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Empirical Modeling of Cosmic Ray Spectra in the 1 MeV - 100 GeV Energy Range

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Abstract: We propose models which generalize the differential $D(E)$ spectra of galactic (GCR) and anomalous cosmic rays (ACR) during the 11-year solar cycle. The models take into account the cosmic ray (CR) modulation in the Heliosphere. We describe the connection between solar activity variation and the values of model parameters. Our analyses show that the contribution of GCRs and ACRs to the ionization of the ionospheres of outer planets (Jupiter, Saturn, Uranus, Neptune) will increase with growth of the planetary distances from the Sun. The modulated energy spectra of galactic cosmic rays are compared with force field approximation for protons and alpha particles. The error is in the order of 1.5%. The model solutions are compared with IMAX92, CAPRICE94 and AMS98 measurements. The proposed analytical models give practical possibility for investigation of experimental data from measurements of galactic cosmic rays and their anomalous component.

1. Introduction

The primary Cosmic Rays (CRs) are mainly composed by protons, alpha-particles and heavier nuclei. Above 100 GeV, the modulation due to the magnetic field of the heliosphere is negligible and the energy spectra of cosmic ray nuclei are described by power laws:

$$D(E) = KE^{-\gamma} \qquad (1)$$

with the spectral coefficient $\gamma \approx 2.75$ for protons and slightly smaller in magnitude for nuclei. The differential spectrum is usually given as number of cosmic ray particles passing through a unit area surface in a unit time from a unit solid angle per energy unit [1]. The unit is particles per m^2 s str GeV/nucl .

Particles with energy below 20-50 GeV are subject to solar modulation. Here the spectrum deviates from the power law.

2. Modelling cosmic ray spectra

The observed CR spectrum can be distributed into the following five intervals [2, 3]:

I ($E = 3.10^6 - 10^{11}$ GeV/nucl),
II ($E = 3.10^2 - 3.10^6$ GeV/nucl),
III (E = 30 MeV/nucl –3.10^2 GeV/nucl),
IV (E = 1 – 30 MeV/nucl),
V (E = 10 KeV/nucl – 1 MeV/nucl),

where E is the kinetic energy of the particles.

A model for calculation of the cosmic ray proton and helium spectra on the basis of balloon and satellite measurements in the energy intervals I – IV is proposed in this paper. The empirical model gives a practical possibility for investigation of experimental data from measurements of galactic cosmic rays and their anomalous component.

The expression for the differential spectrum (energy range E from 30 MeV to 100 GeV) of the protons and other groups of cosmic ray nuclei taking into account the anomalous cosmic rays (energy range E from 1 MeV to about 30 MeV) is [4]:

$$D(E) = D_{LIS}\left(1+\frac{\alpha}{E}\right)^{-\beta}\left\{\frac{1}{2}\left[1+\tanh\left(\lambda\left(E-\mu\right)\right)\right]\right\}+ + xE^{-y}\left\{\frac{1}{2}\left[1-\tanh\left(\lambda\left(E-\mu\right)\right)\right]\right\} \qquad (2)$$

D_{LIS} is local interstellar spectrum. In energies $E >$ 100 GeV the modulation effects are negligible and the main contribution gives the term D_{LIS}. Parameters α and β show the influence of modulation on the galactic spectrum; x and y are related to modulation on the anomalous cosmic ray spectrum. The unit of differential intensity $D(E)$ is [part/m2s.ster.MeV], the energy E is in GeV/nucl. The first term of Eq. (2) gives the main contribution in the interval between the energies 30 MeV and 1 GeV. The energy range 1.8 MeV to 30 MeV is determined predominantly by the second term. The members with tanh are smoothing functions [3]. The parameter $\lambda = 100$. The physical meaning of μ (GeV) is the energy at which the differential spectra of GCR and ACR contribute to the half of their values [5].

Here we present D_{LIS} with the power law spectra (Eq.1). K_{p} = 25.298 GeV2.75/(s.m2ster.MeV) and γ_{p} = 2.75 for protons. The used parameters for the alpha particles are K_α = 1.145 GeV2.68/(s.m2 ster.MeV) and γ_α =2.68 . The normalization constants K_{p} and K_α are chosen to match the modulated data near 100 GeV/nucl, where the modulation effect is negligible.

The calculation of parameters α, β, x, y and μ is performed by Levenberg-Marquardt algorithm [6], applied to the special case of least squares. The described programme is realized in algorithmic language C++ .

Differential energy spectra $D(E)$ of primary protons and helium nuclei are shown in Figs.1 and 2 for solar minimum and maximum for the Earth respectively. The modeled spectra are compared with the measurements for the period near to solar maximum - ■ IMAX92 [7] and periods near to solar minimum – ● CAPRICE94 [8] and ▲ AMS98 [9, 10].

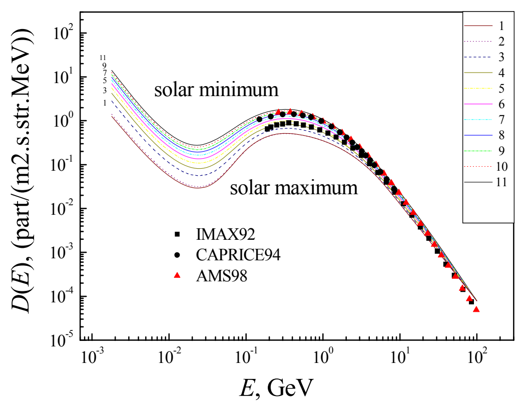

Fig.1. The modeled spectrum *D(E)* of CR protons for eleven levels of solar activity and measurements: ■ IMAX92 [7] and periods near to solar minimum – ● CAPRICE94 [8] and ▲ AMS98 [9]. Curve 1 is related to solar maximum and 11 – to solar minimum.

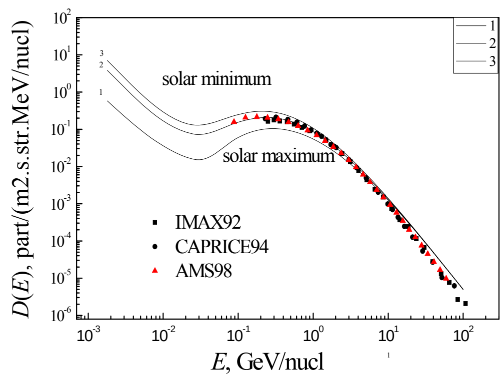

Fig.2. The modeled spectrum $D(E)$ of CR helium nuclei for eleven levels of solar activity and measurements: ■ IMAX92 [7] and periods near to solar minimum – ● CAPRICE94 [8] and ▲ AMS98 [10]. Curve 1 is related to solar maximum 1989, 2 – to comparatively average level of the solar activity and 3 – to solar minimum.

3. Comparison of the modelling cosmic ray spectra with the force field approximation

The force field parameterization of cosmic ray nuclei at 1 AU is given as:

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$$D(E,\Phi) = D_{LIS}(E+\Phi)\frac{E(E+2E_0)}{(E+\Phi)(E+\Phi+2E_0)} \quad (3)$$

D (E, Φ) is differential intensity of cosmic rays and D_{LIS} (E+Φ) is the local interstellar spectra of cosmic ray nuclei. E is the kinetic energy (in MeV/nucl) of cosmic nuclei with charge number Z and mass number A. This model has only one parameter, the modulation potential φ, whose value is given in units of MV. Φ=(Ze/A)φ and E_0= 938 MeV is the proton's rest mass energy. The value of Zeφ corresponds to the average energy loss of cosmic rays to reach the heliosphere [11].

We use D_{LIS} for the protons according to Usoskin et al., (2005) and Burger (2000):

$$D_{LIS}(E) = \frac{1.910^4 P(E)^{-2.78}}{1+0.4866P(E)^{-2.51}} \quad (4),$$

when we compare the modelling cosmic ray spectrum (Eq. 2) with the force field approximation (Eq. 3).

We calculate differential intensities of galactic protons and alpha particles from Eq. (3) at given values of the modulation potential φ. The obtained spectra are fitting to Eq (2) for the proton and alpha particles.

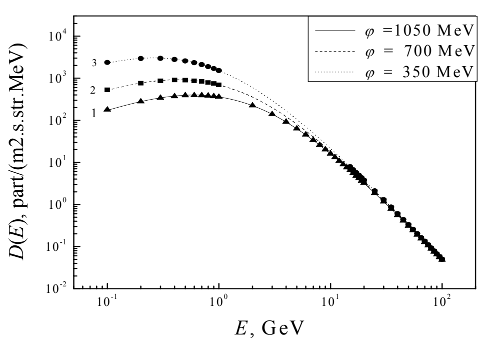

Fig.3. Comparison of the spectrum from Eq. (2) for the protons with force field approximation for three values of the modulation parameter: ●350 MeV, ■ 700 MeV and ▲1050 MeV.

The fitting force field model for the galactic protons at three levels of solar activity to Eq. (2) is shown in Fig. 3. Curve 1 corresponds to φ = 1050 MeV, curve 2 to φ = 700 MeV and curve 3 to φ = 350 MeV. It is seen from Fig. 3 that the values from force field approximation are well fitted to the values of our empirical model (2).

The coefficients α, β and the corresponding values of χ^2_n for the three values of parameter φ from Fig. 3 are given in Table 1.

Table 1

Coefficients α a, β and χ^2_n for the parameter φ = 350, 700 and 1050 MeV for the protons

Co-eff.	φ=350 MeV	φ=700 MeV	φ=1050 MeV
α	1.614906	2.654086	3.559604
β	0.984487	1.324410	1.550514
χ^2_n	0.128163	0.777648	0.873369

Fig. 4 shows that the empirical model (2) well fits the data from force field approximation (3) for the alpha particles for the three values of the modulation parameter φ =350 MeV, 700 MeV and 1050 MeV.

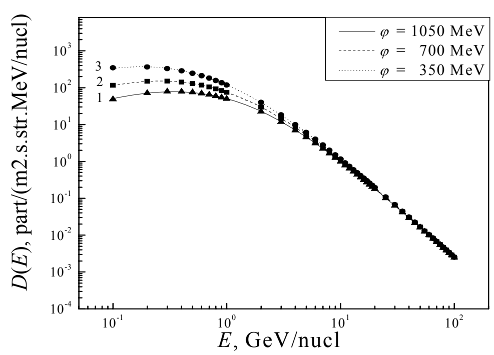

Fig.4. Comparison of the spectrum from Eq. (2) for the alpha particles with force field approximation for three values of the modulation parameter: ●350 MeV, ■700 MeV and ▲1050 MeV

Table 2

Coefficients α a, β and χ^2_n for the parameter φ = 350, 700 and 1050 MeV for the alpha particles

Coeff.	φ=350 MeV	φ=700 MeV	φ= 1050 MeV
α	0.330025	0.650183	0.991097
β	0.742173	0.815748	0.853391
χ^2_n	0.524989	0.479832	0.593435

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The values of coefficients α, β and corresponding values of χ^2_n for the three values of parameter φ for the curves on Fig. 4 are given in Table 2.
The fitted standard deviations for protons and alpha particles are in the range of 1.5%. Therefore $D(E)$ values from force field approximation are well fitted to the modulation equation (2) for protons and alpha particles at different modulation levels.

5. Conclusion

A model for calculation of the cosmic ray spectra on the basis of balloon and satellite measurements is proposed in this paper. It is taken into account in that model the influence of solar modulation on GCR and ACR by parameters α, β, x and y. The computed analytical model gives a practical possibility for investigation of experimental data from measurements of galactic cosmic rays and their anomalous component during the 11-year solar cycle.
Differential $D(E)$ spectrum (Eq. 2) of galactic and anomalous CR can be used for computation of the electron production rate profiles in the planetary atmospheres and ionospheres both for middle and high latitudes at which the ACR component is also taken into account [12]. The electron production rate, together with the chemical and transport (winds, waves, drifts, electric and magnetic fields, etc.) processes in the upper atmospheres, determines the ionization – neutralization balance in the ionospheres and the parameters of the global electric circuits.

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