continuous long period data (1960-2002) of neutron monitors. This phenomenon is observed owing to the essential rearrangement of the structure in the inertial and energy range (10-6 10-5 Hz) of the IMF turbulence throughout the 11-year cycle of solar activity.

Fig. 1: Fig.1abc. Time profiles of (a) the smoothed monthly means of the GCR intensity for Kiel Neutron Monitor; (b) the smoothed monthly means sunspot number and (c) the yearly means rigidity spectrum exponent \( \gamma_k \) for period 2003-2012.
This region of the IMF turbulence is responsible for the scattering of the GCR particles with the energy of 5-50 GeV to which neutron monitors are respond.

References