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MODEL OF GALACTIC AND ANOMALOUS COSMIC RAY SPECTRUM IN THE PLANETARY IONOSPHERES

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Abstract

The proposed model generalizes the differential $D(E)$ and integral $D(>E)$ spectra of galactic and anomalous cosmic ray protons during the 11-year solar cycle. The model takes into account the CR modulation by the solar wind. The measurements with SIS and CRS spectrometers for anomalous component are examined with numerical solutions of the model equations. The radial gradient G_0 of GCR is relatively small in the inner heliosphere. After a transition region between 10 and 20 AU, G_0 increases to a much larger value that remains constant between ~25 and 80 AU. This shows that the contribution of GCRs and ACRs to the ionization of the atmospheres of outer planets Uranus, Neptune and Pluto will be increased drastically. We suppose that the galactic and anomalous cosmic rays (modulated by the solar wind) are important factors in the solar-terrestrial relationships. They influence strongly on the ionization state of the system ionosphere-thermosphere-middle atmospheres. The cosmic rays transfer the solar variability, even in the lower atmosphere – troposphere and they influence on the weather and on the electrical parameters of the atmosphere (electrical conductivities, frequency of lightning, etc.).

1.Introduction

As most energetic radiation (from 10^6 to 10^{21} eV) in the expanding Universe, the cosmic rays create ionized regions in the planetary spheres: magnetospheres, ionospheres, atmospheres, hydrospheres and litospheres. For some planets the cosmic rays form independent ionospheric layers with expressed maxima in altitude in the planetary ionospheres [1]. For the Earth, for example Galactic cosmic ray create the lower part of the planetary ionosphere, at high latitudes and in the polar ionosphere the anomalous CR component and the solar CR have significant contribution also. For the planets of the terrestrial group (Mercure, Venus, Earth and Mars) the contribution of the solar electromagnetic radiation in their energy balance dominates. For the giant planets of the Jupiter group (Jupiter, Saturn, Uranus and Neptune) the contribution of the different cosmic ray (CR) types (galactic, solar, anomalous CR) is already essential.

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:

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

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 [2].
Toward low energies (<1 GeV/nucleon) 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 conditions 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

The observed CR spectrum can be distributed into the following five intervals:
I ($E = 3.10^{6} - 10^{11}$ GeV/n),
II ($E = 3.10^{2} - 3.10^{6}$ GeV/n),
III (E = 30 MeV/n $- 3.10^{2}$ GeV/n),
IV (E = 1 – 30 MeV/n),
V (E = 10 KeV/n – 1 MeV/n),
where E is the kinetic energy of the particles [3,4]. Some methods exist for calculating ionization by relativistic particles in CR intervals I, II and III. For the polar ionosphere, however, intervals IV (30 MeV/n $\geq E \geq$ 1 MeV/n) and V (1 MeV/n $\geq E \geq$ 10 KeV/n) are also significant since they contain solar cosmic ray (SCR) and anomalous cosmic ray (ACR) components (Dorman, 1977; Velinov, 2000) .
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 [5]:

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

This formula is analysed in detail in [6]. 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 (Hillas, 1972). The parameter λ = 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 [7]. 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 [8, 9]:

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

where Q = 35 eV is the energy necessary to produce one electron – ion pair, dE/dh, are the ionization losses of the particles, $D(E, h, \theta) = D_1(E, h)\, D_2(\theta)$ is their differential spectrum, φ is the azimuth angle, θ - the angle towards the vertical, $D_2(\theta) = C_\beta \cos^\beta \theta$ is the function of the particle spatial distribution (β and C_β are constant). As the galactic cosmic rays particles penetrate isotropically from the upper hemisphere and the coefficient $\beta = 0$.

3. ANALYSES AND RESULTS

In Table 1 the mean distances of the planets r_a from the Sun are shown [10]. The parameter P_{EUV} of solar XUV radiation decrease, which is proportional to $1/r_a^2$, and the parameter P_{CR} of intensity increase of galactic cosmic rays, because of solar wind modulation are presented [11, 12]. We assume mean gradient of CR in the interplanetary space as 4% for 1 AU.

Planet	Earth	Jupiter	Saturn	Uranus	Neptune	Pluto
r_a, AU	1.0000	5.2028	9.5388	19.1914	30.0611	39.5294
P_{EUV}	1.0000	3.694E-2	1.099E-2	2.716E-3	1.107E-3	6.400E-4
P_{CR}	1.00	1.17	1.34	1.73	2.16	2.54

Table 1. Values of the mean distances ra of the planets from the Sun, parameter P_{EUV} of solar XUV radiation decrease, and parameter PCR of intensity increase for galactic CR

Table 1 shows only the mean values of the presented parameters. But in some cases the deviations are significant. For example for Pluto the maximal distance from the Sun is 50.2987 AU in aphelium. The parameter P_{EUV} decreases from 6.400E-4 (Table 1) to 3.953E-4, i.e. for Pluto the solar XUV radiation is with almost one order smaller than the intensity of the galactic CR!

It can be seen from this Table, that for Saturn, Uranus and Neptune the solar XUV radiation is comparable with the cosmic ray and the stellar radiation intensity [13].

In Fig.1 and 2 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 from Jovian group. 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 [14,15]. The modeled spectra is compared with the measurements [16,17] for the periods of solar maximum - + Menn et al. and solar minimum - ● Weisskopf - for 1977, respectively for Earth. These data practically coincide with the our results.

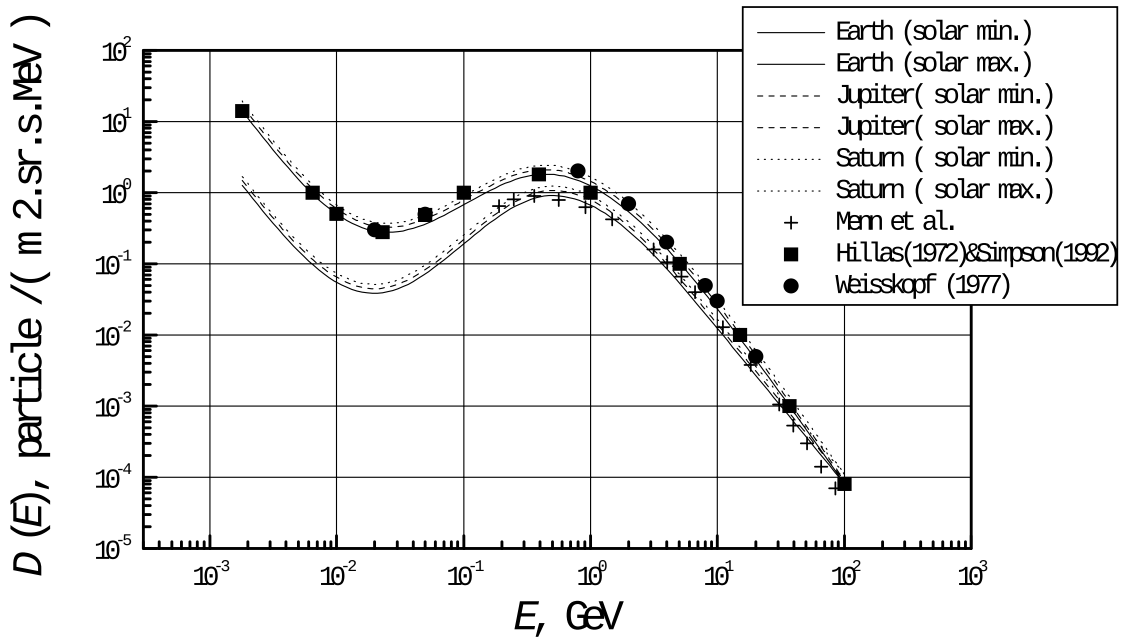

Fig. 1. The modeled differential spectra *D(E)* of galactic CR protons and ACR for solar minimum and maximum for Earth, Jupiter, Saturn and Uranus. These results are in accordance with the experimental measurements: + Menn et al. [16] and ● Weisskopf for 1977 [17] for the Earth.

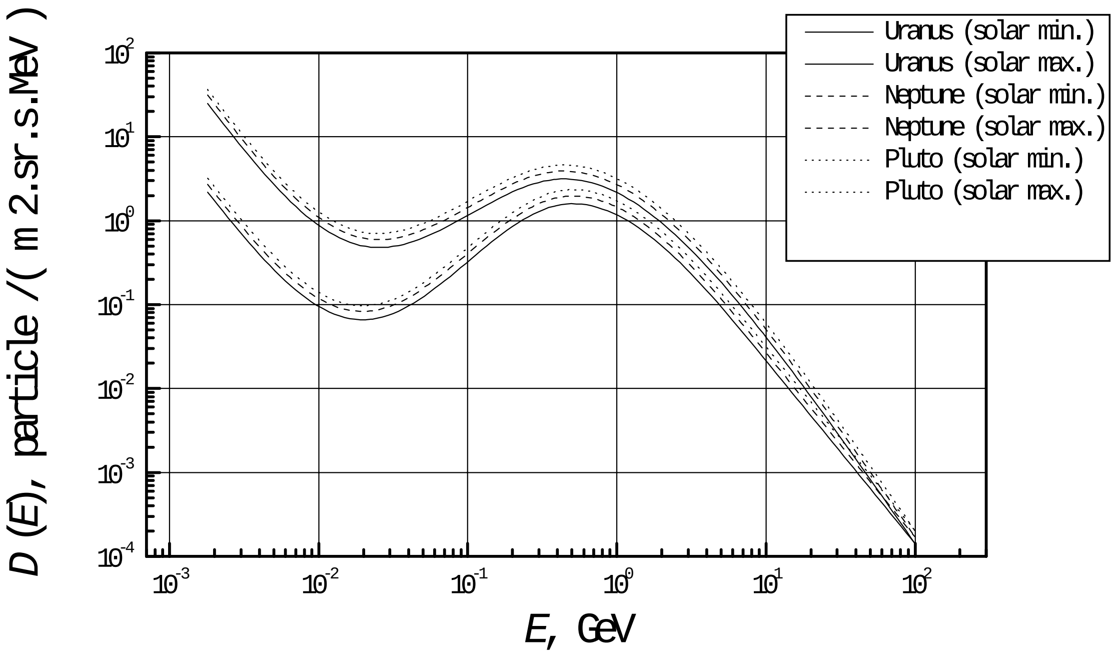

Fig. 2. The modeled differential spectra *D(E)* of galactic CR protons and ACR for solar minimum and maximum for Uranus, Neptune and Pluto.

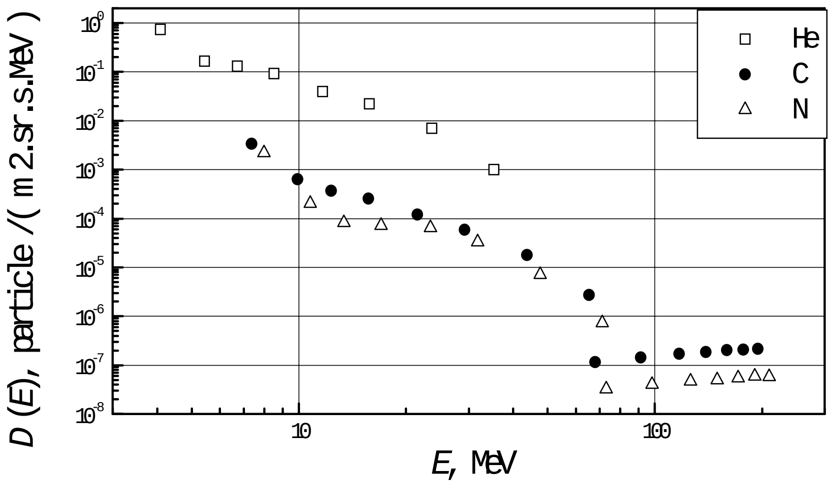

Fig. 3. Differential spectra for He, C and N from 22/2000 to 6/2001, 27day averages (CRIS and SIS date for solar maximum [18]).

SIS and CRIS data set contains data from the Solar Isotope Spectrometer (SIS) and Cosmic Ray Isotope Spectrometer (CRIS) instruments on the Advanced Composition Explorer (ACE) spacecraft, respectively. The CRIS and SIS data (27 day average) of He, C and N for 2000 /2001 year are presented on Fig. 3. This values are obtained on the basis of the SIS data in energy range 5 MeV ÷ 150 MeV [18].

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. This means, that the proposed programme for computation differential spectra of CR works well.

4. CONCLUSION

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 [19]. The ionization model can be applied to the terrestrial planets (Venus, Earth and Mars), which are almost spheres. For the Jovian planets oblateness effects must be included in the modified Chapman function. 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. In periods of high solar activity the role of the solar particle fluxes increases as a factor in the Earth's and planetary environments, affecting the conductivities, currents, electric fields and energetic processes in the ionospheres and atmospheres [20,21].

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