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27-day variations of the galactic cosmic ray intensity and anisotropy

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Abstract. We study the 27-day variations of the galactic cosmic ray (GCR) intensity and three dimensional (3-D) anisotropy in different polarity periods of the solar magnetic cycle. We found that the larger amplitudes of the 27-day variations of the galactic cosmic ray anisotropy and intensity in the minimum epochs of solar activity for the $A>0$ polarity period than for the $A<0$ period are related with the heliolongitudinal asymmetry of the solar wind velocity. We reveal the long - lived (~ 22 years) active region of the heliolongitudes being the sources of the long-lived 27-day variation of the solar wind velocity during the $A>0$ polarity period. The 27-day variation of the GCR 3-D anisotropy has a sporadic character; it appears and disappears as wave packages (wave oscillations) with an average duration of 4–6 solar rotations. We found that the rigidity R power law spectrum of the amplitudes ($A27$) of the 27-day variation of the GCR intensity ($A27 \propto R^{-\gamma}$) is hard ($\gamma=0.54\pm0.11$) in the $A>0$ polarity period (1996–1997) and is soft ($\gamma=0.95\pm0.12$) in the $A<0$ period (1986–1987).

1 Introduction

To study the 27-day variations of the GCR intensity and anisotropy the minimum epoch of solar activity is very useful. Throughout the minimum epochs of solar activity the disturbances in the interplanetary space are minimal and a polarity of the Sun's global magnetic field is well established. For this epoch the contribution of the drift effect of the GCR particles (due to gradient and curvature of the regular interplanetary magnetic field) can be revealed reasonably clearly in different classes of GCR variations; that is especially vital for the GCR variations with relatively small amplitudes, e.g. for the 27-day variation of the GCR anisotropy. The general purpose in this paper is: (1) to study a relationship of the 27-day variations of the GCR intensity and anisotropy with similar changes of the solar wind (SW) velocity, (2) to calculate the rigidity spectrum of the amplitudes of the 27-day variation of the GCR intensity for different polarity periods of solar magnetic cycle, and (3) to demonstrate that the 27-day variation of the GCR anisotropy appears and disappears as the wave oscillations with durations of the several solar rotations.

2 Experimental data

To study the relationship of the 27-day variations of the GCR intensity and anisotropy with the 27-day variation of the SW velocity for different polarity periods of solar magnetic cycle we use data of neutron monitors (1965–2003) and SW velocity (1975–2003) for the $A>0$ and $A<0$ polarity periods during the minimum and near minimum epochs of solar activity. The hourly values of the isotropic intensity I and the components (A_r, A_θ, A_φ) of the 3-D anisotropy of GCR have been calculated by the cosmic ray group of IZMIRAN using the global spherical method (GSM) (Belov et al., 2005, 1995; Krymsky et al., 1966, 1967) based on the experimental data of neutron monitors (http://cr20.izmiran.rssi.ru/AnisotropyCR/index.php).
We calculate daily average values of the isotropic intensity I and 3-D anisotropy components of GCR based on these hourly values. Then the amplitudes and phases of the 27-day variations of the GCR intensity and anisotropy and SW velocity were calculated by the harmonic analysis method for each Carrington rotation (CR) period (27 days) for the positive 1975–1977 and 1995–1997 ($A>0$), and for negative 1965–1967 and 1985–1987 ($A<0$) polarity periods of solar magnetic cycle. Figure 1a presents the heliolongitudinal distributions of the phases of the 27-day variations of the

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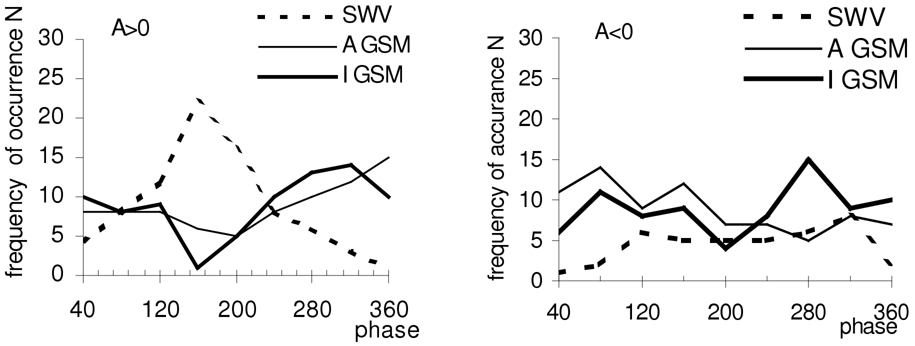

Fig. 1. Heliolongitudinal distributions of the phases of the 27-day variations of the SW velocity, GCR intensity (I GSM) and anisotropy (A GSM). On the ordinate axes are shown summary numbers N (frequency of occurrence) of the phases of the 27-day variations falling to the each heliolongitude interval of 40^0 for the $A > 0$ (a) and for $A < 0$ (b) polarity periods. On the horizontal axes are presented heliolongitudes in degrees.

SW velocity, GCR intensity and anisotropy by GSM for the $A > 0$ polarity periods (1975–1977 and 1995–1997). Figure 1b shows the changes of the same parameters (as in Fig. 1a) for $A < 0$ polarity periods (1965–1967 and 1985–1987). Data of all considered parameters for the $A > 0$ polarity periods consist of 6 years (~ 80 Carrington rotations). Data of the SW velocity are absent for 1965-1967 ($A < 0$). Figure 1a presents that the distributions of the phases of the 27-day variations of the GCR intensity and anisotropy, and that of the SW velocity have maxima. The 27-day variations of the GCR intensity and anisotropy appear to be in opposite phase with the variation of the SW velocity. Figure 1b shows that for the $A < 0$ polarity period there are no clearly recognizable regularities of the heliolongitudinal distributions of the phases of the 27-day variations for the considered parameters. This means that for the $A > 0$ polarity period a structure of the heliolongitudinal asymmetry of the interplanetary medium is more ordered than for the $A < 0$ polarity period. This reveals the long - lived (~ 22 years) active region of the heliolongitudes. A persistent dependence of the solar wind velocity and the radial component of the interplanetary magnetic field on heliolongitudes was shown in Neugebauer et al. (2000). Ruzmaikin and coauthors (Ruzmaikin et al., 2001) demonstrated that nonaxisymmetric magnetic field displays itself in preferred solar longitudes. The expression “preferred” refers to a coherent phenomenon, i.e. the activity tends to concentrate at some heliolongitudes for a time exceeding the rotation period of the Sun. The different structure of the heliolongitudinal asymmetry of the interplanetary medium for the $A > 0$ and $A < 0$ polarity periods should be pronounced in the features of the 27-day variations of the GCR intensity and anisotropy. From this point of view one can underline that the scattered distributions of the phases of the 27-day variations of the GCR intensity and anisotropy (Fig. 1b) for the $A < 0$ polarity period are one of the motivations to state that the amplitudes of the 27-day variations of the GCR intensity (Richardson et al., 1999; Gil and Alania, 2001) and anisotropy are less in the $A < 0$ polarity period than in $A > 0$ (Gil et al., 2005; Alania et al., 2005, 2008). The stable long-lived (~ 22 years) active heliolongitudes can be considered as the general source of the 27-day variations of the GCR intensity and anisotropy. As it was shown in a theoretical hybrid model by Burger and Hitge (2004) the Fisk heliospheric magnetic field can explain some properties of the 27-day cosmic ray variations. However, the amplitudes of the 27-day variation of the GCR intensity generated only by existence of the Fisk’s field are very small in the comparison with the experimental data, and there remains a general problem of the reality of the Fisk’s type heliospheric magnetic field in the minimum epochs of solar activity (Roberts et al., 2007).

Moreover, it is of interest how the power law rigidity spectrum of the amplitudes of the 27-day variation of the GCR intensity behaves in different the $A > 0$ and $A < 0$ polarity periods. The exponent γ of the power law rigidity spectrum

$$\frac{\delta D(R)}{D(R)} = \begin{cases} AR^{-\gamma} & R \le R_{\max} \\ 0 & R > R_{\max} \end{cases} \qquad (1)$$

of the 27-day variation of the GCR intensity was calculated by means of the amplitudes of the 27-day variation of the GCR intensity. The upper limiting rigidity $R_{\max} \le 100\,\mathrm{GV}$ is taken as the rigidity beyond which the 27-day variation of the GCR intensity vanishes. The details of this method are described in papers (Wawrzynczak and Alania, 2008, 2005). We consider two minimum epochs 1986–1987 ($A < 0$) and 1996–1997 ($A > 0$) of solar activity. Figures 2a and b show the changes of the amplitudes of the 27-day variation found by the harmonic analysis method for Moscow and Hermanus neutron monitors data during 1773–1791 Carrington rotations period of 1986–1987 and during 1907–1925 Carrington rotations period of 1996–1997. These figures present the corresponding temporal changes of the rigidity spectrum exponent γ (dashed lines) calculated using 9 neutron monitors (Apatity, Climax, Halekala, Hermanus, Irkutsk, Kiel, Moscow, Oulu, Rome) for both periods; there are plotted the average values of $\gamma \approx 0.95$ for 1986–1987 ($A < 0$) and $\gamma \approx 0.54$ for 1996–1997 ($A > 0$) by solid straight lines as well. Figures 2a and b show that for (a) 1996–1997 ($A > 0$) the rigidity spectrum is hard, average $\gamma \approx 0.54$ for 14 Carrington rotations, while for (b) 1986–1987 ($A < 0$) the rigidity spectrum is soft, the average $\gamma \approx 0.95$ for 16 Carrington rotations period. Thus, there is a distinction between the rigidity spectrum of the amplitudes of the 27-day variation

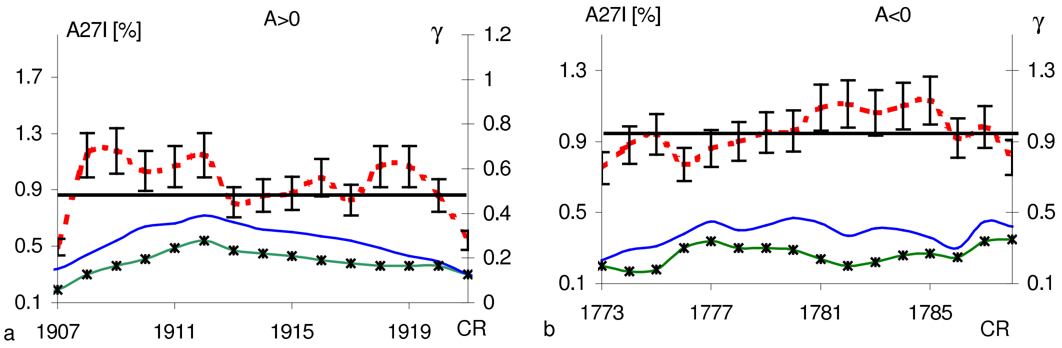

Fig. 2. Temporal changes of the amplitudes of the 27-day variation of the GCR intensity (values on the left axes) by Moscow (blue line), Hermanus (green line) neutron monitors data and changes of the rigidity spectrum exponent γ (values on the right axes, dashed red line) for the period **(a)** 1996–1997 ($A>0$) and **(b)** 1986–1987 ($A<0$) . The average value of $\gamma \approx 0.95$ for 1986–1987 ($A<0$) and $\gamma \approx 0.54$ for 1996–1997 ($A>0$) is plotted by straight lines. Vertical lines are the error bars.

of the GCR intensity for different polarity periods. For the $A>0$ period the structure of the heliolongitudinal asymmetry of the solar wind velocity is established clearer, than in the $A<0$ period (Alania et al., 2008). Besides, the directions of the solar wind velocity and drift velocity of the GCR protons coincide for the $A>0$ polarity period in contrary to the $A<0$ period. Thus, the more established regular structure of the heliolongitudinal asymmetry of the electromagnetic conditions in the interplanetary space for the $A>0$ period modulates relatively higher energy particles of the GCR rather than in the $A<0$ period. However, this result is obtained for specific periods and it cannot be considered as an universal statement.

Using the frequency filters method (Otnes and Enochson, 1972) we demonstrate some features of the 27-day variation of the GCR anisotropy for the sequence of the individual Carrington rotations in the $A>0$ and $A<0$ polarity periods. The frequency filters method decomposes a time series into frequency components. We use band pass filter characterized by two period (frequency) bounds and transmits only the components with a period (frequency) within these bounds. We investigate periodicity bound within 24–32 days (27–28 days in the middle) using daily radial and tangential components of the GCR anisotropy obtained by GSM for the period of 1975–1977 ($A>0$) and 1985–1987 ($A<0$). Results of the filtered daily radial component of the 3-D GCR anisotropy are presented in Figs. 3a and b for the period (a) of 1975–1977 ($A>0$) and (b) 1985–1987 ($A<0$). Figures 3a and b show that the 27-day variation of the daily radial component of the GCR anisotropy appears and disappears as the wave oscillations with various ranges of amplitudes and durations. An average duration of each wave package equals 4–6 solar rotations. Similar changes are observed for the tangential component of the 3-D anisotropy as well. Also, there is seen a clear regularity of the wave oscillations with various ranges of amplitudes and durations for the $A>0$ period.

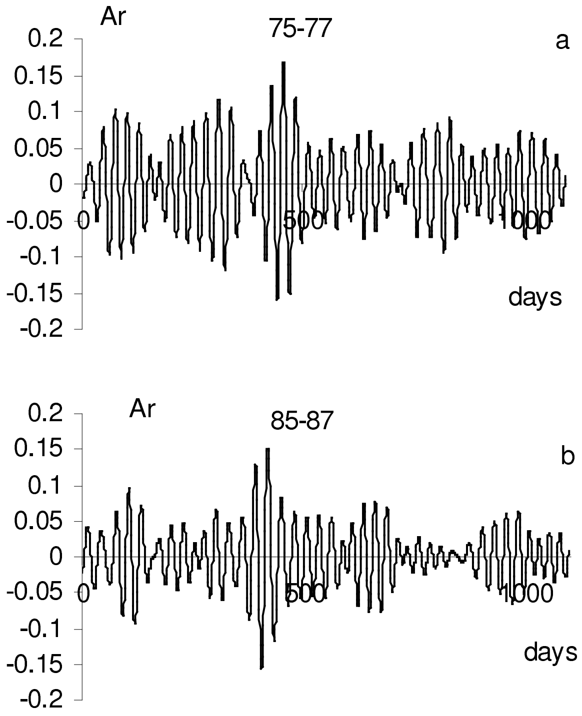

Fig. 3. Results of filtered daily radial component of the 3-D GCR anisotropy obtained by GSM for the period **(a)** 1975–1977 ($A>0$) and **(b)** 1985–1987 ($A<0$).

3 Conclusions

1. The stable long-lived (~ 22 years) active heliolongitudes exist on the Sun, especially for the $A>0$ polarity period of the solar magnetic cycle. It can be considered as a cause of the long-lived 27-day variation of the solar wind velocity, and afterwards, as the general

source of the 27-day variations of the GCR intensity and anisotropy.

2. A sporadic character of the 27-day variation of the GCR 3-D anisotropy is revealed. The 27-day variation appears and disappears as the wave oscillations with an average duration of 4–6 solar rotations for the both $A > 0$ and $A < 0$ polarity periods in the minima epoch of solar activity.

3. The rigidity spectrum of the 27-day variation of the GCR intensity is hard ($\gamma \approx 0.54 \pm 0.11$) for the $A > 0$ polarity period (1996–1997), and is soft ($\gamma \approx 0.95 \pm 0.12$) for the $A < 0$ polarity period (1986–1987) of the minimum epoch of solar activity. For the $A > 0$ period the structure of the heliolongitudinal asymmetry of the SW velocity is established clearer than in the $A < 0$ period. Besides, the directions of the solar wind velocity and drift velocity of the GCR protons coincide for the $A > 0$ period in contrary to the $A < 0$ period. Thus, the more established regular structure of the heliolongitudinal asymmetry of the electromagnetic conditions in the interplanetary space for the $A > 0$ polarity period modulates relatively higher energy particles of the GCR rather than in the $A < 0$ period. However, this result is obtained for specific periods and it can not be considered as an universal statement.

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