Primary Cosmic Ray Spectra in the Planet Atmospheres

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***Abstract* - The primary cosmic rays influence strongly on the ionization state of the planet atmospheres. We propose a model which generalizes the differential *D*(*E*) and integral *D*(>*E*) spectra of galactic (GCR) and anomalous cosmic rays (ACR) during the 11-year solar cycle. The model takes into account the cosmic ray (CR) modulation by the solar wind. The modulated differential spectra of galactic cosmic rays are compared with the force field approximation to the transport equation. The model results are compared with IMAX92, CAPRICE94 and AMS98 measurements. The calculated integral spectra are on basis on mean gradient - 3%/AU. The obtained integral spectra are compared with experimental data for Earth, Voyager measurements in the outer heliosphere and theoretical results. The proposed analytical model gives practical possibility for investigation of experimental data from measurements of galactic cosmic rays and their anomalous component. The obtained parameters are used for determination of profiles of ionization in the ionospheres of Earth and Saturn.**

1. INTRODUCTION

The cosmic rays maintain ionization in ionosphere, atmosphere, hydrosphere, cryosphere and lithosphere of the Earth and planets. CR possess maximal penetration capability in comparison with the other radiations.

CR particle populations are diverse:

- Galactic CR (GCR), with energy range from ~ 10^s MeV to 10^6 GeV, which are accelerated in the space of our Galaxy.
- Meta galactic CR with energies 10^6 GeV - 10^{12} GeV, accelerated in the Meta galaxy.
- Solar CR, with energy range from ~ 10^s of MeV to 100^s of MeV, accelerated on the Sun.
- Anomalous CR, with energy from 1 MeV ~ 100 MeV, accelerated in the interplanetary space.

The intensity of the GCR with E < 20 GeV shows an inverse relationship to the 11 – years solar cycle. This relation for CR protons with energies *E* >190 MeV is given in Fig. 1.

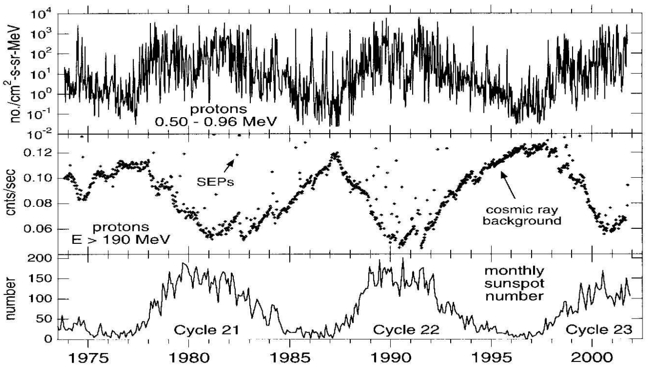

Fig.1. CR (galactic and solar) intensity and 11– year solar cycle (This picture is from F. Nichitiu, CANADA).

2. MODELLING COSMIC RAY DIFFERENTIAL SPECTRUM

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 on account of the anomalous cosmic rays (energy range *E* from 1 MeV to about 30 MeV) is [1], [2]:

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

Here the first term presents the galactic CR, and the last term takes into account anomalous CR [3]. The members with tanh are smoothing functions [4].

Here we take K_p=25.298 (GeV$^{2.75}$/(s.m^{2}ster.MeV)) and γ_p=2.75 for protons. The used parameters for the alpha particles are K_α=1.145 (GeV$^{2.68}$/(s.m^{2}ster.MeV) and γ_α=2.68. The normalization constants K_p and K_α are chosen to match the modulated data near to 100 GeV/n, where the modulation effect is negligible.

The parameters *α*, *β*, *x* and *y* are related with modulation levels in corresponding energy intervals. The dimensionless parameter λ = 100 is inversely proportional to the length of the smoothing interval between the two addends. The physical meaning of μ (GeV) is the energy at which the differential spectrum of GCR crosses the differential spectrum of ACR [2]. The differential spectrum is given as the number of particles

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observed per (m^2s.ster.MeV/n).

The calculation of the parameters α, β, x, y and μ is performed by Levenberg - Marquardt algorithm [5], applied to the special case of a least squares. The described programme is realized in algorithmic language C++.

Experimental data (E_i, D_i) for protons and helium nuclei at energies $E < 10$ GeV was got from [6] for 20 solar cycle.

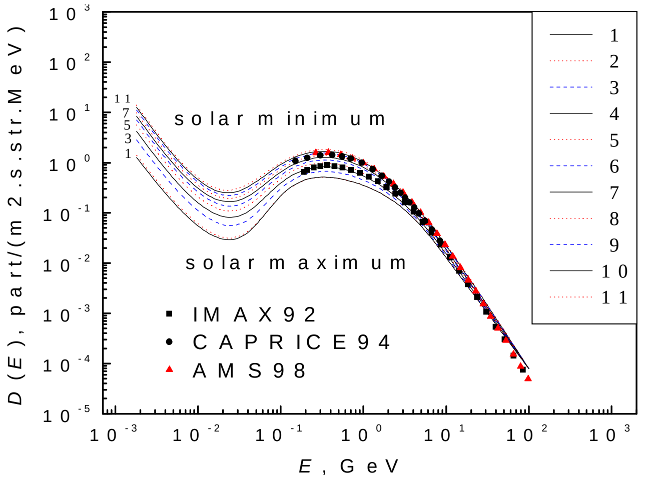

Fig. 2. The modelled spectrum *D(E)* of CR protons for eleven levels of solar activity and measurements: period near to solar maximum - ■ IMAX92 [7] and periods near to solar minimum – ● CAPRICE94 [8] and ▲ AMS98 [9].

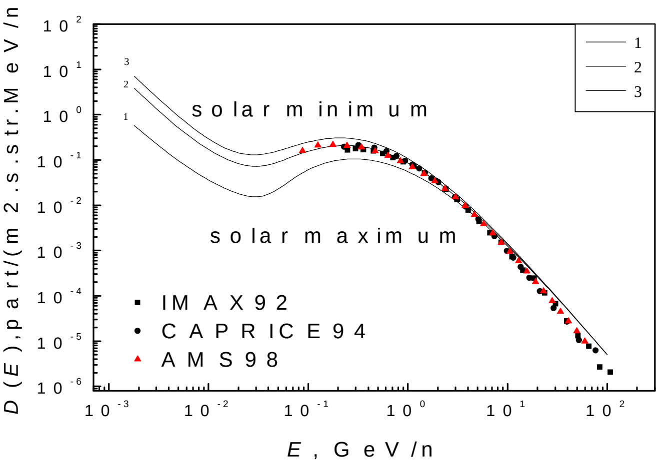

Fig. 3. The modelled spectrum $D(E)$ of CR helium nuclei for three levels of solar activity and measurements: period near to solar maximum - ■ IMAX92 [7] and periods near to solar minimum – ● CAPRICE94 [8] and ▲ AMS98 [10]. Curve 1 relates to solar maximum, 2 – to comparatively average level of the solar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

In Figs. 2 are show the results from the differential energy spectrum D (E) of primary protons for eleven levels of solar activity for the Earth. Fig. 3 gives the modelled spectrum D (E) of CR helium nuclei for solar minimum and maximum and comparatively average level of solar activity. The modelled spectra are compared with measurements for period near to solar maximum - ■ IMAX92 [7] and periods near to solar minimum – ●CAPRICE94 [8] and ▲ AMS98 [9], [10]. This data practically coincides with our results for these periods.

3. COMPARISON OF THE MODELING COSMIC RAY SPECTRUM WITH THE FORCE FIELD APPROXIMATION

Under some simplifying assumption, CR transport equation can be reduced to Force Field approximation. The force field parameterization of cosmic ray nuclei at 1 AU is given as:

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

D (E, Φ) is differential intensity of cosmic ray nuclei and D_{LIS} (E+Φ) – local interstellar spectrum (LIS) of cosmic ray nuclei (was taken from [11]). E is the kinetic energy (in MeV per nucleon) of cosmic nuclei with charge number Z and mass number A, Φ = (Ze/A)φ - modulation strength (in MeV), and E_0= 938 MeV is the proton's rest mass energy.

We calculate differential spectra D (E, Φ) of galactic protons and alpha particles from (2) at given values of the modulation potential φ. The results from the differential energy spectra D (E) of primary protons for four values of modulation parameter: φ = 400, 550, 700 and 1200 MV are shown in Fig.4. These results are given for helium nuclei in Fig. 5. The number ratio α/p = 0.05 in LIS [12] is used for alpha particles. Received spectra are fitted to energy range E from ~ 30 MeV to 100 GeV of (1) using Burger's LIS [11]:

$$D(E) = D_{\mathrm{LIS}}(E+\Phi)\left(1+\frac{\alpha}{E}\right)^{-\beta} \quad (3)$$

On the base on the calculated spectra D (E) at different values of modulation parameter φ are estimated coefficients α and β from (3) for different modulation levels of the proton and alpha particles. On the fit the standard deviations for protons and alpha particles are in the range of 1.5%.

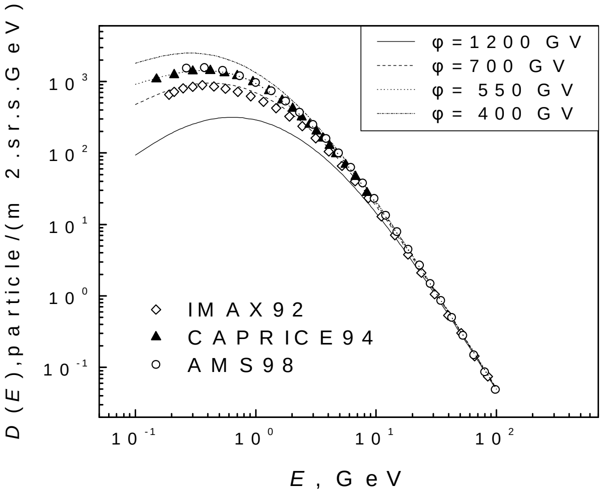

Fig. 4. The differential spectra D(E) of GCR protons for modulation levels φ = 400, 550, 700 and 1200 MV. Measurements with IMAX92 [7] are in the vicinity of $\varphi \approx$ 700 MV, CAPRCE94 [8] and AMS98 [9] of $\varphi \approx$ 550 MV.

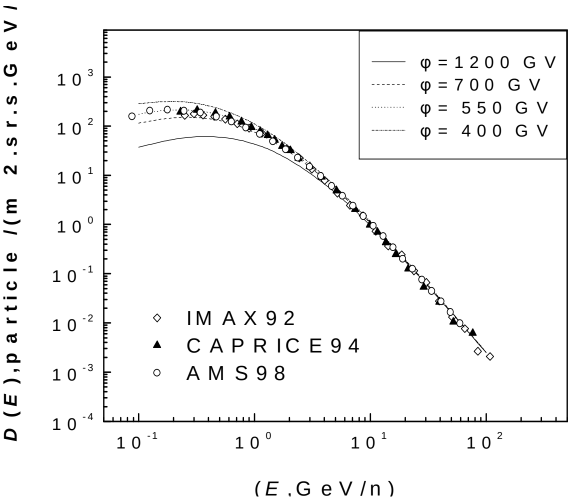

Fig. 5. The differential spectra $D(E)$ of GCR helium nuclei for modulation levels $\varphi = 400$, 550, 700 and 1200 MV. Measurements with IMAX92 [7] are in the vicinity of $\varphi \approx 700$ MV and CAPRCE94 [8] and AMS98 [10] of $\varphi \approx 550$ MV.

In Tables 1 and 2 the calculated values of coefficients α, β from (3) and the corresponding values of normalized chi-square χ^2_n for the experiments IMAX92 [7], CAPRICE94 [8] and AMS98 [9], [10] are given for protons and helium nuclei, respectively**.**

The measurements with IMAX 92 are in the vicinity of $\varphi \approx 700$ MV, while CAPRICE 94 and AMS 98 of $\varphi \approx 550$ MV. Figs. 4 and 5 show that our empirical model (3) well agrees with the results from force field approximation (2) for the protons and alpha particles.

TABLE I

COEFFICIENTS α, β and χ^2_n FOR PROTONS FOR THE EXPERIMENTS IMAX 92 [7], CAPRCE 94 [8] AND AMS 98 [9].

Experiments	IMAX 92	CAPRICE94	AMS98
α	3.910976± 0.082667	2.277076± 0.007783	1.855219± 0.058292
β	1.177608± 0.011403	1.206174± 0.002096	1.278139± 0.021470
χ^2_n	0.266998	2.242491	0.232845

TABLE II

COEFFICIENTS α, β and χ^2_n FOR HELIUM NUCLEI FOR THE EXPERIMENTS IMAX 92 [7], CAPRCE 94 [8] AND AMS 98 [10].

Experiments	IMAX 92	CAPRICE94	AMS98
α	1.934045± 0.087330	1.945276± 0.023703	2.686511± 0.076862
β	0.833586± 0.019206	0.726074± 0.004698	0.683225± 0.008542
χ^2_n	0.603221	4.149506	0.186076

4. COSMIC RAY INTEGRAL SPECTRA

Using analytical expression (2) for $D(E)$, we can obtain the integral spectra of the galactic CR theoretically:

$$D(>E) = \int_{E}^{\infty} D\left(E\right) dE \qquad (4)$$

D ($>E$) is integral spectrum, expressed by the number of particles per unit solid angle, square centimetre, and second, with total energies at least E. The integration on E begins from the energy, corresponding to the geomagnetic cut-off rigidity in the point of measurements. (The spectrum is dependent of the geographical position below a few tens of GeV). Integration in (4) is performed by rule of Simpson [5]. The computer programme is realized in algorithmic language C++. The computation of integral spectra is important, because in many cases the ground based, balloon and satellite instruments measure the integral particle fluxes.

Mean distances r_a of the outer planets from the Sun and a couple of parameters for each planet: P_{EUV} of decreasing of solar EUV radiation (proportional to $1/r_a^2$) and P_{GCR} of increasing of galactic CR intensity (because of solar modulation) are shown in Table III [13]. For 1 AU, the energy flux with wave length below 100 nm is about 3.3 erg/cm^2.s and galactic CR energy flux is $\approx 2\times10^{-2}$ erg/cm^2.s. We assume mean differential gradient of GCR in the interplanetary space as 3%/AU. It can be seen from Table III, the solar EUV radiation is weaker than the galactic cosmic ray intensity for Jupiter, Saturn, Uranus and Neptune. This comparison shows the importance of the galactic cosmic rays in the formation of outer planet ionospheres.

TABLE III

VALUES OF PLANETARY AVERAGE DISTANCES RA FROM THE SUN, PARAMETER PEUV OF DECREASING OF SOLAR EUV RADIATION, AND PARAMETER PCR OF INCREASING OF GALACTIC CR INTENSITY

Planet	Earth	Jupiter	Saturn	Uranus	Neptune
r_a, AU	1.00	5.2028	9.5388	19.1914	30.0611
P_{EUV}	1.00	3.69E-2	1.1E-2	2.72E-3	1.11E-3
P_{GCR}	1.00	1.16	1.29	1.58	1.9

Using the values of the parameters P_{GCR} of increasing of galactic CR intensity for outer planets and the received values of coefficients from (2) for the Earth the integral spectra of the outer planets are obtained.

Integral energy spectrum D ($>E$) of primary protons for solar minimum and maximum for the Earth and the Jovian planets: Jupiter, Saturn, Uranus and Neptune are given in Figs. 6 and 7 [14]. The computations are compared with data: + Schopper [15] and theoretical results: • CREME96 [16] and 2D stochastic model built from Bobik et al. [17].

In our model integral spectra are computed only in first approximation. We assume mean differential gradient of GCR as 3%/AU [18], [19] for all rigidity, irrespectively of the distance in the heliosphere or solar activity level [14].

It is seen from Fig. 6 that in Bobik's model, the integral spectrum of the Earth almost tally with Jupiter's integral spectrum at solar minimum. It is due to a lower average value of integral radial gradient in this model at 5 AU. Actually at solar minimum the radial gradients have lower values in the inner heliosphere.

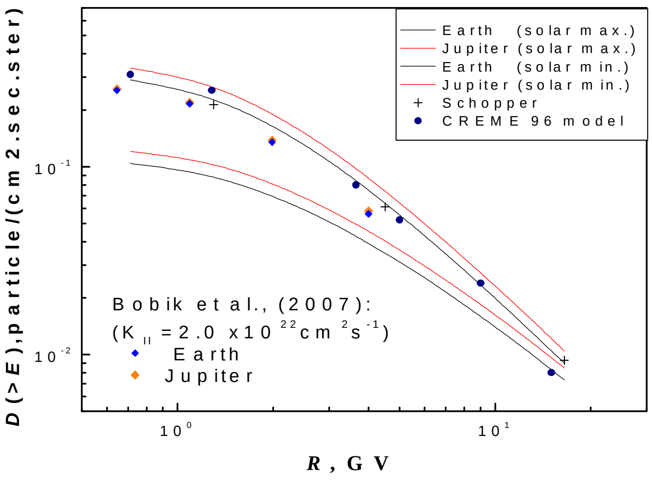

Fig. 6. The modeled integral spectra *D*(>*E*) of CR protons for maximum and minimum levels of solar activity for Earth and Jupiter. The computations are compared with data for Earth: + - Schopper [15] and theoretical results for Earth and Jupiter: • - CREME96 model [16] and 2D stochastic model built from Bobik et al. [17].

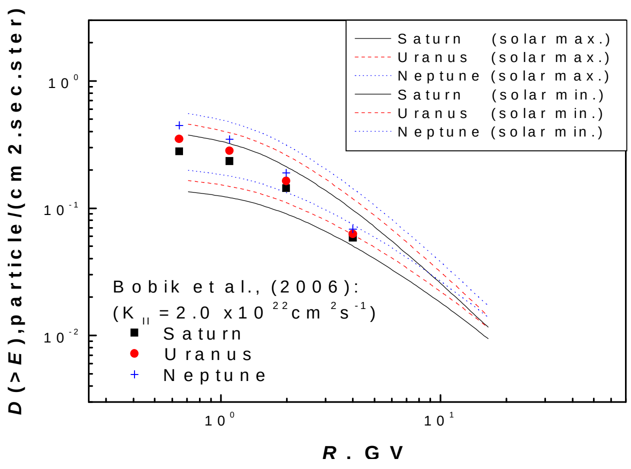

Fig. 7. The modeled integral spectra *D*(>*E)* of CR protons for maximum and minimum levels of solar activity for Saturn, Uranus and Neptune. The results are compared with computations of Bobik et al. for 2D transport model with drift [17].

In Fig. 8 are shown integral energy spectra *D* (>*E*) of primary helium nuclei for solar minimum and maximum for Earth and Jupiter.

In Bobik's model [17] for positive solar period (A > 0) are used the following values: parallel diffusion coefficient $(K_{II})_0 = 2.10^{22}$ cm^{2}s^{-1}, tilt angle θ = 30^0 and the ratio between the parallel and perpendicular diffusion coefficient $(K\perp)_0 = 0.025$. Burger's model [11] is used as local spectrum of protons. Bobik's model with these parameters reproduces the spectrum measured by AMS – 01, corresponding to modulation strength $\varphi \approx$ 510 - 550 MV [17].

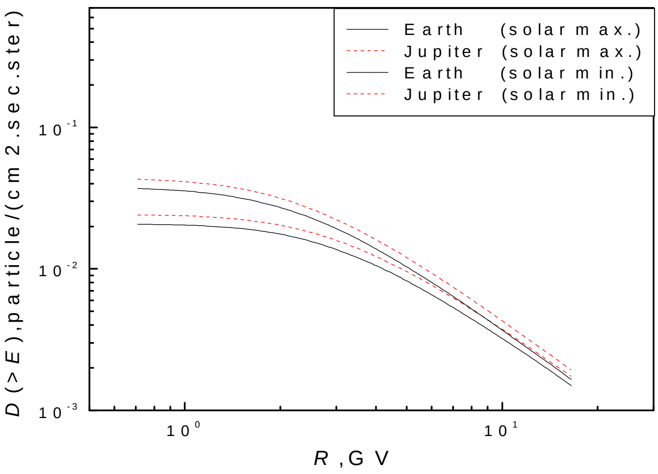

Fig.8. The modeled integral spectra *D*(>*E)* of CR helium nuclei for maximum and minimum levels of solar activity for Earth and Jupiter.

5. Application of the Model for Calculation of the Electron Production Rate *Q(H)* Profiles in Energy Intervals of Galactic CR and Anomalous CR Component

The observed CR spectrum in energy interval from 30 MeV/n to 1.10^2 GeV/n (related to GCR) has important contribution for the physical processes in the ionospheric CR-layers of the planetary ionospheres. Also the energy interval *E* = 1 – 30 MeV/n (related to ACR) is related to the polar cap region in Earth's ionosphere. The particles from this interval can penetrate directly in the cusp regions, where they cause enhanced ionization, heating and excitation of the upper and middle atmosphere.

The differential *D*(*E*) spectra (1) of galactic and anomalous CR are used for computation of electron production rate profiles in the ionospheres, at which the ACR component is also taken [20], [21].

Computational results for terrestrial ionosphere are shown on Fig. 9. The calculations are made for six values of geomagnetic cut-of rigidity R = 0 GV (polar cap region), 1.5 GV (the CR threshold at geomagnetic latitude 55^0), 3 GV, 5 GV (geomagnetic latitude 41^0), 9 GV and 15 GV (geomagnetic equator). The positive deviation in the upper part of the polar cap profile shows clearly the contribution of the anomalous CR component, which has significant influence above 80 km.

These computations are valid above 30 km since we may neglect the nuclear interactions at the height of the ionosphere. At these altitudes more important remain the electromagnetic interactions. Among them the ionization is the process, which creates the largest quantity free electrons in the ionosphere.

We made calculations for electron production rate profiles for the ionosphere of Saturn, which is the most oblate planet in the solar system in two cases: a) taking into account the real planetary oblateness 0.1076 [22], and b) with spherical model.

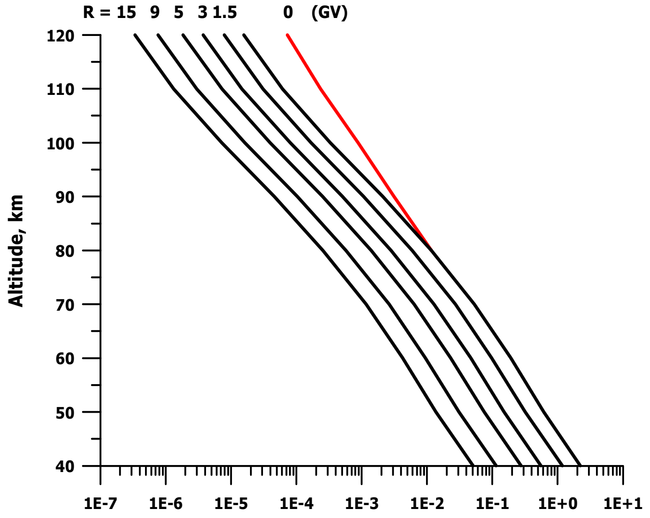

Fig.9. Electron production rate $q(h)$ profiles by galactic CR and anomalous CR component, $cm^{-3}\,s^{-1}$

We denote the ionization in ellipsoidal atmosphere with *q_E*, and the ionization in spherical atmosphere with *q_S*. We calculate the ratio *q_E / q_S* in dependence of altitude and latitude. The results are shown in Fig. 10. The lowest values for electron production rate profiles are obtained in case of spherical geometry. The observed difference is the smallest for the equator and the biggest for the polar regions.

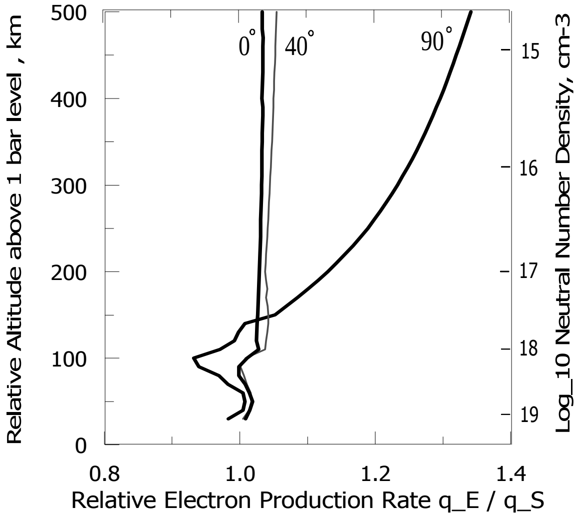

Fig.10. Relative electron production rate profiles (for elliptical per spherical geometry) in Kronian ionosphere for latitudes: 0^o - equator, 40^o - middle latitudes, and 90^o - polar regions.

All data for Kronian atmosphere are from [23]. There profiles are derived, which pertain to h = 2150 km above the level of the ammonia clouds (1 bar pressure level), where one of the ionosphere maximums of Saturn is observed, for latitude 40^0 and for solar declination 0^0. All geometric characteristics of Saturn are taken from [22].

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