29th International Cosmic Ray Conference Pune (2005) **2**, 131–134

Model of Galactic and Anomalous Cosmic Ray Spectrum in the Planetary Ionospheres. Calculation of CR Ionization Effects in the Ionosphere and Middle Atmosphere

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The proposed model generalizes the differential $D(E)$ and integral $D(> E)$ spectra of galactic (GCR)and anomalous cosmic ray (ACR)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]:

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

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 proposed. 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]:

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

This formula is discussed 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 algorithm 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]:

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

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 Figure 1 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 23^{th} 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.

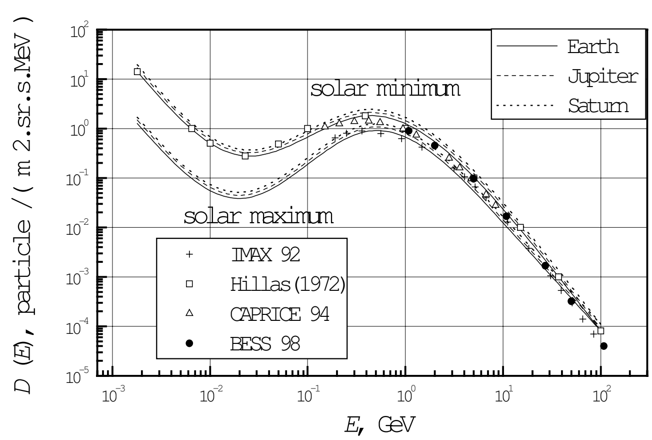

Figure 1. The modeled differential spectra $D(E)$ of galactic CR protons and ACR for solar minimum and maximum for Earth, Jupiter and Saturn These results are in accordance with the experimental measurements: + — IMAX 92 [7], △ — CAPRICE 94 [8], and • — BESS 98 [9] for the Earth.

Table 1. The computed values of the coefficients K, α, β for the modulation parameters Φ of experiments IMAX 92, CAPRRICE 94 and BESS 98.

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

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.

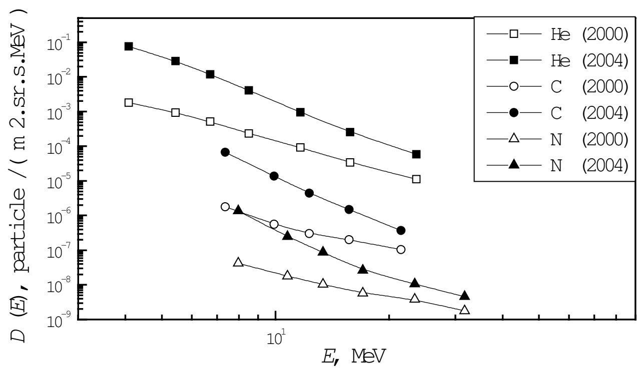

Figure 2. Differential spectra for He, C and N for 2000 (solar maximum) and 2004 year, 27 day averages (SIS data [10]).

The SIS data (27 day averages) for He, C and N from the 103 to 129 day of 2000 and from the 100 to 126 day of 2004 are presented on Figure 2. In Table 2 the computation values of the coefficients x and y for elements He, C and N for solar maximum (2000) and near to minimum (2004) are shown. These values are obtained on the basis of the SIS data in energy range 5-70 MeV.

In Figure 3 the electron production rate $q(h)$-profiles are presented. The computational data present the ionization by galactic CR and their anomalous CR component, which has significant influence above 80 km The profile with maximal values refers to the polar cap region, the one with minimal values presents the electron production rate at the equator. The positive deviation in the upper part of the polar cap profile shows clearly the contribution of the anomalous CR component [11].

Table 2. The computed values of the coefficients x and y for elements He, C and N in the energy interval 5-70 MeV.

	2000		2004	
Z	x	y	x	y
2	0.065926	2.550038	12.91623	3.637579
6	0.001888	3.492098	2.495792	5.272277
7	0.000011	2.69543	0.146882	5.584453

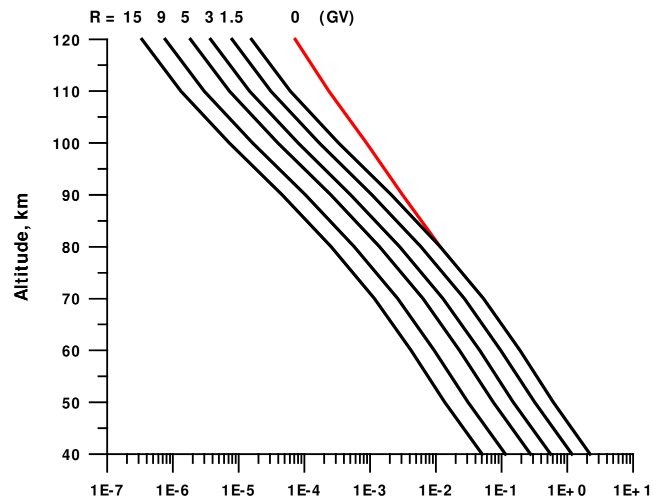

Figure 3. Electron production rate by GCR and anomalous CR component, $\mathrm{cm}^{-3}\mathrm{s}^{-1}$

4. Conclusion

The obtained differential element spectra of CR represent well the 11-year variations of GCRs 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.

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