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# Hypothetic Atmospheric Response to SEP Explaining Peculiar Electric Fields and Currents at High Latitudes

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**Abstract.**

Experimental measurements of atmospheric electric characteristics conducted at high geomagnetic latitudes during several strong solar proton events with ground-level enhancements demonstrate well-expressed peculiarities in variations of the vertical electric field $E_z$ and the related electric current $J_z$ in stratosphere, as well as at surface. Considered here is a specific peculiarity which is observed in each experiment: $J_z$ becomes unusually large for time period which well exceeds the time of relaxation of electric charges in the global atmospheric electrical circuit. An interpretation of this peculiarity is represented based on hypothetical processes in polar mesopause and around during SEP.

**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) (Mironova et al., 2015) accompanied by ground level enhancement (GLE) demonstrate well-expressed typical peculiarities (Holzworth et al., 1987, Kokorowski et al., 2006, Shumilov et al., 2015). 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 (Tonev, 2022). 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) (Rycroft et al., 2008). 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 $\sigma$ in polar mesosphere and around, and later the process of aerosol formation can cause dramatic decrease of $\sigma$. Such process can cause redistribution of atmospheric electric currents leading to the observed peculiar $J_z$ variations.

**The peculiarity observed by experimental measurements**.

During solar cycles 21-23 several experimental studies of atmospheric electrical characteristics and their behavior during SEP have been conducted at high geomagnetic latitudes which coincide by a chance with major SPE/GLEs. These experimental studies represent measurements of electric field **E** and, in some cases, conductivity $\sigma$ (so that current **J** can be obtained from Ohm's law $\mathbf{J} = \sigma\mathbf{E}$) of two types: *i*) balloon-borne measurements in stratosphere; *ii*) at surface. There are only several such experiments because of the rareness of major SEP events, and of their unpredictability. First, obtained are variations of the vertical electric field $E_z$ in stratosphere (at 30 km altitude) on two balloon stations, at (55.75°N, 97.85°W), and (64.9°N, 147.8°W), respectively, during SPE/GLE 4 August 1974 (Holzworth and Mozer, 1979). In spite of incompleteness of measurement data, already this earlier experiment of such type indicates for typical peculiarities (their Fig.1). These peculiarities are demonstrated clearer in two similar, and more complete stratospheric experiments during SPE/GLEs on: *S1*) 16 February 1984 (Holzworth et al., 1987), and *S2*) 20 January 2005 (GLE69) (Kokorowski et al., 2006). Measurements in case *S1* are on two balloon stations located at altitude 26 km: EMA7 (38.7°S, 65.7°E) at invariant latitude $\Lambda$=−48.8° (cutoff rigidity 2.8 GV), and EMA8 (44.6°S, 142.7°E) at $\Lambda$= −56.3° (cutoff rigidity 1.4 GV), respectively. At EMA8 (at the upper latitude) a peculiar response is observed of atmospheric conductivity $\sigma$, 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 about 1/2 hour, longer than the relaxation time $\tau_{RGEC}$ 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 $\sigma$, as well as of components of the electric field **E** and of electric current density **J** are conducted during the whole day of occurrence of SPE/GLE69 (20.01.2005) (Kokorowski et al., 2006). During the day the balloon station moved 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 (>> $\tau_{RGEC}$) 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 (Shumilov et al., 2015). 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 the related current $J_z$, as summarized below.

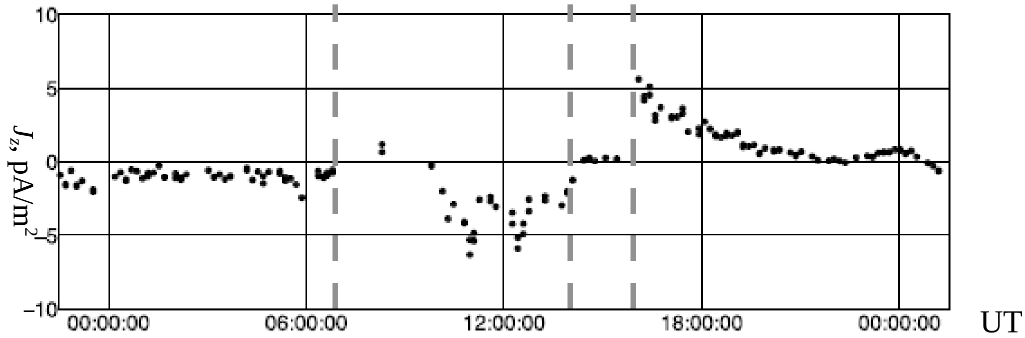


Fig.1. Density of vertical electric current $J_z$ at balloon station MINIS Flight 2 South on January 20, 2005 with coordinates changing from (70.9°S, 10.9°W), 30.9 km altitude, to (71.4°S, 21.5°W), 33.2 km altitude) (Kokorowski et al., 2006). The SPE/GLE 69 onset (06:51 UT) is marked by the left vertical dashed line. From ~09:30 until 14:00 UT (for 4.5 hours) $J_z$ is much bigger (up to ~300+%) than its value by quiet conditions before SPE.

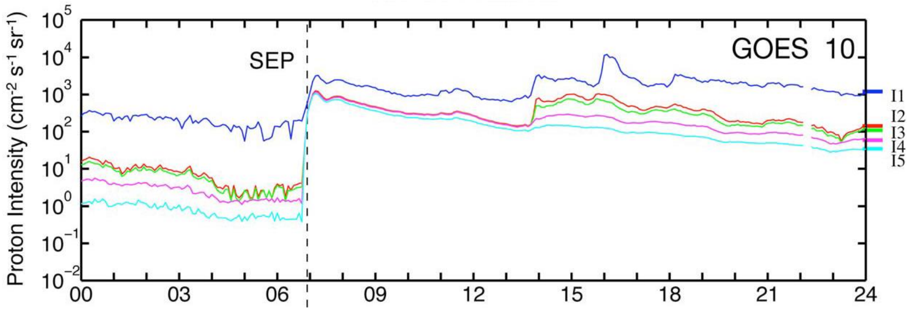


Fig.2. Integrated energetic proton flux on 20.01.2005 from GOES-10 data for channels: >1 MeV, >5 MeV, >10 MeV, >30 MeV, >50 MeV (*I1-I5*) (Kokorowski et al., 2006).

Each case *S1, S2, G1-G3* demonstrates several succeeding typical 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 $\tau_{GEC}$ of electric charge relaxation in GEC, $\tau_{GEC}$ ~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 (Farrell and Desch, 2002). (Dejnakarintra et al., 1985) 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:

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

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.

**Experimentally determined 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 | $\lambda$ | $z$, km | $\sim R_{Amax}$, % | $t_{JA}$, hours | Reference |
|---|---|---|---|---|---|
| *S1*: 16.02.1984 | −56.3° | 26 | 120 | 0.3 | Holzworth et al. (1987) |
| *S2*: 20.01.2005 | −70° | 32 | 300 | 3.6 | Kokoropwski et al. (2006) |
| *G1*: 15.04.2001 | +63.3° | surface | >400 | ~3.0 | Shumilov et al. (2015) |
| *G2*: 18.04.2001 | +63.3° | surface | 400 | 5.5 | Shumilov et al. (2015) |
| *G3*: 04.11.2001 | +63.3° | surface | 200 | ~2.0 | Shumilov et al. (2015) |

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 $t_{JA} >> \tau_{rGEC}$. 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 (Shumilov et al., 1985, Mironova et al., 2012). Here this fact is illustrated for SPE/GLE on 16 February 1984 (case *S1*) in Fig.3 (Shumilov et al., 1985). In this case demonstrated is gradual increase of aerosol density in stratosphere at latitudes $z$ = 15-30 km from the second day until the fourth day of SPE. Also, the disturbance in the profile descends with time. Mironova et. al. (2012) present similar but more thorough and detailed conclusions for SPE/GLE 69 (case *S2*). It is reasonable to conclude from these results 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: 1) Increase of the aerosol density in atmospheric regions above stratosphere in relationship with highly enhanced ionization during SEP in these regions. 2) 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.

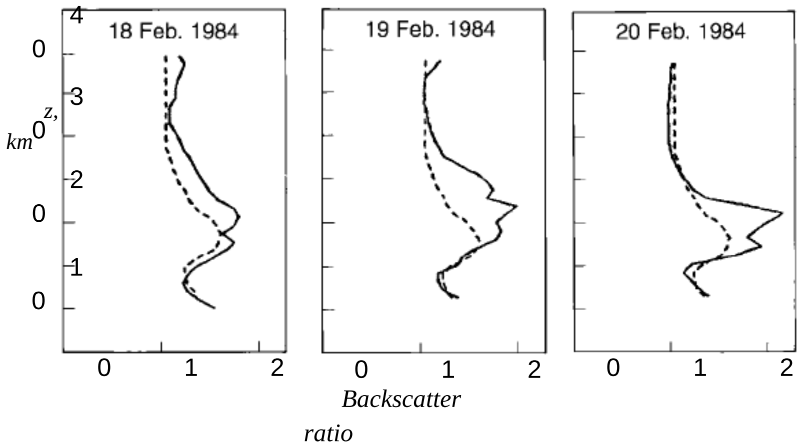


Fig.3. Scattering ratio profiles (solid lines) on 18, 19, and 20 February 1984 (Shumilov et al., 1985). Dashed curves are for quiet conditions before SPE.

**Hypothetic dynamic processes in polar mesopause during SEP**

We consider hypothetical processes 1 - 5 in polar mesopause and close to it 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 hypothetic processes 1 - 5 follows:

1. 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 (Hoppel, 1985), 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).

2. Additional quasi-exponential growth of APs with time can occur by attachment of neutral particles to APs.

3. The size of APs in the mesopause remains limited: $r$ < 50 - 70 nm. By fast growth of APs this implies an effective lost mechanism of large APs. The gravitational sedimentation is too slow to compete with the quasi-exponential growth of APs. A more effective process of effective limitation of the aerosol maximum size is 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 approximately how the density $S$ of APs varies with time under simplest assumptions for the time period of SPE of energetic proton flux peak:

*a*) Once the radius $r$ of an AP reaches its critical value $r_{max}$, it splits into two equal APs with radius $r_{min}=2^{-1/3}r_{max}$;

*b*) 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 ($r_{max}$);

*c*) Growth of APs is unlimited;

*d*) $S(r)$ has uniform distribution by $r$ for $r_{max} \le r \le r_{min}$.

Then, $S$ [$cm^{-3}$] satisfies the equation:

$$dS/dt = f_s = S/t_G \qquad (1)$$

where $f_s$ 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:

$$S = S_0 \exp(t/t_G). \qquad (2)$$

Eq.(2) 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.

4. 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 $\sigma$ 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 $S_\pm(r)$:

$$dn_\pm/dt = q - \alpha n_+ n_- - B_\mp n_\pm \qquad \text{where} \qquad B_\mp = \int_r \nu_{\mp eff}(r) S_\mp(r) dr \qquad (3)$$

Here $q$ is the ionization rate; $\alpha$ is the effective coefficient of recombination, $\nu_{\pm eff}(r)$ 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 $n_+$ and $n_-$ is follows from Eq.(3). This last leads to quasi-exponential decrease of the electron and ion conductivities $\sigma_{i,e} = e\mu_{i,e}n_{i,e}$ with time. At the initial stage of SPE conductivity $\sigma=\sigma_i+\sigma_e$ enhances mainly due to the increase of the electron density, and later $\sigma$ decreases dramatically with the intensified transfer of electric charges to APs and diminishing of $n_\pm$.

5. Formation of dynamic structure of spatial charges in region $R_A$. During SEP uncompensated positive elementary charges are being injected into polar and high-latitudinal middle atmosphere and are being accumulated in region $R_\sigma$ where conductivity $\sigma<$ . As result, a sub-region $R_+$ of positive spatial electric charge with density $\rho>0$ is formed in an upper portion of $R_\sigma$ at polar geomagnetic latitudes. In the rest sub-region $R_-$ 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.

**Conclusion**.

The problem is formulated about the nature of the significant additional electric fields $\mathbf{E}_A$ and currents $\mathbf{J}_A$ 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. Hypothetic processes initialized in polar mesopause are presented as responsible for generation of $\mathbf{E}_A$ and $\mathbf{J}_A$. It is shown that electric source can be created as result of accumulation of incoming charges which can cause variations of the vertical electric current $J_z$ detected by experimental measurements. Hypothetically, this can be achieved by creation and growth of aerosol particles in middle atmosphere at polar and high latitudes during SEP. More detailed description of the hypothetic mechanism of the electric current $J_A$ generation will be subject of further publications. Creation of aerosol, thus hypothesized, can have effect on 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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