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Model of Galactic and Anomalous Cosmic Ray Spectrum in the Planetary Ionospheres

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The proposed model generalizes the differential D(E) and integral D(>E) spectra of galactic and anomalous cosmic ray protons and heavier elements during the 11-year solar cycle. The model takes into account the CR modulation by the solar wind. The measurements with the BESS spectrometer, IMAX and CAPRICE94 experiments for galactic cosmic rays and SIS spectrometer for anomalous component are examined with numerical solutions of the model equations. This computed analytical model gives a practical possibility for investigation of experimental data from measurements of galactic cosmic rays and their anomalous component. The average radial gradient of GCR is accepted 4% / AU (Mcdonald et al., 2001). The contribution of GCRs and ACRs to the ionization of the ionospheres of outer planets will be increased with increase of the planetary distances from the Sun.

1.Introduction

The primary Cosmic Rays (CRs) are mainly composed by protons (≈87%) and alpha-particles (≈12%). The remaining 1% are heavier nuclei. Their energy spectrum follow a power law [1]:

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

with the spectral coefficient $\gamma \approx 2.6$ for protons, and slightly smaller in magnitude for nuclei. The differential spectrum is usually given as the number of particles observed per MeV, unit solid angle, square meter, and second. Toward low energies (<10 GeV/nucl) the power law is not respected and CR intensity is modulated by solar activity. As solar activity varies over the 11 year solar cycle the intensity of cosmic rays at Earth also varies, in anti-correlation with the sunspot number.

During solar minimum there are seven elements (H, He, C, N, O, Ne, and Ar) whose energy spectra have shown anomalous increases in flux above the quiet time galactic cosmic ray spectrum. This so-called "anomalous cosmic ray" (ACR) component is now thought to represent neutral interstellar particles that have drifted into the heliosphere, become ionized by the solar wind or UV radiation, and then been accelerated to energies >10 MeV/nucleon, most likely at the solar wind termination shock.

2. Modeling Cosmic Ray Spectra

In this paper a model for the calculation of the cosmic ray element spectra on the basis of satellite measurements is created. This computed analytical 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 about 30 MeV to 100 GeV) of the protons and other groups of cosmic ray nuclei on account of the anomalous cosmic rays (energy range E from 1 MeV to about 30 MeV) is [2]:

$$D(E) = K(0.939 + E)^{-\gamma}\left(1 + \frac{\alpha}{E}\right)^{-\beta}\left\{\frac{1}{2}\left[1 + tanh(\lambda\,(E - \mu))\right]\right\} + \\ + \frac{x}{E^{y}}\left\{\frac{1}{2}\left[1 - tanh(\lambda\,(E - \mu))\right]\right\} \qquad (2)$$

This formula is analysed in detail in [3]. The coefficients K, α, β, x, y and μ are solutions of the interpolation problem of this function through the points with the six energy values 0.0018 CeV, 0.01 CeV, 0,023 CeV, 0.39 CeV, 10 CeV and 100 CeV. The value for γ is taken as constant, equal to 2.6. The parameter $\lambda = 1000$. The calculation of the other parameters is performed by algotithm that combines the rapid local convergence of Newton's method with a globally convergent method for nonlinear systems of equations [4]. The described programme is realized in algorithmic language C.

Thus modulated CR spectrum can by used for computation of the electron production rate profiles on $q(h)$ for different latitudes and different levels of solar activity. For the quantitative analysis of the ionization profiles in different CR energy intervals we use the expression [5]:

$$q_i(h) = \frac{1}{Q}\int_{E_i}^{\infty}\int_{\varphi=0}^{2\pi}\int_{\theta=0}^{\pi/2+\Delta\theta} D_i(E,\,h,\,\theta)\left(\frac{dE}{dh}\right)_i \sin\theta\,d\theta\,d\varphi \qquad (3)$$

where $Q = 35$ eV is the energy necessary to produce one electron – ion pair, dE/dh, are the ionization losses of the particles, $D(\,E,\,h,\theta\,)$ is their differential spectrum, φ is the azimuth angle, θ - the angle towards the vertical.

3. Results

In Figure1 are shown the results from the differential energy spectrum $D(E)$ of primary protons for solar minimum and maximum for the Earth and the planets: Jupiter and Saturn. The differential spectra for Jupiter and Saturn are calculated, assuming mean gradient of CR in the interplanetary space as 4% for 1 AU. The black curve (Earth) is for the solar minimum of the 23th solar cycle W =119.6 and coincide with the experimental spectra, presented in [6]. The modeled spectra is compared with the measurements for the periods of solar maximum - +IMAX 92 [7], for average level of solar activity – Caprice 94 [8] and near to solar minimum - ● BESS 98 [9], respectively.

On the base of force-field approximation at given values on the modulation strength Φ, we calculate the coefficients K, α and β. In the Table 1 are given the values of coefficients K, α, β for experiments IMAX 92 [7], CAPRRICE 94 [8], BESS 98 [9] and the corresponding values of modulation parameters Φ.

Table 1

Experiments	K	α	β	Φ[GeV]
IMAX 92	7358.411	0.887580	1.099926	0.75
CAPRICE 94	10300.57	0.724373	1.080309	0.71
BESS 98	11781.53	0.679247	1.388319	0.60

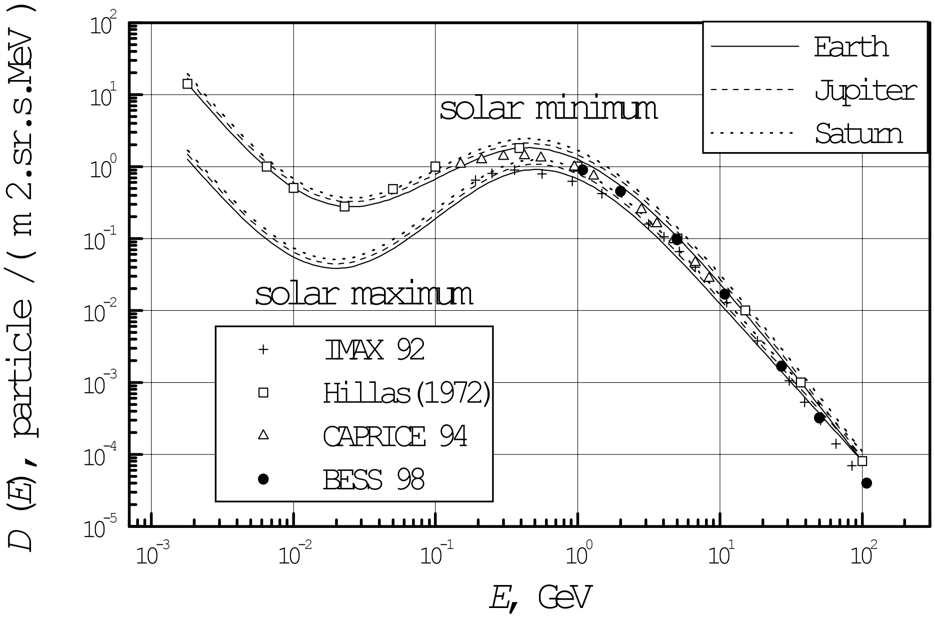

Figure 1. The modeled differential spectra *D(E)* of galactic CR protons and ACR for solar minimum and maximum for Earth, Jupiter and Saturn These results are in accordance with the experimental measurements: + IMAX 92 [7], Δ – CAPRICE 94 [8] and ● BESS 98 [9] for the Earth.

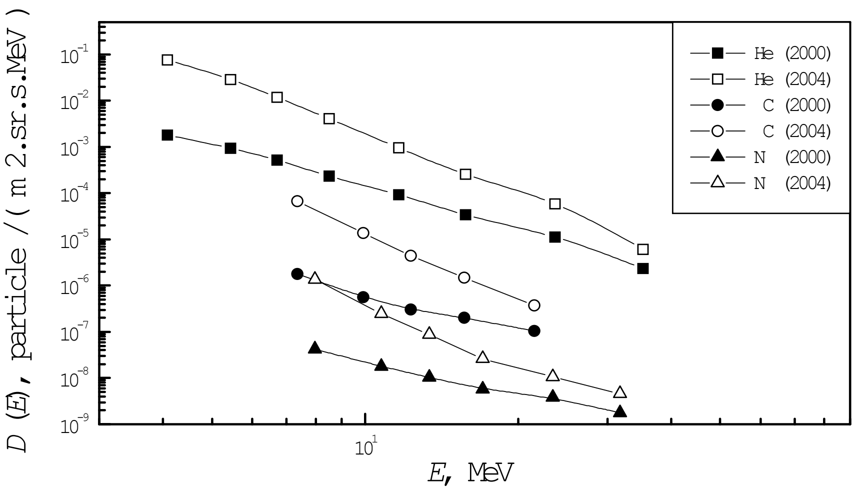

Figure 2. Differential spectra for He, C and N from 2000 (solar maximum) and 2004 year, (SIS data [10]).

Table 2

	2000		2004	
Z	x	y	x	y
2	267.9072	4.192926	9.588306	3.015167
6	78.46837	5.033357	0.784489	4.681027
7	19456.61	7.704085	5.485159	6.002542

The SIS data (27 day average) for He, C and N for 2000 (solar maximum) and 2004 are presented on Figure 2. In Tables 2 the computation values of the coefficients x and y for elements He, C and N are shown for solar maximum and minimum. This values are obtained on the basis of the SIS data in energy range 5 MeV - 70 MeV during the solar maximum (2000) and 2004.

4. Conclusion

The obtained differential element spectra of CR represent well the 11-year variations of galactic cosmic rays and ACRs. The intensity of cosmic rays at Earth has anti-correlation with the sunspot number over the solar cycle. In such a way, our model is in agreement with other models and experimental results. The differential $D(E)$ spectra (2) of galactic and anomalous CR can by used for computation of the electron production rate profiles in the atmospheres and ionospheres both for middle and high latitude, at which the ACR component is also taken into account. The ionization model can be applied to the terrestrial planets (Venus, Earth and Mars), which are almost spheres.

References:

[1.] Velinov, P. I. Y., G. Nestorov, and L. I. Dorman, 1974. Effect of Cosmic Rays on the Ionosphere and Radiowave Propagation. BAS Publ. House, Sofia.

[2.] Velinov, P.I.Y., 2002, C .r. Acad. bulg. Sci., 55, 1, 51 - 56.

[3.] Velinov, P.I.Y., 2003, C. r. Acad. bulg. Sci., 56, 6, 17 - 22.

[4.] Press W. H., B. P. Flannery, S. A. Teukolsky, W. T. Vetterling, 1991, Numerical Recipes in C - The Art of Scientific Computing. Cambridge, Cambridge University Press.

[5.] Velinov, P.I.Y., 1966, C. r. Acad. bulg. Sci.,19, 2, 109 - 112.

[6.] A.M. Hillas, in Cosmic Rays, 1972, Pergamon Press, Oxford.

[7.] W. Menn et al., Astrophys. J. 2000, 533, 281.

[8.] Barbiellini, G. et al., 1997, *Proc. 25th ICRC*, Durban, 28 July - 6 August 1997, Conf. Paper OG 5.2.1, Vol. 3, 369 - 372.

[9.] Sanuki, T. et al., 2000, The Astrophysical Journal, 545, 2, 1135-1142, 2000

[10.] ACE Measurements; **http://www.srl.caltech.edu/ACE/ASC/**