On the quasi-periodic variations of the galactic cosmic rays intensity and anisotropy in the lingering minimum of solar activity

A. Gil, R. Modzelewska, & M.V. Alania

***Abstract*— We study the 27-day quasi-periodic variations of the galactic cosmic ray (GCR) intensity and three dimensional (3-D) anisotropy related with the solar rotation in different polarity periods of solar magnetic cycle. We established that the larger amplitudes of the 27-day variations of the galactic cosmic ray intensity and anisotropy in the minimum epochs of solar activity for the $A > 0$ polarity period than for $A < 0$ polarity period are connected with the heliolongitudinal asymmetry of the solar wind velocity. We found that the long - lived (~22 years) active regions of the heliolongitudes are the sources of the long-lived 27-day variation of the solar wind velocity during the $A > 0$ polarity period. We compare results of calculation based on the data of the lingering minimum epoch of solar activity with our previous findings.**

1. Introduction

The minimum epochs of solar activity are characterised by the relatively quiet Sun, with a well established direction of the regular interplanetary magnetic field (IMF) and minimal disturbances in the heliosphere. For the minimum epochs a contribution of the drift effect of the galactic cosmic rays particles (due to the gradient and curvature of the regular IMF) can be revealed reasonably purely in different classes of the GCR variations; this is essentially important for the GCR variations with relatively small amplitudes, e.g. for the 27-day variations of the GCR intensity and anisotropy. Richardson et al., [1] found incontrovertible evidence that the sizes of the solar wind parameters and recurrent cosmic ray modulations are ~50% larger when A > 0 (A is the direction of the solar global magnetic field) than during A < 0. In our previous papers [2]-[5] was demonstrated that the amplitudes of the 27-day variations of the GCR intensity and anisotropy are greater in the minimum epochs of solar activity for the positive (A>0) polarity period than for the negative (A<0) polarity period of the solar magnetic cycles. Kota and Jokipii in [6] have shown that severe recurrent changes of the stream of protons take place in the positive A>0 polarity periods rather than in the negative A<0 periods. Burger and Hitge [7] in a theoretical hybrid model have shown that the Fisk heliospheric magnetic field can explain several properties of the 27-day cosmic ray variations. Nevertheless, the amplitudes of the 27-day variation of the GCR intensity generated only by the existence of the Fisk's field are very small in the comparison with the experimental results, and there remains a general problem of the reality of the Fisk's type magnetic field in the minimum epochs of solar activity [8]. However, it must be noted that in papers [2]-[4], [6], [7], in order to explain results of Richardson and co-authors [1], the general attention was paid to the drift effect and was not considered the role of the recurrent changes of the solar wind velocity, which is a crucial. Our aim in this paper, on one hand, is to extend our study of the 27-day variations of the GCR intensity and anisotropy using new data for the last negative A<0 solar minimum epoch (2006-2008) and on the other, to demonstrate that the heliolongitudinal asymmetry of the solar wind velocity is ~2 times greater for the A > 0 than for A < 0 in the minimum and near minimum epochs of solar activity being the important reason of the polarity dependence of the amplitudes of the 27-day variations of the GCR intensity and anisotropy.

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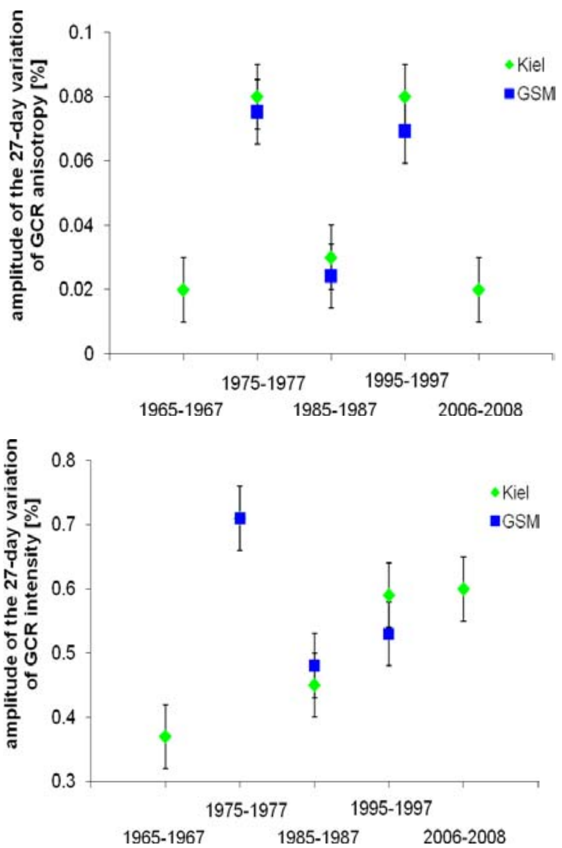
2. Experimental Data

Amplitudes of the 27-day variations of the GCR intensity and anisotropy were found using the all functioned neutron monitors by the global spherical method (GSM) [9]-[12]. We use the components (A_r, A_θ, A_f) of the three dimensional anisotropy and the isotropic component I of the GCR intensity calculated by the IZMIRAN group; calculations have been performed by means of the hourly data of all functioned neutron monitors using the GSM for a long period. (http://helios.izmiran.troitsk.ru/cosray/main.htm).

3. 27-Day Variations of the GCR Intensity and Anisotropy in the A>0 and A<0 Polarity Periods

The daily average values of the isotropic I and 3-D anisotropy components of GCR were found based on the hourly values obtained by GSM; then we calculated the amplitudes of the 27-day variations of the GCR intensity and anisotropy by means of daily data using the harmonic analyses method. The amplitudes of the 27-day variations of the anisotropy and intensity of GCR are presented in the Fig. 1ab found by Kiel neutron monitor data (rhombi) and by the GSM (squares) for the minimum epochs of 1965-67, 1985-1987 and 2006-2008 (A<0), and 1975-1977 and 1995-1997 (A>0).

From the methodical point of view it is worth to mention that, the general features of the 27-day variation of the GCR anisotropy based on the harmonic analyses method for the individual neutron monitors with the cut off rigidity < 5 GV coincide with those calculated using the radial and tangential components determined by GSM [5]. Based on this thesis only the Kiel neutron monitor data are used and results of calculations in the lingering minimum 2006-2008 (A<0) are presented in Fig.1 with the results found before (e. g. [4]).



Figs 1ab Changes of the average amplitudes of the 27-day variations of the GCR anisotropy (top panel) and intensity (bottom panel) by GSM and Kiel neutron monitor data for A>0 (1975-77 & 1995-1997) and A <0 (1965-67, 1985-1987 and 2006-2008) periods.

Figs. 1ab show that the amplitudes of the 27-day variation of the GCR anisotropy (Fig. 1a) are greater in all minimum epochs of solar activity for the A>0 polarity periods than for A<0 polarity periods of the solar magnetic cycles, while the amplitude of the 27-day variation of the GCR intensity for lasting minimum epoch (A<0) has the same level as for previous minimum epoch (A>0). This peculiarity we ascribe to the clearly established 27-day variation of the GCR intensity in 2007-2008, which generally is an exception for the A<0 polarity periods.

The dependence of the amplitudes of the 27-day variations of the GCR intensity and anisotropy on the A>0 and A<0 polarity periods we explained owing to the existence of the heliolongitudinal asymmetry of the solar wind velocity [13], [14]. The directions of the solar wind velocity and the drift velocity of the GCR particles coincide in the A>0 polarity period, while they are in the opposite directions in the A<0 polarity period. This phenomenon is considered as a basic reason that the amplitudes of the 27-day variations of the GCR intensity and anisotropy are greater in the A>0 polarity period than in A<0 polarity period. However, the 27-day variations of the other parameters of solar activity and solar wind could contribute to the behaviour of the amplitudes of the 27-day variations of the GCR intensity and anisotropy in different polarity periods. In connection with this, as we mentioned above (in the introduction) the relationship of the 27-day variations of the GCR intensity and anisotropy with the 27-day variation of the SW velocity [5] ought to be studied.

4. ON THE RELATIONSHIP OF THE 27-DAY VARIATIONS OF THE GCR INTENSITY AND ANISOTROPY WITH THE SOLAR WIND VELOCITY AND TILT ANGLE OF THE HELIOSPHERIC CURRENT SHEET

We found the amplitudes and phases of the 27-day variations of the SW velocity, the GCR intensity and anisotropy, by the harmonic analyses method. Figure 2 presents the distributions of the phases of the 27-day variations of the SW velocity, the GCR anisotropy and intensity versus the heliolongitudes for both polarity periods: 1975-1977 & 1995-1997 (A>0, left panel), 1965-1967 &1985-1987 (A<0, middle panel) and the present minimum epoch 2006 – 2008 (A<0, right panel).

Fig. 2 shows that the distribution of the phases of the 27–day variation of the SW velocity has a sharply established maximum for the A>0 (left panel) polarity periods and there are not any visible regularities in the distributions of the phases of the 27 – day variation of the SW velocity for the A<0 (middle panel) polarity periods. The left panel of Fig.2 shows that the distributions of the phases of the 27-day variations of the SW velocity, the GCR intensity and anisotropy have maxima for the A>0 polarity period; the maxima for the 27-day variations of the GCR intensity and anisotropy basically coincide and they are opposite (about 180^0) with respect to the maximum for the 27-day variation of the SW velocity. The middle panel of the Fig.2 shows that the distributions of the phases of the 27-day variations of the SW velocity, the GCR intensity and anisotropy have not clear maxima for the A<0 polarity period.

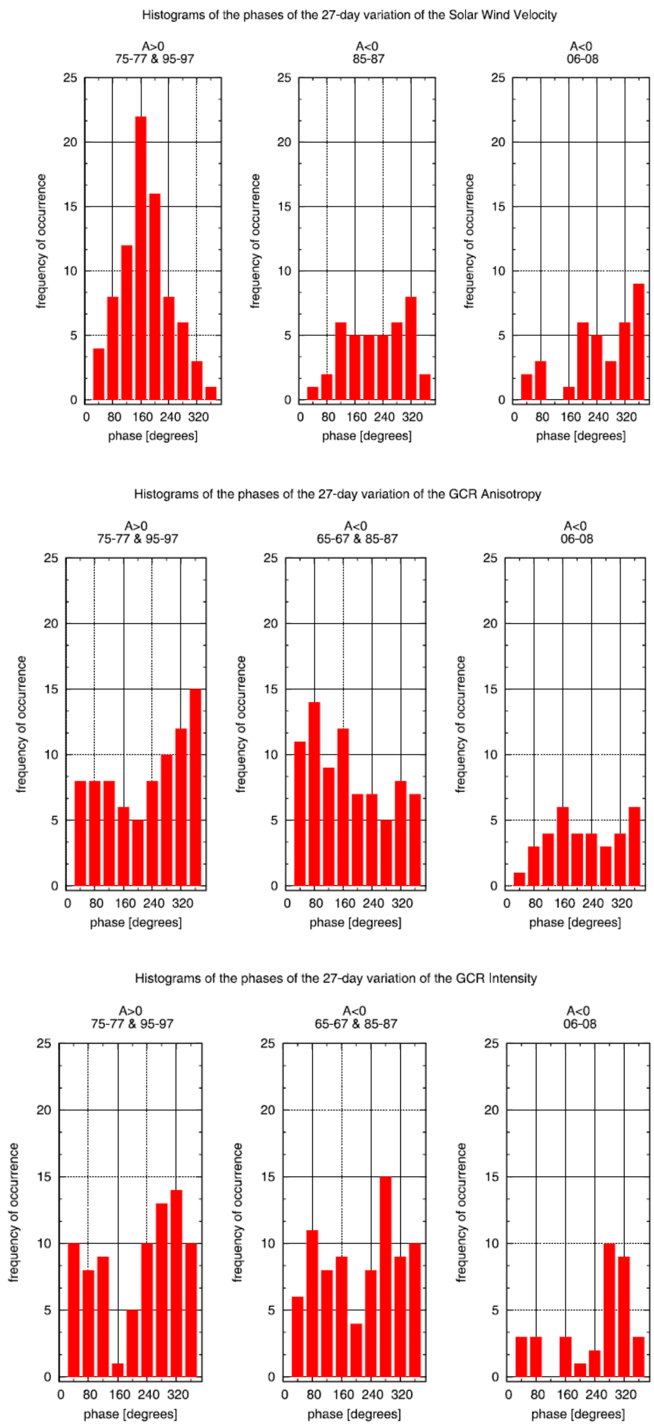


Fig. 2 The distributions of the phases of the 27-day variations of the solar wind velocity (SWV-top), the GCR anisotropy (A GSM-middle) and GCR intensity (I GSM-bottom) versus the heliolongitudes for both polarity periods: 1975-1977 & 1995-1997 (A>0, left panel), 1965-1967 & 1985-1987 (A<0, middle panel) and 2006 – 2008 (A<0, right panel).

There are some tendencies of the existence of the second harmonics of the solar rotation period (~13-14 days).
We assume that the clear 27-day variation of the solar wind velocity in the A>0 polarity period is the reason of the existence of the regular 27-day variations of the GCR intensity and anisotropy.

The scattered distributions of the phases of the 27-day variations of the GCR intensity and anisotropy (Fig. 2 middle panel) for the A<0 polarity period are one of the general motivations that the amplitudes of the 27-day variations of the GCR intensity and anisotropy are greater in the A>0 polarity period than in A<0 polarity period [5], [14]. Analyses of the phase distribution of the 27–day variation of the solar wind velocity show that the long – lived (not less than 22 years) active heliolongitudes exist on the Sun, especially for the A>0 polarity period of the solar magnetic cycles.

In this paper besides the phases of the 27-day variation of the SW velocity we analyze the magnitude of the heliolongitudinal asymmetry of the SW depending on the polarity. In Figs. 3 are presented temporal changes of the superimposed SW velocity with the fitting by a 27-day harmonic wave for 1975-77 (A>0), 1985-87 (A<0), 1995-97 (A>0) and for 2006-2008 (A<0).

One can see that the average amplitudes of the 27-day variation of the SW velocity are greater for the A>0 polarity period, than for A<0, except the last minimum 2006-2008 (A<0). In this case there is observed clear 3rd harmonic (~9 days). Possibly, the sharply established maximum of the phase distribution of the SW velocity (Fig. 2a, left panel) leads to the fact that the size of the heliolongitudinal asymmetry of the solar wind velocity is ~2 times greater for the A > 0 than for A < 0 in the minimum and near minimum epochs of solar activity.
Generally, the point is that the greater amplitudes of the 27 – day variation of the GCR intensity for the A>0 polarity period than for A<0 polarity period observed by neutron monitors experimental data [1], [2], and the similar results obtained for the anisotropy in [3]-[5] can be generally related with the greater amplitudes of the 27-day variation of the solar wind velocity in the A>0 than in A<0.

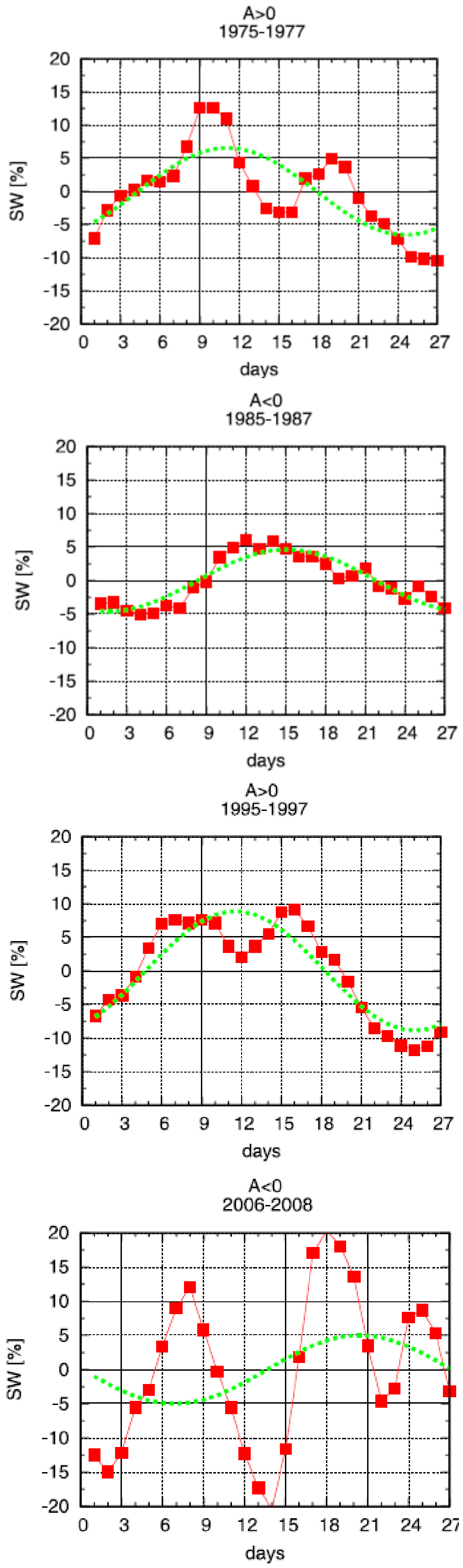
In Figures 4ab are presented dependences of the amplitudes of the 27-day variations of the GCR intensity (Fig. 4a) and anisotropy (Fig. 4b) versus the tilt angles. The linear dependences of the type

$$A27I/A = a\,\theta + b$$

between amplitudes of the 27-day variations of the GCR intensity I/ anisotropy A, and tilt angles θ were found by a least squares method and have the expressions:

$$A27I = (0.0104 \pm 0.0025)\,\theta + 0.5024 \pm 0.0911,$$

$$A27A = (0.0007 \pm 0.0004)\,\theta + 0.1091 \pm 0.0158.$$



Figs. 3 Temporal changes of the superimposed SW data with theirs fitting by a 27-day harmonic wave for 1975-77 (A>0), 1985-87 (A<0), 1995-97 (A>0) and for 2006-2008 (A<0)

The accuracies σ_a of the regression coefficients *a* and σ_b of the free terms *b* were calculated as in [15], where n is the number of the Carrington rotations used in calculations (n=113); the amplitudes of the 27-day variations of the GCR intensity and anisotropy do not noticeably depend on the tilt angles of the heliospheric current sheet (HCS) in January 2000 - May 2008. Thus, we confirm our previous findings (e. g. [5], [13]) that the amplitudes of the 27-day variations of the GCR intensity and anisotropy do not depend on the tilt angles of the heliospheric current sheet.

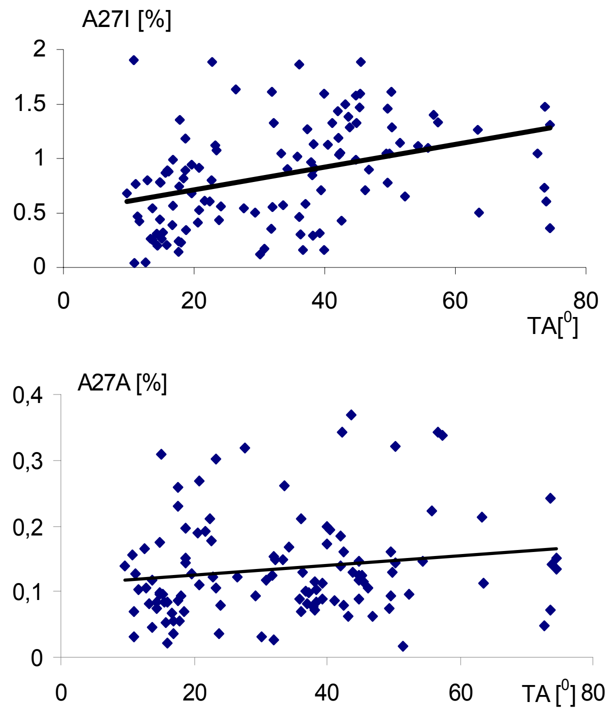


Fig. 4 The distributions of the amplitudes of the 27-day variations of the GCR intensity (A27I) and anisotropy (A27A) versus the tilt angles of HCS in the period January 2000 - May 2008

5. Conclusions

1. The greater amplitudes of the 27 – day variations of the GCR intensity and anisotropy for the A>0 periods than in A<0 periods observed by neutron monitors experimental data can be generally related with the greater amplitudes of the 27-day variation of the solar wind velocity in the A>0 periods than in A<0 polarity periods of solar magnetic cycle.
2. The long-lived active heliolongitudes are the source of the 27-day variation of the solar wind velocity; owing to which is observed the background 27-day variations of the GCR intensity and anisotropy in the minimum epochs of solar activity.
3. The amplitudes of the 27-day variations of the GCR intensity and anisotropy do not depend on the tilt angles of HCS for the current minimum epoch of solar activity agreed with our previous results for other epochs of solar activity.

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