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FEATURES OF THE 27-DAY VARIATIONS OF THE GALACTIC COSMIC RAY INTENSITY AND ANISOTROPY*

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We study features of the 27-day variations of the galactic cosmic ray (GCR) intensity and anisotropy using data of neutron monitors and solar wind (SW) velocity. We found that the larger amplitudes of the 27-day variations of the galactic cosmic ray anisotropy and intensity for the positive polarity period ($A>0$) of solar magnetic cycle than for the negative polarity period ($A<0$) in the minima epoch of solar activity are related with the heliolongitudinal asymmetry of the solar wind velocity. We reveal the long-lived (~ 22 years) active regions of the heliolongitudes being the sources of the 27-day variation of the solar wind velocity during the $A>0$ period. Also, we demonstrate an existence of the clear stable 27-day waves of the GCR intensity and anisotropy with the amplitudes larger in the $A>0$ than in the $A<0$ for the several individual Carrington rotations in the minima epoch of solar activity. We show that the solution of the Parker's transport equation with the heliolongitudinal asymmetry of the solar wind velocity is in the reasonable agreement with the neutron monitors experimental data. We conclude that the larger amplitudes of the 27-day variations of the galactic cosmic ray anisotropy and intensity observed by the experimental data in the $A>0$ are related with the superposition of two effects: (1) the existence of the more regular heliolongitudinal asymmetry of the solar wind velocity, and (2) a coincidence of convective and drift streams of the GCR particles in comparison with the $A<0$.

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1. Introduction

The Sun, like most other astronomical objects rotates on its axis. Unlike Earth and other solid objects, the entire Sun does not rotate at the same rate. Because the Sun is not solid, but is instead a massive sphere of gas and plasma, different parts of the Sun (depending on the heliolatitudes) rotate at different rates it is called differential rotation. The equator and near equatorial regions of the Sun rotate on its axis with the period of about 25–26 days, called the Sun's sidereal period of rotation. For the observer on the Earth this periodicity equals 27–28 days due to the orbital motion of the Earth, called the Sun's sinodial period of rotation. At its poles regions the Sun rotates at rate of about 36 days. The Sun is characterized by solar activity and solar wind (dynamical extension of solar corona) changing in time and having the asymmetrical distributions with the heliolongitudes in general. Owing to the rotation of the Sun there are observed the periodicity of 25–26 days (sidereal period) among the large range of the quasi-periodic changes of different parameters of solar activity and solar wind as viewed from the arbitrary point of the interplanetary space; the same periodicity as viewed from the Earth equals 27–28 days (sinodial period). It is accepted that the periodicities of solar and geomagnetic activities, solar wind, galactic cosmic rays and other parameters characterizing the solar–terrestrial relationships connected with the Sun's rotation are called the 27-day variations, instead this periodicity can be slightly different. The changes of amplitudes and range of the 27-day periodicities of different parameters of solar activity and solar wind occur on the background of two long period variations of solar activity: (1) the largest and powerful 11-year solar cycle (sunspot cycle), and (2) the relatively weakly pronounced 22-year solar magnetic cycle. The 11-year cycle (from one minimum to another minimum epoch) shows temporal changes of the level of solar activity (sunspot numbers in general), while the 22-year solar magnetic cycle is associated with the reversal of the Sun's global magnetic field taking place in the maxima epoch of solar activity. Thus, the 22-year magnetic cycle of the Sun consists of two different polarity periods (from one maximum to another maximum epoch), each lasting 11-years. When the global magnetic field lines are directed outward from the north hemisphere of the Sun and are directed backward to south hemisphere, this 11 year part of the 22-year solar magnetic cycle is called the positive ($A > 0$) magnetic polarity period, while in vice versa case, it is called the negative ($A < 0$) magnetic polarity period of the Sun. Investigation of the 27-day variations of different parameters of solar and geomagnetic activity, solar wind and galactic cosmic rays (GCR) is the fundamental problem in the physics of the heliosphere, solar–terrestrial relationships, magnetosphere and atmosphere of the Earth, and especially in the physics of the space weather [1]. In general lots of papers are devoted to the problem of the 27-day variations of the GCR intensity and anisotropy *e.g.*, [2–14]; a dependence of the 27-day variation of the GCR intensity on the polarity of Sun's global magnetic field is studied in [15–18]. At the same time a relation of the 27-day variation of the GCR anisotropy on the polarity of the Sun's global magnetic field, and on the current sheet's tilt angles are studied in [18–20]. In this paper our aim is to study the features of the 27-day variation of the GCR intensity and anisotropy, and theirs relationship with the 27-day variations of the solar wind (SW) velocity based on the experimental data for different polarity periods of solar magnetic cycle.

2. Experimental data, methods and discussion

We 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. For this purpose we use data of neutron monitors (1965–2004) [21, 22] and SW velocity (1975–2004) [23] for the $A > 0$ and the $A < 0$ periods during the minima and near minima epoch of solar activity. The disturbances in the interplanetary space are minimal and a polarity of the Sun's global magnetic field is well established throughout the minima epoch of solar activity. For the minimum epochs the contribution of the drift effect of the GCR particles (due to gradient and curvature of the regular interplanetary magnetic field (IMF)) can be revealed reasonably purely 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. We study the 27-day variations of the GCR intensity and anisotropy based on the daily means of the GCR intensity and anisotropy for the minimum epochs of 1965-2004. We calculate the daily means of the GCR intensity and anisotropy from the hourly components $(A_\mathrm{r}, A_\theta, A_\mathrm{f})$ of the three dimensional (3-D) anisotropy and the isotropic component I of the GCR intensity [22]. The hourly components of the anisotropy and intensity were obtained by the global spherical method (GSM) based on the hourly data of all functioned neutron monitors [24–27]. 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 period (27 days) for the $A > 0$ (1975–1977; 1995–1997) and for the $A < 0$ (1965–1967; 1985–1987) periods of the minima epochs of solar activity. In Fig. 1 are presented the heliolongitudinal distributions of the phases of the 27-day variations of the SW velocity, GCR intensity and anisotropy found by GSM for the $A > 0$ (Fig. 1(a)) and $A < 0$ (Fig. 1(b)) periods.

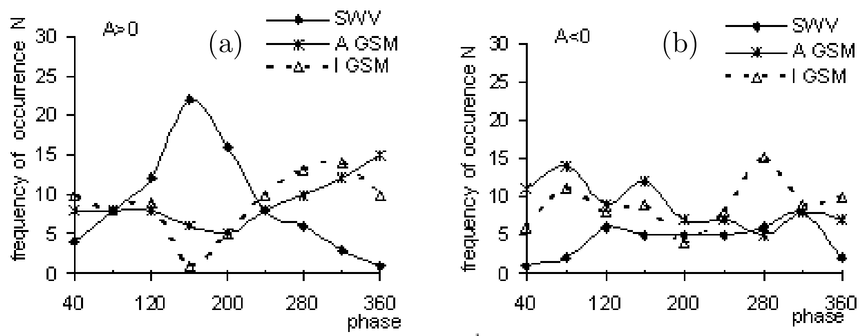

Fig. 1. Heliolongitudinal distributions of the phases of 27-day variations of the SW velocity, GCR intensity (I GSM) and anisotropy (A GSM) obtained by GSM. On the ordinate axes are shown summary number N (frequency of occurrence) of the phases of the 27-day variations falling to the interval of 40^0 of the heliolongitudes in degrees. On the horizontal axes are presented heliolongitudes in degrees with steps of 40^0 (a) — 1975–1977; 1995–1997 ($A > 0$), and (b) — 1965–1967; 1985–1987 ($A < 0$).

Data of all considered parameters consist of 6 years ($\sim$ 80 Carrington rotations) for the $A > 0$ periods. Data of the SW velocity are absent for 1965–1967 ($A < 0$). Fig. 1(a) shows that the distributions of the phases of the 27-day variations of the GCR intensity and anisotropy have minima when the phase distribution of the 27-day variation of the SW velocity has maximum (they are shifted $\sim 180°$ of the heliolongitudes). At the same time there are not any recognizable regularities of the heliolongitudinal distributions of the phases of the 27-day variations for considered parameters for the $A < 0$ period (Fig. 1(b)); possibly, there is some tendency of the two maxima distributions for the 27-day variations of the GCR intensity and anisotropy, and the SW velocity. In Fig. 2 are presented the changes of the average amplitudes of the 27-day variations of the GCR intensity (A27I) and anisotropy (A27A) by Kiel neutron monitor data for four minima epoch of solar activity. We see in Fig. 2 a clear distinction of the average amplitudes of the 27-day variations of the GCR intensity and anisotropy for $A > 0$ and $A < 0$ periods.

We suppose that the smaller amplitudes of the 27-day variations of GCR intensity and anisotropy in the $A < 0$ period than in the $A > 0$ period (Fig. 2(b), also, [18–20]) is caused by the irregular distributions of the phases of the 27-day variations of the GCR intensity and anisotropy (Fig. 1(b)) for the $A < 0$ period. The above mentioned results were obtained based on the averaged data for a long period. It is of interest how the 27-day variations of the GCR intensity and anisotropy behave for the individual Carrington rotations in the $A > 0$ and the $A < 0$ periods. For this aim we

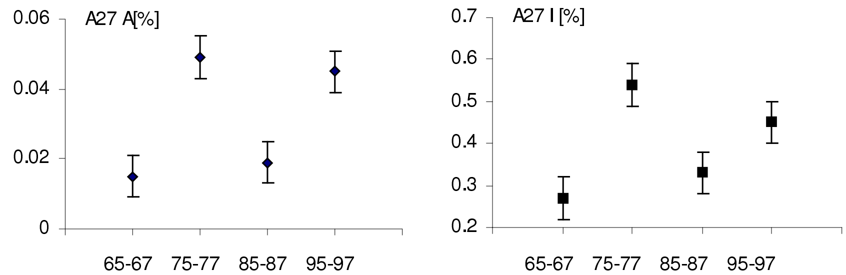

Fig. 2. Changes of the average amplitudes of the 27-day variations of the GCR anisotropy (A27A-left panel) and intensity (A27I-right panel) by Kiel neutron monitor data for $A > 0$ (1975-77 and 1995-1997) and $A < 0$ (1965-67 and 1985-1987) periods.

handle daily GCR intensity, radial and tangential components of the GCR anisotropy obtained by GSM for the period 1997 ($A > 0$) and 1987 ($A < 0$) by the frequency filters method [28]. This technique 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 isotropic intensity, and radial and tangential components of the GCR anisotropy obtained by GSM for the period 1997 ($A > 0$) and 1987 ($A < 0$). Results of filtered daily GCR intensity, radial and tangential components of the 3-D GCR anisotropy are presented in Figs. 3, 4, 5. It is seen (Figs. 3, 4, 5) that the GCR intensity, and both the radial A_{r} and tangential A_{f} components of the 3-D anisotropy of GCR show very clear 27-day periodicities. One can underline that the 27-day periodicities of the GCR intensity I and Ar component of anisotropy generally are larger for the $A > 0$ period than for $A < 0$ period (Figs. 3, 4). The same statement is valid for Af component of GCR anisotropy except for the last five solar rotations, when the amplitudes of the Af are greater for $A < 0$ period than for the $A > 0$ (Fig. 5). However, average amplitude of anisotropy is larger throughout of the considered period for the $A > 0$ case than for $A < 0$ (*e.g.* Fig. 2(left panel)).

To summarize the results obtained using the experimental data we note that the heliolongitudinal distribution of the phase of the 27-day variation of the SW velocity for the $A > 0$ period has a clear maximum, while for the $A < 0$ period it is not so noticeable. The phase distribution of the 27-day variation of the solar wind velocity (Fig.1(a)) confirms that the long-lived ($\sim$ 22 years) active heliolongitudes exist on the Sun preferentially for the $A > 0$ epoch of the solar magnetic cycle [29].

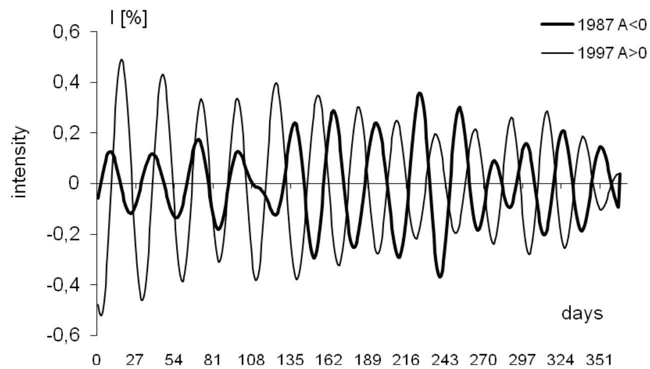

Fig. 3. Results of the filtered daily GCR intensity obtained by GSM. Thin curve corresponds to the period of 1997 ($A > 0$) and thick one — 1987 ($A < 0$).

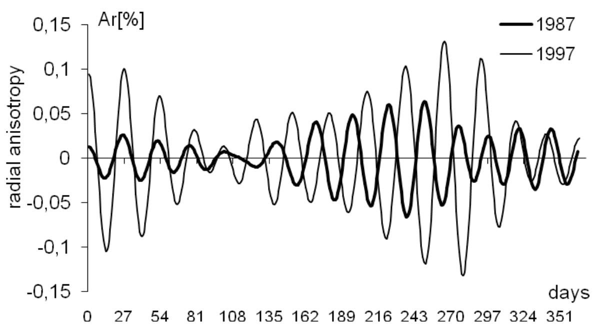

Fig. 4. Results of the filtered daily radial A_r component of the 3-D GCR anisotropy data obtained by GSM. Thin curve corresponds to the period of 1997 ($A > 0$) and thick one — 1987 ($A < 0$).

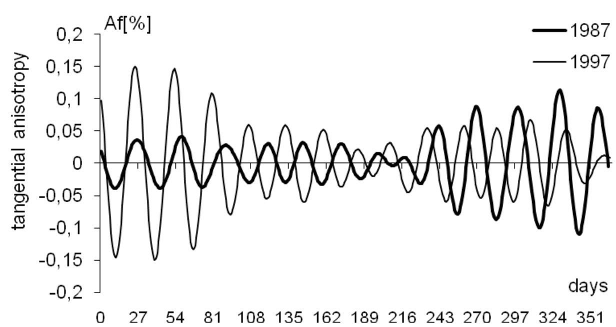

Fig. 5. Results of the filtered daily tangential A_f component of the 3-D GCR anisotropy data obtained by GSM. Thin curve corresponds to the period of 1997 ($A > 0$) and thick one — 1987 ($A < 0$).

The long-lived active heliolongitude is the source of the long-lived 27-day variation of the solar wind velocity, and, afterwards, it can be considered as the general source of the 27-day variations of the GCR intensity and anisotropy. Of course, we do not exclude the existence of other sources of the 27-day variations of the GCR intensity and anisotropy *e.g.* considered in the theoretical hybrid model by Burger and Hitge in [30], however there remains a general problem of the reality of the Fisk's type heliospheric magnetic field [31] in the minima epoch of solar activity [32].

Generally, the point is that the greater amplitudes of the 27-day variations of the GCR intensity (A27I) for the $A > 0$ period than for the $A < 0$ period observed by neutron monitors experimental data [15, 17], and the similar results obtained for the anisotropy (A27A) in [18–20] can be related with the greater amplitudes of the 27-day variation of the solar wind velocity in the $A > 0$ period than in $A < 0$ period. However, the results of solution of GCR transport equation with drift for the 27-day variations of the GCR intensity and anisotropy are in good agreement with the experimental data of neutron monitors when the same heliolongitudinal changes of the solar wind velocity are assumed for the both the $A > 0$ and $A < 0$ periods, as it is seen from Fig. 6 of our paper ([29], Fig. 4). In this model we assume that the stationary 27-day variation of the GCR intensity and anisotropy in the minima epochs of solar activity can be generally caused by the heliolongitudinal asymmetry of the solar wind velocity. The heliolongitudinal asymmetry of the solar wind velocity is gradually dumped *versus* the radial distance up to 7.5 AU. Details of this model are discussed in [29].

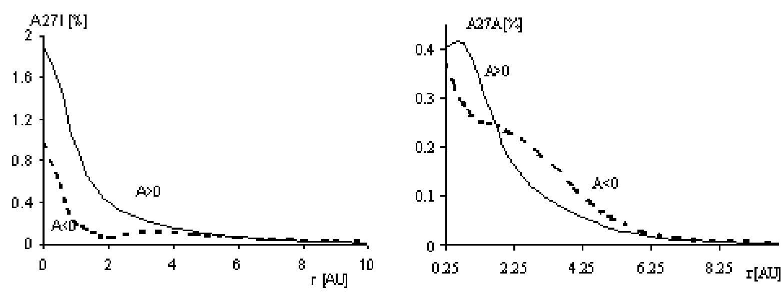

Fig. 6. The changes of A27I and A27A *versus* the radial distance for the $A > 0$ (solid line) and $A < 0$ (dashed line) polarity periods of solar magnetic cycle for galactic cosmic ray particles rigidity $R = 10$ GV [29].

In doing so, results obtained after the inclusion of the heliolongitudinal changes of the other parameters in the transport equation of GCR, *e.g.* as, diffusion coefficient, strength of the IMF, and the state of the IMF turbulence do not show any agreement with the experimental data [33].

3. Conclusions

1. The long-lived ($\sim$ 22 years) active heliolongitudes exist on the Sun, especially, for the $A > 0$ period of the solar magnetic cycle. The stable long-lived active heliolongitude is the reason of the long-lived 27-day variation of the solar wind velocity, and, afterwards, it becomes as the general source of the 27-day variations of the GCR intensity and anisotropy.

2. The clear and stable 27-day waves of the GCR intensity and anisotropy (with the amplitudes greater in the $A > 0$ than in the $A < 0$ period) are revealed for the several individual Carrington rotations in the minima epoch of solar activity.

3. The greater amplitudes of the 27-day variations of the GCR intensity (A27I) and anisotropy (A27A) for the $A > 0$ period than for the $A < 0$ period observed by neutron monitors experimental data can be related with the greater amplitudes of the 27-day variation of the solar wind velocity in the $A > 0$ period than in $A < 0$ period. At the same time a drift could play an important role in the formation of the 27-day variations of the GCR intensity and anisotropy in the $A > 0$ and $A < 0$ periods. The greater A27I and A27A for the $A > 0$ than for the $A < 0$ period observed by neutron monitors experimental data are in a good agreement with the theoretical calculations, only when the heliolongitudinal asymmetry of the solar wind velocity is taken into account in the transport equation (the radial component of the drift velocity of the GCR particles coincides with the direction of the SW velocity in the $A > 0$, while there is a vice versa situation for the $A < 0$).

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REFERENCES

[1] `http://www.swpc.noaa.gov/today.html`
[2] W.H. Fonger, *Phys. Rev.* **91**, 351 (1953).
[3] J.A. Simpson, *Phys. Rev.* **94**, 426 (1954).

[4] S.E. Forbush, *Electromagnetic Phenomena in Cosmical Physics, Proceedings from IAU Symposium no. 6.* Eds B. Lehnert, International Astronomical Union. Symposium no. 6, Cambridge University Press, 1958, pp. 332–344.
[5] L.I. Dorman, *Variations of Cosmic Rays and Space Exploration*, AN SSSR, Moscow 1963 (in Russian).
[6] M.V. Alania, L.Kh. Shatashvili, *Quasi-Periodic Cosmic Ray Variations*, Mecniereba, Tbilisi 1974 (in Russian).
[7] K. Kudela, A.G. Ananth, D. Venkatesan, *J. Geophys. Res.* **96**, 15871 (1991).
[8] D.B. Swinson, S.I. Yasue, *J. Geophys. Res.* **97**, 19149 (1992).
[9] R.B. McKibben, J.A. Simpson, M. Zhang, S. Bame, A. Balogh, *Space Sci. Rev.* **72**, 403 (1995).
[10] M. Zhang, *Astrophys. J.* **488**, 841 (1997).
[11] J. Kota, J.R. Jokipii, *Space Sci. Rev.* **83**, 137 (1998).
[12] J.A. Simpson, *Space Sci. Rev.* **83**, 7 (1998).
[13] J.A. Simpson, *Space Sci. Rev.* **83**, 169 (1998).
[14] I. Sabbah, *Sol. Phys.* **245**, 207 (2007).
[15] I.G. Richardson, H.V. Cane, G. Wibberenz, *J. Geophys. Res.* **104**, 12549 (1999).
[16] M.V. Alania, D.G. Baranov, M.I. Tyasto, E.S. Vernova, **27**, 619 (2001).
[17] A. Gil, M.V. Alania, Proc. 27th ICRC, Hamburg, 9, 3725–3728, 2001.
[18] A. Gil, K. Iskra, R. Modzelewska, M.V. Alania, *Adv. Space Res.* **35**, 687 (2005).
[19] M.V. Alania, A. Gil, K. Iskra, R. Modzelewska, Proc. 29th ICRC, SH34, 215–218, Pune, India 2005.
[20] M.V. Alania, A. Gil, R. Modzelewska, *Adv. Space Res.* **41**, 280 (2008) doi:10.1016/j.asr.2007.06.001.
[21] `http://134.245.132.179/kiel/`
[22] `http://cr20.izmiran.rssi.ru/AnisotropyCR/index.php`
[23] `http://spidr.ngdc.noaa.gov/spidr/`
[24] A.V. Belov *et al.*, *J. Geophys. Res.* **110**, A09S20 (2005), doi:10.1029/2005JA011067.
[25] A.V. Belov *et al.*, *Izvestia RAN, Ser. Fiz.* **59**, 79 (1995).
[26] G.F. Krymski *et al.*, *Geomagnetism and Aeronomy* **6**, 991 (1966).
[27] G.F. Krymski *et al.*, *Geomagnetism and Aeronomy*, **7**, 11 (1967).
[28] R.K. Otnes, L. Enochson, *Digital Time Series Analysis*, John Wiley and Sons, New York 1972.
[29] R. Modzelewska, M.V. Alania, A. Gil, K. Iskra, *Acta Phys. Pol. B* **37**, 1001 (2006).
[30] R.A. Burger, M. Hitge, *Astrophys. J.* **617**, L73 (2004).
[31] L.A. Fisk, *J. Geophys. Res.* **101**, 15547 (1996).
[32] D.A. Roberts *et al.*, *J. Geophys. Res.* **A8**, 112 (2007), CiteID A08103, doi:10.1029/2007JA012247.
[33] R. Modzelewska, M.V. Alania, A. Gil, Proc. 20th ECRS, ecrs06-s0-63, Lisbon, Portugal, 2006.