GALACTIC COSMIC RAY SPECTRA DURING SOLAR CYCLE

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Abstract: *Parker's transport equation expresses the basic physical processes affecting the cosmic ray (CR) transport in the heliosphere. However, adequate theoretical description of the modulated galactic cosmic ray (GCR) spectra in the heliosphere during solar cycle is a difficult task because the theoretical models consider many parameters whose values are not known throughout the heliosphere. That is why the development of empirical and theoretical approximations is recommended, especially for calculation of CR's atmospheric effects and for practical tasks [1]. A model, whose parameters can be given as a function of the solar-heliospheric and geomagnetic parameters, is presented. Because the flux of GCRs has a delay relatively to the values of determined parameters, we can use them to predict the intensity of the galactic cosmic rays. The BESS (Balloon-borne Experiment with Superconducting Spectrometer) experimental spectra of GCRs are fitted by the model. Because measurement data contain both random and systematic errors, a constrained least squares method for the calculation of the unknown model parameters is applied [2].*

СПЕКТРИ НА ГАЛАКТИЧНИТЕ КОСМИЧЕСКИ ЛЪЧИ ПРЕЗ СЛЪНЧЕВИЯ ЦИКЪЛ

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Ключови думи: *космични лъчи, модулация, слънчев цикъл*

Резюме: *Транспортното уравнение на Паркер обобщава основните физични процеси, влияещи върху транспорта на космическите лъчи (КЛ) в хелиосферата. Въпреки това точното описание на модулираните спектри на галактичните КЛ в хелиосферата през слънчевия цикъл си остава трудна за решаване задача, тъй като теоретичните модели разглеждат множество параметри, чиито стойности често са неизвестни в даден момент и за дадено място в хелиосферата. Затова е препоръчително развитието на емпирични и теоретични апроксимации, които да се използват при пресмятане на атмосферните ефекти на космическите лъчи и за други практически задачи [1]. Ние даваме модел, чиито параметри са функция на подходящо избрани слънчево-хелиосферни параметри. Тъй като интензитетът на галактичните космически лъчи за дадена енергия показва известно закъснение спрямо стойностите на тези параметри, ние можем да използваме това, за да предскажем спектъра на космическото лъчение. Данните за спектрите на галактичните космически лъчи, получени от BESS измерванията, са фитнати към предложения моделен спектър. Понеже измервателните данни съдържат и случайни и систематични грешки за пресмятане на неизвестните моделни параметри е приложена една модификация на метода на най-малките квадрати - constrained least squares method [2].*

Introduction

The 11-year cosmic-ray heliospheric modulation in the energy range from several hundred MeV to tens of GeV is determined by convection–diffusion, adiabatic energy changes as well as drift effects, which play a specific role in the changes of the profiles of the GCR intensity (flat or picked) in different 11-year cycles of solar activity [2]. The 22-year cosmic-ray cycle is dominated by the 11-year solar cycle. The drift effects in the modulation of cosmic rays enhance during periods of weak to moderate solar activity, *i.e.* around solar minima and during negative polarity periods [2].

Adequate theoretical description of the modulated galactic cosmic ray (GCR) spectra in the heliosphere during solar cycle is a difficult task because the theoretical models consider many parameters whose values are not known throughout the heliosphere. That is why the development of empirical and theoretical approximations is recommended, especially for calculation of CR's atmospheric effects and for practical tasks [1]. A model, whose parameters can be given as a function of the solar-heliospheric and geomagnetic parameters, is presented. Because the flux of GCRs has a delay relatively to the values of determined parameters, we can use them to predict the intensity of the galactic cosmic rays.

Cosmic-ray-spectrum approximation model

The *cosmic-ray-spectrum approximation (CRSA) model* [2, 3] is given by the following dependence using a logarithmic scale (see fig.1)

$$\beta = \frac{\ln(D_{\mathrm{LIS}}(E+E_0)) - \ln(D(E))}{\ln(E+\alpha) - \ln(E)} \quad , \tag{1}$$

Here α and β are model parameters, $\beta = \tan\tau$; where τ is the angle at a point corresponding to energy $E + \alpha$; $D_{\mathrm{LIS}}(E + E_0)$ is the local interstellar spectrum.

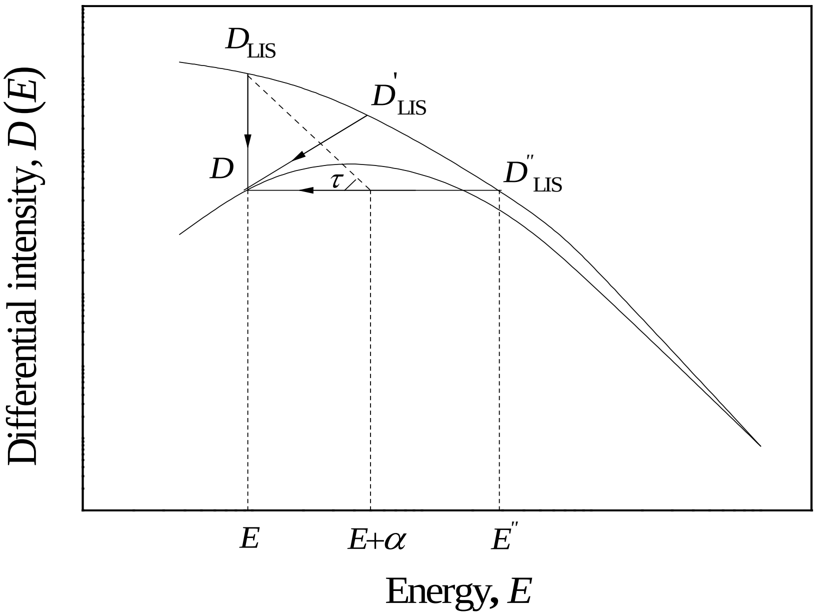

Fig. 1. Local interstellar spectrum $D_{\mathrm{LIS}}(E)$ and differential cosmic ray spectrum $D(E)$ as a function of kinetic energy E. Representation of the trigonometric dependence $\tan\tau$ (equation (1)) using a logarithmic scale [2, 3].

After some transformations equation (1) is written in the form of CRSA model in terms of $D(E)$ [2,3]:

$$D(E) = D_{\mathrm{LIS}}(E)\left(1 + \frac{\alpha}{E}\right)^{-\beta} \quad . \tag{2}$$

In fig. 2 the geometric interpretation of the CRSA model in terms of $f(P)$ and P is given by [2]

(3) $$\beta_P(P) = \frac{\ln(f_{\mathrm{LIS}}(P)) - \ln(f(P))}{\ln(P + \alpha_P) - \ln(P)},$$

$\beta_P = \tan\theta$. Equation (3) can be written in the form [2]

(4) $$f(P) = f_{\mathrm{LIS}}(P)\left(\frac{P + \alpha_P}{P}\right)^{-\beta_P}.$$

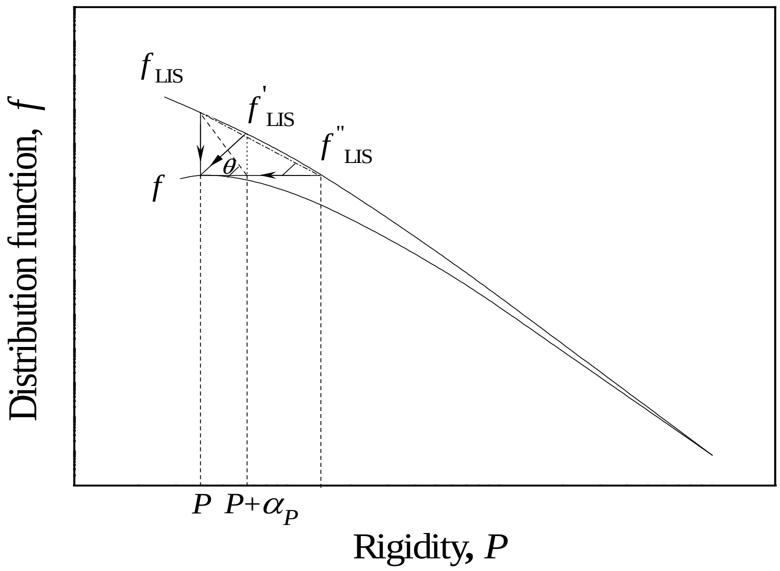

Fig. 2. Local interstellar spectrum $f_{\mathrm{LIS}}(P)$ and modulated cosmic ray spectrum $f(P)$ described by the distribution function f. Representation of the trigonometric dependence tan θ (equation (3)) using a logarithmic scale [2].

The drawbacks of the CRSA model approximation is that parameters α and β are not dependent on the time t and rigidity P, and the model does not take into account general trends in the variations of the heliospheric magnetic field; therefore the influence of the drift effects on the shape of the spectral curves for different magnetic field polarity swings is ignored [2]. The development of the CRSA model is related to finding of functional dependences between the coefficients α and β and different heliospheric and solar variables [2]. These dependences can be derived on the base of finding correlations between the variations in CR intensity and various solar (sunspot number, coronal index, number of grouped solar flares) and heliospheric (number of coronal mass ejections, heliospheric current sheet tilt) parameters [2].

The integral GCR spectrum on the Earth is determined by

(5) $$D(>P) = \int_{P_C}^{\infty} D(P)Y(P)\mathrm{d}P,$$

where P_C is the geomagnetic cut-off rigidity in the point of measurement; $Y(P)$ is the yield function in the atmosphere.

Buchvarova and Draganov in [1] show that exists a rigidity P_ξ such that

(6) $$\ln D(>P) = \ln D(>P)_{\mathrm{LIS}} - \beta_P \ln\left(1 + \frac{\alpha_P}{P_\xi}\right).$$

Let $g\left(\alpha_P, \beta_P, P_\xi\right) = \beta_P \ln\left(1 + \frac{\alpha_P}{P_\xi}\right)$. Using equation (6), Nagashima and Morishita model [4,5] that gives a relation between cosmic ray intensity and solar activity indices and taking into account some considerations, Buchvarova and Draganov derive a dependence between parameters α_P, β_P, and time-lagged solar-heliospheric parameters for a given rigidity P_ξ in the form [1]:

(7) $$g\left(\alpha_P, \beta_P, P_\xi\right) = G\left(\sum_i a_i X_i\right) ,$$

Here $G = G\left(\sum_i a_i X_i\right)$ is function of a linear combination of appropriately selected indices X_i; a_i are coefficients [6].

CRSA model, experimental data and numerical method

Buchvarova, Velinov, and Buchvarov in [3] show that the inverse problem for the nonlinear equation (2) is well-posed and the Levenberg-Marquardt (LM) algorithm [7] can be used. However, the data for cosmic ray differential spectra contains both systematic and random errors and the LM algorithm based on the simple chi-square minimization is not entirely adequate for these data sets [2]. That is why we use a constrained least squares method (CLAM) as an alternative to the traditional chi-square minimization technique [2, 8].

In our calculations the program Aplcon [8] is used for solving the constrained least squares fit with correlated data and systematic uncertainties [2]. The program is extended to non-Gaussian variables [2]. Aplcon is a method used for difficult problems, which follows accurately the assumed physical and statistical model of the measurement process, and avoids a bias in the result [8]. Because the measured data are not normally distributed, we determine contours for the calculated parameters α and β by profile analysis [2]. In Tables 1 and 2 we list the parameters α and β for the experiments BESS 1997, 1998, 1999, 2000 and 2002 [9, 10] for protons and helium nuclei, respectively [2]. The values of α and β for the helium nuclei for BESS 1997 and BESS 1998 show that the measured spectra $D(E)$ approach a power spectrum [2].

Table 1. Fitting parameters α, β and χ^2 for protons for experiments BESS97, BESS98, BESS99, BESS2000 and BESS2002 [9], γ = 2.7320±.022 and K=13.700±1.200 [2, 10]

Experiments	BESS97	BESS98	BESS99	BESS2000	BESS2002
α	2.567±0.168	1.149±0.050	1.718±0.092	2.454±0.083	2.044±0.058
β	0.723±0.013	1.280±0.019	1.185±0.018	2.033±0.019	2.142±0.019

Table 2. Fitting parameters α, β and χ^2 for helium nuclei for experiments BESS97, BESS98, BESS99, BESS2000 and BESS2002 [9], γ = 2.699±0.059 and K=0.706±0.115 [2, 10].

Experiments	BESS97	BESS98	BESS99	BESS2000	BESS2002
α	0.0±0.029	0.0±0.026	0.147±0.091	1.903±0.019	1.600±0.018
β	0.0±0.015	0.0±0.015	1.700±0.015	1.016±0.015	1.001±0.016

Conclusion

In this work a model, whose parameters can be presented as a function of the solar-heliospheric and geomagnetic parameters, is given. Because the flux of GCRs has a delay relatively to the values of determined parameters, we can use them to predict the intensity of the galactic cosmic rays. We have calculated the unknown model parameters from the proposed model equation (2) for the experiments BESS 1997, 1998, 1999, 2000, 2002 [9, 10] for protons and helium nuclei by using the constrained least squares method [2, 8, 11, 12, 13]. This method is an alternative to the standard chi-square minimization method because the data for cosmic-ray differential spectra do not only contain random errors, but also systematic ones, and often the systematic errors are significantly bigger than the random errors [2]. A further development of the CRSA model is related to finding functional dependences between the coefficients α and β and different heliospheric and solar variables [2]. These dependences can be derived on the basis of finding correlations between the variations in CR intensity and various solar (sunspot number, number of grouped solar flares) and heliospheric (number of coronal mass ejections, heliospheric current sheet tilt) parameters [2]. The study of the contributions of these parameters to the long-term CR modulation would lead to a better approximation to the observed intensities during solar cycles [2].

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