Computation of ion production rate and short, mid and long term ionization effect by cosmic rays during Bastille day event

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The galactic cosmic rays are the main source of ionization in the Earth stratosphere and troposphere. The induced by primary cosmic ray particles ionization is important in various processes related to atmospheric physics and chemistry, specifically the minor constituents. The ion production in the atmosphere is enhanced compared to the average following major solar energetic particles events, specifically over the polar caps. During the solar cycle 23 we observed several strong ground level enhancements, one of the strongest among them been the Bastille day event on 14 July 2000. In the work presented here we apply a full Monte Carlo 3-D model in order to compute the cosmic ray induced ionization. The model is based on atmospheric shower simulation with the PLANETOCOSMICS code and the ion production rate is considered as a superposition of cosmic rays with galactic and solar origin. The ion production rate is computed as a function of the altitude above the sea level and the short, mid and long term ionization effect relative to the average due to galactic cosmic rays is computed.

I. INTRODUCTION

The possible effect of high energy cosmic ray particles on various atmospheric processes related to atmospheric chemistry and physics is debated over the last years. Recent findings suggest an apparent influence of cosmic rays on various atmospheric processes and electric circuit, as well as on minor constituents of the atmosphere [1], [2]. Up to present, in most of the proposed and debated models, the induced by cosmic rays, both from galactic and/or solar origin atmospheric ionization plays a key role.

Our planet Earth is constantly bombarded by high, very high and ultra-high energy nuclei, known as cosmic rays, which are the main source of ionization in the troposphere [3]. The contribution of this particles to the atmospheric ionization is continuous with slight variation in time due to modulation effects in the Heliosphere. Occasionally solar energetic particles (SEPs) enter the Earth atmosphere, penetrate deep into in the atmosphere or even reach the surface, in a such way leading to ground level enhancements (GLEs). As a result they cause an excess of ionization, specifically over the polar caps [4], [5].

At recent as a result of numerical methods, based on enhanced knowledge of high-energy interactions and nuclear processes several models for estimation of cosmic ray induced ionization in the Earth atmosphere have been proposed within good agreement with experimental results [6], [7], [8], [9].

These models are based on a full Monte Carlo simulation of the atmospheric cascade. As was recently reviewed they agreed within 10–20 % [3]. These full target models allow one to compute the ion production rate, accordingly ionization effect in the atmosphere during major GLEs as superposition of the contribution of cosmic rays with galactic and solar origin [10], [11]. Here we present the results of computation of ion production rate and corresponding ionization effect relative to the average due to galactic cosmic rays during one of the most interesting and major events of the previous 23 solar cycle, namely the GLE 59 on Bastille day of 14 July 2000.

II. MODEL

Here we use model similar to [7], the full description given elsewhere [8, 12]. The ion production rate is given by:

$$q(h,\lambda_m) = \frac{1}{E_{ion}} \sum_i \int_{E_{cut}(R_c)}^{\infty} \int_{\Omega} D_i(E) \frac{\partial E(h,E)}{\partial h} \rho(h) dE d\Omega \quad (1)$$

where ∂E is the deposited energy in an atmospheric layer ∂h, h is the air overburden above a given altitude in the atmosphere expressed in g/cm^2 subsequently converted to altitude above the sea level (a.s.l.), $D_i(E)$ is the differential cosmic ray spectrum for a given component i: protons p, Helium (α-particles), Light nuclei L ($3 \leq Z \leq 5$), Medium nuclei M ($6 \leq Z \leq 9$), Heavy nuclei H ($Z \geq 10$) and Very Heavy nuclei VH ($Z \geq 20$) in the composition of primary CR nuclei (Z is the atomic number), ρ is the atmospheric density in $g.cm^{-3}$, λ_m is the geomagnetic latitude, E is the initial energy of the incoming primary nuclei on the top of the atmosphere, Ω is the geometry factor - a solid angle and $E_{ion} = 35$ eV is the energy necessary for creation of an ion pair in air [13]. The integration is over the kinetic energy above $E_{cut}(R_c)$, which is defined by the local rigidity cut-off R_c for a nuclei of type i at a given geographic location by the expression:

$$E_{cut,i} = \sqrt{\left(\frac{Z_i}{A_i}\right)^2 R_c^2 + E_0^2} - E_0 \qquad (2)$$

where $E_0 = 0.938$ GeV/n is the proton's rest mass. Accordingly, for SEPs spectra in equation (1), which are considerably varying from event to event, we consider results derived on the basis of ground based measurements with neutron monitors. In this study, the propagation and interaction of high energy protons with the atmosphere are simulated with the PLANETOCOSMICS code [6] assuming a realistic atmospheric model NRLMSISE2000 considering seasonal influence [14] [15], [16]. PLANETOCOSMICS provides detailed simulation of particle interaction with atmosphere in a wide range of energy and altitudes with a very good resolution and allows one to simulate realistically the interactions and, when appropriate, decay of nuclei, hadrons, muons, electrons and photons in the atmosphere. In addition to the detailed detailed information about the flux of secondary particles at a given atmospheric depth it provides the energy loss and deposition, necessary for the computations with Eq. (1). Therefore the model allows one to estimate the ion production rate, accordingly the ionization effect in a whole atmosphere.

III. ION PRODUCTION RATE DURING THE BASTILLE DAY GLE 59

As mentioned above, the ion production rate during major GLEs is a superposition of the contribution of galactic cosmic rays (GCR) and GLE particles, which typically possess an essential anisotropic part. Therefore, it is necessary to compute the rigidity cut-off at given geographic position and to apply the described above model using an appropriate model for GCR spectrum as well as to consider explicitly the anisotropy by computation of the asymptotic cones in the region of interest.

The mid July 2000 was characterized by intense solar activity, resulting on three X-class solar flares (including the Bastille Day flare) and two halo coronal mass ejections (CME) [17]. The GLE 59 event was related to the Bastille day X5.8/3B solar flare and the associated full halo CME. The event started at 10:03 UT, reached peak at 10:24 UT and ended at 10:43 UT [18]. Accordingly, the GLE onset began between 10:30 and 10:35 UT at several stations with strongest NM increases observed at the South Pole (58.3 %) and SANAE (54.4 %) compared to pre-increase levels. In general the event was characterized by a large anisotropy in its initial phase [19, 20].

With the reconstructed spectra used as input (see Eq. 1) the ion production rate during the Bastille day event on 14 July 2000 was computed at 1GV and 2 GV rigidity cut-off [21]. The time evolution of ion production due to CR of galactic and solar origin during the GLE 59 is presented in Fig. 1 for 1 GV rigidity cut-off, accordingly in Fig.2 for 2 GV rigidity cut-off.

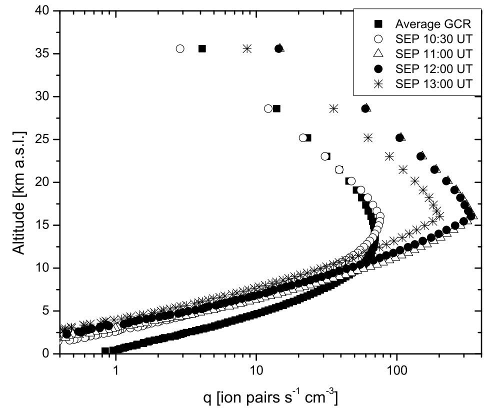

FIG. 1: Ion production rate during the Bastille day GLE on 14 July 2000 in the polar and sub-polar region with rigidity cut-off $R_c \leq 1$ GV

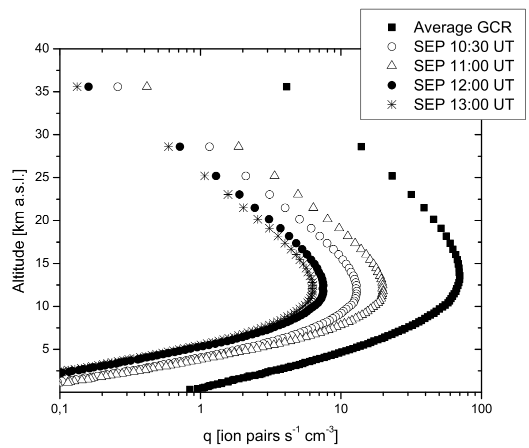

FIG. 2: Ion production rate during the Bastille day GLE on 14 July 2000 in the polar and sub-polar region with rigidity cut-off $R_c \leq 2$ GV

The computed ion production rate is significant during the main phase of the event at the polar and sub-polar region with rigidity cut-off of about 1 GV. The ion production is significant in the low stratosphere (Fig. 1). During the initial and late phases of the event the ion production is comparable to the average due to GCR, but at altitudes of about 10 km a.s.l. and below the ion production due to GCR is greater than SEPs, because of the rapidly falling spectra of the solar particles. At high mid latitudes and mid latitudes with rigidity cut-off of about 2–3 GV, the ion production due to GCR dominates in the whole at-

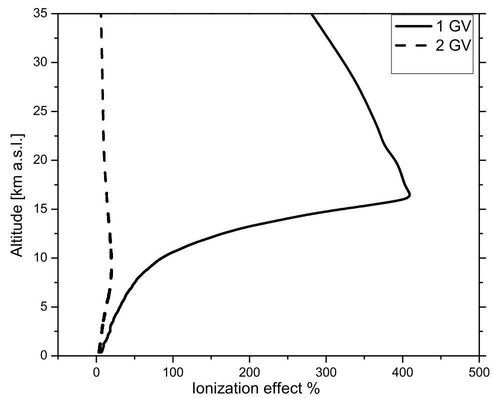

FIG. 3: Maximal ionization effect averagen over the event (5h) during the Bastille day GLE on 14 July 2000 in the region with $R_c \leq 1$ GV and $R_c \leq 2$ GV

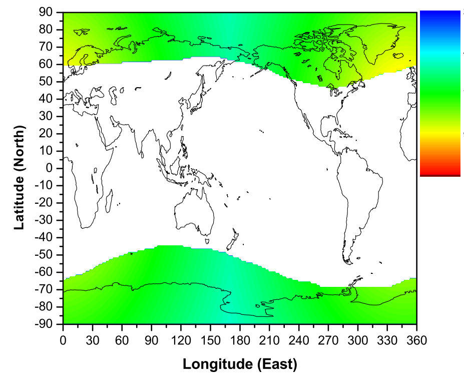

FIG. 4: Event averaged ionization effect during the Bastille day GLE on 14 July 2000 in the polar and sub-polar region with rigidity cut-off $R_c \leq 1$ GV

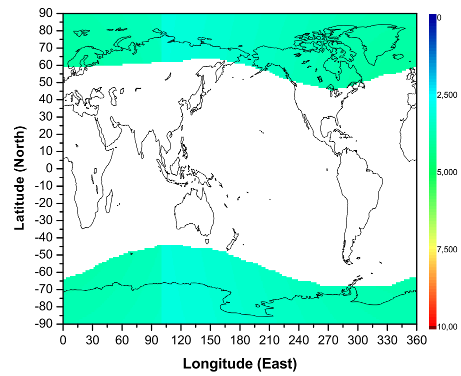

FIG. 5: 24^h ionization effect during the Bastille day GLE on 14 July 2000 in the polar and sub-polar region with rigidity cut-off $R_c \leq 1$ GV

mosphere throughout the event (Fig. 2), because the very soft SEPs spectra.

IV. IONIZATION EFFECT

The computed on a step ranging from 5 to 30 min. ion production due to CR of solar and galactic origin allows one to estimate the ionization effect during the GLE 59 on 14 July 2000 at several altitudes [22]. The expected maximal ionization effect relative to the average due to GCRs at 1 GV and 2 GV rigidity cut-offs without considering the anisotropy is shown on Fig. 3.

Accordingly on Fig. 4 is presented the computed total 5 h ionization effect in the Earth atmosphere during the GLE 59 in the polar and sub-polar region at altitude of about 12 km a.s.l.. The corresponding 24h ionization effect is presented on Fig. 5.

The event averaged ionization effect at this altitude (12 km a.s.l.) is maximal (nearly 80 %) in the regions $0° - 30°$ E and $300° - 360°$ E, particularly in the Northern hemisphere. Accordingly the minimal ionization effect at altitude of 12 km a.s.l, is about 50%, and it is observed in anti-sunward direction, namely in the region 120–225° E. The computed total 24 h ionization effect as shown in Fig. 5 is not significant and it is in the order of 5%. In the low troposphere is drops to about a 1%.

V. CONCLUSION

The relative to the average due to GCR ionization effect in the polar and sub-polar regions of the Earth (with geomagnetic cut-off rigidities between 0 GV in the cusp, and 1 GV) is significant during the whole event, specifically in the region of the Pfotzer maximum, thus in the lower stratosphere, the tropopause and in the upper troposphere. In the region of high-middle latitudes, as well as in low- middle latitudes the ionization effect is weak during the initial and main phases of the event and negligible during the late phases of the event. The ionization effect rapidly diminishes in the middle and lower troposphere, where the ion production is comparable to the average due to GCR or even smaller, i.e. GCRs produce greater quantity of ions than SEPs below some 8 km a.s.l., because the rapidly falling spectra of the latter.

Acknowledgments

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