Proceedings of ICRC 2001: 3725 © Copernicus Gesellschaft 2001

ICRC 2001

27-day variations of cosmic rays for the minima epochs of solar activity: Experimental and 3-D drift modelling results

A. Gil and M. V. Alania

Neutron monitors, solar and geomagnetic activities data have been used to study the first and the second harmonics (27 and 13.5 days) of the variations of galactic cosmic rays connected with the rotation of the Sun. To compare the features of the character of the modulation of galactic cosmic rays in different solar magnetic cycles for the near minima and the minima epochs of solar activity, 1964-1966 and 1985-1987 (qA<0), and 1953-1955, 1975-1977 and 1995-1997 (qA>0) have been considered. It is shown that the amplitudes of both of the first and the second harmonics (27 days and 13.5 days) of galactic cosmic ray variations connected with the Sun's rotation are greater for the qA>0 solar magnetic cycle, than for the qA<0 magnetic cycle based on the data of neutron monitors.

INTRODUCTION

Richardson et al [1] have found clear evidence that the size of recurrent cosmic ray modulations is ~ 50% larger during the qA>0 cycle than during the qA<0 cycle. The behavior of the amplitudes of the 27-day variations of galactic cosmic rays in the minima epochs of solar activity for different solar magnetic cycles of the qA>0 and the qA<0 has been recently studded by Alania et al [2]. The noticeable quasiperiodic wave of the 27-day variation of GCR about (1-1.5)%, generally arises sporadically and exists during the 5-7 rotations of the Sun and then disappears. However, the quasiperiodic wave of the 27-day variation of GCR of (0.3-0.5)% continuously is existed even during the deep minima epochs of solar activity, when any recognizable quasiperiodic changes of the solar wind velocity are not observed. However, some heliolongitudinal asymmetry of the diffusion coefficient over the background white noise level must be present to cause the continuously existence of the amplitude of the 27-day variation of GCR of (0.3-0.5)%.

EXPERIMENTAL RESULTS OF 27-DAY AND 13.5 DAY VARIATIONS OF GCR

Using the harmonic analysis method the amplitudes of 27-day and 13.5 day variations of galactic cosmic rays have been calculated based on the data of neutron monitors, Climax and Huancayo-Halecala (1953- 1999), and

Table 1.

Station	Cut off rigidity in GV	Amplitudes of 13.5-day variations of GCR for different qA>0 and qA<0 magnetic cycles		Ratio of amplitudes of 13.5-day variations of GCR for different qA>0 and qA<0 magnetic cycles	Amplitudes of 27-day variations of GCR for different qA>0 and qA<0 magnetic cycles		Ratio of amplitudes of 27-day variations of GCR for different qA>0 and qA<0 magnetic cycles
		1975-77 qA>0	1985-87 qA<0		1975-77 qA>0	1985-87 qA<0	
Climax	3.03	0.42 ± 0.05	0.32 ± 0.04	1.31 ± 0.24	0.56 ± 0.05	0.39 ± 0.04	1.44 ± 0.31
Huancayo	13.45	0.25 ± 0.02	0.19 ± 0.03	1.32 ± 0.23	0.26 ± 0.01	0.21 ± 0.04	1.23 ± 0.32
Roma	6.32	0.31 ± 0.03	0.19 ± 0.01	1.63 ± 0.15	0.36 ± 0.02	0.21 ± 0.01	1.71 ± 0.19
Kiel	2.29	0.42 ± 0.05	0.32 ± 0.03	1.31 ± 0.21	0.54 ± 0.03	0.34 ± 0.04	1.59 ± 0.31
Tokyo	11.61	0.26 ± 0.02	0.19 ± 0.01	1.37 ± 0.13	0.29 ± 0.02	0.21 ± 0.03	1.38 ± 0.34

Kiel, Roma and Tokyo (1957-1999) for the five minima and near minima epochs of solar activity (1953-1955, 1964-1966,1975-1977, 1985-1987 and 1995-1997). Results of calculations are presented in Table 1 for two minima and near minima epochs of solar activity, qA>0 (1975-1977) and qA<0 (1985-1987). It is seen from this Table 1 that the amplitudes of 27-day variations as well of 13.5 day variations of GCR are greater in the qA>0 solar magnetic cycle than in the qA<0 cycle. The similar results for 27-day variations of GCR were obtained in [2]. This conclusion is dealing with the all minima and near minima epochs of solar activity and with the all neutron monitors data. Nevertheless, this conclusion is clearer dealing with the neutron monitors Climax, Kiel and Roma, whose cut off rigidities are less than 8-10 GV. The study of energy dependence of the above mentioned effect based on long period data is in progress.

MODELING OF 27- DAY VARIATION OF GCR

To describe the 27-day variations of GCR Parker's three dimensional (3-D) transport equation [4] 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.

As it has been mentioned above, the 27-day variation of GCR is sporadically phenomenon. However, if not to say anything about the minima epochs, even during the maxima epochs of solar activity there are observed lots of cases when the amplitude of the 27-day variation of GCR is relatively constant for the period of 4-5 rotations of the Sun. Thus, in order to show a dependence of the amplitude of the 27-day variation of GCR on the distances from the Sun in different solar magnetic cycles of the qA>0 and the qA<0, a steady-state case can be considered. Neglecting the term ∂N/∂t and taking into account that $K_{r\theta} = -K_{\theta r}$ and $K_{\theta\phi} = -K_{\phi\theta}$, the equation (1) in spherical coordinate system ρ , θ, ϕ, can be written:

$$A_1\frac{\partial^2 n}{\partial r^2} + A_2\frac{\partial^2 n}{\partial \theta^2} + A_3\frac{\partial^2 n}{\partial \phi^2} + A_4\frac{\partial^2 n}{\partial r\partial \phi} + A_5\frac{\partial n}{\partial r} + A_6\frac{\partial n}{\partial \theta} + A_7\frac{\partial n}{\partial \phi} + A_8\frac{\partial n}{\partial R} + A_9 n = 0 \qquad (2)$$

In the equation (2) the 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; the dimensionless distance $r = \rho/r_o$, where r_o is the size of the modulation region and ρ is the distance from the Sun; $A_1, A_2, \ldots, A_9$, are the functions of r, θ, ϕ, and R. Parameters being responsible for the 27-day variation of GCR have the following expressions:

1) the heliolongitudinal asymmetry of the solar wind velocity changes as,

$U = U_0\ (1 + 0.2\ Sin\phi)$. (3)

The interplanetary magnetic field (IMF) lines corresponding to the solar wind velocity $1.2U_0$ reaches to the IMF lines corresponding to the solar wind velocity U_0 at the radial distance of 7-8 astronomical units (AU). So, in order to exclude an intersection of the interplanetary magnetic field (IMF) lines in space the dependence of U on the heliolongitudinal angle ϕ (the expression (3)) takes place only up to the distance of 7 AU on the Sun's equatorial plane. This distance changes with the heliolatitudes according to the Parker's spiral rule of the IMF.

2)The parallel diffusion coefficient, $K_{||}$ is represented by the following way:

$K_{||}=K_0 K(r)\ K(r,\theta,\phi)\ K(R)$, where (4)

$K(r) = 1 + \alpha_0 r^{\beta}$, $K(R) = R^{\gamma}$, and

$K(r,\theta,\phi) = 1 + 0.5\ Sin\phi Sin(3\theta) Exp(-\alpha_1 r)$.

K_0 is equal to the 2×10^{22} $cm^2 s^{-1}$ for the energy of 1 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 $120^0 < \theta \le 180^0$, $K(r,\theta,\phi)=1$, $K(r) = 1 + \alpha_0 r^{\beta}$, 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 as:

1) $\alpha = (1 + \omega^2\tau^2)^{-1}$, where $\omega\tau = 300H\lambda R^{-1}$; H is the strength of the IMF and λ- the transport free path of GCR particles. At the Earth's orbit H = 5 nT, $\lambda = 2 \times 10^{12}$ cm, and ωτ =3, for the energy of 10GeV 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.

2) α= 0.1 and it is a constant for the whole heliosphere and

3) α= 0.1 near the helioequatorial region and enhances in the solar polar direction [5, 6]. The equation (2) has been solved numerically using the difference grid method taking into account drift due to gradient and curvature of the IMF and the heliospheric neutral sheet (HNS) drift.

The solutions of the equation (2) for the rigidity of 10GV of GCR are presented in Figures 1ab-3ab for the solar magnetic cycles, qA>0 (solid line) and qA<0 (dashed line) taking into account the above-mentioned expression of the solar wind velocity (3), diffusion coefficient (4), different ratios of α of the perpendicular $K_\perp$ and parallel $K_{||}$ diffusion coefficients ($\alpha = K_\perp / K_{||}$), for the constant values of the coefficients, α_0 =100, β =1, γ =1, and for different values of $\alpha_1 = 0$ (an absence of the radial decay of the HA) and $\alpha_1 = 0.07$ (an existence of the radial decay of the HA). In figure 1ab are represented the radial changes of the expected amplitudes of the 27- day variations of GCR for the $\alpha = 0.1$ at the Earth orbit and then changes depending on the spatial coordinates, as mentioned above, 1a) $\alpha_1 = 0$, and 1b) $\alpha_1 = 0.07$.

It is seen from the figure 1ab that the amplitudes of the 27-day variations of GCR for the both solar magnetic cycles of qA>0 and qA<0 are greater when the radial decay of the HA is absent. The amplitudes of the 27-day

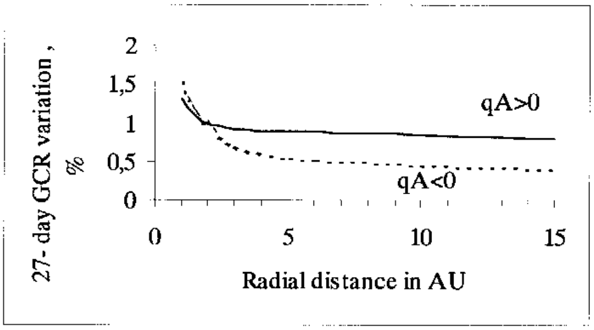

Fig. 1a. Radial changes of the amplitudes of the 27- day variation of GCR in the absence of the radial decay of the HA for changeable α (see text); solid line (qA>0) and dashed line (qA <0).

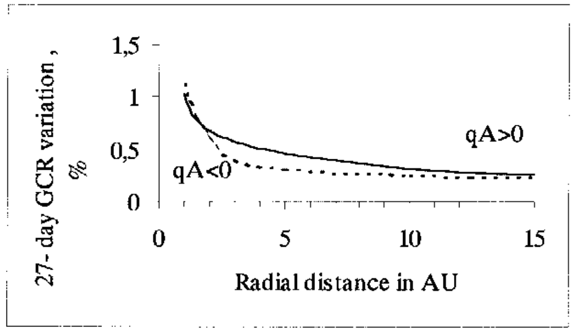

Fig. 1b. Radial changes of the amplitudes of the 27- day variation of GCR in the existence of the radial decay of the HA for changeable α (see text); solid line (qA>0) and dashed line (qA <0).

variations of GCR near the Earth's orbit are greater in the qA<0 solar magnetic cycle than in the qA<0 cycle for the both cases when the radial decay of the HA is absent, and when the radial decay of the HA exists. However, for distances greater than 1.5-2 AU the amplitudes of the 27-day variations of GCR for the case of qA>0 are greater than in the qA<0 case. These results do not coincide with our results of modeling for the Earth's orbit [3] and contradict the experimental results (Table 1). Here is necessary to underline the following. Unfortunately, we did not investigate yet how much the experimental results presented in Table 1 are freed from the influences of the changes of the parameters of the solar wind and solar activity (this work is in progress) on the one hand, and in our modeling we have not include any processes taking place during the different qA>0 and qA<0 solar magnetic cycle (structure of coronal holes, asymmetry of the heliosphere and so on) besides drifts due to gradient and curvature of the IMF and the HNS drift.

In figure 2ab are represented the radial changes of the expected amplitudes of the 27- day variations of GCR for the constant α ($\alpha = 0.1$) in the whole heliosphere, 2a) for $\alpha_1 = 0$, and 2b) $\alpha_1 = 0.07$.

From the figure 2ab one can see that the amplitudes of the 27-day variations of GCR for the both solar magnetic

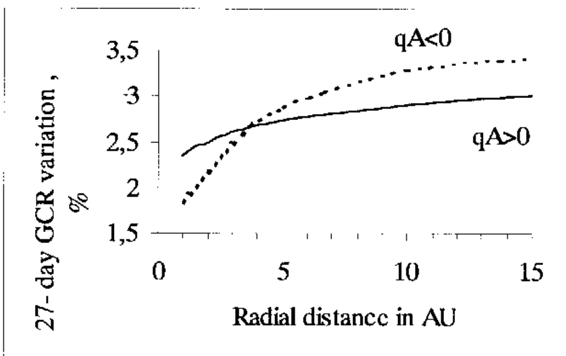

Fig. 2a. Radial changes of the amplitudes of the 27- day variation of GCR in the absence of the radial decay of the HA for constant α; solid line (qA>0) and dashed line (qA <0)

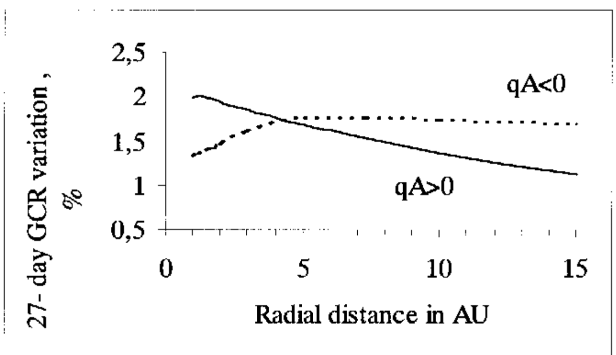

Fig. 2b. Radial changes of the amplitudes of the 27- day variation of GCR in the existence of the radial decay of the HA for constant α; solid line (qA>0) and dashed line (qA <0).

cycles of qA>0 and qA<0 are greater when the radial decay of the HA is absent. The amplitudes of the 27-day variations of GCR near the Earth's orbit are greater in the qA>0 solar magnetic cycle than in the qA<0 cycle for the both cases when the radial decay of the HA is absent, and when the radial decay of the HA exists. However, for distances greater than 4AU ($\alpha_1 = 0$) the amplitudes of the 27-day variations of GCR for the case of qA<0 are greater than in the qA>0 case. These results are in qualitatively agreements with the experimental results at the Earth's orbit (Table 1) and with results of modeling [2].

In figure 3ab are presented the radial changes of the expected amplitudes of the 27- day variations of GCR, 3a) for $\alpha_1 = 0$, and 3b) for $\alpha_1 = 0.07$. In the both figures 3ab, $\alpha = 0.1$ near the helioequatorial region and then enhances in the solar polar directions as,

$$\alpha = 0.2 - 0.06\theta, \text{ for } 0 \le \theta < \pi/2, \text{ and } \quad \alpha = 0.1 + 0.06\,(\theta - \pi/2), \text{ for } \pi/2 \le \theta \le \pi. \qquad (5)$$

It is seen from the figure 3ab that the amplitudes of the 27-day variations of GCR for the both solar magnetic cycles of the qA>0 and qA<0 are greater when the radial decay of the HA is absent. The amplitudes of the 27-day variations of GCR near the Earth's orbit is greater in the qA>0 solar magnetic cycle than in the qA<0 cycle for the both cases when the radial decay of the HA is absent, and when the radial decay of the HA exists. For distances less than 5AU the amplitudes of the 27-day variations of GCR for the case of qA>0 are greater than in the qA<0 case. These results qualitatively coincide for the Earth's orbit with results of modeling [2] and with the experimental results (Table 1).

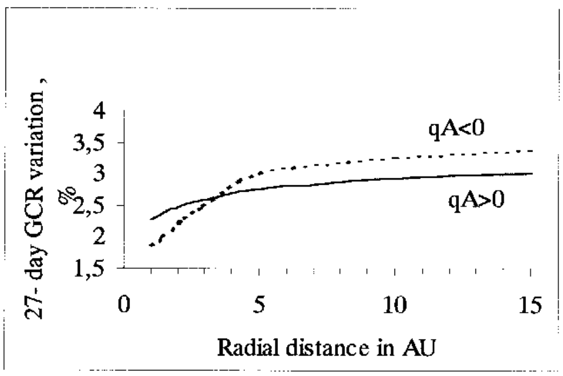

Fig. 3a. Radial changes of the amplitudes of the 27- day variation of GCR in the absence of the radial decay of the HA for changeable α; solid line (qA>0) and dashed line (qA<0).

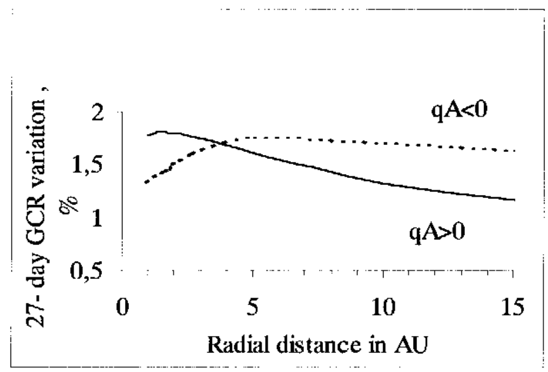

Fig. 3b. Radial changes of the amplitudes of the 27- day variation of GCR in the existence of the radial decay of the HA for changeable α; solid line (qA>0) and dashed line (qA<0).

CONCLUSION

1. The amplitudes of 27- day and 13.5 day variations of GCR are greater for the qA>0 solar magnetic cycle, than for the qA<0 magnetic cycle based on the data of neutron monitors [1, 2].
2. Results of modeling of 27-day variation of GCR qualitatively coincide with the experimental results when the value of parameter α is constant or changes with the heliolatitudes according to the expression (5).
3. The problem of the dependence of the amplitudes of the 27-day variations of GCR on the solar magnetic cycles (qA>0 and qA<0) needs a farther investigation based on the experimental data and theoretical modeling.

REFERENCES

1. Richardson, I.G., G. Wibberenz, and H.V.Cane, J.Geophys. Res., 104, 12549, 1999
2. Alania, M.V., D.G. Baranov, M.I. Tyasto, and E.S. Vernova, Adv. Space Res. 2001 (in press)
3. Alania, M.V., E.S. Vernova, M.I. Tyasto, and D.G. Baranov, Izvestia RAN, ser. fiz., 3, 2001 (in press)
4. Parker, E. N., Planet. and Space Sci., 13, 9, 1965
5. Kota, J., and J.R. Jokipii, 24th ICRC (Roma), 4, 680, 1995
6. Potgieter, M.,S.,Geophys. Res. 101, 24411, 1996
7. Potgieter, M., S., and S.,E.,S Ferreira., 26th ICRC (Salt Lake City), 7, SH 3-4, 21, 1999