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Numerical Model of Cosmic Ray Induced Ionization in the Atmosphere

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Abstract: We present a full numerical model to calculate cosmic ray induced ionization in the atmosphere. The model is based on detailed Monte-Carlo simulations using the CORSIKA tool, which simulates full development of an electromagnetic-muon-nucleonic cascade in the atmosphere, with the FLUKA package used for low energy interactions. The model is applicable to the entire atmosphere, from the ground up to the stratosphere. A comparison to fragmentary direct measurements of the ionization in the atmosphere confirms the validity of the model in the whole range of geographical latitudes and altitudes. This provides a useful tool for a quantitative study of the space weather influence upon the Earth's environment. Some practical applications are discussed.

Introduction

Energetic galactic cosmic rays (CR) form an important outer space factor affecting the physical-chemical properties of the Earth's atmosphere. In particular, CR are a dominant source of ionization of the lower/middle atmosphere, producing the cosmic ray induced ionization (CRII). Until recently it was commonly considered that the CRII is proportional to the cosmic ray flux, as measured by ground based neutron monitors (e.g., [7]). However, that is not fully correct [3, 1], and explicit computations of the CRII are required for a detailed quantitative study (e.g., [10, 13, 17]). Here we present a new numerical CRII model [14, 16], based on Monte-Carlo simulations of the nucleonic-electromagnetic cascade initiated by CR in the atmosphere and discuss its possible applications.

The model

The present model is based on the full Monte-Carlo simulation of the electromagnetic-muon-nucleonic cascade, initiated by primary cosmic rays in the Earth's atmosphere (see full description in [16]). The simulations were performed using the CORSIKA simulation tool [4] (v. 6.204). Electrons, positrons and photons were simulated by the EGS4 routine, while high and low (< 80 GeV) energy hadronic interactions were simulated using the HDPM and FLUKA sets of routines, respectively. We used a realistic curved atmosphere model for computations of the CRII at high altitudes. The chemical composition of the atmosphere was taken as N_2, O_2 and Ar in the volume fractions of 78.1%, 21% and 0.9%, respectively. The atmosphere's density profile was modeled using the standard U.S. atmosphere model parameterized by [5].

Using this Monte-Carlo model we have computed the ionization yield function Y which gives the number of ion pairs produced in one gram of the ambient air at a given atmospheric depth by one nucleon of the primary CR particle with the given energy per nucleon. Simulations were done for primary CR particles with the fixed energy isotropically (within 2π of the solid angle) entering the curved atmosphere. We considered the energy range of the primary CR between 0.07 GeV/nuc and 1000 GeV/nuc. It is important that all the three main components of the cascade (electromagnetic, muon and hadron) contribute significantly into CRII at different altitudes and different energy ranges of primary particles, and none of them can be neglected. The computed Y function is shown in Fig. 1A (a tabulated version is available

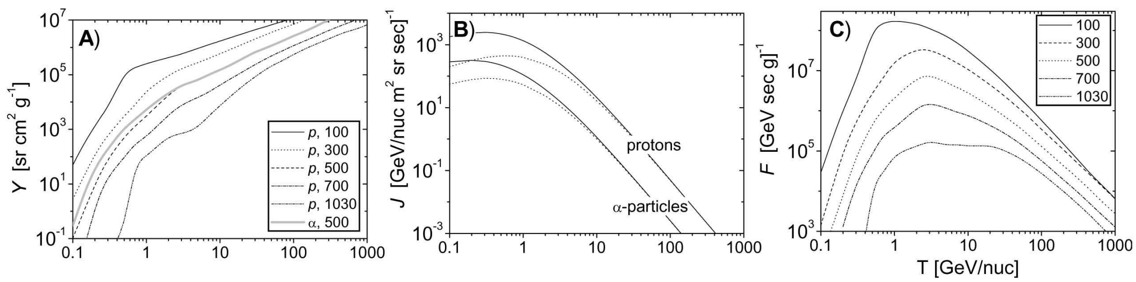

Figure 1: A) Computed ionization yield functions of CR (protons p and $\alpha-$particles) for different atmospheric layers (denoted in the legend in units of [g/cm^2]). B) Differential energy spectra of CR (protons and $\alpha-$particles) near Earth for the solar activity minimum (solid curves) and maximum (dotted curves) conditions. C) The differential ionization function F for primary protons at different atmospheric depths. The proton spectrum corresponds to a medium solar modulation.

in Tables 1 and 2 in [16]). Note that Y decreases with the atmospheric depth and increases with the energy of primary particles. By multiplying of the pre-calculated ionization yield function (Fig. 1A) with the CR spectrum J_i (shown in Fig. 1B), one obtains the differential ionization function for the i^{th} specie of CR (Fig. 1C):

$$F_i(x,T) = Y_i(x,T) \cdot J_i(T). \qquad (1)$$

The effective energy of CR for ionization depends on the atmospheric depth: it increases from 1 GeV/nuc in the stratosphere up to about 10 GeV/nuc at the sea-level. The summary rate of CRII, Q, is then computed as

$$Q = \sum_i \int_{T_{c,i}}^{\infty} F_i(x,T)\, dT, \qquad (2)$$

where integration is over the kinetic energy, T, above $T_{c,i}$, which corresponds to the local geomagnetic rigidity cutoff P_c.

We have compared our computed CRII with real balloon-borne measurements of the ionization rate in the atmosphere (Fig. 2). A good agreement between the model and the measurements is clear below ≈17 km (x >100 g/cm^2), but the model slightly underestimate CRII above 20 km. Overall, the model reproduces the measured results within 10% accuracy. This can be considered as a good agreement, since individual measurements, performed during short balloon flights, can vary depending, e.g., on the exact atmospheric profile, the

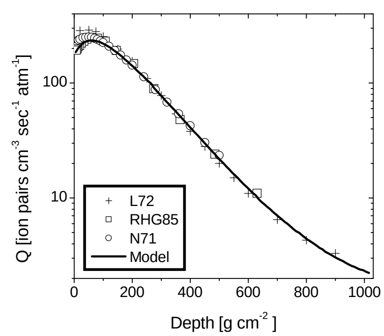

Figure 2: Comparison of the model CRII calculations (solid curve) with direct ionization measurements (symbols): L72 [6]; RHG85 [11] and N71 [8].

instrumentation, etc. [6], while the model CRII was computed for the average static conditions. The model is also in good agreement with other model results. It agrees with the GEANT-based ATMOCOSMIC Monte-Carlo model [2] within 10%, where the difference can be attributed to the different Monte-Carlo models and atmospheric profiles used. A reasonable agreement is found also with a model by O'Brien [9], based on analytical approximations of the atmospheric cascade development.

Using the same approach, we evaluated also the ionization effect of solar energetic particle (SEP) events, when the flux of less energetic charged par-

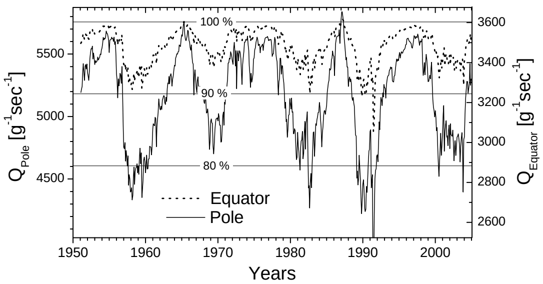

Figure 3: Time profiles of the CRII since 1951 at the atmospheric depth $x = 700$ g/cm^2 (about 3 km altitude) for the polar (left axis) and the equatorial regions (right axis). Thin horizontal lines denote the percentage with respect to the values for May 1965 (100 %).

ticles may increase by orders of magnitude during minutes-hours. We conclude that only a severe SEP event may produce an effect at middle and high latitudes down to the troposphere, but moderate events produce no additional ionization in the troposphere, even in polar regions. The global effect of moderate-to-strong SEP events in the ionization is negligible. Since most of strong SEP events are accompanied by Forbush decreases, which reduce the CRII background by GCR, the net effect of such events is negative (suppressed ionization).

Temporal variations of CRII

By means of the method presented here, we can calculate CRII variations for the last 55 years, using the temporal variability of the CR spectrum as reconstructed in [15] since 1951. Fig. 3 depicts a time profile of the computed CRII at the atmospheric depth of $x = 700$ g/cm^2 (at about 3 km altitude) for the polar and equatorial regions. The amplitude of the 11-year cyclic variations of the ionization rate depends on the latitude, and is 20-25% in the polar region but only about 10% at the equator. The amplitude increases with the altitude, e.g., it is 40% (10%) in the polar (equatorial) regions at the atmospheric depth $x = 300$ g/cm^2 (about 9 km).

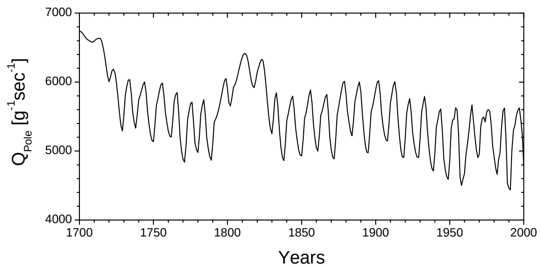

Figure 4: The time profile of the CRII ($x = 700$ g/cm^2 in the polar region) computed after 1700 AD.

Using a reconstruction [12] of the CR modulation for the last 300 years, we also evaluated the expected CRII in the polar region (Fig. 4). One can see that the CRII was about 40% higher during the Maunder minimum, when the Sun was extremely quiet, than during the recent solar cycle minima, which is double the variation of the solar cycle.

Conclusions

We have presented a full numerical model, which computes the cosmic ray induced ionization in the entire atmosphere, from the ground level up to the stratosphere, all over the Globe. The model computations reproduce actual measurements of the atmospheric ionization in the full range of parameters, from equatorial to polar regions and from the solar minimum to solar maximum. The model allows evaluating variations of the CRII on different time scales – from days to millennia. For shorter time scales, a dynamical atmosphere model should be used instead of the static one, to account for the day-night difference. Using the model, we have estimated temporal variations of the CRII during the last 50 years and during the last 300 years, using recent reconstructions of the cosmic ray modulation over these time scales.

An ionization effect of SEP events in the troposphere is found to be noticable only for severe events and can be neglected for the bulk of the events. On the other hand, stratospheric ionization is affected by SEP, especially in polar regions.

Concluding, we have presented a useful and easy-to-use tool to compute the cosmic ray induced ionization in the atmosphere, which can be applied directly to studies of the solar-terrestrial relations and outer space influence on the terrestrial environment.

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