The model of galactic cosmic ray modulation during 21-23 solar cycles

Anatoly V. Belov, Raisa T. Gushchina, Vladimir N. Obridko, Berta D. Shelting, Victor G. Yanke

Abstract— **The previously-proposed model of cosmic ray (CR) modulation in the heliosphere, which considers the relation of the long-term CR variations with the changes of characteristics of the solar magnetic field, has been used to estimate the observed CR variations for 1976-2005. It is shown that the discrepancy between the model and observations increases beginning from the middle of 2000 till 2005 and this period is the most complex for the considered model. In order to improve the semi-empirical model of the CR modulation it is proposed to consider jointly characteristics of the solar magnetic field and solar flares indices N_x and n_x. The special flares indices N_x calculated for the different parameters characterizing the power and longitude distribution of the intensive X-ray flares. In addition to selected indices of the solar magnetic field, which allow describing the long - term CR variations, the updated model has been tuned for more reliable presentation of short - term variations.**

I. Introduction

The present study of galactic cosmic ray modulation in the heliosphere through the 19-23 cycles of the solar activity is a continuation of our previous works [1-5] and is based on the long term distribution of CR obtained by the neutron monitor network. For the semi-empiric model of CR modulation a combination of characteristics of the solar magnetic field (with detailed justification of such a choice) and the index of solar flare activity additionally introduced have been used. The purpose of such a choice is to express the solar cycle observed in CR variations as a complex interaction of two systems of fields in the heliosphere: global and local. A rather adequate model description of long term CR variation (and partly short term) up to 2000 can be obtained using structural and quantitative characteristics of the solar global magnetic field as: a heliospheric current sheet tilt - η, a module and sign of the solar polar field - H_{pol} and the average magnetic field intensity B_{ss} calculated on the surface of solar wind source. Beginning from 2000 a discrepancy between the observed CR variations and their model representation is increased. In order to understand a modulating influence of local solar activity on CR it is proposed to use N_x, a specially calculated index of solar flares.

Improving of the modulation model, caused by a necessity to represent adequately a role of variations with the shortest period and the modulation during the declining phase of the 23rd solar cycle in the global picture of CR modulation, is a purpose of this work.

II. Data and Method

Initial data for modeling of CR variations are long-term observations of CR intensity and characteristics of the solar global magnetic field. The rigidity spectrum of CR variations for each month was obtained from the data of neutron monitors of the entire global network of CR stations, stratospheric sounding data and space monitoring of CR variations for 1976–2005. Here we study amplitude variations of CR with 10 GV rigidity, excluding variations associated with ground level enhancements of CR intensity. Note that a value of this effect is greater than 3% even for monthly averaged amplitude values for some events and particular CR stations used in our analysis. Thus, in this case amplitude of long term CR variations with 10 GV rigidity obtained by using the method of global survey becomes a value of pure galactic origin and free from influence of solar particles. Calculations of CR modulation have shown that such amplitude improves the proposed modulation model.

Characteristics of the solar field (η, B_{ss} and H_{pol}) are calculated for surface of the solar wind source. The choice of such a set of solar activity indexes and methods of their evaluation were described in details previously in [1-2] and [5,6]. Here we used data of measurements of the large - scale photosphere magnetic field with magnetometer resolution of (3′) performed in Stanford in 1976 – 2005 [7] and processed by the original method described in [8]. There is a problem of the magnetometer sensitivity in results of solar field observations in 2000-2002 and, possibly, after recalibration the data set is not uniform. In this model of CR modulation have been used observable magnitude and sign of the polar magnetic field H_{pol}. Magnetic field data were corrected according to [9] for saturation of the magnetograph signal in dependence on the cycle phase and latitude of the point of observation. Model description of CR variations allowed the preferable version of correction to be chosen from those offered by heliophysicists under processing of the observed solar magnetic fields.

This program has been supported in part by the RFBR (grants 05-02-17251, 04-02-16763 05-02-16090) and the Presidium of Russian Academy of Sciences (the program "Neutrino physics").

All authors are with the Pushkov Institute of Terrestrial Magnetism, Ionosphere and Radio Wave Propagation (IZMIRAN) Russian Academy of Sciences, 142190, Troitsk, Moscow region, Russia. Fax: +7 - 495 - 334 01 25. (corresponding e-mails: abelov@izmiran.ru, rgus@izmiran.ru, obridko@izmiran.ru, shelting@izmiran.ru), yanke@izmiran.ru.

In order to understand a modulating influence of local solar activity on CR it is proposed to use N_x, a specially calculated index of solar flares. The index of solar flares N_x accounts a class of X-ray event (events of >M1 have been selected) and its longitude position. The daily average flare index $N_x = \Sigma F_x / n_d$, where n_d - a day number per month, has been calculated for

$$F_x = \left[1 + \alpha \ln\left(\frac{I_x}{I_c}\right)\right] \exp\left(-\left(\frac{\varphi - \varphi_0}{\sigma_\varphi}\right)^2\right) \qquad (1)$$

where $F_x = 0$ if $I_x \langle I_c$ (I_x – the maximum flux of X-ray event, $I_c = 10^{-5}$ W/m^2), $\sigma_\varphi = \sigma_E$ for $\varphi \langle \varphi_0$; $\sigma_\varphi = \sigma_W$ for $\varphi \rangle \varphi_0$. It is supposed $\sigma_W = \sigma_E / 2$. The evaluation of N_x is performed for longitudes $\varphi_0 = -15^\circ, -10^\circ, -5^\circ, 0^\circ$ and $\sigma_\varphi = 20^\circ, 30^\circ, 40^\circ, 48^\circ, 50^\circ, 56^\circ$. Given values of the α parameter are $\alpha = 0.5; 0.8; 1.0; 1.2; 1.5; 2.0$ in this work.

The n_x index, a total number of $\geq$M1 X-ray events, was used in this work for reasons of comparison and determination of a role of longitude distribution of active regions on the Sun for created CR modulation. The performed modeling allows estimating a relative impact of temporal changes of each parameter with its own time delay τ to the total modulation. Fitting of the CR modulation becomes much more accurate, if it is performed for cycles of the same polarity.

III. MODEL RESULTS OF CR MODULATION

The analysis of expected CR variations for the whole period of 1976-2005 has showed that for three model parameters (the current sheet tilt η, average magnetic field intensity on surface of the solar wind source B_{ss} and polar field H_{pol}) the observed details are not presented properly in the picture of expected CR modulation (Fig.1a) especially during the maximums of the solar activity, however, the model describes rather well general tendencies of CR variations and provides good regression characteristics (the correlation coefficient ρ = 0.89 and the mean square deviation σ = 2.75).

Improving of the model was performed by solving the four parameter problem with adding flare indexes (N_x or n_x). This allows improving representation of observed CR variations (Fig.1b). The results for both variants appears to be rather close with ρ = 0.93 and σ = 2.13%. The description of flare influence on CR modulation with the N_x index provides the best result for effective range of longitudinal distribution σ_φ =40°, 48°, 56° for all parameters φ_0 and α =1.0 ; 1.2; 1.5; 2.0 presented above τ In a case of the N_x index delay times are τ_{Nx} = 11months, τ_{Bss} = 2 months, τ_η = 12 months, τ_{Hpol}= 8 months and in a case of using n_x these times are τ_{nx} = 7months, τ_{Bss} =4 months, τ_η = 14 months, τ_{Hpol}= 0 months. The delay time of CR modulation relative the flare activity obtained in our model of long - term modulation shows that the flare influence is rather prolonged in the heliosphere. However, one needs to keep in mind that values of the time delay have been obtained from regression analysis and may not be recommended for evaluation of dimensions of the modulation region.

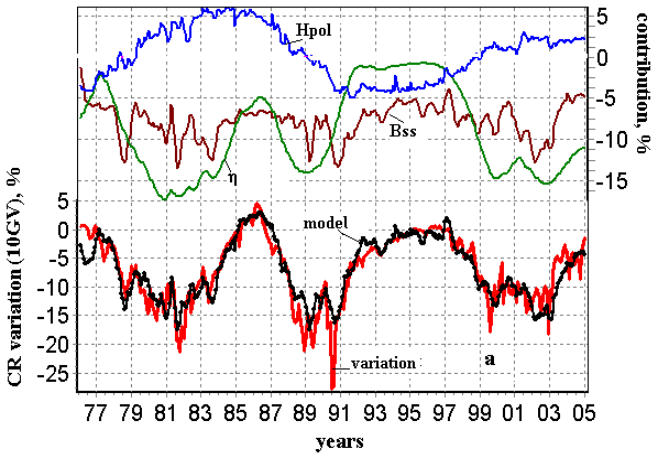

Fig.1 a) Monthly CR variations observed and simulated by the 3-parameter model for 1977 – 2005 (% of CR intensity in 1976, bottom); impact (%) of H_{pol}, B_{ss} and η changes to the model variation (top);

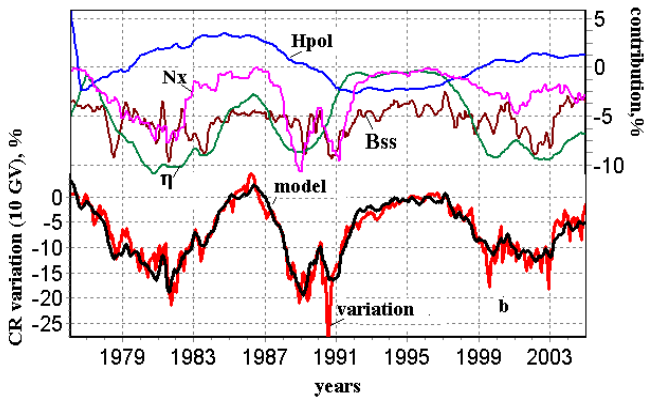

Fig.1 b) The observed and model variations for the same parameters as in (a), but considering as well the flare index N_x.

IV. CR MODULATION DURING THE DECAY PHASE OF THE 23rd CYCLE

The model for both analyzed flare indexes shows sharply a large discrepancy with observations in the beginning of 2000, before that time in 1977-1999 (Fig. 1c) ρ = 0.948 and σ = 2.0%.

The period of 7.1999- 12.2005 is very difficult for separate analysis and description in the frame of the proposed model. In this case with using the N_x index for description of the modulation the regression parameters are ρ = 0.87 and σ = 1.87% (for the n_x index - ρ = 0.85 and σ = 1.97%), the current

sheet tilt and changes of the flare index are most effective for the modulation (Fig.2).

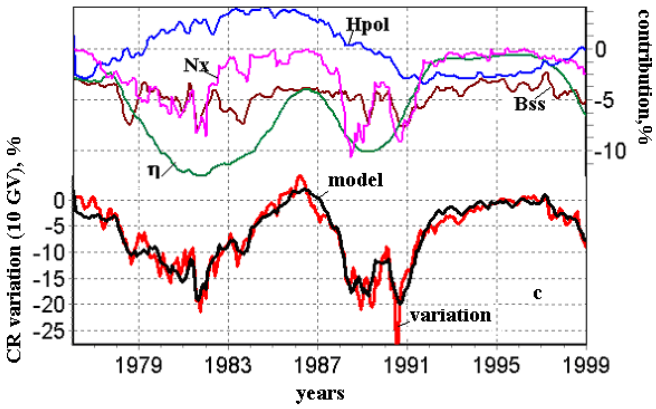

Fig.1 (c) the observed and model CR variations for the four parameter model (see (b)).

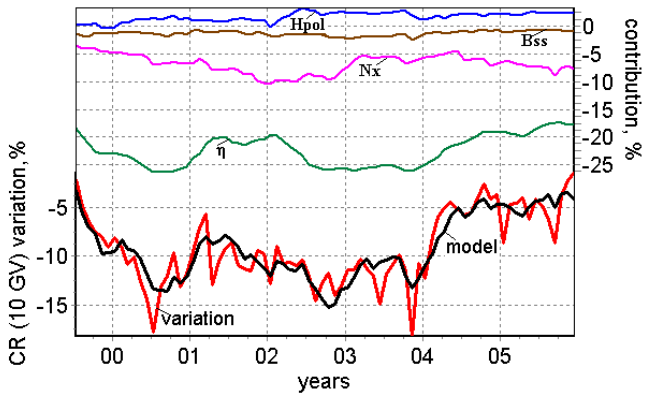

Fig. 2 Expected and observed CR variations during the decay phase of the 23rd solar cycle (bottom), impacts of N_x, B_{ss}, H_{pol} and η changes to the modulation (top).

The neutral current sheet plays an important role in the CR modulation by intensification of their radial and latitudinal (for large tilt values) transport, a dimension of low latitudinal region of the solar wind with lower values of average solar wind velocity and more effective interaction of flows with different velocities are associated with the tilt. This region has, apparently, a better ability of CR modulation. Possibly, it is important that coronal mass ejections occur preferably near the current sheet.

Another feature of the declining phase of the 23rd cycle is its enhanced disturbances. This decay phase is the most active considering the Sun and the solar wind (the events of 2003 and 2004 autumns) for the whole history of solar-terrestrial studies. This period differs by the large input of solar mass and energy into the heliosphere, not only the equatorial region has been active, but also the magnetic flux from polar regions has been enhanced that according to [10] might be associated with increased dipole component of the solar magnetic field. All these facts are directly associated with the integral heliospheric index as the CR density.

Possible reasons for discrepancy between the observed and expected CR variations are: a) Using of non-uniform data set of solar field observations in this study (during the period of 2000-2002 there was a problem with the magnetometer sensitivity and, possibly, data after the recalibration were not sewed well with previous data). Possibly, verifying this assumption it would be necessary to use CR variations together with IMF observations as a test for checking the data processing of solar magnetic field observations; b) Particular features of the current solar cycle need to account an influence of other modulating parameters. Note, the 2-nd maximum of solar Sun spot number has been observed in 2001, the current sheet tilt has not been decreased considerably during about 5 years (till the middle of 2004 it was varied from 74º to 60º and was ≈ 40º in the end of 2005) as also shown by the impact of η changes to the observed CR variations.

Note that by incorporating the flare index into the model we improve the model description of CR variations as for the whole period considered well as for periods of same polarity of the solar global magnetic field. Separately were modeled long - term CR modulation during periods of 5.90-6.99 (qA>0), 3.80-4.90 (qA<0), for 7.99-12.05 (a part of the qA<0 cycle) and 01.77- 3.80 (a part of the qA>0 cycle). Initially the model with three parameters was used (η, *Bss* and two variants of the flare index (N_x and n_x). It is obtained that in both cases the model describes well the observed variations (ρ = 0.95÷0.96 and σ =1.87÷1.92), but a more close connection is obtained for *Nx* and the qA>0 cycle. It seems that the model description provides, however, different pictures of the process: if for qA>0 the main role play the flare index and a filed value on the source surface, but for qA<0 the current sheet plays this role (according to the drift theory in a such field configuration a drift of particles occurs along the current sheet and its structure is important for the modulation).

V. CONCLUSION

Excluding an influence of variations associated with particles of ground level enhancements for description of long-term CR modulation during the 21-23 solar cycles helps to create the adequate model of CR modulation. In order to account short - term CR variations and, therefore, improve the CR modulation model it is proposed to use the flare indexes along with combination of characteristic of the solar magnetic field used previously (the heliospheric current sheet tilt, the average solar magnetic field intensity and the solar polar field with its sign). One of them is a total number of X-ray events (>M1) - n_x, the other - N_x - is evaluated from the maximum X-ray intensity and longitude position of the event.

It is shown that additional accounting of the flare activity improves the model description of long - term variations for both proposed indexes providing similar results (for all values of effective longitude dimension σ_φ, φ_0 and α given above). This picture, but with increasing of tight correlation, is observed for modeling of CR variations during periods with same solar magnetic field polarity as well.

The model provides with high accuracy the picture of long term variations till 2000, after that the discrepancy with observations is increased. The features of modulation behavior during the declining phase of the 23rd cycle are revealed, which are problematic for the considered model description of CR modulation.

ACKNOWLEDGMENT

The authors thank the Russian Foundation for Basic Research and the Presidium of Russian Academy of Sciences (the program "Neutrino physics") for supporting this theme of works, as well as the staff of CR stations, who have obtained the data used in this analysis

REFERENCES

[1] Belov A.V. et al. "Global magnetic field of the sun and long-term variations of galactic cosmic rays", J. Atmos. Terr. Phys., Vol .63, N18, 2001, pp. 1923 - 1929.

[2] Belov A.V. et al. "Relation of the Long-Term Modulation of Cosmic Rays to the Characteristics of the Global Solar Magnetic Field," Geomagnetism and Aeronomiya, Vol. 42, N 6, 2002, pp. 693 -- 700.

[3] Belov A.V. et al. "On the possibility to forecast long – term variations of galactic cosmic rays", Izv. RAN. Ser. Fiz., Vol. 67, 2003, pp. 508 - 510.

[4] Belov A.V. et al. "Prediction of GCR Variations during the Next Solar Cycle Based on Various Magnetic Observations", Geomagnetism and Aeronomiya, Vol. 45, N 2, 2005, pp.155 - 161.

[5] Belov A.V. et al. "Long term variations of galactic cosmic rays in the past and future from observations of various solar activity characteristics", J. Atmos. Terr. Phys, Vol. 68, N 11, 2006, pp.1161 – 1166.

[6] Belov A.V. et al. "The spectrum of cosmic rays variations during 19-22 solar cycles", Proc. 23-rd ICRC, Vol. 3, 1993, pp. 605 - 608.

[7] Belov A.V. et al. The relation of the global magnetic solar field indices and the solar wind characteristics with the long-term variations of galactic cosmic rays", Proc. 29th ICRC, Vol.2, 2005, pp. 239 - 243.

[8] R.K. Ulrich Analysis of Magnetic, "Fluxtubes on the Solar Surface from Observations at Mt. Wilson of A5250; A5233", 7th Cambridge Workshop on "Cool Stars", ASP Conference series, Vol. 26, 1992, pp. 265 - 267.

[9] Obridko V.N., B. D. Shelting "Structure of the heliospheric current sheet as considered over a long time interval (1915-1996)", Solar Phys. Vol.184, 1999, pp. 187 - 200.

[10] Makarov V.I. et.al. "The Increase in the Magnetic Flux from the Polar Regions of the Sun over the Last 120 Years Astronomy Reports, Vol. 45, No. 9, 2001, pp. 746 – 750. Translated from Astronomicheski Zhurnal, Vol. 78, No. 9, 2001, pp. 859 – 864.