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Annual variation of galactic cosmic ray intensity and the role of the heliospheric current sheet

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Abstract. The data of Kiel, Tbilisi and Tokyo neutron monitors have been used to study the features of the annual variation of the galactic cosmic ray (GCR) intensity during the last solar cycle (1986-1997). The study was conducted with the original data and with the data excluding Forbush decreases with a high latitude amplitude >3 %. To find the days of the Earth's maximum distance from the heliospheric current sheet, data from the computed source surface field maps of the Wilcox Solar Observatory were used. An attempt to reliably reveal a drift effect in the neutron monitors data without Forbush decreases was made. The mean free path of GCR drift in interplanetary space was calculated. For the qA>0 solar magnetic cycle the expected magnitude of the annual variation and of the bi-directional heliolatitudinal gradient (caused by the gradient and curvature drift of GCR in the interplanetary magnetic field) based on the solution of the steady state Parker 2-D transport equation are in fair agreement with the results deduced from neutron monitors. However, we found noticeable differences between the modelling and the experimental results for the qA< 0 period of the solar magnetic cycle.

1 Introduction

The annual variation is subject for investigation during long time (see e.g. Dorman and Gushchina 1977, Alania et al., 1990, Gigolashvili et al., 1997). In spite of this fact, there are many different opinions about its existence and features. Earth's heliographic latitude changes during Earth's annual moving around the Sun and produces CR annual variation. The existence of the latitudinal gradient from equator toward poles from the CR direct measurements (Ulysses data, see e.g. McKibben, 1998) is obvious.

Latitudinal gradients direct measurements in the space are limited by fixed time interval and by low energies of particles. Therefore, it is very interesting to study features of latitudinal gradients using data of ground based observations.

It is possible to investigate some characters of interplanetary media using amplitude of the annual variations and drift effects, observed during different phases of different solar activity cycles, which couldn't be obtained by other methods.

2 The Data and Method

The average monthly data of CR neutron monitors of the stations Tbilisi, Kiel, Tokyo, and daily data of the station Kiel during last solar activity cycle (1985-1997) were used. To reveal drift effects, caused by latitudinal gradients, data from the computed source surface field maps of the Wilcox Solar Observatory (WSO) (http://wso.stanford.edu) and interplanetary magnetic field (IMF) direct measurements (http://nssdc.gsfc.nasa.gov/omniweb) were used. As usual, CR intensity Forbush decreases (Fds) have significant influence on the other CR variations and it is very difficult to separate them. Therefore, the study was conducted with the original data and with the data excluding Fds with a high latitude amplitude >3 % according to Despotashvili et al. (2001).

CR daily detrended intensity was treated by standard Fourier analysis to determine the phase and amplitude of annual variations. Also, monthly data of CR neutron monitor stations Kiel, Tbilisi and Tokyo were used to determine the rigidity dependence of annual variation.

The distribution of phases and amplitudes of the first harmonic of the annual variation during 1986-1996 are given in Fig.1. The differences between the results, based on the monthly and daily data are neglected. From Fig.1 it is clear that the phases of the annual variation during 1987 and 1996 are near March (when the Earth is maximally shifted to the Sun's South pole), and – near September (when the Earth is maximally shifted to the Sun's North pole) during 1988, 1989, 1992 – 1994. Below we discuss

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details of only the above mentioned years. It is found that the annual variation is described very well by the first and second harmonics.

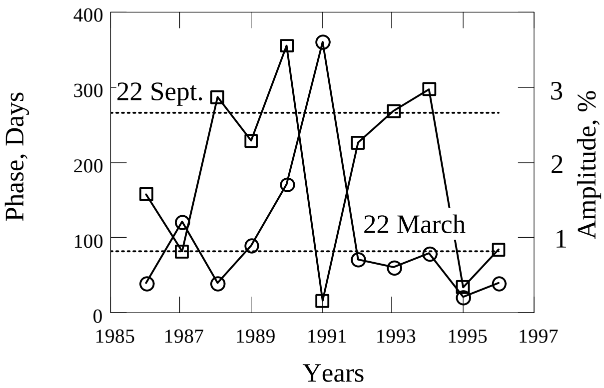

Fig.1. Distribution of the phases (boxes) and amplitudes (circles) of the first harmonics of the annual variation during 1986-1996 according to the corrected for the Fds daily data of Kiel (Germany) neutron monitor.

For the analysis of the connection of annual variations with neutral sheet, we defined 2 days for each 13 Bartels rotation of each year, when the Earth is maximally shifted from the neutral sheet to the South or to the North. For this purpose the computed source surface field maps of WSO were used. In contrast to Gigolashvili et al. (1997) we used the following value to reveal annual variations:

$$D_N = (I_N^+ + I_N^-) / 2 \tag{1}$$

where I_N^+ corresponds to the CR daily intensity during N[th] rotation, when the Earth is in the positive sector (the magnetic field is directed away from the Sun) and I_N^- – to the negative sector (the magnetic field is directed toward the Sun) and the Earth is at maximum distance from the neutral sheet.

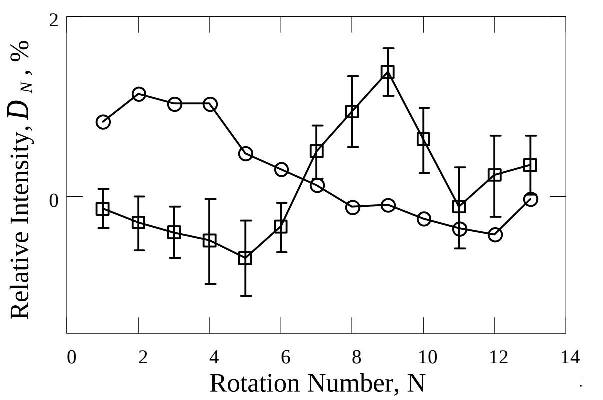

Fig.2. The annual variation of the averaged value of D_N during 1988, 89, 92 – 94 (boxes) and 1987, 1996 (circles). Two values of detrended 3-day running averaged daily data of Kiel (Germany) neutron monitor corresponding to the Earth's maximum distances from the neutral sheet were used for each rotation. Data are corrected for all Fds (and some observed CR flares).

3 Discussion of the Results

In Fig.2 we show the average changes of D_N according to the Sun's rotations for the following years: 1988, 1989, 1992-1994 (boxes) and 1987,1996 (circles). It is clearly visible that phases of annual variation are near March or September (compare with Fig.1).

The analysis Fig. 2 allows us to conclude that D_N is a very good quantity to describe CR annual variations. Therefore, we suppose, that I_N^+ and I_N^- are suitable quantities for determination of drift effects during 1-year variations.

Let us assume that the galactic CR relative intensity during the positive and negative IMF sector polarity (I_+ and I_- respectively) equals to :

$$I_+ = I_0 \pm l_{Drift} \cdot |G_Z| \tag{2}$$

$$I_- = I_0 \mp l_{Drift} \cdot |G_Z| \tag{3}$$

where signs '+' and '-' correspond to latitudinal gradients directed northward (1988,1989, 1992-1994 years) and southward (1987 and 1996 years) respectively. Here I_0 – average relative intensity during the Sun's one rotation; λ_{Drift} (AU) - is the free path of particles for the drift diffusion; and G_z (% / AU) – is the latitudinal gradient in interval of heliolatitude -7.25^0 – $+7.25^0$ (about 0.25 AU). From Eq(s). (2), (3) we have:

$$d = I_+ - I_- = \pm 2 l_{Drift} \cdot |G_Z| \tag{4}$$

We found that the signs of value d ('drift effect'), determined this way were exactly as it was expected. Only, for 1996 it was necessary to shift zero days (moments of maximum distance between the Earth and neutral sheet) forward on three days in contrast to another years.

On the Fig. 3 we present the distributions of average value d for the periods, when the heliolatitude gradient is directed to the North (boxes) and South (circles).

In the assumption – the amplitude of annual variation is direct proportional to the CR heliolatitude gradient, we found that the mean free path for drift during 1987 and 1996 equals to 1.4 $\pm$ 0.6 (AU) and for years 1988, 89, 92-94 – to 3.0 $\pm$ 0.8 (AU). It's clear that they are comparable with parallel mean free path (see e.g. fig.5 in Bieber, 1998).

3.1 Important Note about Terminology

A bi-directional latitudinal gradient was predicted and determined from different observations (see e.g. Kota and Jokipii, 1983; Bieber and Chen,1991; Chen and Bieber, 1993; Simpson et al., 1996; Heber et al., 1996; Hall et al., 1996, 1997; Bieber, 1998; McKibben, 1998; McKibben et al., 1998). The bi-directional latitudinal gradient has a maximum at the neutral sheet during the negative solar activity polarity state and reverses in the positive solar activity polarity. During the positive solar activity polarity the southward displacement of the axis of symmetry with > 7.25^0 leads to the annual variation with maximum in September, when one uses the ground level observation. The northward displacement of the axis of symmetry with > 7.25^0 leads to the annual variation with maximum in March. So when we say that the latitudinal gradient of the CR density is directed in the North or South, we mean its direction in interval of the heliolatitude -7.25^0, $+7.25^0$.

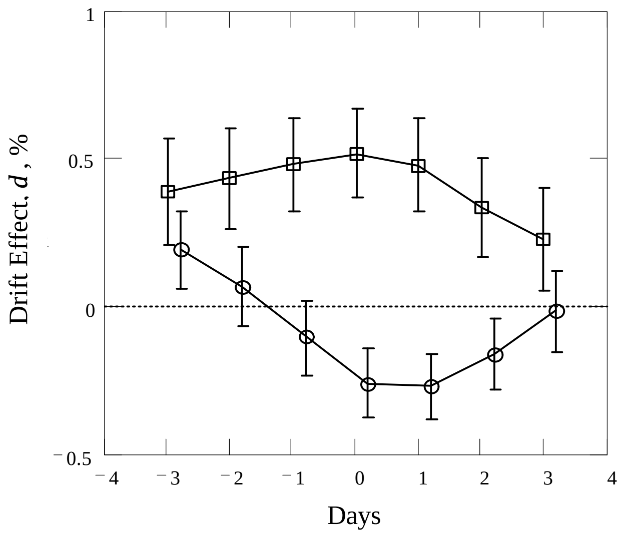

Fig.3. The results of superposed epoch analysis for the 'drift effect' (*d*) during the periods, when the heliolatitude gradient is directed to the North (boxes, 65 zero days) and South (circles, 26 zero days). To guide the eye the bottom plot is little shifted.

3.2 About 3-days Shift

Above we noted that to reveal the drift effect during 1996 year, we had to shift zero days (moments of the Earth's maximum distance from the heliospheric current sheet) forward on three days in contrast to another years. We compared magnetic field directions determined by WSO magnetic field maps with IMF direct measurements (OMNI data) to investigate this effect. We observed that good agreement between these data is for only 65 % during 1987 if we don't use any shift of days. When shift (delay) is +3 days, good agreement is for only 50% of data. But, during 1996 we have the contrary situation – for +3-4 days shift the best agreement is for 80 % of cases, and without shift – only for 50% of cases. This fact explains the nature of 3-days delay. So, we conclude that the data of the computed source surface field maps of WSO are very useful for the investigation of the CR variation depended on IMF direction.

4 Numerical Calculation

Most modelling of the latitudinal gradient has not fully taken into account the neutral sheet effects and assumed a flat current sheet. Kota and Jokipii (1983) have discussed the effect of a wavy neutral sheet on the CR density and found that the minimum will be shifted from the sheet, but there aren't any displacements if one considers averaged data during one rotation.

The surprising phenomena observed during the Ulysse's fast latitude scan – the southward displacement of the axis of symmetry of CR modulation, cannot be supported by IMF and solar wind observation (Simpson et al., 1996; McKibben et al., 1998; McKibben 1998). However the numerical calculation of the simple 2-D transport equation with drift in the stationary case for the Parker's IMF for the flat neutral sheet gives some good agreements with observed annual variation and bi-directional latitudinal gradients. In the same boundary conditions as Alania et al. (1997), we present results of the numerical calculation of the GCR transport equation (Dorman , 1975) below:

$$\nabla_i (K_{ik} \nabla_k n) - \nabla_i (U_i n) + R/3\, (\partial n / \partial R)(\nabla_i U_i) = 0 \quad (5),$$

where K_{ik}, n and R are diffusion tensor, density and rigidity of GCR respectively, U is the solar wind velocity.

Under the assumptions that the parallel diffusion coefficient $K_{||}$ and solar wind velocity vary with heliolatitude as shown below (Fig.4), we present results of the numerical calculation for the CR density distribution with heliolatitude at 1 AU for the particles with rigidities 20GV and 100GV (Fig.5).

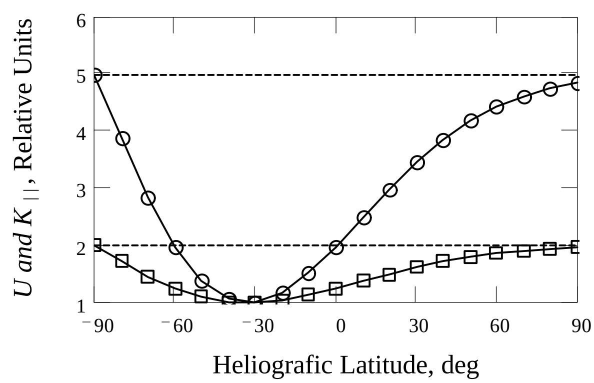

Fig.4. Solar wind velocity (U, boxes) and parallel diffusion coefficient ($K_{||}$, circles) against the heliografic latitude at 1 AU.

Expected values of the latitude gradients are 2.8 % / AU and 0.5%/AU for the particles with rigidities 20 GV and 100 GV respectively, which are in good agreement with results calculated from the solar diurnal variation recorded by neutron monitors and meson telescopes (Hall et al.,1997).

The spectral index of the latitudinal gradient is equal to -1.07. This value is in satisfactory agreement with the annual variation rigidity dependence received by monthly data of Kiel, Tbilisi and Tokyo neutron monitors – -(0.6-0.9).

We investigated the influence of the solar wind velocity and parallel diffusion coefficients on the density distribution. We found that the solution of CR 2-D transport equation is weakly dependent on the asymmetry and value of the solar wind velocity. A best fit to observational data occurs when the parallel diffusion coefficient increases 4-5 times from equator toward poles. However our model does not fit the observational data during the negative solar activity polarity.

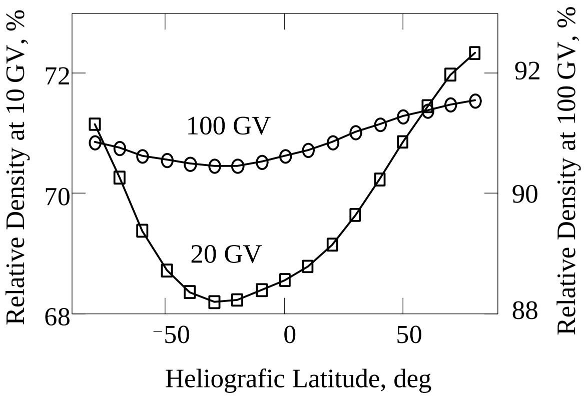

Fig.5. The distribution of the expected relative density of GCR at 1 AU, for the different rigidities.

5 Summary

The observation of CR intensity annual variation gives possibility to investigate important features of the latitudinal behaviour of CR density.

To investigate the fine structure of CR variations it is important to exclude the influence of Fds on the different types of CR variations. The drift effect in the CR intensity was revealed, which is impossible without taking into account Fds.

We calculate the mean free path for drift. It is comparable with parallel mean free path.

The numerical calculation of the simple 2-D transport equation with the drift in the stationary case for the Parker's IMF for the flat neutral sheet gives good agreement with the observed annual variation and bi-directional latitudinal gradients. We found that the solution of the CR transport equation is weakly dependent on the asymmetry and value of the solar wind velocity. A best fit to observational data occurs when the parallel diffusion coefficient increases 4-5 times from equator toward poles. However, we found noticeable differences between the modelling and the experimental results for the qA< 0 period of the solar magnetic cycle.

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References

Alania, M.V., Bochorishvili, T.B., Despotashvili, M.A., Nachkebia, N.A., and Rogava, O.G., *The influence of the sun's magnetic moment change on the different classes of cosmic ray variations, Proc. 21th ICRC, 6,* SH 6.1-25, 1990.

Alania, M.V., Bochorishvili, T.B., and Iskra, K., *Feachures of galactic cosmic ray modulation in different epochs of solar activity, Adv.Space Res. 19, 6,* 925-928, 1997.

Bieber, J.W., *Remarks on the diffusion tensor in the heliosphere. Space Sc. Rev., 83/1-2,* 336-344, 1998.

Bieber, J. W. and Chen, J., *Cosmic ray diurnal anisotropy, 1936-1988: Implications for drift and modulation theories, Astr. J., 372,* 301-313, 1991.

Chen, J. and Bieber, J. W., *Cosmic ray anisotropies and gradients in three dimensions, Astr. J., 405,* 375-389, 1993.

Despotashvili, M.A., Nachkebia, N.A., and Flückiger, E.O., *Recurrent variations and Forbush decreases of galactic cosmic ray intensity, Proc. 27th ICRC,* 2001.

Dorman, L.I., *Variations of galactic cosmic rays,* 122-144, Moscow, 1975 (in Russian).

Dorman, L.I. and Gushchina, R.M., *Relation of the 11-year and annual cosmic ray variations to the heliolatitude index of solar activity according to the spots and the green corona line. Proc. 15th ICRC, 3*, 263-267, 1977.

Gigolashvili, M.Sh., Nachkebia, N.A., Novalov, A.A., and Shatashvili, L.Kh., *Annual variations of cosmic ray intensity and anizotropy, Proc. 25th ICRC , 2,* 141-144, 1997.

Hall, D.L., Duldig, M.L., and Humble, J.E., *Analyses of sidereal and solar anisotropies in cosmic rays, Sp. Sc. Rev., 78,* 401-442, 1996.

Hall, D.L., Duldig, M.L., and Humble, J.E., *Cosmic ray modulation parameters derived from the solar diurnal variation, Astr. J., 482*, 1038-1049, 1997.

Heber, B., Droge, W., Kunow, H., Muller-Mellin, R., Wibberenz, G., Ferrando, P., Raviart, A., and Paizis, C., *Spatial variation of > 106 Mev proton fluxes observed during Ulysses rapid latitude scan: Ulysses COSPIN/KET results, Geophys. Res. Lett. 23,* 1513-1516, 1996.

Kota, J. and Jokipii, J.R., *Effects of drift on the transport of cosmic rays. A three-dimensional model including diffusion, Astr. J., 265*, 573-581, 1983.

McKibben, R.B., *Three-dimensional solar modulation of cosmic rays and anomalous components in the inner heliosphere, Space Sc. Rev., 83/1-2,* 21-31, 1998.

McKibben, R.B., Burger, R.A., Heber, B., Jokipii, J.R., McDonald, F.B., and Potgieter, M.S., *Latitudinal structure of modulation in the inner heliosphere. Space Sc. Rev., 83/1-2,*188-193, 1998.

Simpson, J.A., Zhang, M., and Bame, S., *A solar polar north-south asymmetry for cosmic ray propagation in the heliosphere: The Ulysses pole-to-pole rapid transit, Astr. J., 456,* L69-L72, 1996.