IONIZATION EFFECT IN THE REGION
OF REGENER–PFOTZER MAXIMUM DUE TO COSMIC
RAYS DURING HALLOWEEN GLE EVENTS
IN OCTOBER–NOVEMBER 2003

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Abstract

One of the main drivers of the possible effect of cosmic ray particles on atmospheric physics and chemistry is connected to the Induced Atmospheric Ionization (IAI) due to high-energy precipitating particles. IAI by cosmic rays, which can be considerably enhanced during solar proton events, was extensively discussed over the last decade. In most of the recent models, IAI plays a key role on the physics and chemistry of the atmosphere, specifically on minor constituents. It is known that the contribution of galactic cosmic ray particles to ion production in the atmosphere is nearly constant, slightly influenced by the solar activity. On the other hand, the relativistic solar particles could produce a significant excess of ion pair production, particularly over polar caps. This effect is normally strong at short time scales. The sequence of three ground level enhancements GLE 65, 66 & 67 in October–November 2003 gives an unique opportunity to study impact ionization on enhanced manner and extended time scale. Using Monte Carlo simulation and derived solar proton spectra, we computed the ion production and the corresponding ionization effect in the Earth atmosphere in the region of Regener–Pfofzer maximum during the so-called Halloween events in October–November 2003.

Key words: cosmic rays, Ground Level Enhancement (GLE), Induced Atmospheric Ionization (IAI), atmospheric physics and chemistry

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Introduction. When high-energy particles precipitate in the Earth's atmosphere, they ionize the ambient air [1]. Various populations of precipitating particles and/or radiation contribute to the atmospheric ionization viz. cosmic rays of galactic and/or solar origin, particles from radiation belts, auroral electrons, UV and X-ray solar radiation, etc. While in the upper atmosphere, the ion production is governed by the solar UV and X-rays, below 100 km, i.e. in the mesosphere, stratosphere and troposphere, the atmospheric ionization is mostly due to the almost constant slightly variable flux of galactic cosmic rays (GCRs) and sporadic but considerably enhanced flux of solar energetic particles (SEPs), for details see [2]. Here, we focus on Induced Atmospheric Ionization (IAI) in the troposphere and stratosphere, specifically during extreme solar particle events (SPEs) [3], when the flux of high-energy particles is greatly above the background due to GCRs.

IAI in the troposphere and stratosphere is a result from a complicated nuclear-electromagnetic-muon cascade, produced by series of consecutive interactions of the primary cosmic ray particles with the atmospheric nuclei, which eventually lead to production of large amount of secondary particles losing their energy via ionization [1,2]. When a primary cosmic ray particle, e.g. proton and/or heavier nucleus interacts with an atmospheric atom's nucleus it produces many energetic secondary particles, mostly hadrons. The main part of produced particles after the first interaction are pions, but also kaons, and baryons are presented. Pions and kaons are not stable and decay into other particles.

Most of the produced secondary hadrons are unstable and decay into other particles, including electromagnetic radiation. As example, neutral pions decay into photons. Accordingly, photons form an electromagnetic cascade, produced by electromagnetic particles and/or muons and small amount of hadrons, also contribute to the shower development. The charged pions mostly decay into muons, giving rise of the muon component of the shower. The secondaries, in their turn also interact with atmospheric nuclei and produce particles, feeding the development of the shower, until a threshold energy for production of new particles is reached. All particles ionize the ambient air with deposited energy necessary for creation of one ion pair of about 35 eV. The maximum of ion production is observed at altitude of about 12–15 km above sea level (a.s.l.), known as Regener–Pfofzer maximum [4,5].

The flux of GCRs is slightly modulated in the Heliosphere. Hence, GCRs produce continuously background ionization in the atmosphere. Occasionally, as a result of active processes in the Sun as solar flares and coronal mass ejections, SEPs are produced. In some extreme cases, their energy can reach MeV or even GeV range, therefore similarly to GCRs they produce atmospheric shower [6]. When the energy of SEPs is about 1 GeV/nucleon or even greater, they induce similarly to GCRs nuclear-electromagnetic-muon cascade, penetrate deep into the atmosphere or even reach the ground leading to ground level enhancements (GLEs) [7].

Therefore, GLE particles may cause a significant excess of ionization, specifically over the polar caps [8–12]. The contribution of GCR particles to IAI in the atmosphere is nearly constant, but the relativistic solar particles could produce a significant excess of ion pair production, particularly over polar caps.

A systematic study of the impact ionization due to precipitating high-energy particles is very important in order to clarify their influence on different atmospheric processes, global electric circuit and atmospheric physics and chemistry, specifically of minor components [2]. As a result, over the last decade the energetic particles impact ionization is extensively studied. The enhanced cosmic ray flux during GLEs, gives unique opportunity to deepen our knowledge about those effects. During the solar cycle 23, sixteen GLEs were observed, the first event occurred on 6 November 1997 (GLE 55) and the last event occurred on 13 December 2006 (GLE 70). The full list is available online at the Oulu Cosmic Ray Station (<http://cosmicrays.oulu.fi/GLE.html>). GLEs occur sporadically and differ from each other in spectra, particle fluence, apparent source position, geomagnetic conditions, ergo are usually studied case by case. In this work, for the first time a sequence of three consecutive GLEs is studied, viz. the three so-called Halloween events of October–November 2003. The ion production rates during the events are evaluated on the basis of full target Monte Carlo simulation model using recently derived GLE particles spectra. The integrated over 24 h ionization effect in the region of Regener–Pfofzter maximum is accordingly assessed.

Model for energetic particles impact ionization. In this work we apply a model similar to Oulu CRAC-CR2 model [13] following a procedure, the full description of which is given elsewhere [14]. The ion production rate is given in the following equation:

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

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 or very heavy nuclei), $\rho(h)$ is the atmospheric density (g.cm^{-3}), ΔE is the deposited energy in layer Δx in the atmosphere and Ω is a geometry factor, integration over solid angle; $E_{\text{ion}} = 35$ eV is the energy necessary for production of one electron-ion pair [15].

The full target model allows one to model in great details, the propagation of high-energy particles in the atmosphere of the Earth, accordingly the evolution of cosmic ray induced particle showers in the atmosphere. Here, we derive the deposited energy in the atmosphere released by GCRs and SEPs. 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, which is naturally related to the extensive air shower development. Subsequently the mass overburden is transformed as altitude above sea level in [km].

For the GCR spectrum we employ the force field model with the corresponding local interstellar spectrum approximation [16,17], while for SEPs we use the derived by neutron monitor data analysis spectra, considering explicitly their temporal evolution throughout the event [18,19].

Induced Atmospheric Ionization (IAI) during Halloween events. An extreme solar activity was observed in late October – beginning of November 2003. During this period a sequence of three GLEs was produced, accordingly observed by the global neutron monitor network with onsets occurring on 28 October (GLE 65), 29 October (GLE 66) and on 2 November (GLE 67), respectively. The peak ground-based neutron monitor count rate increases were about 45%, 34% and 35%, respectively.

The GLE on 28 October 2003 was associated with a large X17.2 flare which occurred in the active region AR10486. The GLE 65 followed significant interplanetary disturbance related to previously ejected coronal mass ejection on 26 October.

The GLE 66 was characterized by a smaller NM count rate increase, thus this event was weaker. This event occurred during complicated magnetospheric and interplanetary magnetic field conditions. As a consequence strong Forbush decrease was also observed prior to and during this event, which is explicitly considered in this study, i.e. a GCR flux reduce is taken into account during the computations.

The GLE 67 event on 2 November 2003 was related to an X8.3 solar flare, with onset at about 17:30–17:35 UT. Detailed study of this event is given in [18].

Using the model described above and the derived GLE particles spectra [18] we computed the ion production rate in the whole atmosphere, as superposition of GCRs and SEPs contributions at different regions, correspond to different geomagnetic cut-offs. Here we give the most important values, specifically in the polar and sub-polar region with rigidity cut-off $R_c < 1$ GV (Fig. 1a, b, c) and high mid-latitudes region with rigidity cut-off $R_c < 2$ GV (Fig. 1d, e, f). The computed over GLE 65 ion production rate was significant during the initial and main phase of the event, specifically in the polar low stratosphere (Fig. 1a). The ion production rate diminished but remained significant during the late phase of the event. The ion production rate during GLE 66 is considerably smaller (Fig. 1b), because of softer SEP spectra, not so important compared to the previous GLE SEP flux and the accompanying Forbush decrease. IAI rate during GLE 66 is almost constant throughout the event. The ion production rate during the last event GLE 67 is greater than GLE 66, specifically during the initial and main phase of the event, but rapidly diminished during the late phase (Fig. 1c).

In the region of mid latitudes with $R_c < 2$ GV, IAI rate induced by SEPs is comparable to the average due to GCR even in the case of the most strong event viz. GLE 65 (Fig. 1d), while for GLEs 66 & 67 the GCR contribution is slightly greater. Moreover, at low mid latitudes with rigidity cut-off of about 3 GV and

greater, IAI due to GCR dominates in the whole atmosphere throughout all the events. The ion production rate during the GLEs is determined by both: particle flux and hardness of the SEP spectra. Obviously, SEPs with harder spectra can impact also mid-latitude regions, while soft SEPs contribute mostly in the polar region. The increased SEP flux, accordingly govern the rate of IAI.

Using the computed ion production rates during the Halloween GLEs, here, we compute the corresponding averaged over 24 h ionization effect during the GLE 65–67, similarly to [20,21]. The ionization effect represents the averaged over 24 h ion production rate during a GLE considering the SEP and actual GCR contribution versus 24 h averaged ion rate due to GCR prior to the event. Therefore, here we consider reduced by Forbush decrease GCR flux, specifically during GLE 66. The computations have been performed in the region of Regener–Pfotzer maximum, where the expected ionization effect would be maximal (Fig. 1).

The results of those computations are shown in Fig. 2 for GLE 65, Fig. 3 for GLE 66 and Fig. 4 for GLE 67, respectively. Note, that here we computed the cut-off rigidity during the events, explicitly considering the complex magnetospheric conditions. This allowed us to perform realistic high precision computations of the global distribution of ion production over the globe, accordingly the corresponding ionization effect [22].

The ionization effect during GLE 65 is significant in the high-latitude region, where it ranges at about 100–200%. The ionization effect diminishes at lower latitudes, in practice negligible in lower mid and equatorial latitudes (Fig. 2). This is due to softer SEP spectra compared to GCRs. Therefore, SEPs contribute significantly in the polar region (Fig. 1a, b, c).

As was mentioned above, GLE 66 occurred during deep Forbush decrease of GCRs. This resulted in complicated interplay of SEP contribution and significantly reduced GCR flux contribution on the IAI. The SEP spectra are slightly softer and with reduced flux than those during GLE 65. The ionization effect during GLE 66 is marginal even in the polar region. It is about 5% and even is considerably negative in the equatorial region, mostly due to reduced GCR flux (Fig. 3).

Accordingly, the IAI effect during GLE 67 is not significant in mid latitudes and it is marginal in the equatorial region (Fig. 4). The last of the sequence of Halloween events, GLE 67, occurred during the recovery phase of a deep Forbush decrease. Therefore, the reduced GCR flux within temporal evolution was explicitly considered for the computation of background ion rate production (Fig. 1c, f). The ionization effect during GLE 67 was of about 40% in the polar region. It diminishes to about 10% at lower latitudes. The effect is marginal or even null in the Equatorial region.

Discussion and conclusion. Detailed study of the impact ionization due to high-energy particles, specifically during strong solar particle events, allows one to perform a thorough analysis of various mechanisms related to minor components

Fig. 1. Ion production rate profiles (0–40 km) in the atmosphere during the sequence of three Halloween GLE events in October–November 2003. Panels a, b, c, correspond to region with cut-off rigidity of 1 GV for GLE 65 on 28 October 2003, GLE 66 on 29 October 2003, and GLE 67 on 2 November 2003, respectively. Panels d, e, f refer to the same cases for region with cut-off rigidity 2 GV. Everywhere the thick black line represents the IAI due to GCRs. All curves are smoothed over the computed data points

Fig. 2. Global map of Induced Atmospheric Ionization (IAI) effect in the region of Regener-Pfotzer maximum due to CRs of galactic and solar origin during the first Halloween event – GLE 65 on 28 October 2003

Fig. 3. Global map of Induced Atmospheric Ionization (IAI) effect in the region of Regener-Pfotzer maximum due to CRs of galactic and solar origin during the second Halloween event – GLE 66 on 29 October 2003

Fig. 4. Global map of Induced Atmospheric Ionization (IAI) effect in the region of Regener-Pfotzer maximum due to CRs of galactic and solar origin during the third Halloween event – GLE 67 on 2 November 2003

physics, because of the enhanced compared to the background ion production. For realistic assessment of the possible effect of precipitating high-energy particles on atmospheric chemistry and physics, it is necessary to compute the ionization effect at various time scales, possibly over large scales. Therefore, the presented here averaged 24 h effect during several GLEs, computed in the region of Regener–Pfotzer maximum, where the ionization effect reaches its greatest values, is an important contribution in the field of atmospheric physics. In this work, using reconstructed from ground-based and space-borne instruments SEP spectra we derived the ion production rate and the corresponding IAI effect during the sequence of Halloween GLE events in October–November 2003. For the first time the IAI effect due to high-energy SEP was computed during a sequence of several GLEs. The dynamics of GCRs and GLE particles flux was explicitly considered, which allowed us to make a realistic assessment of the ionization effect. It was shown that the IAI effect in the polar and sub-polar region is significant, except for GLE 66. The ionization effect is considerably greater compared to other events during GLE 65. The role of the Forbush decrease is significant and considerably reduces the total, i.e. the integrated over three events IAI effect, specifically in mid and low latitudes. The computed ionization effect during the Halloween events in October–November 2003 gives a good basis for further studies related to the space weather and the possible impact of precipitating high-energy particles of solar origin on atmospheric chemistry and physics and are important for the improvement of the recent models of cosmic ray induced ionization and the studies of solar-terrestrial influences on the space weather and space climate [23,24].

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