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IONIZATION EFFECTS IN THE MIDDLE STRATOSPHERE DUE TO COSMIC RAYS DURING STRONG GLE EVENTS

Alexander Mishev*,*, Peter I. Y. Velinov****

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Abstract

An important topic in the field of solar-terrestrial and space physics is the highly discussed possible effect of cosmic ray (CR) particles on atmospheric chemistry and physics, specifically by induced ionization. In most of the recently developed models, the induced by CRs atmospheric ionization plays a significant role. Nowadays, it is clear that the contribution of galactic cosmic ray particles to electron-ion production in the atmosphere slightly varies with the solar modulation and transient effects. On the other hand, high energy solar particles could produce complicated hadron-electromagnetic-muon cascade in the atmosphere of the Earth and significantly enhance the electron-ion pair production, particularly over polar caps. This effect is usually strong on a short time scales, being more important in the region of Regener–Pfotzer maximum. However, for some atmospheric chemistry and physics purposes it is important to estimate the ionization effect in the middle stratosphere. The Ground Level Enhancement GLE 59 on Bastille Day 14 of July 2000 and the maverick GLE 70 on 13 December 2006 are among the strongest recorded events during the previous solar cycle 23. Herein, using recently proposed full target Monte Carlo simulation and previously derived high energy solar particles energy spectra we estimated the electron-ion production rate and corresponding ionization effect in the Earth middle stratosphere during two moderately strong ground level enhancement events.

Key words: Cosmic Rays (CRs), Ground Level Enhancements (GLEs), CR ionization effect, electron-ion production rate, middle atmosphere physics and chemistry

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Introduction. Nowadays, the effect of various populations of energetic particles precipitating or entering deeply in the Earth's atmosphere is highly and extensively discussed. In most of the proposed mechanisms the key role of the cosmic ray induced ionization is pointed out. While the direct effect is not apparent or marginal, recent findings suggest an important influence of cosmic rays on various atmospheric processes, global electric circuit and minor constituents of the atmosphere by the induced atmospheric ionization [1,2]. Particles with different composition, spectra and occurrence contribute to the atmospheric ionization, namely galactic cosmic rays (GCRs), solar energetic particles (SEPs), precipitating protons and electrons from radiation belts [2,3]. The GCRs are the main source of particles inducing ionization in the troposphere and stratosphere. When GCR particles penetrate into the atmosphere they produce complicated nuclear-electromagnetic-muon cascade with large amount of secondary particles loosing their energy via ionization. The ionization effect due to GCRs is continuous and depends mainly on the solar activity. Occasionally, the Sun emits SEPs, produced during solar eruptive processes [4]. In some cases, SEPs are with energy of about 1 GeV/nucleon or even higher. As a result they induce similarly to GCR nuclear-electromagnetic-muon cascade with secondary particles, which can penetrate to the ground level, i.e. they produce Ground Level Enhancement (GLE) events. High energy SEPs, specifically during GLEs significantly enhance the ionization, especially over the polar caps [5–8]. GLE events are usually identified as percentage increase of counting rate of neutron monitor above the background, due to GCRs averaged over the last two hours preceding the event onset. For instance, during the solar cycle 23, sixteen GLE events were observed, while in the present solar cycle 24 only two, so far (`http://gle.oulu.fi/#/`). While, the ionization effect in the troposphere is extensively and well-studied [9–11], the influence of high energy part of GLE particles to the atmospheric ionization in the upper and middle stratosphere is poorly investigated and deserves special attention, because the possible influence on Ozone [2,12].

In the present work we estimate the ionization effect in the stratosphere, specifically the middle part during the moderately strong GLEs, namely the GLE 59 on Bastille day, 14 July 2000, and the maverick GLE on 13 December 2006.

Atmospheric ionization model. In this work we employ a model similar to Oulu model [13] following the procedure [14]:

$$q(h,\lambda_m) = \sum_i \int_{E_0}^{\infty} \int_{\Omega} D_i(E,\lambda_m) \frac{\Delta E}{E_{\text{ion}} \Delta x} \cdot \rho(h) \Omega \, dE \, d\Omega, \tag{1}$$

where $D_i(E,\lambda_m)$ is the differential primary CR spectrum at given geomagnetic latitude λ_m for a given component of primary cosmic rays i (proton, alpha-particle, light, medium, heavy, very heavy and super heavy nuclei), $\rho(h)$ is the atmospheric density (g.cm^{-3}), ΔE is the deposited energy in layer Δx in the

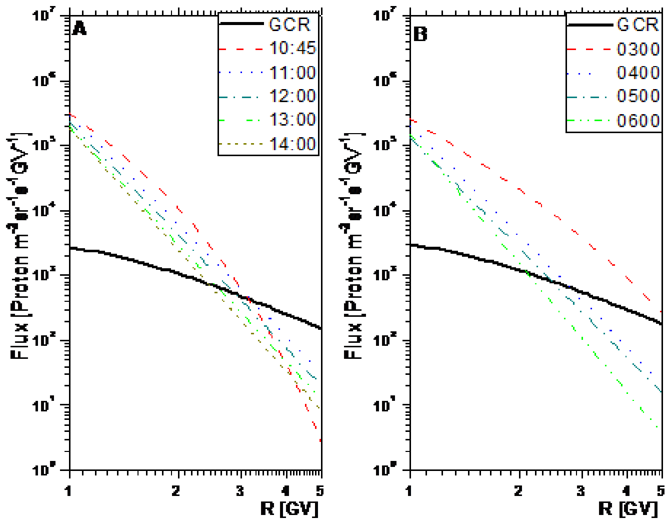

Fig. 1. Rigidity spectra for various stages of GLE events on 14 July 2000 and 13 December 2006. Time (UT) refers to the start of the corresponding interval as denoted in the legend over which the spectra are derived. The solid line denotes GCR flux. **A**) Rigidity spectra during Bastille day GLE 59 on 14 July 2000; **B**) Rigidity spectra during maverick GLE 70 on 13 December 2006

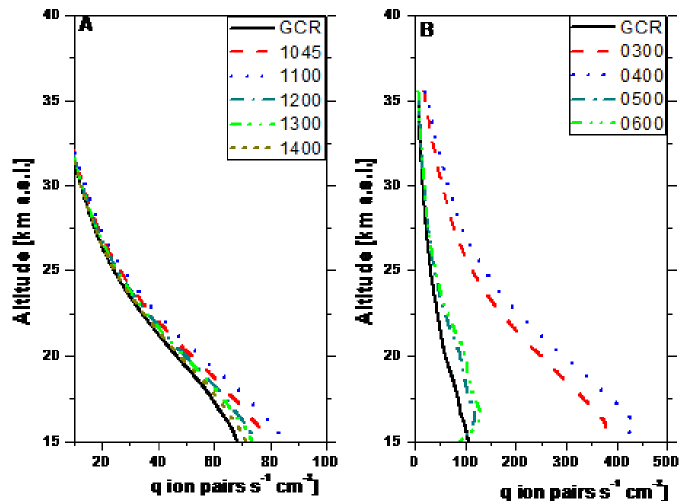

Fig. 2. Ion production rate for various stages of events on 14 July 2000 and 13 December 2006 due to GCRs and GLE particles in the region above the Regener–Pfotzer maximum. Time (UT) refers to the start of the corresponding interval as denoted in the legend. **A**) Ion production rate profiles during Bastille day GLE 59 on 14 July 2000; **B**) Ion production rate profiles during maverick GLE 70 on 13 December 2006

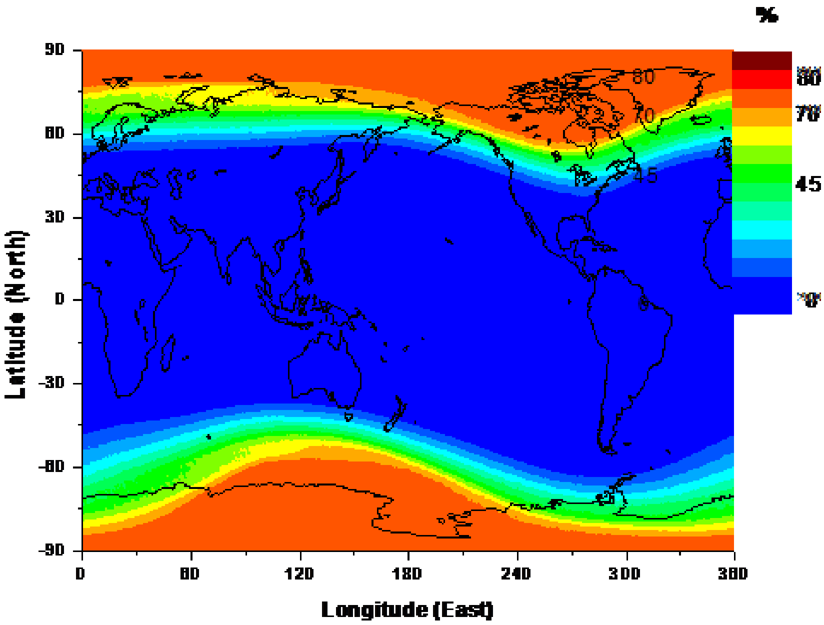

Fig. 3. Map of event averaged ionization effect during the Bastille day GLE 59 on 14 July 2000 at altitude of 25 km a.s.l., i.e. in the middle stratosphere

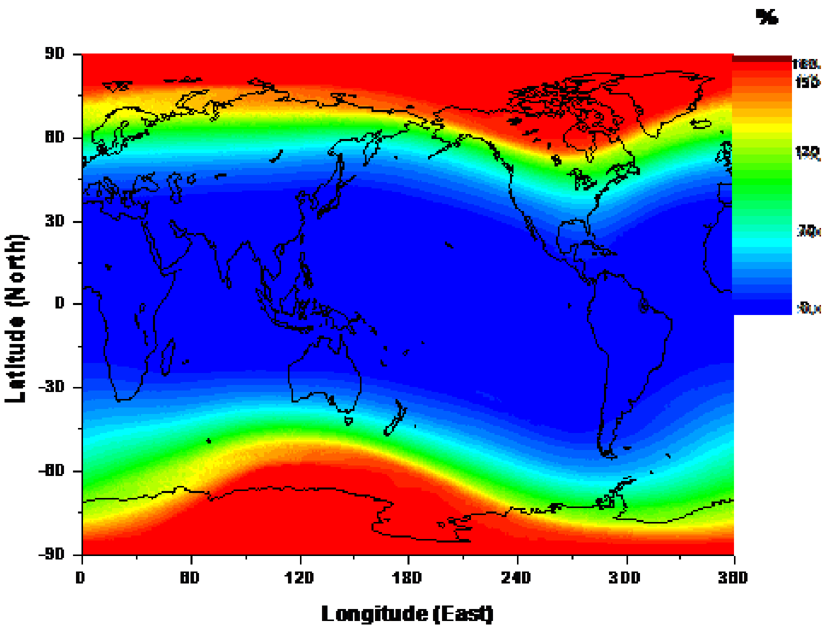

Fig. 4. Map of event averaged ionization effect during the maverick GLE 70 on 13 December 2006 at altitude of 25 km a.s.l., i.e. in the middle stratosphere

atmosphere and Ω is a solid angle; $E_{\rm ion} = 35$ eV is the energy necessary for production of one electron-ion pair [15,16]. The integration is over $E_0(\lambda_m)$ energy, which is function of the cut-off rigidity at given location. The model is based on a detailed simulation of the atmospheric cascade. Similarly to other full target models it provides good agreement with recent experimental results [17]. The cosmic ray induced ionization models allow one to possess a realistic information for the type, energy, momenta, location and arrival time of the produced secondary particles at given selected altitude above sea level as well as the energy deposit. In equation (1) we express x in g.cm^{-2}, which is a residual atmospheric depth, i.e. the amount of matter (air) overburden above a given altitude in the atmosphere. This is naturally related to the development of the cascade. Subsequently the mass overburden is transformed as altitude above the sea level (a.s.l.) in [km].

Ion production and ionization effect during GLE 59 and GLE 70. There were several strong and moderately strong GLE events which occurred during solar cycle 23, namely the Bastille day event on 14 July 2000, the Easter event on 15 April 2001 (GLE 60), the sequence of three Halloween events in October-November 2003 (GLEs 65, 66 & 67), the major event GLE 69 on 20 January 2005, the maverick GLE 70 on 13 December 2006. They induced a significant increase of ion production in the atmosphere – for more details refer to [5–8]. Here, using the model described above, and GLE particles spectra derived on the basis of neutron monitor data analysis (Fig. 1) [18], we compute the ion production rate during the Bastille day event on 14 July 2000 and the maverick GLE 70 on 13 December 2006, specifically in the middle part of the stratosphere (Fig. 2). The onset of Bastille day event was around 10:35 UT with significant neutron monitor count rate increase observed at the South Pole (58.3%). The event onset of the maverick GLE 70 event was around 03:00 UT with maximum neutron monitor count rate increase observed at Oulu neutron monitor ($\approx 90.0\%$). The duration of both events at neutron monitor energies was over 5 h, which is explicitly considered here for the computation of the event averaged ionization effect. While the ion production and the corresponding ionization effect is relatively well studied in the low stratosphere and troposphere [8–11], the effect in the middle stratosphere above the Regener–Pfotzer maximum is not studied. Here we focus on ion production and ionization effect at altitude of about 25 km a.s.l., which is important for further studies related to Ozone chemistry and physics [12,19]. The ion production during the event was computed as a superposition of the ion production rate due to SEPs and GCRs. The latter has been estimated by the force field model – similarly to [5], where the heavy nuclei were considered explicitly according to [20].

The ion production rate, accordingly the ionization effect is computed for different rigidity cut-offs. One can see that the ion production rate due to high energy GLE particles is well above the background due to GCRs, specifically in the polar and sub-polar region (Fig. 2). However, at mid latitudes the ion production rapidly diminishes, because the SEP particles are much softer than GCR solar energetic particles spectra [8,9]. During both events, the SEP spectra were relatively hard, particularly during the onset of the events and their main phase, but considerably soften during the late phase. As a result the ion production rate during the Bastille day event is only slightly greater than the ion production due to GCRs in the region near and above the Regener–Pfotzer maximum. The situation is different during the maverick GLE 70 event on 13 December 2006, where a significantly greater ion production is observed between 15 and 35 km region, because of the enhanced GLE particles flux.

Using the computed ion production rates during the events, we calculate the event averaged ionization, relative to GCR ionization effect. The corresponding maps of ionization produced by the SEPs at altitude of 25 km a.s.l. are presented in Fig. 3 for the Bastille day GLE 59, and in Fig. 4 for the maverick GLE 70 on 13 December 2006.

We establish a good agreement with recent experimental results [17]. Comparison with data from balloon measurements up to 30 km (with Geiger counters) [17] shows a difference of 10–15%, which may be due to the used US standard atmospheric model. The latter differs from the real atmospheric profiles by ±10%.

Discussion and conclusion. The enhanced ionization above the GCR levels is easily noticeable in the polar and sub-polar regions (Fig. 3 and 4). In general, the ionization effect in the middle stratosphere is smaller than that in the upper troposphere and low stratosphere. The ionization effect above the Regener–Pfotzer maximum rapidly diminishes in mid and low latitudes. In the upper stratosphere the ion production rate and the corresponding ionization effect due to SEPs and GCRs are comparable to each other, because of the not fully developed high energy particle hadron-electromagnetic-muon cascade and marginal direct ionization loss [9–11].

In this study it was shown that even above the Regener–Pfotzer maximum, namely at altitudes in the middle stratosphere, the event averaged ionization effect is important during moderately strong GLEs. The estimated maximum ionization effect is in the range of 80% (GLE 59) to 160% (GLE 70).

The obtained results are important for the improvement of the recent models of cosmic ray induced ionization and studies of solar and solar-terrestrial physics [21,22] and their applications – space weather and space climate.

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**Space Climate Research Unit*
University of Oulu
P.O.Box 8000
FI-90014 University of Oulu
Finland
e-mail: `alex_mishev@yahoo.com`

***Institute for Space Research and Technology*
Bulgarian Academy of Sciences
Acad. G. Bonchev St, Bl. 1
1113 Sofia, Bulgaria
e-mail: `pvelinov@bas.bg`

****Sodankylä Geophysical Observatory*
University of Oulu
Tähteläntie 62
99600 Sodankylä, Finland