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Hypothetic Explanation of Peculiar Atmospheric Electric Response to SEP at High Latitudes. Experimental Evidence.

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Abstract.

Measurements of atmospheric electric characteristics which have been conducted at high geomagnetic latitudes during several strong solar proton events with ground-level enhancements include in each case a long time interval of unusually large (twice or bigger) increase of the vertical electric current J_z in stratosphere, or of the atmospheric electric field E_z at surface. Since these enhancements are not transient variations they demonstrate presence of an additional electric circuit superimposed to the global atmospheric electric circuit during SPE. An explanation is proposed based on the following processes: *i*) positive charge injection into polar atmospheric regions R_p; *ii*) gradual, yet eventually dramatic decrease of conductivity in R_p due to aerosol increase. This explanation is confirmed by rocket-borne data for electric characteristics in stratosphere and mesosphere during a major solar proton event.

Introduction.

Studied are the results from measurements of the vertical electric field E_z and related current J_z in the stratosphere (*Holzworth et al., 1987*; *Kokorowski et al, 2006*), as well as at surface (*Shumilov et al, 2015*) at high/ sub-high geomagnetic latitudes during four strong solar proton events (SPE) with ground level enhancement (GLE) (*Mironova et al., 2015*). In the first two cases, *S1*, *S2*, we consider the variations of E_z, conductivity σ, and $J_z=\sigma E_z$ in stratosphere during two SPE/GLE, respectively: *S1*) on 16-th February 1874 (*Holzworth et al., 1987*); *S2*) on January 20 2005 (*Kokorowski et al., 2006*). The next two cases concern measurements at surface of the atmospheric electric field E_z during two SPE/GLE in 2001, respectively, on 15-th (case *G1*), and 18-th April (case *G2*) (*Shumilov et al., 2015*). Each of these experiments demonstrate a well-expressed peculiarity of the similar type (*Tonev, 2022; Tonev and Asenovski*, *2023*). This peculiarity is represented by unusually large (100% or more) long-term (tens of minutes to several hours) positive deviation of the vertical electric current J_z (and of related electric field E_z) from the electric current J_{FW} ~2 pAm^{-2} Sm^{-1} from the ionosphere to surface by fair-weather conditions (*Tonev, 2022*). These extremely large deviations of J_z and E_z from their typical values occur close to the SPE peak in each case.

The peculiar large deviations of J_z and E_z from their usual values cannot be explained by the theory of an isolated global atmospheric electric circuit (GEC) (Rycroft et al., 2008). Similarly to (*Tonev, 2022*; *Tonev and Asenovski*, *2023*) we conclude that an additional electric circuit (current $\mathbf{J}_S$) is created during SPE and is superimposed to GEC. This circuit is responsible for modifications of the vertical electric current J_z in cases *S1,2, G1,2*, as follows:

$$J_z = J_{FW} + J_{Sz} \qquad (1)$$

Here J_{Sz} is the vertical component of superimposed current $\mathbf{J}_S$ below ~35 km at high latitudes.

Experimentally determined characteristics of peculiarity in cases *S1,2, G1,2*.

We characterize the peculiarity represented by (1) in each of cases *S1,2*, *G1,2* by the time interval Δt of the peculiar increase of J_z or E_z, and the maximum deviation J_{zmax} or E_z during Δt, similarly to (*Tonev and Asenovski, 2023*). In case *S1* (*Holzworth et al., 1987*) we study the variations of current $J_z=\sigma E_z$ at altitude 26 km at two balloon stations located at: *a*) (44.6°S, 142.7°E) with invariant latitude Λ= –56.3° (cutoff rigidity 1.4 GV); *b*) (38.7°S, 65.7°E),

Λ=–48.8° (cutoff rigidity 2.8 GV). At location *a*) J_z increases twice (from J_z= 2.25 pAm^{-2} to $J_{z\max}$= 4.5 pAm^{-2}), and remains modified for Δt ~ 0.5 hour. No modifications of σ, E_z and J_z take place at balloon station *b*) located at the lower latitude. This shows that an additional electric current J_{Sz} in (1) is generated only at high latitudes.

In case *S2* for SPE/GLE69 on January 20 2005 we study the variations of electric current J_z obtained by measurements of σ and E_z on the balloon station MINIS Flight 2 in the Antarctic stratosphere (*Kokorowski et al., 2006*) whose drift during that day is from (70.9°S, 10.9°W) at altitude z = 30.9 km to (71.4°S, 21.5°W) at z=33.2 km. The variations of J_z are demonstrated by (*Kokorowski et al., 2006*, their Fig.2d). J_z shows a similar, as in case *S1*, yet better expressed positive deviation from J_{FW}. This deviaiton begins 3.5 hours after the onset of SPE/GLE69 at 06:51 UT, and continues for about Δt = 4.5 hours. This deviation is characterized by $J_{z\max}$ ~ 6.5 pAm^{-2} – about three times bigger than J_z~1 - 2 pAm^{-2} measured before SPE. The average J_z during the deviation for 4.5 hours exceeds 3 pAm^{-2}. Such large increase of J_z cannot be supported by the inner electric generator of GEC only. We conclude that an additional electric source and related additional electric circuit superimposed to GEC are presented in cases *S1,2*.

In cases *G1* (15 April 2001) and *G2* (18 April 2001) measured have been the variations of the atmospheric electric field E_z at ground level in Apatity, Russia (Λ=63.3°) (*Shumilov et al., 2015*). Similar effect of peculiarly big and long-lasting increase of E_z takes place in each case. In case *G1* Δt ~ 45 minutes, $E_{z\max}$ ~ 600 V/m . In case *G2* Δt is more than three hours, $E_{z\max}$ ~ 550 V/m. $E_{z\max}$ is several times bigger than the typical value under fair-weather conditions (E_z < 200 Vm^{-1}). Again, cases *G1,2* demonstrate presence of an additional electric circuit superimposed to GEC during the respective SPE/GLE, similarly to *S1,2*.

Hypothetic mechanism of generation of electric current J_S during SPE/GLE

Here we consider shortly hypothetic processes *P1-3* in polar atmosphere and around during SPE/GLE which can cause generation of the electric current J_{Sz} in stratosphere and below at high latitudes – for more details see (*Tonev, 2022; Tonev and Asenovski, 2023*). Processes *P1-3* are subject of further elaboration in publications to follow.

P1. Injection of positive elementary charges into atmospheric regions R_p situated at high latitudes in each hemisphere together with the penetrating energetic protons. Hence, the proton flux into R_p regardless of their energy is of interest. The lower boundary z_0 of R_p is determined to be z_0~35 km – protons penetrating below z_0 (that is, of energies >~ 100 MeV) can be neglected related to the common flux. Region R_p is within geomagnetic latitudes $\Lambda > \Lambda_p$ where Λ_p is function of geomagnetic activity (*Rodger et al., 2006*). Λ_p=70° is a reasonable latitudinal boundary for quiet geomagnetic conditions. The injected charge is uncompensated positive charge in GEC and should be taken into account. We present an estimation of the total positive uncompensated electric charge Q_I injected into GEC in case *S2*, but only until 14:00 UT when geomagnetic activity is relatively low. By assumption that protons of energies >1 MeV penetrate into region R_p with Λ_p=70°, the total injected charge is at least 8×10^5 C – this is more than the total charge of 5×10^5 C generated by in GEC tropospheric sources (*Rycroft et al., 2008*). Hence, the uncompensated charge Q_{UC} injected into GEC during SPE/GLE should not be neglected.

A simplified representation of GEC during SPE is shown in Fig.1 as an equivalent electric circuit (EEC). The accumulation of uncompensated charge Q_{UC} in both polar regions R_p needs recovery of the impaired global charge balance in GEC by atmospheric electric current $\mathbf{J}_{HL}$ which usually flows from R_p to lower geomagnetic latitudes through the resistance r_{HL}. By non-diminished conductivity σ in the lower ionosphere (>~10^{-8} Sm^{-1}) the recovery of charge balance is actually immediate: within <~10^{-3} s. We show that SPE/GLE can cause modifications in GEC by redirection of current $\mathbf{J}_{HL}$ as shown in Fig.1 by thick dashed lines.

P2. Hypothetic process of enforced production of aerosol particles (AP) in region R_p initiated by the increased ionization during SPE/GLE which eventually leads to decrease of conductivity σ in R_p (*Tonev, 2022*; *Tonev and Asenovski, 2023*). Process *P2* includes three simultaneous sub-processes, *P2G*, *P2M*, *P2T*.

P2G. Growth and multi-charging of existing aerosol particles (AP) driven by increased ionization in sub-regions of R_P with significant initial density S_0 of APs. Such can be the mesopause, or the upper stratosphere (*Tinsley and Zhou, 2006*). (*Rapp, 2000*) studies this sub-process in the mesosphere by representing any AP as a sphere with a radius r_{AP} and with k elementary electric charges (k>0 corresponds to positive charging of AP, and vice/versa). Growth of APs takes place by faster attachment of ions and neutral particles to APs than the loss processes. In the case of mesopause (*Rapp 2000*): 1) The attachment coefficient ν is increasing function of r_{AP} and $|k|$. 2) The mean number of charges $|k_m|$ when k_m<0 increases almost proportionally with r_{AP}. We obtain that the AP radius r_{AP} increases with time approximately as t^a where a>1 (a is close to 1). Actually, *P2G* is a positive feedback process of growth of APs by increasing of r_{AP} and $|k|$ (*Tonev, 2022*).

P2M. APs undergo multiplication due to segmentation of any AP into two or more separate smaller APs when critical pair of parameters (r_{AP}, k) is reached. As result, the density of APs S increases exponentially with time t: $S \sim S_0 \exp(t/t_S)$ where t_S is the mean time needed by a new-born AP to fulfill the criteria of segmentation.

The result of processes *P2G* and *P2M* is a dramatic decrease of the life time of free electrons and ions to their attachment to APs. This leads to gradual, yet eventually dramatic depletion of electrons and ions, hence, to dramatic decrease of total conductivity σ_p in R_p (the charges are captured by APs whose mass is many orders of magnitude bigger than those of electrons and ions). The conductivity σ_p in R_p can become as low as 10^{-15} Sm^{-1}, or even less.

P2T. Transportation of APs from regions with large density S to ones with negligible S_0 before initiation of *P2G*, *P2M* by electric field $\mathbf{E}_S$ (for multi-charged APs), and sedimentation.

P3. Redistribution of the electric charges injected into the atmosphere at high latitudes to lower latitudes by a superimposed electric current $\mathbf{J}_{HL}$ in order to re global charge balance. The dramatic decrease of conductivity σ_p in region R_p by process *P2* during SPE leads to redirection of electric current $\mathbf{J}_{HL}$ in GEC. Initially, $\mathbf{J}_{HL}$ flows from high towards lower latitudes through resistance r_{HL} as shown in Fig.1 by thick solid arrow. With the increase of resistance r_{HL} determined by decrease of σ, later electric current $\mathbf{J}_{HL}$ is redirected essentially into vertical current which flows towards the surface through columnar resistances r_{MH} (for altitudes z>35 km at high latitudes) and r_{TH} (z<35 km) (shown in Fig.1 by a vertical thick dashed arrow). The redirection of $\mathbf{J}_{HL}$ is controlled by the increasing resistances r_{TH} and r_{MH}. The total columnar resistance at high latitudes $r_{CH} = r_{TH} + r_{MH}$ is affected by the decrease of conductivity σ_p in region R_p only when σ_{pmax} <~10^{-13} Sm^{-1}. In order to determine resistance r_{HL} the assumptions is used that the protons with energies >1 MeV penetrate into R_p at geomagnetic latitudes $\Lambda > \Lambda_p = 70°$ (Rodger et al., 2006). Then

$$r_{HL} > (1 - 2^{-1/2}) R_e \varphi_p / \sigma_{pmax} \sim 6\times10^6/\sigma_{pmax} \ \Omega\text{m}^2 \quad (2)$$

Here R_e~6.471 10^6 m is the average earth's radius; $\varphi_p = 0.5\pi(1 - \Lambda_p/90°)$ is the geomagnetic co-latitude $90° - \Lambda_p$ represented in radians; σ_{pmax} is the maximum conductivity in region R_p. Resistance r_{HL} becomes equal to r_{CL} when $\sigma_{pmax} \sim 5\times10^{-11}$ S/m. If the following condition is fulfilled at time $t \geq t_r$:

$$\sigma_{pmax} <\sim 10^{-11} \text{ S/m}, \quad (3)$$

actually the whole (>80%) electric current $\mathbf{J}_{HL}$ will flow towards surface, and then through the earth to lower latitudes (shown in Fig.2 by horizontal thick dashed arrow). It is important to note that below ~35 km where process P2 is not active σ<~10^{-11} S/m by undisturbed conditions. The redirection of electric current $\mathbf{J}_{HL}$ determines appearance of term $J_{Sz} \equiv J_{HLz}$ in Eq.(1) in atmosphere below region R_p. Electric current J_{Sz} in (1) depends by series of parameters and conditions; its model estimation is subject of future publications.

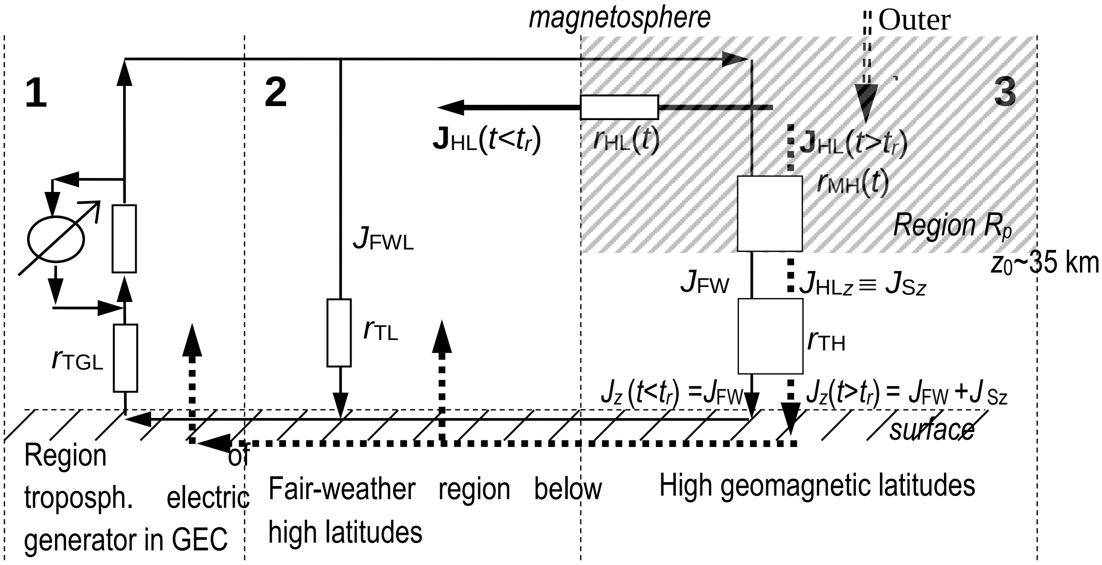

***Figure 1**. Representation of GEC by an equivalent electric circuit during SPE/GLE. The dashed vertical lines determine regions 1, 2, 3: 1 is region of thunderstorm activity and electrified clouds (the electric source of GEC); 2 is region with fair-weather conditions below polar latitudes; 3 is region of polar geomagnetic latitudes with shaded segment R_p above z_0~35 km where uncompensated positive charges are injected (represented by double dashed arrow). The balance of charges in GEC is being recovered by electric current J_{HL} shown by horizontal thick arrow by $t<t_r$, and by dashed thick arrows at $t>t_r$. By $t>t_r$ current $J_{Sz}=J_{HLz}$ is added to J_z below R_p. Here r_{T*} represent columnar resistances of troposphere in regions 1-3.*

Confirmation by rocket-borne measurements during SPE/GLE from 19 October 1989

We analyze the profile of the vertical electric field E_z which have been measured at altitudes 24 - 70 km within a rocket experiment conducted at 19:31 UT on 21 October 1989 at geographic coordinates (58.5°S, 51.2°E) (*Zadorozhni et al., 1994; 1998*). This experiment is during the strong SPE/GLE on 19-22 October 1989; it is conducted 54.5 hours after the SPE onset. On 20-21 October this SPE/GLE was accompanied by a major geomagnetic storm with planetary geomagnetic index Kp=8 at the time of the rocket flight. Fig.2 (*Zadorozhni et al., 1994*) demonstrates the profile of the vertical electric field E_z (the solid curve) by convention that E_z>0 corresponds to downward electric field. The dashed curve shows the profile of the spatial charge density ρ computed from the profile of E_z by Gauss's law. The profile of ρ forms three main layers: L_{PL} [36-46 km] (ρ > 0); L_N [46-58 km] (ρ < 0); L_{PU} [58-64 km] (ρ > 0). By quasi-DC conditions conductivity σ in layers is estimated: in layer L_N σ is at least as low as ~10^{-15} S/m (*Tonev, 2022*). As far as we know, there is no satisfying explanation of the most striking feature - existence of negative layer L_N (*Zadorozhni et al., 1994*) until now.

The results in Fig.2 agree well with the hypothetic mechanism of generation of the additional current $\mathbf{J}_S$ proposed above at time t > t_v when electric current $\mathbf{J}_S$ is re-oriented vertically towards surface, represented by dashed line in Fig.2. This mechanism can explain the dramatic decrease of conductivity σ in mesosphere and in stratosphere observed at time t_{EXP} of rocket experiment (on a late phase of SPE, 54.5 hours after its onset).

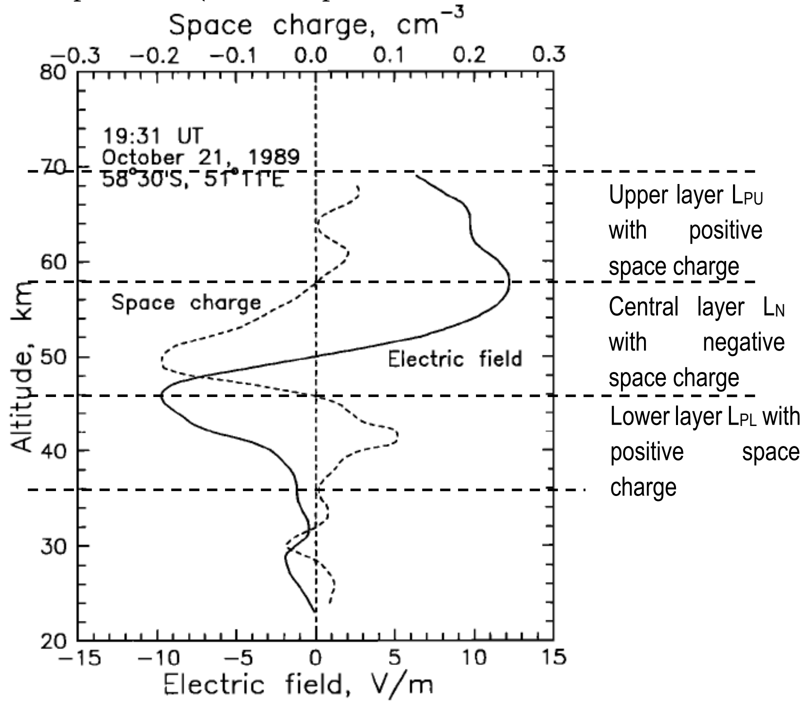

***Figure 2**. Rocket-borne profile (solid curve) of the vertical electric field E_z at (58.5°S, 51.2°E) obtained on October 21 1989 at 19:31 UT (Zadorozhni et al, 1994). The dashed curve shows the profile of the spatial charge density ρ.*

An explanation is given here of the creation of a negative layer L_N. During time a period well preceding t_{EXP} process *P2* causes a gradual decrease of conductivity σ in region R_p situated above z_0~35 km and at geomagnetic latitudes above Λ_p~60° corresponding to major geomagnetic storm with Kp=8 (*Rodger et al., 2006*). We accept that conductivity σ below ~35 km remains unaffected by process *P2*. The profile of spatial charge density ρ in Fig.3 (the dashed curve) shows that the maximum effect of process *P2* on conductivity σ is at altitude z_m=58 km where σ reaches its minimum σ_{min} in the modified conductivity profile. This determines negative conductivity gradient, $d\sigma/dz < 0$, in layer L= [z_0=36 km, z_m=58 km], and accumulation of negative spatial charge by downward electric current $\mathbf{J}_{HL}$. We accept that current J_{Sz} is identical to its vertical component: $J_{Sz} \equiv J_{HLz}$.

During accumulation of negative charge in layer L_N the following expression is valid:

$$|J_{HLz}\,(z=z_0)| = |J_{HLz}\,(z=z_m)| - dq_c(t)\,/dt > |J_{HLz}\,(z=z_m)|, \tag{4}$$

since $dq_c(t)\,/dt$ <0. This demonstrates that at altitudes below z_0=35 km the electric current J_{Sz}, hence the total current J_z (1), have significant increase during the formation of layer L_N, if the formation of layer L_N follows that of L_{PU}. The result is redirection of $\mathbf{J}_{HL}$ into downward electric current $J_{Sz}=J_{HLz}$ at time t_v which leads to enhancement of current J_z by addition of term J_{Sz} in (1) at altitudes $z<z_0$=35 km and amplification of J_{Sz} according to (4). This gives an explanation of the peculiar enhancement of the electric current J_z and field E_z in each of cases *S1,2, G1,2* considered here. These are not transient variations since their duration is much larger than the relaxation time of GEC ~500 s (*Rycoft et al., 2008*).

The explanation proposed here concerns the peculiarity in the variations of electric characteristics discussed above, as well as the creation of the layer L_N with negative spatial charge in Fig.3 (*Zadorozhni et al., 1994*). The time of accumulation of spatial charge in layer

L_N is much before the rocket launch at t_{EXP}. Similarly, the formation of the upper positive layer L_{PU} is explained by the downward current J_{HLz} along decreasing conductivity σ which is the case in Fig.3 above altitude z_m=58 km. Possibly, the lower positive layer L_{PL} is created after layers L_{PU}, L_N as result of gradual degradation of layer L_N well after time t_r.

Conclusions

- An additional electric circuit is created in GEC during four considered SPE/GLE with significant vertical component in middle stratosphere, and at surface, at high latitudes.
- For explanation of this peculiarity a hypothetic mechanism is proposed which is consistent with the peculiar experimental rocket-borne data of the profile of electric field E_z on high geomagnetic latitude during SPE/GLE October 19 1989.

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