Cosmic Rays and 11-Year Solar Modulation

M. Buchvarova[1], **P.I.Y. Velinov**[2]

[1]Space Research Institute, Bulgarian Academy of Sciences (BAS), Sofia, Bulgaria, marusjab@space.bas.bg

[2] Solar-Terrestrial Influences Laboratory, BAS, Sofia, Bulgaria, pvelinov@bas.bg

The proposed model generalizes the differential D(E) and integral D(>E) spectra of galactic (GCR) and anomalous (ACR) cosmic ray protons and heavier elements during the 11-year solar cycle. The model takes into account the cosmic ray (CR) modulation by the solar wind in the heliosphere. The measurements with the CAPRICE94 and IMAX experiments are examined with numerical solutions of the model equations. We analyze variations of the parameters during the solar activity for outer and Earth planets. The radial gradient G0 of GCR is relatively small in the inner heliosphere. After a transition region between 10 and 20 AU, G0 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 discuss here the errors in the predictions of the model and we compute the limits on estimated model parameters.

Introduction

The *galactic* (GCRs) and *anomalous* (ACRs) *cosmic rays* form the lower parts of the planetary ionospheres. 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) and V(E = 10 KeV/n – 1 MeV/n), where E is the kinetic energy of the particles [1, 2]. Some methods exist for calculating ionization by relativistic particles in CR intervals I, II and III. For the high latitude and 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 [1, 2]. In this paper a model for the calculation of the cosmic ray element spectra on the basis of balloon and satellite measurements is created. The model based on measured data, assuming power laws and taking into account the solar modulation at low energies.

This computed analytical model gives a practical possibility for investigation of experimental data from measurements of galactic cosmic rays and their anomalous component.

Modeling cosmic ray differential spectra

When GCRs enter our solar system, they must overcome the outward-flowing solar wind. This wind impedes and slows the incoming GCRs, reducing their energy and preventing the lowest energy ones from reaching Earth. This effect is known as solar modulation.

The Sun has an 11-year activity cycle which is reflected in the characteristics of the solar wind and the ability of the solar wind to modulate Galactic and Anomalous Cosmic Rays. The CR intensity at Earth is anti-correlated with the level of solar activity, i.e., when solar activity is high and there are lots of sunspots, the GCR intensity at Earth is low, and visa versa.

Solar Cycle 21 started in June 1976 with a smoothed sunspot number of 12.2. Cycle 22 started in September 1986 at 12.3. Cycle 23 started in May 1996 with the monthly SSN at 8.0 and peaked in April 2000 at 120.8. The last smoothed monthly sunspot number is 47.1 for March 2004.

In this work the primary differential energy spectrum of protons and other groups of cosmic ray nuclei will be obtained analytically with the expression [3]:

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

This formula is analysed in detail in [4]. The value for γ is taken as constant, equal to 2.6 [5] while the parameter λ = 140. Taking into account that at 100 GeV there are not modulation, we give K = 12.6791 $[\mathrm{m^2 \cdot s \cdot ster \cdot MeV}]^{-1}$. The coefficients α, β, x, y and μ are determined by Levenberg-Marquardt algorithm [6], applied to the special case of a least squares through the points with the eleven energy values: 0.0018, 0.0065, 0.01, 0.05, 0.023, 0.1, 0.39, 1.0, 5.054, 10 and 100 GeV. By inserting eleven experimentally measured points (E_i, D_i), one will get five unknowns α, β, x, y and μ. Here we use individual standard deviation 15%. The described programma is realized in algorithmic language C++.

The proposed semi-empirical model can be applied for conveniently and easily calculation of cosmic ray spectrum. The modulation of cosmic rays in the heliosphere appears to be dominated by four major mechanisms: convection, diffusion, drifts (gradient, curvature and current sheet drifts), and adiabatic energy losses [7]. In this model the common influence of these mechanisms is presented with the parameter's change α and β during the 11-year solar cycle. Drifts play a dominant role through around solar minimum modulation, and that this role gradually subsides to be replaced by *propagating diffusion barriers* (PDBs) as the dominating modulation process around solar maximum modulation [8, 9].

Thus modulated CR spectrum can by used for computation of the ionization profiles for different latitudes and different levels of solar activity. The electron production rate q($\mathrm{cm^{-3}s^{-1}}$) as a function of height h (km) for particles of type i from the cosmic ray composition is given by the following expression [10, 11, 12]:

where Q is the energy required for the formation of one

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

electron-ion pair and depends on the atmospheric composition; $D_i(E)$ is the differential spectrum of the particles; E is their kinetic energy; E_i is the energy (GeV/nucl), which corresponds to the geomagnetic cut-off rigidity R_C(GV); dE/dh represents the ionization loss of the penetrating CR particles, expressed by the Bohr-Bethe-Bloch formula; A is the azimuth angle; θ is the angle towards the vertical; $\Delta\theta$ takes into account that at a given height the particles can penetrate from the space angle (0°, $\theta_{max} = 90^o + \Delta\theta$), which is greater than the upper hemisphere angle (0°,90°) for flat model.

Results

In Table 1 the mean distances of the planets r_a from the Sun are shown [12]. 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 [13, 14]. We assume mean gradient of CR in the interplanetary space as 4% for 1 AU.

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

Planet	Earth	Jupiter	Saturn	Uranus	Neptune	Pluto
r_a, AU	1.000	5.203	9.539	19.191	30.061	39.529
P_{EUV}	1.000	3.69E-2	1.099E-2	2.72E-3	1.107E-3	6.40E-4
P_{CR}	1.000	1.17	1.34	1.73	2.16	2.54

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 [15].

Experimental data (E_i,D_i) for eleven different levels of the energy E are taken from Hillas [5], taking into account that at minimal and maximal level of solar activity integral proton spectra have the following values [12]:

$D(1.5\ \text{GeV})_{min.}/\ D(1.5\ \text{GeV})_{max.} \approx 2.00$

$D(5\ \text{GeV})_{min.}/\ D(5\ \text{GeV})_{max.} \approx 1.3(3)$

$D(12\ \text{GeV})_{min.}/D(12\ \text{GeV})_{max.} \approx 1.1(6)$

$D(15\ \text{GeV})_{min.}/\ D(15\ \text{GeV})_{max.} \approx 1.00$

For the energies $E < 390$ MeV a strong solar wind modulation of the CR intensity is observed. For each energy E in the interval between the energies 1.8 MeV and 100 GeV two values of the solar activity level are given: solar maximum and solar minimum. In Table 2 and 3 the values of $D(E)$ for low and high solar activity are given. After computation the coefficients α, β, x, y and μ obtained accuracy was 10^{-7}. Table 4 contains the computation values of the coefficients α, β, x, y, μ and χ^2 for protons at solar minimum and maximum for the Earth.

TABLE 2. Data for protons $D(E)$ (particle/(m^2.s.str.MeV /nucleon)) for solar minimum and maximum at eleven energy E (GeV) levels for the Earth

Earth		
E, GeV	$D(E)_{min[given]}$	$D(E)_{min[received]}$
100.0	8.00E-5	0.000077
10.00	2.35 E-2	0.022749
5.054	1.00 E-1	0.099224
1.000	1.00E-0	1.083335
0.390	1.80E-1	1.585892
0.100	1.00E-0	0.947872
0.050	4.86E-1	0.558202
0.023	2.78E-1	0.252128
0.010	5.05E-1	0.427493
0.0065	1.00E-0	1.067221
0.0018	1.405E-1	14.547283

TABLE 3. Data for protons $D(E)$ (particle/(m^2.s.str.MeV /nucleon)) for solar minimum and maximum at eleven energy E (GeV) levels for the Earth

Earth		
E, GeV	$D(E)_{max[given]}$	$D(E)_{max[received]}$
100.0	0.00008	0.000076
10.0	0.02100	0.020340
5.054	0.08330	0.080882
1.000	0.50306	0.562793
0.690	0.70000	0.619892
0.100	0.19000	0.187942
0.050	0.08091	0.082172
0.039	0.05522	0.054966
0.010	0.06892	0.050113
0.0065	0.10100	0.113709
0.0018	1.26450	1.303332

TABLE 4. The computed values of the coefficients α, β, x, y, μ and χ^2 for protons for solar minimum and maximum for the Earth

Coefficients	Earth	
	Solar minimum	Solar maximum
α	0.915406	1.509651
β	1.011998	1.426534
x	0.000046	0.000008
y	2.006260	1.898948
μ	0.016712	0.030802
$\chi 2$	3.828488	5.457800

It is seen from Table 4 that parameters α and β increase from solar minimum to solar maximum. In this case we obtain the right shift of the spectral maximum as well as decreasing of it's amplitude with increased solar activity.

Like galactic cosmic rays, ACR are also subjected to the four major modulation mechanisms: convection, diffusion, drifts, and adiabatic energy losses. As such a change in the diffusion coefficients and in gradient and curvature drifts over a solar activity cycle, together with a changing current sheet, should influence the acceleration and the modulation of ACR [16].

The effect of the solar cycle on ACR observations at 1 AU is extreme. There is an increasing presence of very large solar energetic particle (SEP) events in which the intensities can rise above the ACR intensities by many orders of magnitude.

At solar maximum, quiet periods are rare and limited in duration. For this reason, nearly all ACR measurements have been made near solar minimum, and the behavior of the ACRs at solar maximum has not been known. In fact, it is common to say that the ACRs “disappear” during each solar maximum and that their “recovery” afterward is often welcomed like the first robin of spring [17, 18]. In this paper we present the ACR spectrum during their full decline from solar minimum to solar maximum.

Correctly accounting for solar modulation of the ACRs as they are transported inward from the termination shock and distinguishing the effects of acceleration and modulation is a difficult task [19]. In our model we take into account simultaneously the effects of acceleration and modulation using a power low. It is seen that x and y values increase from solar maximum to solar minimum. It results in higher amplitude at transition from higher to lower solar activity.

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.

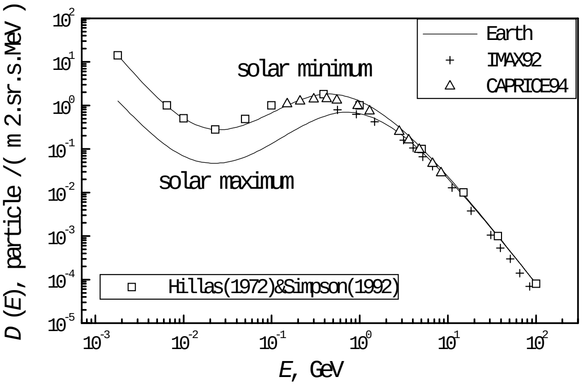

Fig.1. The modeled differential spectra D(E) of galactic CR protons and ACR for solar minimum and maximum for Earth. These results are in accordance with the experimental spectra, presented by □ Hillas (1972) and Simpson (1992), and measurements: Δ - Caprice94 [22] and + IMAX92 [23] for the Earth.

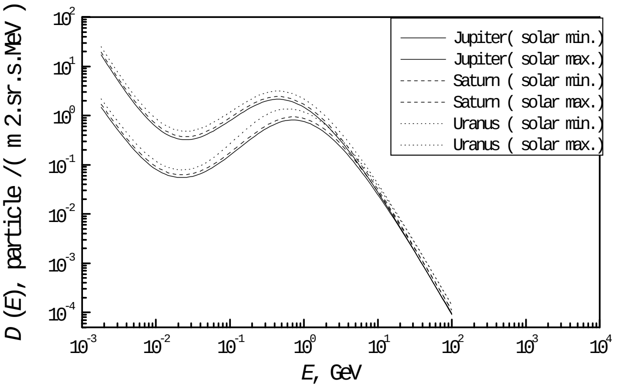

Fig. 2. The modeled differential spectra D(E) of galactic CR protons and ACR for solar minimum and maximum for Jupiter, Saturn and Uranus.

The spectra for Jupiter, Saturn and Uranus are calculated, assuming mean gradient of CR in the interplanetary space as 4% for 1 AU [20]. The experimental data give small variations of this gradient 3–5%/AU.

The black curves (Earth) from Fig.1 are for the solar minimum and maximum of the 21st solar cycle and coincide with the experimental spectra, presented in [3, 21]. The modeled spectra are compared with the measurements: for the periods near to solar minimum (one year before the solar minimum 1995) – Δ Caprice 94 [22] and for solar maximum- + IMAX92 [23]. In Table 5 the values of coefficients K, α, β and the corresponding values of χ^2 for these experiments are given.

TABLE 5. The computed values of the coefficients K, α, β and χ^2 for experiments IMAX 92 and CAPRRICE 94

Experiment	IMAX 92	CAPRICE94
K	9.007503	10.528764
α	1.423870	0.804554
β	0.990710	1.034256
$\chi 2$	15.568030	13.238451

Conclusion

This computed model gives a practical possibility for presentation of experimental data from CR measurements by means of analytical expression. The expression (1) is basic for determination of ionization profiles (2) in the planetary ionospheres. In such a way our formula (2) modeled the CR differential spectra $D(E)$ in whole energy interval 0.001–100 GeV. The other models are numerical or represent data bases. They relate only to some energy intervals.

From electron production rates we can determine the electron density and electrical conductivities in the planetary ionospheres. This is very important for the physics of the ionospheres and solar-planetary relationships. GCR influence significantly, through atmospheric conductivity, the electric fields and currents in the Earth environment, generated by thunderclouds [24, 25] and by thunderstorm activity [26]. GCR cause an exponential increase of the conductivity with altitude, and thus orientation of the conductivity currents generated by a thunderstorm within a relatively narrow (<100 km) vertical tube into the magneto/ionosphere [25, 26]. Since the conductivity in the troposphere and the lower stratosphere is determinative for the electric resistance between the ionosphere and the ground, GCR can play a role of an important factor, which controls the parameters of the global atmospheric electric circuit and of the ionospheric potential variations.

However, the expression (2) takes into account only the electromagnetic interactions of CR with the substance of the atmosphere. That is why (2) is valid only in the planetary ionospheres and not in the whole atmospheres. The mean path of the nuclear interactions for the protons is about 70 g cm^{2}. That means the ionization model (2) works well above 12 - 15 km for terrestrial atmosphere [12, 27]. Under that altitude the nuclear interactions enforce and the secondary rays must be taken into account. But the test of the model gives real values of the ionization rates, even at 25 and 20 km. That means the electron production rate q does not ‘‘feel’’ if the ionization factor is primary or secondary cosmic rays. Below 20 km the effect of Pfotzer maximum [28] begins and the model (2) is not valid.

The average radial gradient of GCR is accepted 4%/AU [13] for the determination of CR differential spectrum around the outer planets. 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. The obtained differential and integral 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 program for computation differential and integral spectra of CR works well. In periods of high solar activity the role of the solar particle fluxes increases as an ionization factor in the Earth's and planetary environments, affecting the conductivities, electric fields and energetic processes in the ionospheres and atmospheres [12, 27].

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