INFLUENCE OF FORBUSH EFFECT ON ATMOSPHERIC IONIZATION DUE TO SOLAR ENERGETIC PARTICLES

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Abstract

High-energy precipitating particles of cosmic origin viz. cosmic ray (CR) protons of heavier nuclei of galactic and/or solar origin induce complicated nuclear-electromagnetic-lepton cascades in the Earth's atmosphere, eventually leading to an ionization of the ambient air. The induced by CRs ionization is related to possible effect of precipitating particles on physico-chemical processes in the atmosphere. These effects can be considerably enhanced during solar proton events. While the contribution of galactic CRs to ion production in the atmosphere is slightly variable throughout a solar cycle, relativistic solar particles could produce a significant excess of electron-ion pair production, particularly over polar caps. This effect is strong on short time scales. On the other hand, depressions of the galactic CR flux, that is, Forbush decreases, can significantly impact on induced ionization. The sequence of three ground level enhancements (GLEs) 65, 66 and 67 in October-November 2003, specifically GLE 66 occurred during a giant Forbush decrease, provides unique opportunity to study impact ionization on enhanced manner and extended time scale, explicitly considering the reduced galactic CR flux. Using Monte Carlo simulations and appropriate solar proton spectra we computed the ion production rate and the corresponding ionization effect in the Earth atmosphere during GLE 66 which occurred on 29 October 2003.

Key words: cosmic rays, ground level enhancement, Forbush effect, atmospheric ionization, atmospheric physics and chemistry

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Introduction. High-energy particles precipitating in the Earth's atmosphere induce complicated nuclear-electromagnetic-lepton cascades, eventually leading to an ionization of the ambient air [1]. In the different atmospheric regions, various populations of precipitating particles and/or radiation determine the atmospheric ionization. Solar EUV and X-ray radiations dominate in the upper atmosphere. The energetic particles precipitation govern stratospheric and tropospheric ionization, that is, below 50 km the atmospheric ionization is mostly due to the quasi-constant slightly variable modulated in the Heliosphere 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 ion production 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, but explicitly considering the significant reduction of the latter during one of the strongest Forbush decreases.

The ion production in the Earth's atmosphere, specifically in the troposphere and stratosphere results from a complicated nuclear-electromagnetic-lepton cascade, produced by series of consecutive interactions of the primary particle with the atmospheric constituents, which eventually lead to production of large amount of secondaries, which deposit their energy mostly via ionization [1,2,4,5]. For instance, when a primary cosmic proton and/or heavier nucleus interacts with an atmospheric atom's nucleus it produces energetic secondary particles, mostly hadrons. Essential part of the produced after the first interaction particles are pions, though kaons and baryons can be also generated. Pions and kaons are not stable and decay almost instantly to other particles, that is, the unstable particles in turn decay or produce other particles and/or are emitting stopping radiation. As example, neutral pions decay into two gammas, accordingly gammas can produce electron-positron pairs. In such a way within the produced stopping radiation photons, they lead to the electromagnetic component evolution of the developed extensive air shower (EAS). The charged pions mostly decay into muons, giving rise of the muon component of the EAS. The energetic secondaries, in their turn also interact with atmospheric nuclei and produce particles, feeding the development of the cascade, until threshold energy for production of new particles is reached. All particles ionize the ambient air, where the deposited energy necessary for creation of one ion pair is roughly 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 [6].

Two reverse processes in space ionization – SEP effect and Forbush effect. The flux of GCRs is slightly modulated in the Heliosphere, inversely follows the 11-year solar cycle, responding also to transient phenomena such as Forbush decreases [7,8]. Therefore, GCRs produce continuously background ionization in the atmosphere, yet it can be considerably decreased in periods with significant transients, when a non-negligible reduction of the primary CR flux can

be observed. Occasionally, following active processes on the Sun as solar flares and/or coronal mass ejections (CMEs) solar ions are accelerated to high energies. In some cases, their energy can reach GeV range. Hence, similarly to GCRs they produce EAS resulting in enhancement of the stratospheric and tropospheric ionization [9].

During ground level enhancement (GLE) events, i.e. strong SEPs causing enhancement of the count rate of ground based detectors such as neutron monitors (NMs) [10], solar ions may cause a significant excess of ionization, specifically over the polar caps [11,12]. Therefore, the contribution of GCRs to the ion production in the atmosphere can be significantly influenced by reductions of their flux or by the relativistic SEPs.

Systematic study of energetic particles impact ionization gives a reliable basis to decipher and clarify their influence on global electric circuit and different physico-chemical processes in the atmosphere, specifically of minor constituents, e.g. ozone [2]. Hence, the enhanced cosmic ray flux during GLEs, gives unique opportunity to deepen our knowledge about energetic particles ionization 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 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. Here, we study the sequence of consecutive GLEs, viz. the three events of October-November GLEs, specifically the ionization effect in the region of Regener-Pfotzer maximum during the second event. GLE 66 occurred during giant Forbush effect, a suppression of the GCR flux. Therefore, there was a non trivial interplay between significantly suppressed GCRs and enhanced SEP flux contributions to the atmospheric ionization, which resulted in complicated ionization effect in different regions of the atmosphere. The ion production rate and the corresponding ionization effect are evaluated on the basis of full target Monte Carlo simulation model using recently derived GLE particles spectra.

Employed model for computation of SEP ionization. In this work we apply a model similar to Oulu model [13] following a procedure, the full description of which is given elsewhere [14]. Here, we briefly summarize the model. The ion production rate is given in

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

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 and 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 models 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 cascades in the atmosphere. Here, we derived 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 the EAS development. Subsequently the mass overburden is transformed as altitude above the sea level (a.s.l.) in [km], depending on the assumed atmospheric model.

For the GCR spectrum we employ the force field model with the corresponding local interstellar spectrum approximation, while for SEPs we use the derived by neutron monitor data analysis spectra, considering explicitly their temporal evolution throughout the event. The reduction of the GCRs was explicitly considered, taking into account the variation of neutron monitor count rates at different cut-off rigidities.

Ion production rate and ionization effect during GLE 66. A violent solar activity was observed in late October and the beginning of November 2003. During this period a sequence of three GLEs was produced registered by the global neutron monitor network with onsets occurring on 28 and 29 October and on 2 November, respectively [6,16]. These events, referred to as the Halloween solar storms, are among the most interesting in terms of their properties and the related atmospheric and space weather consequences [17,18]. The disturbances associated with two of the October–November 2003 eruptions arrived at Earth in less than a day, namely they were the so-called “fast transits” similarly to the famous Carrington event of 1 September 1859.

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 previous CME on 26 October. The GLE 66 was characterized by a smaller NM count rate increase, thus this event was weaker. On the other hand, the sequence of several CMEs and interplanetary CMEs, in addition to accelerating high-energy particles, they resulted significantly on the background CRs, whereas one of the biggest of about 28% Forbush decreases was observed (Fig. 1). Hence, the GLE 66 occurred during the recovery phase of a giant Forbush decrease. We note that extremely large magnetic storms are usually accompanied by strong Forbushes, e.g. the events in August 1972, July 1982 and about half of the biggest Forbushes during the last 50 years were followed by extreme geomagnetic storms [6,16,18]. Indeed, this is the case of the October–November 2003 events. In late October 2003 occurred the strongest in 30 years (since March 13–14, 1989) geomagnetic storm. The planetary Ap index reached values $A_p = 204, 191$ and 116 on 29, 30 and 31 October, respectively, see

Fig. 1. Count rate time variation of selected neutron monitor stations during GLE 66 on 29 October 2003. The Forbush decrease is clearly seen before the event onset

the site: <https://www.spaceweatherlive.com/en/auroral-activity/top-50-geomagnetic-storms.html>.

The resulting extreme geomagnetic activity, the giant Forbush effect and the sequence of three GLEs led to complicated atmospheric ionization effects as discussed below.

Using the model described above and the derived SEP spectra for GLE 66 we computed the ion production rate as superposition of the considerably reduced GCRs and SEPs contribution at different regions, the details are given in Fig. 1. While the ion production rate during GLE 65 on 28 October 2003 was significant, specifically over the polar region and at the initial and main phases of the event, the ion production rate during GLE 66 was considerably smaller, because of the softer SEP spectra. Yet, the ion production rate during GLE 66 was almost constant throughout the event (Fig. 2 and 3), since the assumed SEP spectra during GLE 66 revealed marginal changes. One can see that the ion production rate during the initial phase of GLE 66, that is at 22:00 UT, is slightly greater than that during the late phase of the event, i.e., at 24:00 UT. Here, we computed the cut-off rigidity during the event in a grid of $1^\circ \times 1^\circ$, explicitly considering the complex magnetospheric conditions employing a combination of IGRF and Tsyga-

Fig. 2. Global map of ion production rate in the region of Regener–Pfotzer maximum due to CRs of galactic and solar origin during the *initial* phase of GLE 66 on 29 October 2003

Fig. 3. Global map of ion production rate in the region of Regener–Pfotzer maximum due to CRs of galactic and solar origin during the *late* phase of GLE 66 on 29 October 2003

nenko models, which allowed us to perform realistic high-precision computations of the global distribution of ion production over the globe. These computations have been performed in the region of Regener–Pfotzer maximum, where the ion production rate is maximal.

The ion production rate during the GLE 66 is determined by: particle flux and hardness of the SEP spectra, SEPs with harder spectra impact in addition to the high-latitudes also mid-latitude regions, while soft SEPs contribute mostly in the polar region; the considerably reduced GCR flux is greatly impacting the ion production rate, specifically in mid and low latitudes; and the complex magnetospheric conditions.

Using the computed ion production rates during the second Halloween GLE, we computed the corresponding averaged over 24 h ionization effect during the GLE 66 similarly to [19–21]. Naturally, the averaged ionization effect represents the computed over 24 h ion production rate during the event considering the SEP and actual GCR contribution versus 24 h averaged ion rate due to GCR prior to the event. Here we considered the giant Forbush decrease of GCR flux at different rigidity cut-offs by adjusting the GCRs as a function of the NM count rates located at different latitudes.

Fig. 4. Global map of 24 h *averaged* ionization effect in the region of Regener–Pfotzer maximum due to CRs of galactic and solar origin during the GLE 66 on 29 October 2003

The results of those computations are shown in Fig. 4. In contrast to the significant ionization effect during GLE 65, which ranges about 100–200%, specifically in the high-latitude region, while the ionization effect during GLE 66 was marginal of about 5%. Moreover, the 24 h averaged ionization effect during GLE 66 was considerably negative in the mid-latitudes and specifically the equatorial region, due to the reduced GCR flux (Fig. 4). Besides, at altitudes below the Regener–Pfotzer maximum, the 24 h averaged ionization effect during GLE 66 is clearly negative throughout the globe. An additional assessment of the ionization effect, assuming an absence of the Forbush decrease during the GLE 66, namely computation of the ion production considering SEPs and non reduced GCRs flux, was performed. In this case, the ionization effect during GLE 66 would be comparable with GLE 67, but is still smaller than GLE 65.

Discussion and conclusion. Realistic and detailed study of the precipitating high-energy particles impact ionization, specifically during strong solar particle events, allows one to perform a thorough analysis of various mechanisms related to their influence on minor components in the Earth's atmosphere and to decipher the physics of the processes involved. In case of strong and major GLEs, these studies are particularly important, because of the enhanced compared to the background ion production. However, in some cases, a significant reduction

of GCR flux due to transients can compete to the enhanced ion production due to SEPs. Therefore, for realistic assessment of the possible effect on precipitating high-energy particles on atmospheric physics and chemistry, it is necessary to compute the ionization effect at various time scales, e.g. to perform a normalization over a 24 h period. It was shown that the role of the giant Forbush effect is essential, i.e. in practice it governs the averaged ionization effect, suppressing the enhanced ion production due to SEPs, eventually leading to negative ionization effect over most of the globe. Therefore, deep Forbush effects can compensate the short term excess of ion production in the atmosphere due to SEPs, specifically below the Regener–Pfotzer maximum.

In this work, using reconstructed from ground-based and space-borne instruments SEP spectra we assessed the ion production rate and the corresponding ionization effect during the second of sequence of Halloween GLE events in October–November 2003, namely the GLE 66 which occurred on 29 October 2003. The computation was as realistic as possible, since the dynamics of GCRs and SEPs was explicitly considered, including the giant Forbush decrease, within the complex magnetospheric conditions, which allowed us to make a precise assessment of the ionization effect. It was shown that the ionization effect in the polar and sub-polar region was greatly impacted by the reduced GCR flux, leading to negative values. Therefore, the role of the Forbush decrease is significant. It considerably reduced the integrated over three events ionization effect, specifically in mid and low latitudes and shall be accounted in other similar studies. Here, we would like to stress, that large number of GLEs occurred during the recovery phase and/or after Forbush effects, which shall be explicitly considered. The computed ionization effect presented here is a good basis for further studies related to the space weather and the possible impact of precipitating high-energy particles of solar origin on ionospheric and atmospheric physics and chemistry [22–24].

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