Numerical model of cosmic ray induced ionization in the atmosphere CRAC:CRII

ILYA USOSKIN[1], G.A. KOVALTSOV[2], I.A. MIRONOVA[3]
[1] *Sodankylä Geophysical Observatory, University of Oulu, Finland*
[2] *Ioffe Physical-Technical Institute, St.Peterersburg, Russia*
[3] *St. Petersburg State University, Russia*
ilya.usoskin@oulu.fi

Abstract: Cosmic rays form the main source of the atmospheric ionization in low and middle atmosphere. A major progress has been recently achieved in numerical modelling of this process, basing on a full Monte-Carlo simulation of the complicated cascade initiated by cosmic rays in the atmosphere. Here we present a new version of the CRAC:CRII model computing ionization induced by cosmic rays in the atmosphere, that extends from low and middle to the upper atmosphere. The model is able to compute the ionization rate in the atmosphere at any given location and time provided the energy spectrum of incoming cosmic rays is known. It computes the background ionization due to galactic cosmic rays in the upper atmosphere in a more correct way comparing to earlier models. Using this a new model we evaluate the ionization effects in the atmosphere caused by several major solar energetic particle (SEP) events for the last decades. It is shown that the direct ionization effect due to SEP is often overcompensated by the accompanying Forbush decreases of galactic cosmic rays. The enhanced ionization appears only in the polar atmosphere, where it can be dramatic in the middle and upper atmosphere.

Keywords: Cosmic Rays, atmosphere, ionization

1 Introduction

Galactic cosmic rays (GCR) provide the main source of ionization of the Earth's low and middle atmosphere, which produce important physical and chemical changes in the atmosphere (see, e.g., [1]). However, measurements of the cosmic ray induced ionization (CRII) in the atmosphere are rare, and numerical models, calibrated for the direct data, are used. Modern models are based on Monte-Carlo simulations of the nucleonic-electromagnetic-muon cascade, initiated by cosmic rays in the atmosphere, to compute CRII. One of the first models of this kind was the CRAC:CRII (Cosmic Ray Atmospheric Cascade: Application for Cosmic Ray Induced Ionization) model based on CORSIKA and FLUKA Monte-Carlo tools [2, 3]. This model has been recently updated, including the upper atmosphere [4]. This new CRAC:CRII model can be applied also to the solar energetic particle (SEP) events, which occur rarely but may lead to large enhancement of the energetic particle fluxes near Earth.

Here we discuss details of the CRII computations using the CRAC:CRII model, with special emphasis paid upon the relative contribution of SEP and GCR in the atmospheric. ionization.

2 Ionization yield function

For the computation of CRII, it is often used the approach based on the yield function concept [3], which is the number of ion pairs produced in one gram of the ambient air, at the atmospheric depth h, by cosmic rays with the fixed energy T and unit flux intensity on the top of the Earth's atmosphere. An integral of the product of the yield function and the energy spectrum of CR gives the the ionization rate Q at a given depth h as:

$$Q(h) = \sum_i \int J_i(T) \cdot Y_i(T,h)\, dT, \qquad (1)$$

where J_i is the intensity (in number of nucleons per second·cm^2·sr·GeV/nuc) of primary cosmic rays of sort i with energy per nucleon T. Summation is over the sort of primary particles (protons, $\alpha-$particles and heavier species). Integration is over the kinetic energy of primary particles above the energy corresponding to the local geomagnetic cutoff for the particles. If the yield function Y is expressed in units of [sr cm^2 g^{-1}], the ionization rate is obtained as the number of ion pairs produced in one gram of air per second. The computed yield function is tabulated in [3, 4]. Some examples of the yield function are shown in Fig.1 for different atmospheric depths. One can see that the ionization rate is almost independent on the particle's energy in the upper atmosphere ($h = 1$ g/cm^2, grey curve), because it is a simple direct ionization of the ambient air by flying by cosmic rays. However, already at the atmospheric depth of 10 g/cm^2 (dotted curve, altitude about 30 km), the contribution of atmospheric cascade becomes important, which can be observed as an increase of the yield at higher energies ($>$ 10 GeV). At the depth of 100 g/cm^2 (dashed curve, 15–17 km altitude), the direct ionization by primaries is small, with the bulk ionization originating from the atmospheric cascade. Ionization at the sea-level (solid curve, 1000 g/cm^2) is totally dominated by the development of an atmospheric cascade. We note that, because of this, simple analytical models of ionization, which neglect the development of the cascade, are valid only in the upper atmosphere (above 1 g/cm^2) and get progressively worth downwards.

3 Computations of CRII

The CRAC:CRII model has been tested vs. direct measurements and other models [5] and is in a good agreement, providing a useful and reliable tool to study CRII in the lower atmosphere. An example of the agreement is shown in Fig. 2. Panel A depicts a general agreement between the model computations and several direct measurements for the solar maximum conditions (modulation potential $\phi =$ 1000 MeV) in the polar atmosphere. Once can see that the agreement is pretty good in the entire altitude range, from the lower troposphere up to 10 g/cm^2 (30-35 km). Panel B) depicts measurements (dots) of the ionization rate for a single balloon flight on August 18, 2005 performed at the University of Reading, UK [9]. The model simulation (solid curve), performed for the particular conditions for that day and location, perfectly reproduces the overall shape but misses the fine structure, which may be due to random fluctuations or inhomogeneities during the balloon ascend/descend.

By using the CRAC:CRII model, we can calculate the CRII level for several solar cycles, by employing the GCR variability as reconstructed from the network of ground-based neutron monitors [10], and SEP events reconstructed in [12, 11]. An example of thus computed daily ionization rate at the depth 100 g/cm^2 (15-17 km altitude) in the polar atmosphere is depicted in Fig. 3 for solar cycles 19–23. One can clearly see the solar cycle variability of a factor 2, due to the GCR modulation. On top of that, there are sporadic ionizing pulses caused by SEP events, observed as vertical spikes in the Figure. They are not numerous (a few per solar cycle) and do not contribute to the overall ionization level. A detailed consideration of the strongest type of SEP events, ground-level enhancements (GLE) of cosmic rays, was done in [11]. It was shown that the CRII effect from SEP/GLE events is essential only in the middle (stratosphere) and upper atmosphere in the polar region. When going to the lower altitudes, the direct effect of even strongest SEP events becomes negligible, and are largely overcompensated by Forbush decreases of GCR often accompanying the SEP events.

4 Conclusions

We present here a full version of the CRAC:CRII model [3, 4], which can be applied to the entire atmosphere, from the ground to the top, and include galactic cosmic rays and solar energetic particles. We note that other sources of the upper atmosphere ionization, such as solar electromagnetic radiation or precipitating particles of magnetospheric origin, are not considered in the framework of this study, since they do not require Monte-Carlo modelling, but can be calculated straightforwardly by analytical models.

Acknowledgements

Support from the Academy of Finland is acknowledged. IAM acknowledges grant 11.37.26.2011 of St.Petersburg State University. This work was performed in relation with the international Programmes CAWSES-II, COST ES1005 and ISSI.

References

[1] Bazilevskaya, G.A., *et al.* , Space Sci. Rev., 2008, **137**, 149-173.
[2] Usoskin, I. G., O. G. Gladysheva, G. A. Kovaltsov, 2004, J. Atmos. Solar-Terr. Phys., **66**, 1791–1796.
[3] Usoskin, I.G., G.A. Kovaltsov, 2006, J. Geophys. Res., **111**, D21206.
[4] Usoskin, I.G., G.A. Kovaltsov, I.A. Mironova, 2010, J. Geophys. Res., **115**, D10302.
[5] Usoskin, I.G. *et al.* , 2009, Acta Geophys., **57**, 88-101.
[6] Lowder, W.M., P.D. Raft, H.L. Beck, 1972, in *Proc. National Symp. on Natural and Manmade Radiation in Space*, ed. by E.A. Warman, NASA, 908-913.
[7] Rosen, J.M., D.J. Hofmann, W. Gringel, 1985, J. Geophys. Res. **90**, 5876-5884.
[8] Neher, H.V., 1971, J. Geophys. Res. **76**, 1637-1651.
[9] Harrison, R.G., 2005, Rev. Sci. Inst. **76**, 126111.
[10] Usoskin, I.G., G.A. Bazilevskaya, G.A. Kovaltsov, J. Geophys. Res., 2011, **116**, A02104.
[11] Usoskin, I.G. *et al.* , 2011, Atmos. Chem. Phys., **11**, 1979-1988.
[12] Tylka, A., W. Dietrich, 2009, in 31 International Cosmic Ray Conference, Universal Academy Press, Lodź, Poland.

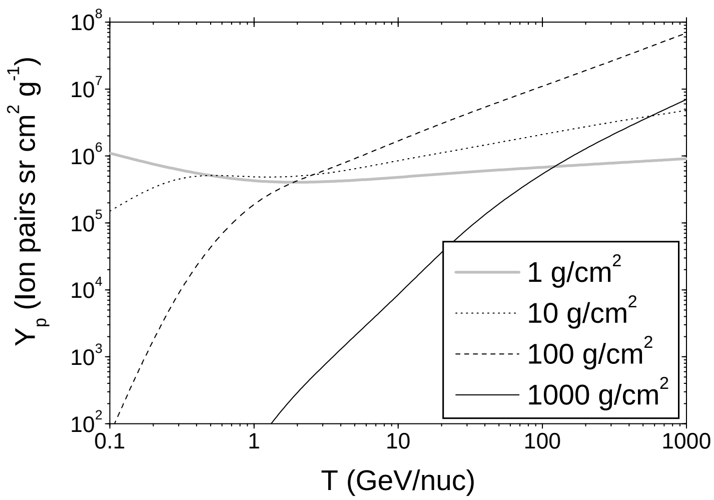

Figure 1: Ionization yield function for primary cosmic protons as function of their kinetic energy T_o for different atmospheric depths h (as denoted in the Legend).

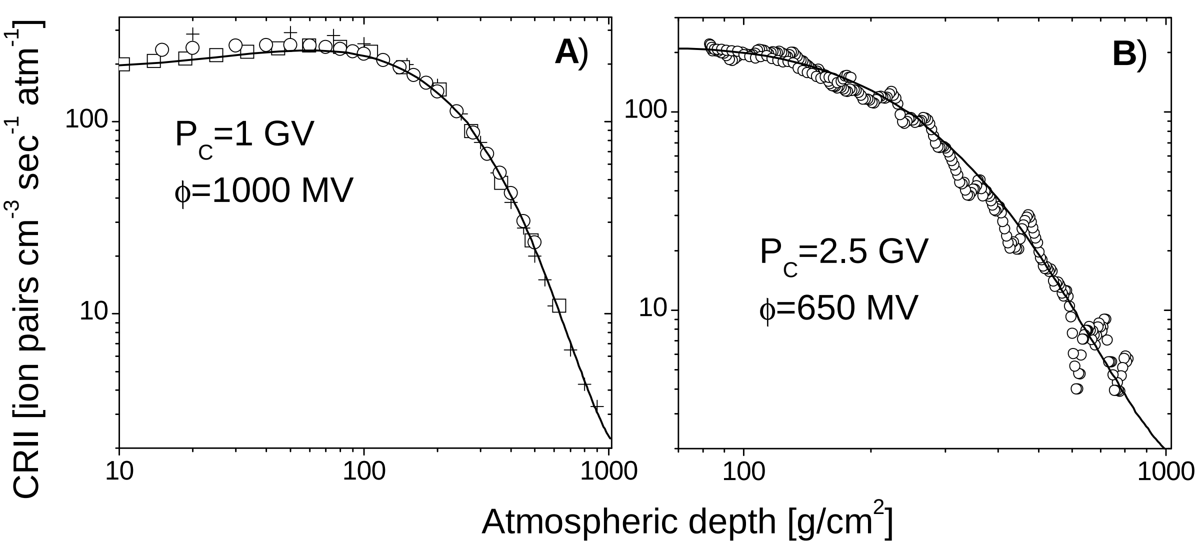

Figure 2: Comparison between measured (symbols) and modelled (curves) CRII for different conditions (cf. [1]). The values of the modulation potential ϕ and geomagnetic cutoff rigidity P_C, used in calculations, are denoted in each panel. Panel A corresponds to various measurements in the polar atmosphere around solar maximum, crosses, squares and circles being referenced to the measurements results from [6, 7, 8], respectively. Panel C corresponds to a balloon-borne detailed measurement of the atmospheric ionization rate performed at the University of Reading on August 18, 2005 [9].

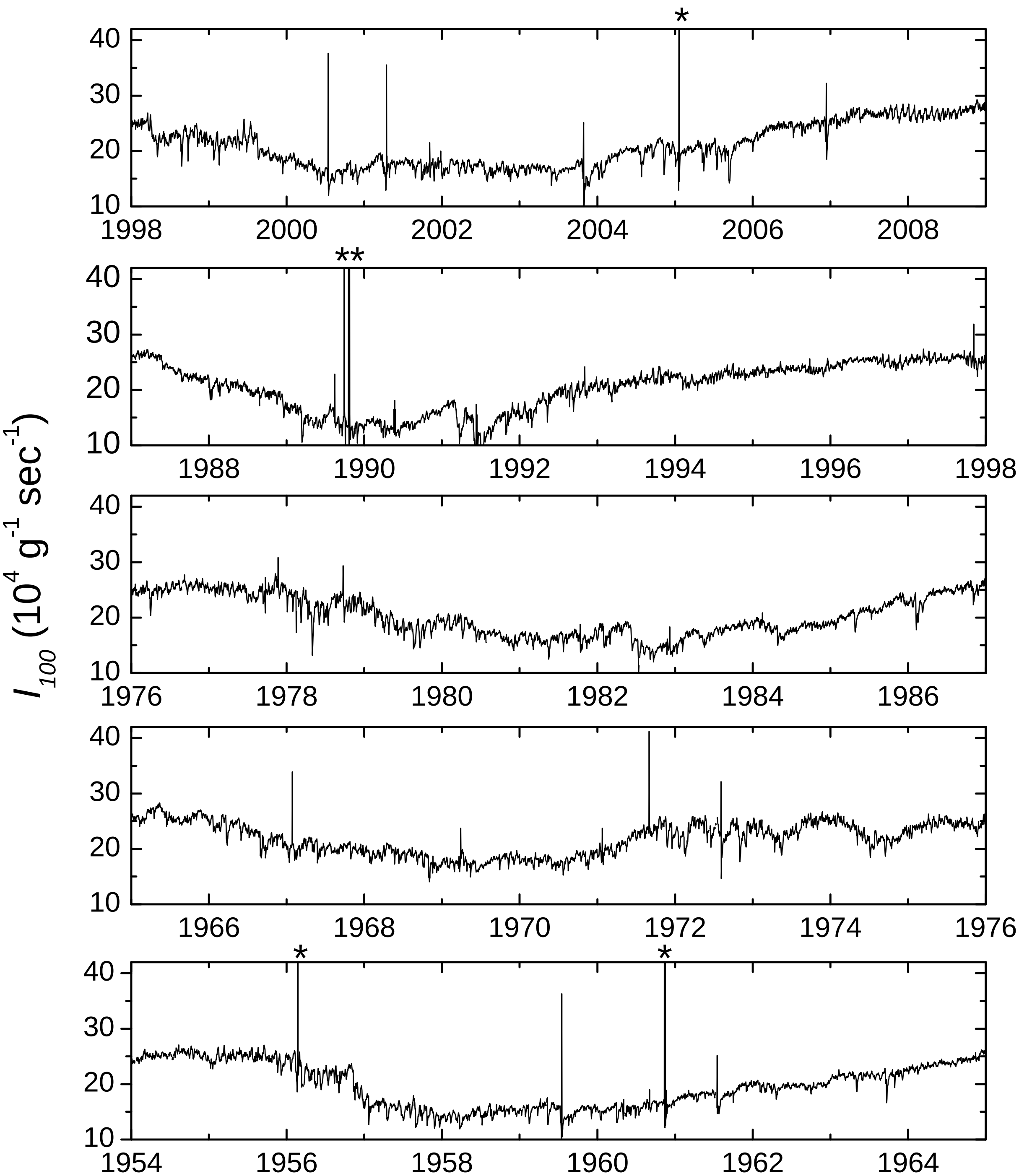

Figure 3: Daily values of the cosmic ray induced ionization rate in the middle polar atmosphere (atmospheric depth 100 g/cm^2, corresponding to 15–17 km altitude, computed by the present model using the reconstructed GCR flux [10] and SEP spectra [11]. Each panel represents solar cycle from 19 through 23 (bottom to up respectively). Asterisks on top of the panels denote that the computed ionization rate extends beyond the shown range.