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Peculiar Atmospheric Electric Field Response at High Latitude to Three Major SEP Events in 2001 and Possible Interpretation

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Abstract.

The results are analyzed here from measurements of the atmospheric electric field (AEF) E_z at ground level which had been obtained at high-latitude observatory in Apatity (geomagnetic latitude 63.8°) during three major solar proton events (SPE) with GLE in 2001 (on 15.04, 18.04, and 04.11, respectively). We find strong AEF peculiarities and propose a hypothetical interpretation for them. For each of the SPE E_z demonstrates specific extremely large and unusual variations in two separate time periods: a) during SPE; and b) before the SPE and its causative solar flare. The AEF behaviour cannot be explained by classical theory for the global atmospheric electrical circuit. To interpret the peculiarities we propose hypothetically that the energetic proton flux into atmosphere at polar and high latitudes leads to creation and enlargement of aerosol layers and dramatic decrease of conductivity which causes re-balance in the global electric circuit and to the observed peculiar modifications of E_z at ground level at high latitudes. E_z peculiarities before SPEs can be explained in similar way.

Keywords: *Aerosol creation; conductivity modification; uncompensated electric charge*.

1. Introduction

Our goal in this paper is to consider and hypothetically interpret the effects during three major solar proton events (SPEs) in 2001 accompanied by ground level enhancement (GLE) on the vertical atmospheric electrical field (AEF) E_z at ground level at high latitudes, derived from experimental measurements in Apatity, Russia (geomagnetic latitude Λ=63.8°) [Shumilov et al. (2015)]. The experimental results for AEF E_z have been obtained for SPEs on 15 April (case 1), 18 April (case 2), and 4 November (case 3), respectively. Variations of the electric field E_z demonstrate peculiarities of several types which occur during SPE, but also can are found long before SPE. The experimental data [Shumilov et al. (2015)] are analyzed. Peculiarities during and before SPE are classified in Sections 2 and 4, respectively. Hypothetical interpretations for these two time periods are proposed in Sections 3 and 4.

2. Analysis of experimental data [Shumilov et al. (2015)] during SPE

The results of [Shumilov et al. (2015)] are presented in Figure 1 for each case 1–3. The uppermost panel presents the E_z variations during the entire day of the SPE. The middle panel is for X-ray variations according to GOES-10 data in ranges 0.1–0.8 nm and 0.05–0.4 nm (curves 1 and 2). The lower panel shows the integral fluxes, derived from GOES-10 data, of: *i*) E>2 MeV electrons (curve 1); *ii*) protons with energies E>1 MeV, >10 MeV and >100 MeV (curves 2-4, respectively). Surprising peculiarities in variations of AEF E_z take place which comprise two separate time periods:

- Time period (***A***) when the energetic proton flux is sufficiently high. It is characterized by strong deviations of AEF E_z from its usual behavior, as response to SPE.
- Time period (***B***) **b**efore (***A***): it precedes the SPE onset and the related solar flare and can start several hours before the flare). Unusual and extremely big E_z oscillations can be observed during period (***B***). No obvious agent of sun-earth links presents in this case.

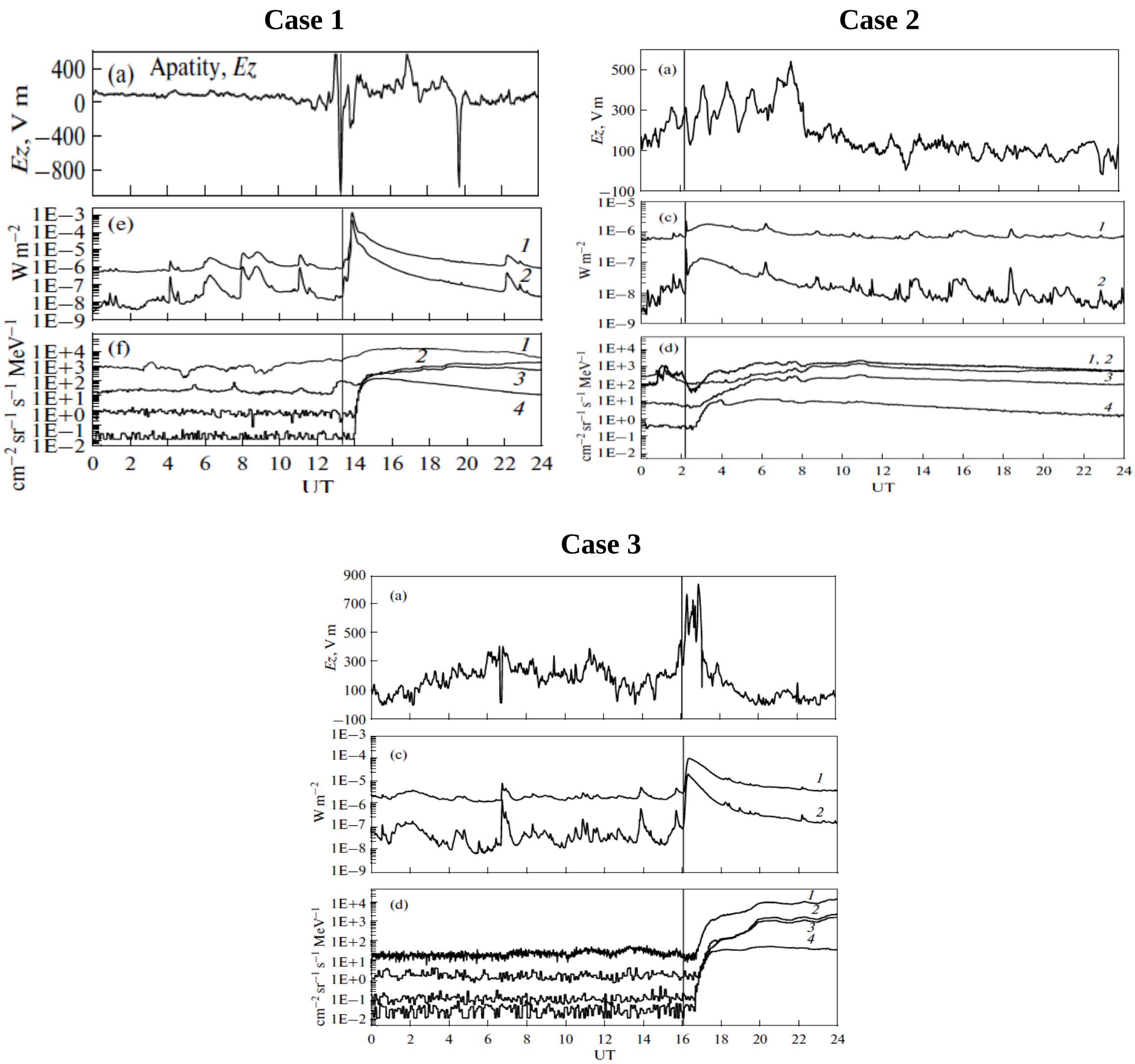

***Figure 1**. Results from measurements in Apatity of AEF E_z response to three SPE/GLE in 2001: on 15.04 (case 1); 18.04 (case 2); and on 04.11 (case 3). For each case variations of E_z are presented in panels (a) (E_z >0 corresponds to downward Ez orientation). Panels (b) show X-ray variations in ranges 1–8 Å (curve 1) and 0.5–4 Å (curve 2). Panels (c) are for integral fluxes of E>2 MeV electrons (curve 1), and protons of energies E>1 MeV, E>10 MeV, and E>100 MeV (curves 2-4, respectively) from GOES-10 data) [Shumilov et al., 2016].*

During time period (***A***) (**a**fter the SPE onset) the following main peculiarities take place:

1. There are two separate phases of E_z variations which approximately correspond to the rise and decay phases of SPE: 1) During its first phase E_z is positive (downward) and has unusually large and fast variations; 2) On the second phase E_z reaches much smaller positive peaks, but can have reversals to upward direction with unusually high peaks reached.

2. During the first phase of SPE AEF Ez reaches extremely large (several times bigger than the usual ones) and persisting (indication for non-transient variations) positive values.

i) In case 1 (15 April): a) soon after the onset of SPE at ~1400 UT AEF E_z reaches a double peak larger than 300 V/m; b) at ~1650 UT E_z rises above 600 V/m. Large E_z peaks persist for more than half an hour, thus indicating for non-transient variations.

ii) In case 2 (18 April) E_z has four separate peaks close to or larger than 400 V/m before reaching its mean peak, E_{zp}>500 V/m.

iii) In specific case 3 (4 November) AEF E_z reaches two large peaks on the first phase: ~400 V/m and ~300 V/m at 1700 and 1750 UT, respectively.

3. On the second phase of AEF variations E_z can reverse to upwards (E_z<0) and reach extremely large negative values. The following peculiarities are observed:

i) In case 1 the second phase begins at ~1730 UT. E_z becomes upward for ~20 minutes (seemingly, non-transient variation) and reaches a negative peak value −1 kV/m at 1945 UT;

ii) In case 2 the second phase begins close after 0800 UT. Close before midnight E_z has small transient reversal to upward direction;

iii) In case 3 the second phase begins after 1800 UT; E_z exhibits a series of reversals.

3. Possible hypothetical interpretation of peculiarities

According to classical theory of the global atmospheric electrical circuit (GEC) [Rycroft, 2012], AEF in cases 1-3 should be oriented downwards and should not exceed 150-200 V/m, since no local thunderstorm activity or electrified clouds take place. But actually, E_z large variations and E_z reversals strongly impair these theoretical limitations. The enumerated peculiarities do not seem to be result of local factors. On the other hand, SPE can affect parameters of GEC, schematically represented in Figure 2, due to ionization at polar and high latitudes which leads to modification of conductivity σ. Significant effect of SPE on conductivity at these latitudes takes place only above about 20-30 km, so that only the partial columnar resistance $r_{PH} = r_{PS} + r_{PM} + r_{PA}$ (Figure 2) can be affected. However, since $r_{P2} << r_P$, the r_{P2} change would affect the total resistance $r_P = r_{PT} + r_{PH}$ negligibly; also, modification of E_z can be up to 5% [Farrell and Desch, 2002].

To resolve the discrepancy between experimental data and theory we propose hypothetic generalized picture of physical processes excited during SPE which can have much stronger effects on AEF at polar and high latitudes than the predicted by [Farrell and Desch, 2002]. Two principal processes are considered: *i*) accumulation of large uncompensated electric charge (UC) in GEC; *ii*) dramatic decrease of conductivity in specific layers above ~40 km caused by: *a*) creation and growth of aerosol particles (AP), *b*) transportation of ions and charged APs caused by electric fields. Process *i*) is result of penetration of protons into atmosphere. The elementary positive charges, thus injected into atmosphere, cannot leave back to the magnetosphere because of the insufficient energy of their carriers after protons' energy loss. The total positive UC accumulated in atmosphere during a strong SPE can be significantly larger than the total electric charge in GEC [Tonev, 2021]. Additional electric fields and currents can be generated in GEC due to UC redistribution which can play role in *b*) and can explain the peculiarities in AEF at ground level. Processes *i*) and *ii*) occur in specific atmospheric layers at polar and high latitudes simultaneously with, and stimulated by the enhanced ionization during SPE.

The hypothetical assumption for strong decrease of conductivity σ in specific atmospheric layers above ~40 km during SPE is supported by experimental measurements. An evidence for severe drop of σ in layer L_S 45-57 km at high geomagnetic latitudes is demonstrated on the base of rocket-borne measurement data for the profile of vertical electric field E_z in strato/mesosphere at a late phase (54.5 hours from the onset) of the major SPE from 19 October 1989 [Zadorozhni and Tyutin, 1998]. The conductivity σ in layer L_S is estimated to be of the order of magnitude as low as ~10^{-15} S/m [Tonev, 2021]. Such decrease of σ in layer L_S determines that $r_{??} >> r_T$, and thus, significant increase of the total columnar resistance *r*. [Zadorozhni, 2001] consider the formation of aerosol particles to explain the decrease of σ.

[Holzworth and Goldberg, 2004] found from rocket-borne data in a noctilucent cloud around ~81 km altitude in noctilucent clouds in mesopause unusually large vertical electric field E_z which indicates for extremely low conductivity there (4×10^{-12} S/m). They assumed

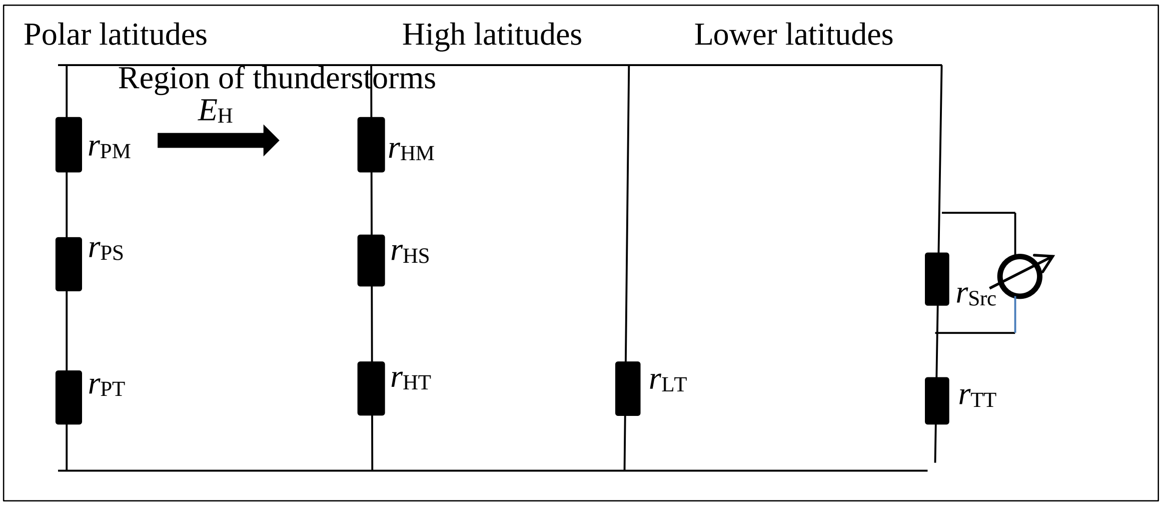

***Figure 2**. Equivalent GEC during SPE. Vertical links are for polar, high, and lower latitudes; and region of troposphere electric activity. r_* are partial columnar resistances with first index P/H/L for latitude, and second index T/S/M for troposphere/ strato- and mesosphere. SPE can lead initially to increase of r_{PM} to value $>r_{PT}$, and next to increase of r_{HM}, r_{PS}, and r_{HS}.*

that this decrease is caused by aerosol particles readily created in summer mesopause where ice crystals play role of nuclei. [Shumilov et al., 1996; Mironova and Usoskin, 2014] find experimentally appearance of aerosol particles in stratosphere after (tens of hours) SPE.

We assume that at initial phase of SPE creation and growth of APs is intensified gradually in an atmospheric layer L_{AP} at polar latitudes where the processes *i*) and *ii*) are active. Layer L_{AP} is initially presented mainly by the polar mesopause. Formation of an AP originates from a cosmic dust particle or a water ice crystal playing role of nuclei. Creation of an AP is determined mainly by the coefficients of attachment β_* to it of smaller particles of different type: neutral molecules (β_{nir}), electrons (β_{eir}), positive and negative ions ($\beta_{\pm ir}$), and larger particles (neutral or carrying electrical charge). These coefficients depend on the AP's size determined by the AP's radius *r*, and on the number of elementary electric charges *i* carried by AP (*i*>0 if charges are positive, and vice-versa; *i*=0 for neutral AP), $-m\leq i\leq m$ where *m* is the maximum number of charges carried by AP. *m* depends on the AP's size; we accept that *m* increases proportionally with the surface of AP, i.e. with r^2. Further, we hypothesize that in layer L_{AP} the attachment coefficients β_* significantly increases during SPE under the applied electric field E_H (Figure 2) which causes the initial slow growth of APs. By neglecting the detachment from APs we assume stable APs whose life is from many hours to few days: usually longer than the time period of interest of processes *i*), *ii*). Also, the gravitational sedimentation of APs is slow and can be neglected. We describe approximately further growth of an AP with time *t* by the equation:

$$dV_{AP}/dt = \gamma_0 S_{AP} \tag{1}$$

Here V_{AP} is the AP volume, S_{AP} is its surface, γ_0=const. According to Eq.(1), the attachment rate (cross-section) of a particle (molecule or ion) is proportional to the area of the AP's surface. By assumption for spherical AP we have $S_{AP} \sim 4\pi r^2$, $V_{AP} \sim 4/3\pi r^3$ where *r* is the AP's radius. In this case Eq.(1) is represented as an ordinary differential equation for *r* (here *r* is function of time *t*). Its solution yields linear increase of the AP radius *r* with time *t*:

$$r \propto t, \tag{2}$$

Then, the attachment coefficients will increase as t^2:

$$\beta_* \propto t^2, \tag{3}$$

and the increase of the AP mass m_{AP} will be as t^3. These simplest estimations concern neutral APs. If take into account the number i of its electric charges and its increase at least with r^2, as well as the fact that the AP and the smaller ionized particles are polarized in the applied electric field E_H, the increase of parameters r, β_*, m_{AP} will be faster, at least, according to:

$$r \propto t^2, \qquad \beta_* \propto t^4, \qquad m_{AP} \propto t^6 \tag{4}$$

under assumption that two polarized particles attach easier to each other. These estimations show that AP grows ever faster with time according to a strong positive feedback. Hence, we hypothesize that the density and average size of APs can increase enough in few hours during SPE in order to realize bite-outs of small ionized particles. In this case the time for attachment of electrons and ions to APs is quite short because of large coefficients β_*.

With the account of ionized APs the total conductivity σ is:

$$\sigma = \sigma_e + \sigma_+ + \sigma_- + \sum_{j=r_1}^{r_2} \sum_{i=-m}^{m} \sigma_{Aij} \tag{5}$$

Here σ_e, σ_+, and σ_- are conductivities of free electrons, and positive and negative ions. σ_{Aij} is conductivity of aerosol particles of (i,j) type where index j corresponds to the AP's radius r when it varies from r_1 to r_2; i shows the sign and number of elementary charges carried by the AP. The conductivity σ_s of charged particles of any type in Eq.(5) is represented in the form $\sigma_s = q_s \mu_s N_s$ where q_s is the amount of elementary charges carried, μ_s is the mobility of the particle reciprocal to its mass m_s, N_s is the particle number density. We note that the last term in Eq.(1) will be negligible under quiet conditions (without SPE) since the large mass of APs which determines their actual immobility (μ_s~0), as well as their low density. However, during SPE first three conductivities σ_e, σ_+, σ_- in (5) in layer L_{AP} can undergo dramatic decrease as result of decrease of their densities N_e, $N_\pm$, as predicted above, so that the total conductivity σ can drop to values many orders of magnitude smaller than usually: the relative absence of small ions and the large AP mass determine extremely low σ. As result of the drastic drop of σ the resistance r in GEC (Figure 2) can increase sufficiently to become dominant in the total columnar resistance r_P. In such case downward electric field E_A and current J_A in atmosphere below layer L_{AP} will be generated by the positive UC accumulated in L_{AP}. The AEF E_z below layer L_{AP} will be:

$$E_z = E_{z0} + E_A > E_{z0} \tag{6}$$

where E_{z0} is the electric field under quiet conditions. This case corresponds to the first phase of AEF variations considered in Section 2 and explains it. During the second phase of declining SPE there are periods when conductivity σ in layer L_{AP} recovers to larger values which leads to fast drop of resistance $r_{HM} + r_{HS}$. This causes rearrangement of atmospheric spatial charges and of electric currents. This can yield reversals of the electric field E_A at ground level to large enough negative values to obtain upward total electric field E_z.

Another effect of SPE considered here is the gradual extension of layer L_{AP}, controlled by electric field E_H, to lower latitudes (i.e. it comprises high latitudes besides polar latitudes). The result is generation of an additional electric field E_A also at these lower latitudes, and validity of the upper conclusions for variations of the total AEF E_z.

4. Analysis of AEF variations before SPE

Main peculiarities of AEF E_z in time period ***B*** are extremely large and unusual E_z fast oscillations with AEF reversals to upward direction ($E_z < 0$). In case 1 E_z oscillates from 1300 UT until 1410 UT between extremely large positive ($E_z > 600$ V/m) and negative ($E_z \sim -1.1$ kV/m) values. In case 2 E_z oscillations are smaller, between 100 and 320 V/m, one hour before the solar flare. In case 3 E_z oscillations have large amplitude between +100 and +850 V/m, and occur from 1600 UT (solar flare time) until 1705 UT (before the proton flux rise). We also note the significant X-ray variations, especially in cases 1 and 3 which, in general, may be an indicator for unknown processes on sun preceding solar flare and affecting earth.

These peculiarities cannot be explained by theory of GEC. They resemble those during SPE, however E_z multiple fast oscillations are typical for time period ***B*** with larger amplitudes (>1 kV/m). They can be interpreted as conducted by similar mechanism, as the described one n Section 3 for time period ***A***, but under assumption that energetic electron precipitation takes part at polar latitudes. The proposed mechanisms for both ***A*** and ***B*** time periods are subject of our future publications.

Conclusions:

- Atmospheric electric field E_z at geomagnetic latitude 63.8° (Apatity) during three GLE in 2001 (on 15.04, 18.04, and 04.11) show peculiar variations during solar proton event (SPE), as well as in long time period before SPE.
- During SPE two phases of typical AEF behavior are discriminated: *i*) in first one E_z is downward and reaches unusually large (600 V/m) peaks; *ii*) in the second phase AEF E_z can have alternating direction with extremely large (~ −1 kV/m) upward peaks;
- AEF peculiar modifications during SPE are hypothetically interpreted as result of accumulation of uncompensated electric charge in the polar and high-latitude atmosphere, and of creation, growth, and charging of aerosol particles, and their transportation, together with extreme increase of the average mass of charge carriers.
- Before SPE E_z demonstrates big oscillations which hypothetically can be result of EEP.

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