STUDYING EXAGGERATED ATMOSPHERIC ELECTRIC CURRENTS AT HIGH LATITUDES DURING MAJOR SEP EVENTS

Peter Tonev

Space Research and Technology Institute – Bulgarian Academy of Sciences
e-mail: peterton@abv.bg

Keywords: *aerosol, attachment, multiplication, atmospheric conductivity, spatial electric charges*

Abstract: *The experimental measurements of atmospheric electric characteristics conducted at high geomagnetic latitudes during strong solar proton events with ground-level enhancements demonstrate well-expressed specific peculiarities in variations of the vertical electric field and the corresponding electric current J_z in stratosphere, as well as at surface. For example, on the first phase of these events the electric current Jz becomes significantly bigger than the current from ionosphere to ground by fair-weather conditions. Besides, the time period of this variation well exceeds the relaxation time of global electric circuit. An explanation of this peculiarity is represented based on hypothetical processes in polar mesopause and around during SEP.*

ИЗУЧАВАНЕ НА НЕОБИЧАЙНО ГОЛЕМИТЕ АТМОСФЕРНИ ЕЛЕКТРИЧЕСКИ ТОКОВЕ НА ВИСОКИ ШИРИНИ ПРИ СИЛНИ СЛЪНЧЕВИ ПРОТОННИ СЪБИТИЯ

Петър Тонев

Институт за космически изследвания и технологии – Българска академия на науките
e-mail: peterton@abv.bg

Ключови думи: *аерозоли, прилепване, размножаване, атмосферна проводимост, пространствени електрически заряди*

Резюме: *Експерименталните измервания на атмосферните електрически характеристики проведени на високи геомагнитни ширини по време на мощни слънчеви протонни събития с приемно нарастване на фона демонсрират добре изразени специфични особености на вариациите на вертикалното електрическо поле и на съответния електрически ток Jz в стратосферата, както и на земната повърхност. Например, в първата фаза на тези събития електричекият ток Jz става значително по-голям от тока протичащ от йоносферата към земята в условията на ясно време. Освен това, продължителността на тази вариация е много по-голяма от времето на релаксация в глобалната атмосферна електрическа верига. Представено е обяснение на тази особеност основана на хипотетични процеси в полярната мезосфера и около нея.*

Introduction

Experimental investigations of the atmospheric electric fields and currents in the stratosphere and at surface at high geomagnetic latitudes during major solar energetic particles events (SEP) [1] accompanied by ground level enhancement (GLE) demonstrate well-expressed typical peculiarities [2,3,4]. Essentially, these are strong (usually more than 100%) and long-continuing (from tens of minutes to many hours) deviations of the vertical electric current J_z from the fair-weather current J_{FW} by fair-weather conditions [5]. These deviations include increases of J_z on the first phase of SPE, as well as decreases or even reversals of J_z on a later phase, which cannot be explained by the theory of the global atmospheric electric circuit (GEC). Hypothetic processes are considered here as response of the polar upper atmosphere to SEP which can lead to such peculiarities. The basic hypothetic process is dynamic creation of aerosol particles in the polar mesopause and around. Indirect experimental confirmations of this process are considered. The enhanced ionization during SEP leads initially to increase of conductivity σ in polar mesosphere and around, and later the process of aerosol formation can cause dramatic decrease of σ. Such process can cause redistribution of atmospheric electric currents leading to the observed peculiar J_z variations.

Peculiarities observed

There are only few experimental studies of atmospheric electrical characteristics at high geomagnetic latitudes during strong SEP events for solar cycles 21-23. These experimental studies represent measurements of electric field **E** and, possibly, conductivity σ; current **J** is obtained from Ohm's law $\mathbf{J}=\sigma\mathbf{E}$. Two types of experiments have been conducted: *i*) balloon-borne measurements in stratosphere [2,3]; *ii*) measurements at surface [4]. These first concern SPE/GLEs on: *S1*) 16 February 1984 [2], and *S2*) 20 January 2005 (GLE69) [3]. Measurements in case *S1* are on two balloon stations located at altitude 26 km: EMA7 (38.7°S, 65.7°E) at invariant latitude Λ= –48.8° (cutoff rigidity 2.8 GV), and EMA8 (44.6°S, 142.7°E) at Λ= –56.3° (cutoff rigidity 1.4 GV), respectively. At EMA8 (at the upper latitude) a peculiar response is observed of atmospheric conductivity σ, as well as of vertical electric field E_z and corresponding electric current J_z. Particularly, J_z increases more than twice, and this variation is not transient since it lasts for almost half an hour, much longer than the relaxation time τ_{RGEC} of GEC (~7 minutes). None effect is detected on EMA7 at lower latitude. Thus, strong and peculiar response of electrical characteristics in stratosphere occurs at high (sub-high) geomagnetic latitudes, but not at lower latitudes.

In experimental case *S2* balloon-borne measurements of conductivity σ, as well as of components of the electric field **E** and of electric current density **J** are conducted during the day of occurrence of SPE/GLE69 (20.01.2005) [3]. During the day the balloon position changes from (70.9°S, 10.9°W) at 30.9 km altitude to (71.4°S, 21.5°W) at 33.2 km altitude. Similar peculiarities appear in variations of vertical electric field E_z and current $J_z=\sigma E_z$: too big (>100%) enhancement of J_z for too long (>> τ_{RGEC}) time. Experiment *S2* is used in this paper as a sample case which is best illustration of the peculiarities studied.

Similar experimental measurements are conducted at ground level, as well, at high geomagnetic latitudes (Apatity, geomagnetic latitude 63.3°) during three major SPE/GLEs in 2001 [4]. Measured are the atmospheric electric field (AEF) E_z at surface during SPE/GLEs, respectively, on: *G1*) 15 April; *G2*) 18 April; and *G3*) 4 November. The results of these experiments demonstrate similar, as in stratosphere, peculiarities in variations of vertical electric field E_z and current J_z. Each case *S1, S2, G1-G3* demonstrates several succeeding types of peculiarities in variations of the electric current J_z. The first peculiarity in each case is an unusually big enhancement of electric current J_z so that it becomes much larger than the fair-weather electric current J_{FW} within time period well exceeding the time τ_{GEC} of electric charge relaxation in GEC, τ_{GEC} ~7 minutes.

The goal of this work is to give a hypothetic explanation of this initially occurring peculiarity in each case. Fig.1 illustrates this type of peculiarity for case *S2*: it shows variations of J_z in Antarctic stratosphere (~32 km altitude) during the day of GLE 69. Fig.2 shows simultaneous data of integrated energetic proton flux from GOES-10 data of energetic proton intensity for channels: >1 MeV, >5 MeV, >10 MeV, >30 MeV, >50 MeV (*I1-I5*). The peculiarity considered is represented by an unusually strong (up to about 300+%) positive deviation of J_z from J_{FW} for time t_{P1}~4.5 hours: from ~09:30 until 14:00 UT. Here both J_{FW} and J_z are downward. One can see that the time period of deviation begins well after the onset of SPE at 06:51 UT. We just note occurrence of peculiarities of other types after 14:00 UT: *a*) from 14:00 UT until 15:56 UT J_z almost vanishes (J_z~0); *b*) from 15:56 UT until the end of the day J_z reverses to upward (J_z>0), yet $|J_z|>|J_{FW}|$ for the most of time. Peculiarities *a*) and *b*) will be studied in another publication.

The same type of extremely big positive deviations of J_z from J_{FW} within time period $t_{P1} >> \tau_{GEC}$ occurs in each of considered cases of SPE/GLE under fair-weather conditions. Such peculiarity cannot be explained by the theory of GEC considered as isolated from outer electric sources [6]. [7] also show that the detected large variations of electric field and current cannot be result of conductivity changes in polar middle atmosphere caused by enhanced ionization. Our conclusion is that the electric current J_z is a result of superposition of the fair-weather current J_{FW} with an additional current J_A produced by unknown electric source which is external with respect to GEC:

(1) $J_z = J_{FW} + J_{Az}$

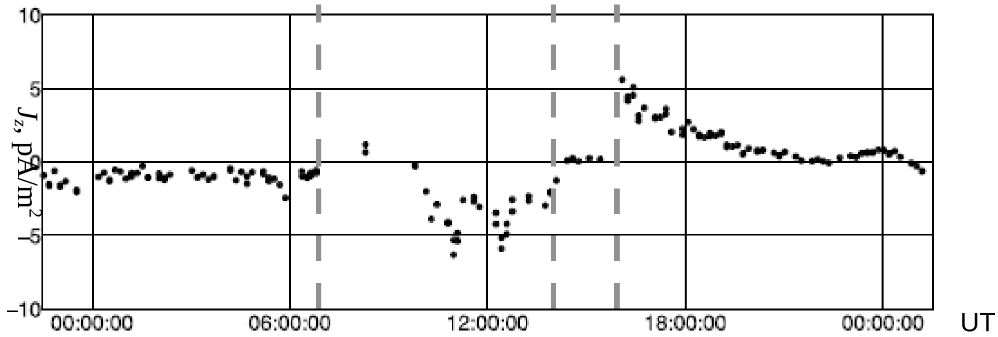

Fig. 1. Density of vertical electric current J_z at balloon station MINIS Flight 2 South on January 20, 2005 with coordinates changing from (70.9°S, 10.9°W), 30.9 km altitude, to (71.4°S, 21.5°W), 33.2 km altitude) [3]. The SPE/GLE 69 onset (06:51 UT) is marked by the left vertical dashed line. From ~09:30 until 14:00 UT (for 4.5 hours) J_z is much bigger (up to ~300+%) then its value by quiet conditions before SPE.

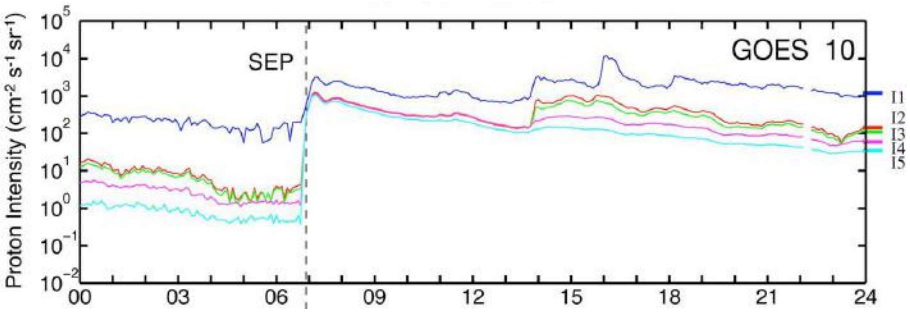

Fig. 2. Integrated energetic proton flux on 20.01.2005 from GOES-10 data for channels: >1 MeV, >5 MeV, >10 MeV, >30 MeV, >50 MeV (*I1-I5*) [3].

Here J_{Az} is the vertical component of the electric current J_A superimposed to the fair-weather current J_{FW}. The peculiarity in case *S2* (Fig.1) is characterized by downward current J_{Az} (J_{Az}<0) which is comparable to, or bigger than J_{FW}. We show below that in other cases, *S1, G1-G3*, the peculiarity considered has similar characteristics. In this paper we propose a hypothetic mechanism of generation of J_{Az} during strong SPEs.

Relative deviations of current J_z from fair-weather current

We characterize peculiarity considered in each experimental case *S1*, *S2* (in stratosphere), and *G1-G3* (at surface) by the ratio between the additional current J_{Az} and the fair-weather current, $R_A = J_{Az} / J_{FW}$. Used are the parameters: *i*) maximum positive value of R_A (R_{Amax}); *ii*) time period t_{JA} of the peculiar variation. These are presented below for cases *S1, S2, G1 - G3*:

Case	SPE/GLE	λ	Altitude, km	~R_{Amax}, %	t_{JA}, hours
S1 [2]:	16.02.1984	–56.3°	26	120	0.3
S2 [3]:	20.01.2005	–70□°	~32	300	3.6
G1 [4]:	15.04.2001	+63.3°	at surface	>400	3.0
G2 [4]:	18.04.2001	+63.3°	at surface	400	5.5
G3 [4]:	04.11.2001	+63.3°	at surface	200	2.0

For each case parameters R_{Amax} and t_{JA} demonstrate presence of large additional electric current J_{Az} compared to the fair-weather current J_{FW} for time t_{JA}>>τ_{rGEC}. This means that J_{Az} is dominant current in Eq.(1) for this time, thus, it is generated by an external electric source. There is difficulty with determination of such source due to the fast (quasi-exponential) increase of conductivity with altitude *z*. Here we present a hypothetic source of electric current J_{Az} activated during SEP.

Aerosol dynamics in stratosphere during SEP

A series of experimental studies shows that few days after major SPEs significant increase of aerosol particle density occurs in stratosphere at high latitudes. This fact is experimentally demonstrated first for SPE/GLE on 16 February 1984 (case *S1*) [8]. In this case demonstrated is gradual increase of aerosol density in stratosphere at high latitudes at latitudes z=15-30 km from the second day (18.02.1984) until the fourth day (20.02.1984) of SPE. The results [8] are summarized below by the following characteeristics: *a*) the maximum relative increase of the backscatter ratio BR; *b*) the mean altitude z_d of the disturbance.

Days after SPE	2	3	4
BR, %	28	35	46
z_d, km	18	17	16

These results also show descending of the disturbance with time. Similar, but more thorough and detailed results are presented for SPE/GLE 69 (case *S2*) in [9]. [8,9] possibly demonstrate that the aerosol enhancement during SEP has a relationship with enhanced ionization at polar and high geomagnetic latitudes which is strongest above the stratosphere, at altitudes up to ~95 km. The lower latitudinal boundary of this enhancement depends on the geomagnetic cutoff rigidity for the specific geomagnetic activity conditions. The delayed aerosol increase in stratosphere at high latitudes is hypothetically manifestation of two processes. First, aerosol increase in atmospheric regions above stratosphere in relationship with highly enhanced ionization during SEP in these regions. Second, transport of newly created aerosol particles (AP) to lower atmospheric regions as result of sedimentation or electrostatic force together with simultaneous growth of descending APs. The descending of APs to regions of bigger atmospheric density is slowed down: accumulation of grown-up APs would occur in a stratospheric layer situated well below the creation of APs.

Hypothetic dynamic processes in polar mesopause during SEP

We consider five hypothetical processes in polar mesopause (and at close altitudes and latitudes) during major SPEs. These processes imply presence of aerosol particles in the undisturbed mesopause before the onset of SPE which is experimentally demonstrated by structures in summer mesopause, such as noctilucent clouds (NLC), and polar mesopause summer echoes (PMSE). Short description of the following hypothetic processes. First, the enhanced ionization during SPE leads to gradual growth of APs in the mesopause due to faster attachment of ions to APs. An AP (in general, multi-charged) is assumed to be spherical, and is characterized by its radius r and by the number q_e of elementary charges carried. According to theoretical investigations [10], the attachment coefficients $v_\pm$ of an ion or electron of respective polarity to an oppositely charged AP with radius r and charge number q_e (q_e>0 for positively charged AP, and q_e<0 in the opposite case) increases quasi-exponentially with q_e. Also, the average number of elementary charges $q_{ea}(r)$ carried by an AP with radius r increases quasi-linearly with r. As result, the effective coefficients of attachment of ions to APs with radius r $v_{\pm eff}(r)$ can be represented as follows: $v_{\pm eff}(r) = v_\pm(r, q_{ea}(r))$. From these properties we find that during the enhanced production of ions in polar mesopause related to SPE the attachment rate increases at least quasi-exponentially with time t. r also will increase quasi-exponentially with time. The process of aerosol growth occurs in a region R_A with significant initial AP density S_0 (initially, the polar mesopause).

Attachment of neutral particles to APs is an additional factor of quasi-exponential growth of APs. The size of APs in the mesopause should remain limited: r < 50 - 70 nm which implies an effective lost mechanism of large APs. An effective limitation of the aerosol maximum size can be achieved by segmentation of large enough APs into two or more new APs. This process leads to multiplication of APs and thus to an increase of their density S. We estimate how the density S of APs varies with time by simplest assumptions during SPE of energetic proton flux peak: *i*) Once the radius r of an AP reaches its critical value r_{max}, it splits into two equal APs with radius $r_{min}=2^{-1/3}r_{max}$; ii) APs grow exponentially with time t as result of attachments of ions and neutral particles:

$$r_{AP}(t) \sim \exp(t/t_G),$$

where t_G is time of increase of AP radius r_{AP} from minimum (r_{min}) to maximum (r_{max}); *iii*) Growth of APs is unlimited; *iv*) $S(r)$ has uniform distribution by r for $r_{max} \le r \le r_{min}$. Then, S [cm^{-3}] satisfies the equation:

(2) $$dS/dt = f_s = S/t_G$$

Here f_s is splitting frequency per cm^3: $f_s = S/t_G$ [cm^{-3}s^{-1}]. Eq.(1) is solved with initial condition at start time t_s of the process of splitting, $S(t_s) = S_0$. The solution is:

(3) $$S = S_0 \exp(t/t_G).$$

Eq.(3) shows that the AP density increases exponentially with time *t* by idealistic conditions. Hence, processes 1-3 demonstrate initial quasi-exponential growth of 'seed' APs up to their maximum size. Then, multiplication of APs leads to exponential increase of *S* with time.

Both, the quasi-exponential growth of APs size due to ion-to-AP attachment, as well as the quasi-exponential increase of their density *S* after time t_s, determine transfer of electric charges from small carriers (ions) to large carriers (APs) and decrease of ion and electron densities with time. This transfer of charges leads to diminishing of conductivity σ because of the decrease of electron and ion densities leading also to decrease of the charge carrier mobility in average. Actually, the conductivity variations follow changes in the balance between ions and multi-charged APs. It is described by the following balance equations for positive and negative ions (including electrons) with densities $n_{\pm}$ and positively/negatively charged APs with densities $S_{\pm}(r)$:

(4) $$dn_{\pm}/dt = q - \alpha n_{+} n_{-} - B_{\mp} n_{\pm} \qquad \text{where} \qquad B_{\mp} = \int_r v_{\mp eff}(r) S_{\mp}(r) dr$$

Here *q* is the ionization rate; α is the effective coefficient of recombination, $v_{\pm\mathrm{eff}}(r)$ is the effective coefficients of attachment of ions to AP with radius *r*. As we show, coefficients $B_{\pm}$ increase quasi-exponentially with time, and thus exponential decrease of $n_{\square}$ and $n_{\square}$ is follows from Eq.(4). This last leads to quasi-exponential decrease of the electron and ion conductivities $\sigma_{\mathrm{i,e}} = q_e \mu_{\mathrm{i,e}} n_{\mathrm{i,e}}$ with time (q_e is the elementary charge). At the initial stage of SPE conductivity $\sigma = \sigma_{\mathrm{i}} + \sigma_{\mathrm{e}}$ enhances due to increase of the electron density; later σ decreases with enhanced transfer of electric charges to APs and with diminishing of $n_{\pm}$. During SEP uncompensated positive elementary charges are being injected into polar and high-latitudinal middle atmosphere and are being accumulated in region R_{σ} where conductivity $\sigma < \varepsilon_0/\tau_{\mathrm{RGEC}}$; ε_0 is the dielectric constant. As result, a sub-region R_{+} of positive spatial electric charge with density $\rho > 0$ is formed in an upper portion of R_{σ} at polar geomagnetic latitudes. In the rest sub-region $R_{\square}$ negative electric charge is being accumulated including a layer below R_{+}. The electric current J_{Az} is interpreted here as an upward electric current of negative ions which is feeding the negative screening charge in this layer.

Conclusions

1. The problem is formulated about the nature of the significant additional electric fields $\mathbf{E}_{\mathrm{A}}$ and currents $\mathbf{J}_{\mathrm{A}}$ superimposed to the fair-weather current J_{FW} in GEC at high latitudes during major SPE/GLEs according to measurements in stratosphere and at surface at high latitudes.
2. Hypothetic processes initialized in polar mesopause are proposed to respond for generation of $\mathbf{E}_{\mathrm{A}}$ and $\mathbf{J}_{\mathrm{A}}$. Electric source is result of accumulation of incoming charges which can cause variations of the vertical electric current J_z detected by experimental measurements. This can be achieved by creation and growth of aerosol particles in middle atmosphere at polar and high latitudes during SEP.
3. Creation of aerosol can control formation of weather and climate. Significant changes in electric currents in GEC can affect also processes in troposphere responsible for weather formation.

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