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EXPLORATIONS COSMIQUES

DETERMINATION OF THE SPECTRA AND IONIZATION OF ANOMALOUS COSMIC RAYS IN POLAR ATMOSPHERE

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Abstract

Multiply Charged Anomalous Cosmic Rays (MCACR) have similar differential spectra like the singly ionized anomalous cosmic ray components. In the present paper, it is shown that they cause enhanced ionization rate in the polar cap and cusp regions and that the obtained values are comparable to the galactic cosmic ray ionization rate values. This leads to hypothesis that even its relatively low energies, MCACR, may have some contribution to the electrodynamic processes in the Earth's atmosphere. The model CORIMIA is successfully applied for calculation of MCACR ionization rate profiles. Input differential spectra which are approximated as polynomial expressions are in good agreement with the satellite experimental data.

Key words: multiply charged anomalous cosmic rays, ionization, middle atmosphere, lower ionosphere

Introduction. In the composition of the Anomalous Cosmic Rays (ACR) there is evidence for Multiply Charged ACR (MCACR). Measurements from the SAMPEX spacecraft show that the oxygen nuclei with energies above 20 MeV/nucl are mainly multiply ionized [1]. The investigation of the MCACR influence on the ionization state of the atmosphere and ionosphere is not yet developed. This motivates us to examine its contribution to the total ionization. Because of their energy spectrum, we can expect that MCACR produce ionization over the region with relatively small geomagnetic and atmospheric cut-offs – over polar cap and cusp regions. However, the model for calculation of ionization rate CORIMIA (COsmicRay Ionization Model for Ionosphere and Atmosphere) shows that the electron production rate in the atmosphere is proportional to the charge square of penetrating CR nuclei [2–4]. Therefore, it is important to know the contribution of MCACR fluxes depending on the altitude (influence of the

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atmospheric cut-offs) over polar region and how the different MCACR charge magnitudes act on the corresponding ionization state.

When we consider MCACR, it is important to mention that this type of CR strongly depends on the solar activity. During periods of high solar activity and because of relatively low energies (in most cases under 100 MeV in 1 AU [5–7]), the fluxes of ACR including MCACR cannot be well recognized and therefore determination of their contribution to the ionization of atmosphere is difficult to study [5]. In our previous paper [2], we calculated the singly ionized ACR oxygen and helium. Now we are solving the more complex task using MCACR oxygen spectra.

Model description. The newly developed operational model CORIMIA for calculation of electron production rate caused by galactic CR (GCR), ACR and solar energetic particles (SEP) [2, 3, 8] is modified with account to MCACR contribution to the total ionization of the atmosphere and ionosphere. The input parameters of the CORIMIA include charge and atomic weight of the penetrating particles, analytical expression of measured differential spectrum, geomagnetic latitude (geomagnetic cut-off) and altitude (atmospheric cut-off). Most of the experimental data show that the MCACR energy spectra are situated under 200 MeV, i.e. they include only the first three low energetic intervals of ionization loss function [9]. Unlike the case of single ionized particles, now we include as second energy interval the charge decrease interval. In this way, the expression of the ionization loss function becomes

$$(1)\qquad -\frac{1}{\rho}\frac{dE}{dh} = \left\{\begin{array}{ll} 2.57\times 10^{3}E^{0.5} \ \text{ if } \ kT \le E \le 0.15 \text{ MeV/n}, & \text{interval 1}\\ 1540E^{0.23} \ \text{ if } 0.15 \ \le E \le E_a = 0.15Z^2 \text{ MeV/n}, & \text{interval 2}\\ 231\times Z^2E^{-0.77} \ \text{ if } \ E_a \le E \le 200 \text{ MeV/n}, & \text{interval 3}\end{array}\right.$$

The electron production rate expression is characterized by the following main terms:

$$q\left(h\right) = \frac{\rho\left(h\right)}{Q}\left\{2.57\times 10^{3}\int_{E_{\min}}^{0.15} D\left(E\right)\left[E_1\left(h\right)\right]^{0.5}dE\right.$$

$$(2)\qquad +2.57\times 10^{3}\int_{0.15}^{E_{0.15;2}(h)} D\left(E\right)\left[E_{21}\left(h\right)\right]^{0.5}dE + 1.54\times 10^{3}\int_{E_{0.15;2}(h)}^{E_a} D\left(E\right)\left[E_2\left(h\right)\right]^{0.23}dE$$

$$+1.54\times 10^{3}\int_{E_a}^{E_{a;3}} D\left(E\right)\left[E_{32}\left(h\right)\right]^{0.23}dE + 231\times Z^2\int_{E_{a;3}}^{200} D\left(E\right)\left[E_3\left(h\right)\right]^{-0.77}dE,$$

where $Q = 35$ eV is the energy necessary to form one electron-proton pair; $\rho(h)$ is the atmospheric density at height h; $E_1(h)$, $E_2(h)$, $E_3(h)$, $E_{21}(h)$ and $E_{32}(h)$ are the corresponding interval energy decrease laws. $D(E)$ is the differential spectrum in (cm^{-2}.s^{-1}. st^{-1}.MeV^{-1}). $E_{\min}$ is the energy cut-off. $E_{0.15;2}(h)$ and $E_{a;3}$ are the initial energies of particles (before entering of the spectrum in the atmosphere), which have energy $E(h) = 0.15$ and $E(h) = E_a$ (MeV) at altitude h (km) respectively [2].

Evaluation of the differential spectra. There are a few spacecrafts (SAMPEX, ACE, GOES, etc.) which measure the differential spectra of CR. Particularly in this study, we use experimental data from SAMPEX spacecraft concerning MCACR [1]. The input parameters for CORIMIA include two sets of spectral curves which are presented in two figures in [1]. We intend to calculate the effects of MCACR oxygen for both cases. For this purpose, we perform an approximation for every separate spectral curve using the possibilities of Mathematica programme [10]. The fit procedure generates polynomial expressions for the differential spectra which are used as input data for CORIMIA code. These polynomial expressions are in very good agreement with the experimental data. The expressions below represent the output results from Mathematica programme concerning differential spectra approximations. The first set of expressions includes the fit output for MCACR oxygen with charges $Z = +1, +2, +3, +4$. They are the following:

$$D_{O+1}(E) = 6.4 \times 10^{-3} - 6.9 \times 10^{-3} e^{-E} - 1.07 \times 10^{-4} E, \tag{3}$$

$$D_{O+2}(E) = 2.7 \times 10^{-3} - 3.15 \times 10^{-3} e^{-E} - 1.7 \times 10^{-7} E^2, \tag{4}$$

$$D_{O+3}(E) = 8.2 \times 10^{-4} - 9.57 \times 10^{-4} e^{-E} - 7.9 \times 10^{-8} E^2, \tag{5}$$

$$D_{O+4}(E) = 1.8 \times 10^{-4} - 2.1 \times 10^{-4} e^{-E} - 1.78 \times 10^{-8} E^2. \tag{6}$$

These differential spectra are shown in Fig. 1. The second set of expressions is the following:

$$D_{O+1}(E) = 4.4 \times 10^{-3} - 4.6 \times 10^{-3} e^{-E} - 8.68 \times 10^{-7} E^2, \tag{7}$$

$$D_{O+2}(E) = 3.8 \times 10^{-3} - 4.3 \times 10^{-3} e^{-E} - 3.8 \times 10^{-7} E^2, \tag{8}$$

$$D_{O+3}(E) = 1.5 \times 10^{-3} - 1.8 \times 10^{-3} e^{-E} - 1.57 \times 10^{-7} E^2, \tag{9}$$

$$D_{O+4}(E) = 1.1 \times 10^{-3} - 1.2 \times 10^{-3} e^{-E} - 1.06 \times 10^{-7} E^2, \tag{10}$$

$$D_{O+5}(E) = 3.8 \times 10^{-4} - 4.4 \times 10^{-4} e^{-E} - 3.6 \times 10^{-8} E^2, \tag{11}$$

$$D_{O+6}(E) = 1.8 \times 10^{-4} - 2.2 \times 10^{-4} e^{-E} - 1.74 \times 10^{-8} E^2. \tag{12}$$

In Figure 2 are shown the differential spectra which are described by expressions (7)–(12). Both Figures 1 and 2 are used as CORIMIA input data.

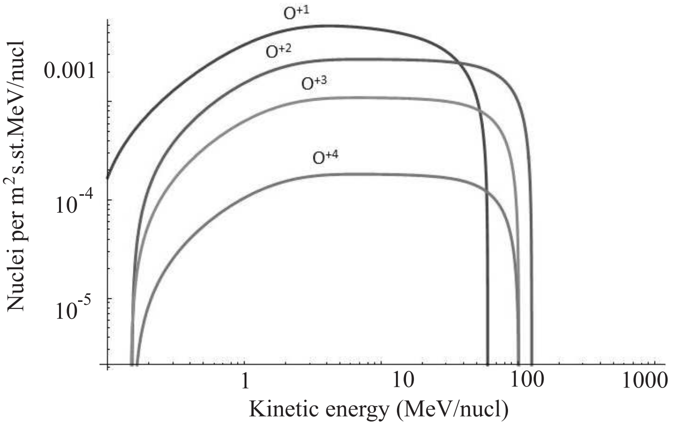

Fig. 1. Differential spectra $D(E)$ for MCACR oxygen nuclei (O^{+1}, O^{+2}, O^{+3} and O^{+4}) from experimental data in [1]

Results. The main results of the CORIMIA simulation concerning the MCACR ionization in the middle atmosphere and lower ionosphere are presented in Figs 3 and 4. These results suggest that electron production rate by MCACR is significant over polar cap regions and the obtained values are comparable with the total GCR ionization rate. We have established the contributions of separate constituents O^{+1}–O^{+6} in Figs 3 and 4, including the sum of profile values for charge $Q > 1$. The lower part of the profiles is dominated by high energy particles of differential spectra in spite of the higher part of the profiles where the low energy particles dominate. These results are due to the differential spectra magnitude of the different MCACR oxygen nuclei. Higher charge nuclei are characterized by smaller magnitude of their spectra [1]. Nevertheless, their ionization rate is proportional to the charge square which makes the problem complex and nonlinear.

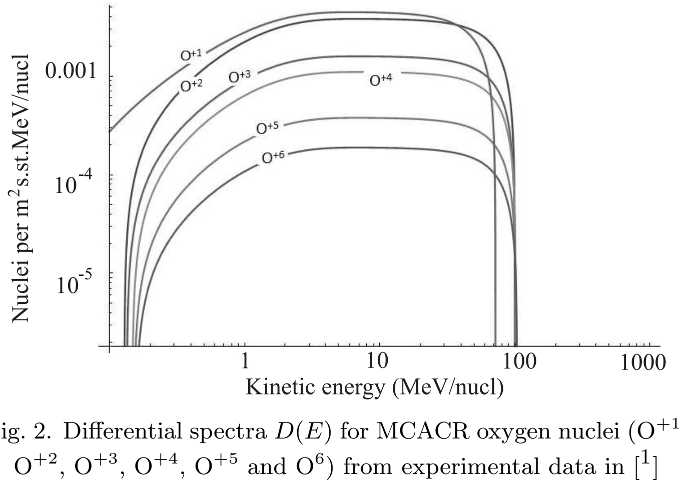

Fig. 2. Differential spectra $D(E)$ for MCACR oxygen nuclei (O^{+1}, O^{+2}, O^{+3}, O^{+4}, O^{+5} and O^{6}) from experimental data in [1]

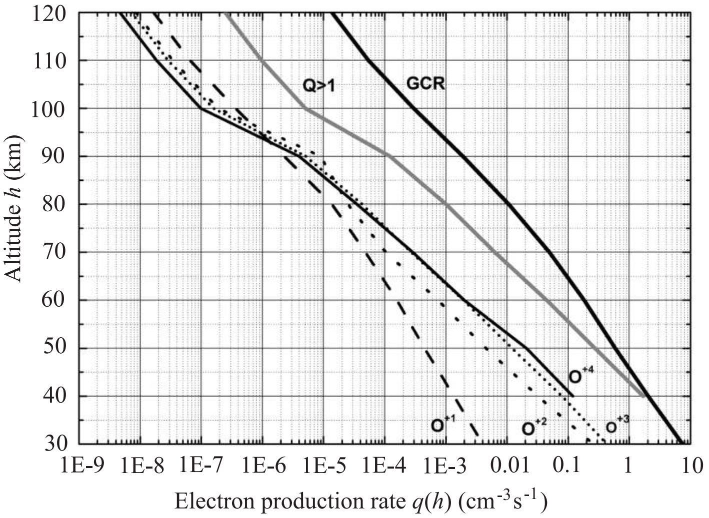

Fig. 3. Electron production rate MCACR profiles $q(h)$ depending on altitude h over polar cap regions simulated by CORIMIA with the input spectra from Fig. 1

Conclusion. There are several main factors which characterize ionization rate caused by CR. The kinetic energy E_k of the penetrating CR particles gradually decreases along the travelling substance path $\tilde{h}$ through the atmosphere. Except for the kinetic energy, ionization rate $q(h)$ strongly depends on the atmospheric density ρ, which varies exponentially with height h. The charge Z

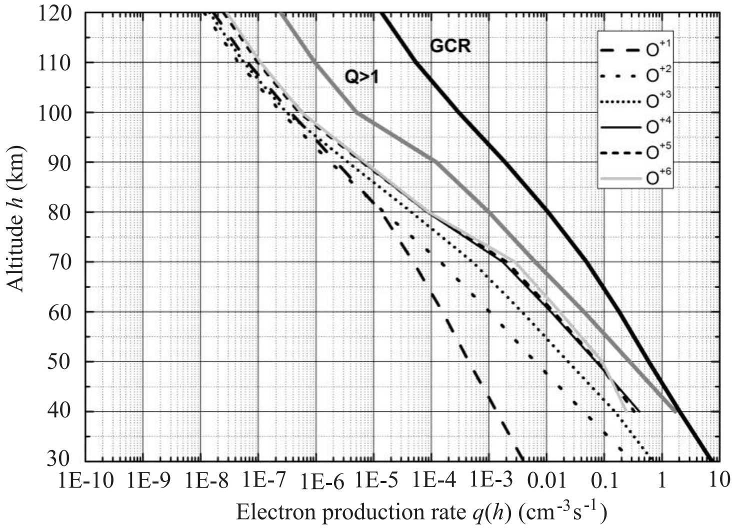

Fig. 4. Electron production rate MCACR profiles $q(h)$ depending on altitude h over polar cap regions simulated by CORIMIA with the input spectra from Fig. 2

also plays a significant role especially when we consider MCACR. According to the presented results from CORIMIA simulation we may conclude that the ionization rate during MCACR penetration increases with the increasing depth into the atmosphere and the obtained values are of the same order as those of GCR penetration over polar cap regions. This leads to the hypothesis that even its relatively low energies, MCACR, may have some contribution to the electrodynamic processes in the Earth's atmosphere.

If we summarize the results from [2, 8, 9] together with those presented in this work, we reach some basic features about CR ionization in the atmosphere. During periods of quiet times, the CR ionization rate over polar cap regions is mainly caused by GCR and ACR (including MCACR). Otherwise the contribution of SEP to $q(h)$ significantly overwhelms that of any other CR. Depending on the atmospheric and geomagnetic cut-offs and because of the mentioned factors, characterizing $q(h)$, every flux of CR must cause a maximum of the electron production at some altitude. This maximum mainly depends on the CR differential spectrum. For example, in the case of SEP the maximum can be observed at higher altitudes than those of GCR and ACR.

REFERENCES

[1] Mewaldt R. A., R. S. Selesnick, J. R. Cummings, E. C. Stone, T. T. von Rosenvinge. The Astrophysical Journal, **466**, 1996, L43–L46.

[2] Velinov P. I. Y., S. Asenovski, L. Mateev. Compt. rend. Acad. bulg. Sci., **65**, 2012, No 9, 1261–1268.

[3] Velinov P. I. Y., S. Asenovski, L. Mateev. ActaGeophys., **61**, 2013, No 2, 494–509, DOI 10.2478/s11600-012-0084-y.

[4] Dorman L. Cosmic rays in the Earth's atmosphere and underground, Dordrecht, Kluwer Academic Publishers, 2004.

[5] Leske R. A., A. C. Cummings, R. A. Mewaldt, E. C. Stone. Space Sci. Rev., DOI 10.1007/s11214-011-9772-1, 2011.

[6] McDonald F. B., B. Klecker, R. E. McGuire, D. V. Reames. J. Geophys. Res., **107**, 2002, No A8, 10.1029/2001JA000206.

[7] Cummings A. C., E. C. Stone, W. R., Webber. Astrophys. J., **287**, 1984, L99–L103.

[8] Velinov P. I. Y., S. Asenovski, L. Mateev. Compt. rend. Acad. bulg. Sci., **65**, 2012, No 8, 1135–1144.

[9] Velinov P. I. Y., S. Asenovski, L. Mateev. Compt. rend. Acad. bulg. Sci., **66**, 2013, No 2, 235–242.

[10] Wolfram Research Inc., Mathematica, Version 7.0, Champaign, IL, 2008.

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