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The asymmetric heliosphere's role in the 27-day variations of galactic cosmic rays

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ABSTRACT

The temporal changes of the amplitude of the 27-day variation of galactic cosmic rays (GCR) has been compared with the changes of the longitudinal asymmetry of the sunspot area distribution over the Sun's disc, with the tilt angle of the heliospheric current sheet (HCS) and with the polar coronal hole area for three magnetic cycles of the Sun (1970-2000). A good correspondence of the amplitude of the 27-day cosmic ray variation with the longitudinal asymmetry and the tilt angle is observed when qA<0, whereas at qA>0 the change of the amplitude of the 27-day cosmic ray variation follows to the polar coronal hole area.

To study an influence of the heliolatitudinal asymmetry of the heliosphere and the radial decay of the heliolongitudinal asymmetry of solar wind velocity and diffusion coefficient on the 27-day variation of GCR 3-dimentional Parker's transport equation with drift has been numerically solved for different solar magnetic cycles, qA>0 and qA<0.

INTRODUCTION

The presence of the 22-year periodicity in the intensity of GCR can be considered as an established fact confirmed both by experimental data and theoretical models. This periodicity manifests itself in the time-dependence of the GCR intensity as alternation of sharp and flat peaks at the maxima of GCR intensity.

There are good grounds to believe that some features of the temporal changes of the amplitude of the 27-day GCR variation are also connected with the global magnetic field of the Sun. It was shown in [1,2,3] that in the period when qA>0 (solar magnetic field is directed outward at the North pole) the variation amplitude is higher than in the period when qA<0. New evidence confirming the presence of the 22-year pattern in the relationship of sunspot number and tilt angle to GCR intensity was obtained in [4]. It was shown that the sunspot number and the tilt angle of the HCS are in phase with GCR intensity during even cycles, whereas at odd cycles the GCR intensity lags for about 1 year. It is of interest to consider from this point of view the temporal changes of the 27-day GCR variation amplitude and its relationship with the Sun's magnetic cycle.

EXPERIMENTAL RESULTS AND DISCUSSION

As parameters characterizing the low-latitude structure of the modulation region the asymmetry of the longitudinal solar activity distribution and tilt angle of heliospheric current sheet were used. The value of the asymmetry for each solar rotation was calculated as the geometric sum of vectors corresponding to the individual sunspots; vector module was set equal to the sunspot area, direction of the vector was defined as the Carrington longitude of the sunspot [5]. Asymmetry values were averaged over 13 solar rotations with sliding shift of 1 rotation.

We consider the longitudinal asymmetry to be a suitable parameter for the study of the relationship between the solar activity and the 27-day GCR modulation since low-latitude streams of the solar wind bear the imprint of this distribution in the form of alternation of fast and slow streams and of regions with different radial diffusion coefficient.

As another solar parameter we have taken the tilt angle of the HCS. As it was shown in [6] a strong correlation was found between the inclination of HCS and solar wind speed in the ecliptic plane, the speed of solar wind streams being one of the key parameters in the recurrent modulation models.

The 27-day GCR variation amplitude was obtained as the first harmonic of the Fourier analysis for the GCR intensity (Climax neutron monitor). The amplitude values were averaged as described above. Time-dependence of the 27-day variation (with respect to the intensity of 1976) is compared both with the asymmetry of the longitudinal distribution (Fig. 1a) and with the tilt angle of HCS (Fig. 1b). The scaling and the relative shift of the curves were chosen so that to get the best possible match for all the range of parameters.

In spite of the significant fluctuations of the 27-day variation amplitude, especially at the period of the change of the sign of the Sun's global magnetic field, a certain quasisperiodicity can be noted in relation between the time-dependence of the 27-day variation amplitudes of GCR and those of the solar parameters. At the period when qA<0 (1982-1989) that is on the decrease phase of the 21st and on the increase phase of the 22nd solar cycles a close coincidence of the temporal changes of the 27-day GCR variation both with the asymmetry of the longitudinal solar activity distribution and with tilt angle is observed. At this epoch positively charged particles propagate mostly along the heliospheric current sheet. Completely different pattern is observed at the period when qA>0 (the particles penetrate into the heliosphere from the Sun's poles). In this case the time-dependence of the 27-day variation differs considerably from the change of the asymmetry and the tilt angle; moreover these differences are seen in both of the magnetic cycles - in the years 1972-1979 (for the tilt angle from 1976) and in 1992-1999: the increase of the amplitude of the variation starts earlier than the corresponding changes of solar parameters, whereas the decrease lags in time.

An inverse picture [7] is seen when comparing the time-dependencies of the amplitude of the 27-day GCR variation and the area of polar coronal holes (Fig. 2 in which the ordinate axis for the area of polar coronal holes has been inverted). Here the coincidence of the time dependencies is observed at the epoch of qA>0 (1972-1979). On the contrary, when qA<0 the decrease and increase phases of the amplitude of the 27-day GCR variation differ considerably from the time-dependence of the polar coronal holes' area.

These results may be interpreted as a some indication of the 22-year periodicity of the 27-day GCR variation. As a possible mechanism of the formation of the 22-year periodicity the interaction of two competing factors - the asymmetry of the low-latitude streams of solar wind and the latitudinal extent of the modulation region - can be proposed. At the epoch when qA<0 the particles propagate along HCS and the first factor is the determining one, whereas when qA>0 the size of the polar coronal holes' region is decisive for the penetration of the particles from the polar regions of the Sun.

These conclusions do not contradict the results obtained earlier [3] which show that generally there is no detailed correlation between the amplitudes of the 27-day variation and tilt angles.

MODELING OF 27-DAY VARIATION OF GCR

For the modelling of the 27-day variations of GCR Parker's 3-D transport equation [8] has been used.

$$\frac{\partial N}{\partial t} = \nabla_i \left(K_{ij} \nabla_j N\right) - \nabla_i \left(U_i N\right) + \frac{1}{3R^2} \frac{\partial \left(R^3 N\right)}{\partial R} \left(\nabla_i U_i\right) \qquad (1)$$

where N, and R are density in interplanetary space and rigidity of GCR particles, respectively; K_{ij} is diffusion tensor consisting from the symmetric and antisymmetric (responsible for drift) parts; U_i is the solar wind velocity and t- time. The amplitude of the 27-day variation of GCR is generally time-dependent. Nevertheless, in order to show a dependence of the amplitude of the 27-day variation of GCR on the different direction of the Sun's global magnetic field (qA>0 and qA<0), on the character of the asymmetry of the heliosphere and on the distances from the Sun, a steady-state case is considered (the term $\partial N/\partial t$ in Eq(1) is neglected). The equation (1) in spherical coordinate system r , θ, ϕ, for relative density $n = N/N_0$ (where N_0 is density of GCR in the interstellar medium accepted as, $N_0 \propto R^{-4.5}$ for the rigidities to which neutron monitors are sensitive) was solved including gradient and curvature drift and HNS drift for the following assumptions: in order to avoid an intersection of the magnetic field lines in space there is assumed that the heliolongitudinal asymmetry of the solar wind velocity changes as,

$$U = U_0 \,(1 + 0.2\, \mathrm{Sin}\phi) \qquad (2)$$

up to the distance of 7 astronomical units (AU) on the Sun's equatorial plane (corotating interaction region is not taken into account). The parallel diffusion coefficient, $K_{||}$ is represented by the following way,

$$K_{||}=K_0\, K(r)\, K(r,\theta,\phi)\, K(R), \qquad (3)$$

Where $K(r) = 1 + \alpha_0 r^{\beta}$, $K(R) = R^{\gamma}$, and $K(r,\theta,\phi) = 1 + 0.5\, \mathrm{Sin}\phi \mathrm{Sin}(3\theta)\mathrm{Exp}(-\alpha_1 r)$. K_0 is equal to the 2×10^{22} $cm^2 s^{-1}$ for the energy of 10 GeV. The existence of the heliolongitudinal asymmetries (HA) of the diffusion coefficient and of the solar wind velocity in the range of the heliolatitudes $60^0 \le \theta \le 120^0$ ($\pm 30^0$ with respect to the solar equatorial plane) are determined by the Sin(3θ), which equals zero at the $\theta = 60^0$ and at the $\theta = 120^0$. For heliolatitudes of the range of $0^0 \le \theta < 60^0$ and $120^0 < \theta \le 180^0$, $K(r,\theta,\phi)=\mathrm{Exp}(-\alpha_1 r)$, $K(r)= 1 + \alpha_0 r^{\beta}$, and K(R) = R (in units of GV); the radius of the modulation region is 100 AU and the solar wind velocity U equals 4×10^{7} cm/s. The ratio α of the perpendicular $K_{\perp}$ and parallel $K_{||}$ diffusion coefficients ($\alpha = K_{\perp}/K_{||}$) is assumed to be equal to 0.1 at the Earth orbit for the energy of 10 GeV, and then it changes depending on the spatial coordinates according to the expression $\alpha = (1 + \omega^2\tau^2)^{-1}$, where $\omega\tau = 300 H\lambda R^{-1}$; H is the strength of the IMF and λ- the transport free path of GCR particles. At the Earth's orbit H = 5 nT, $\lambda = 2 \times 10^{22}$ cm^2 s^{-1}, and

$\omega\tau$ =3, for the energy of 10 GeV and then it changes depending on the spatial coordinates according to the Parker's spiral magnetic field [4]. At the boundary of the modulation region α tends to 1.This assumption seems natural in the case when the regular interplanetary magnetic field tends to zero at the boundary of modulation; but it differs from the very much accepted assumption that α is constant and equals ≈ 0.1 near the helioequatorial region and enhances in the solar polar direction [9-11].
The data obtained by Ulysses revealed an asymmetry in GCR intensity with higher values in the Northern hemisphere, which was the first indication of the existence of such the asymmetry of GCR modulation [12]. As one of the reasons of the above mentioned asymmetry of heliosphere can be considered a shift of the HNS to the southern hemisphere. In connection with this possibility it is of interest to show how this asymmetry of heliosphere could influence on the amplitude of the 27-day variation of GCR. The heliolatitudinal asymmetry of the heliosphere has been taken into account by changing of the location of the flat HNS with respect to the geographic equator of the Sun. Eq(1) is solved numerically for different solar magnetic cycles (qA> 0 and qA<0) and for the following values of constants in (3): $\alpha_0 = 100$, $\beta = 1$, $\gamma = 1$, and $\alpha_1 = 0.07$ (an existence of the radial decay of the HA), and $\alpha_1 = 0$ (an absence of the radial decay of the HA). It is seen from Figure 3 that for the qA>0 solar magnetic cycle (in other equal conditions) the amplitude of 27-day variations is greater at the Earth's orbit when the HA of the solar wind velocity and diffusion coefficient have maximum at the helioequator, than that when only the HNS or both the HA and the HNS are shifted together to the southern hemisphere for -10^0 S; for the qA<0 solar magnetic cycle this difference is much less. In Figure 4ab are presented the radial dependences of the 27-day variation amplitudes of GCR (for the 10 GeV) for different solar magnetic cycles (qA >0 and qA<0) in the case of the existence and in case of the absence of the radial decay of the HA. It is seen from this figure, that the amplitudes of the 27-day variations behave very peculiar. In both cases for the existence and for the absence of the radial decay of the HA the amplitudes of 27- day variation of GCR are greater up to 1.5 –2 AU in the qA<0 magnetic cycle than that in the qA>0 cycle. This dependence qualitatively remains when HA and the HNS are shifted together to the southern hemisphere, too. These modelling results are a little different from our results obtained in [2],where amplitude of the 27- day variation was greater for all the distances in period of the qA>0 magnetic cycle, than in the qA<0.

CONCLUSIONS

1. An indication of the 22-year quasiperiodicity of the 27–day variation of GCR has been recognized.
2. A good correspondence of the amplitude of the 27-day cosmic ray variation with the longitudinal asymmetry is observed when qA<0, whereas at qA>0 the change of the amplitude of the 27-day cosmic ray variation follows to the polar coronal hole area.
3. For given model of modulation there are different dependences of the amplitude of the 27 day- variation of GCR in different epochs of the qA>0 and qA<0 solar magnetic cycles. In both cases, for the existence and for the absence of the radial decay of the HA, the amplitudes of the 27- day variation of GCR are greater up to 1.5 –2 AU in the qA<0 magnetic cycle than that in the qA>0 cycle. A shift of HA and HNS to the southern hemisphere (asymmetry of the heliosphere) and radial decay of HA diminishes the expected amplitude of the 27- day variation of GCR at Earth's orbit.

ACKNOWLEDGEMENTS

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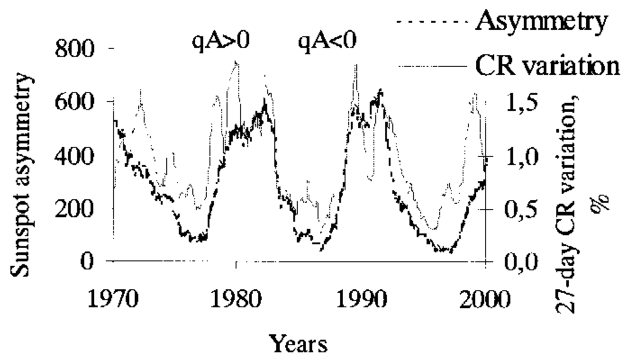

Fig. 1a Amplitude of the 27- day GCR intensity variation (Climax) compared with the longitudinal asymmetry of the sunspot area distribution in arbitrary units

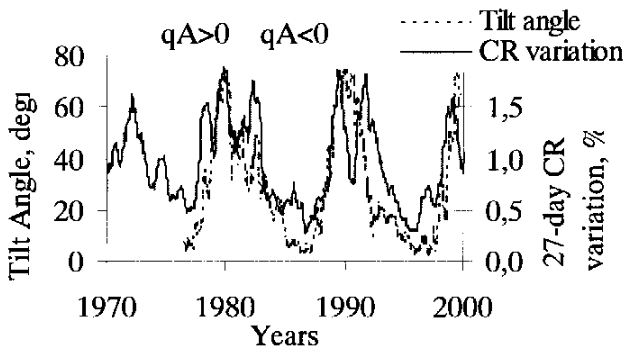

Fig. 1b Amplitude of the 27- day GCR intensity variation (Climax) compared with the tilt angle of HCS

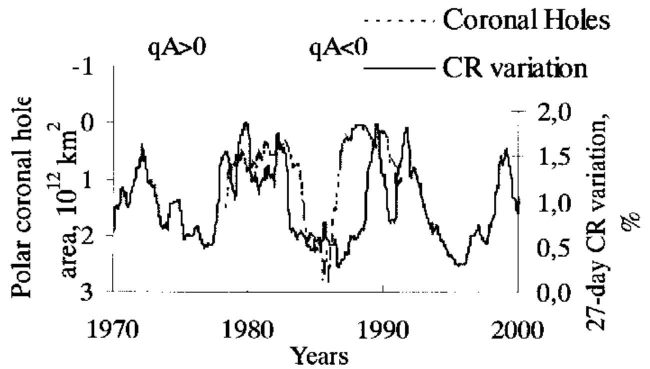

Fig. 2 Amplitude of the 27- day GCR intensity variation (Climax) compared with the polar coronal hole area (inverted)

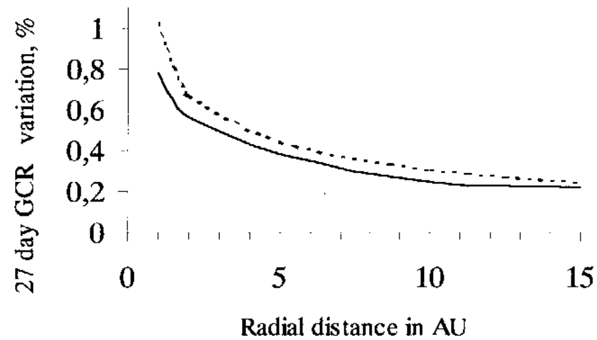

Fig.3. Changes of the amplitudes of the 27-day variation of GCR for the qA>0 solar magnetic cycle in the absence of the radial decay of HA. Solid line corresponds to the HA and the HNS shifted to–10^0S; dashed line - HA and HNS at the helioequator.

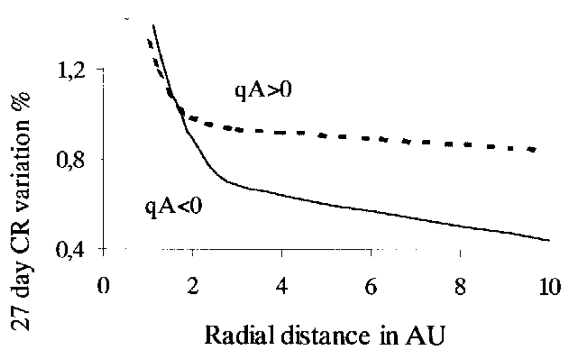

Fig.4a. Changes of the amplitudes of the 27-day variation of GCR for the qA<0 (solid line) and qA>0 (dashed line) in the absence of radial decay of HA

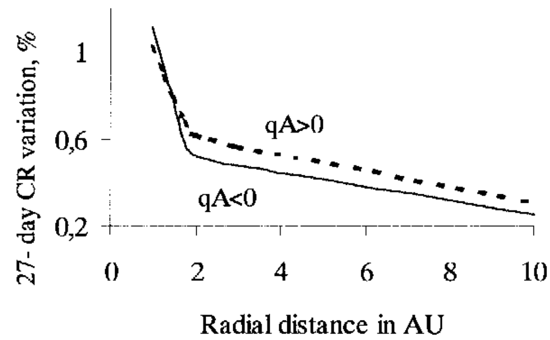

Fig.4b. Changes of the amplitudes of the 27-day variation of GCR for the qA<0 (solid line) and qA>0 (dashed line) in the existence of radial decay of HA