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GROUND-LEVEL MODIFICATIONS IN GLOBAL ATMOSPHERIC ELECTRICAL CIRCUIT DURING SOLAR PROTON EVENTS

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Abstract: *Large modifications in global atmospheric electrical circuit (GEC) are observed during major solar proton events (SPE), namely, experimentally measured variations of the potential difference (or atmospheric electric field, AEF) Ez at surface both at high and low latitudes. AEF E_z at high latitudes shows unexplained large variations: |Ez| can be as high as ~1 kV/m, yet E_z can untypically change its direction from downwards to upwards for time larger than the relaxation time in GEC. At low latitudes significant variations of AEF (10% and more) are also observed. There is typical mutual dependence between E_z variations at both latitudes: at high latitudes E_z exceeds its average value at the first phase of SPE and becomes smaller in the second phase; at low latitudes the reverse relations take place. Such behavior of AEF E_z cannot be explained only as result of enhanced ionization during SPE leading to conductivity changes in high-latitude middle atmosphere. We consider the role of SEP particles in formation of additional electric currents and fields in GEC. To clarify the role of this factor, 1D modeling is performed based on the continuity equation for the Maxwell current. Initial results show that the role in GEC of the penetrating solar proton flux is considerable.*

НАЗЕМНИ МОДИФИКАЦИИ В ГЛОБАЛНАТА ЕЛЕКТРИЧЕСКА ВЕРИГА ПО ВРЕМЕ НА СЛЪНЧЕВИ ПРОТОННИ СЪБИТИЯ

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Резюме: *По време на големи слънчеви протонни събития (СПС) експериментално са наблюдавани големи модификации в глобалната атмосферна електрическа верига (ГЕВ), изразени в чатност, чрез вариации на потенциалната разлика (или атмосферно електрическо поле, АЕП) E_z на нивото на земята както на високи, така и на ниски географски ширини. АЕП E_z на високи ширини имо необяснени големи вариации до ~1 kV/m, а също може да сменя направлението си в насочено нагоре, за време, по-голямо от времето на релакция в ГЕК. На ниски ширини също са наблюдавани значителни (над 10%) модификации на АЕП. Има взаимна зависимост между вариациите на АЕП E_z на двете ширини: на високи ширини E_z първо значително превишава средното си значение преди СПС, а след това става по-малко от него, а на ниски ширини става обратното. Това поведение на АЕП E_z не може да се обясни само като резултат на усилената йонизация от СПС, водеща до изменения на проводимостта в средната атмосфера на високи ширини. Ние изследваме ролята на частиците от SEP при формирането на добавъчни електрически токове и полета в ГЕВ. За да се изясни ролята на този фактор, предложен е 1D модел базран върху уравнението на непрекъснатост за пълния ток. Първите резултати показват, че ролята в ГЕВ на потока слънчеви протони е значителна.*

Consideration of observations

First, we consider observations of atmospheric electric fields E_z at surface ($z = 0$) done at high latitudes in periods of major solar proton events (SPE) of GLE type. Observations are used here of atmospheric electric field (AEF) E_z at surface ($z = 0$) performed in Apatity, Russia, (67.3°N, 33.2°E) at geomagnetic latitude 63.8° during three SPE in 2001, namely on: *i*) 15.04, *ii*) 18.04 (Fig. 1), and *iii*) 04.11 [1]. For this events the maximum proton flux > 1 MeV is 1.4×10^3 for *i*), 1.5×10^3 for *ii*) и 2.3×10^3 for *iii*) [particles/cm^2/ster/s], according to GOES-10 data. The time period of principal rise of the solar proton flux is 20–40 minutes, although its very maximum may be reached up to 10 hours after the SPE arrival. Data from measurements show unusually large variations of AEF E_z with typical features which are more pronounced for last two events, *ii*) and *iii*). Fig.1. shows E_z variations in case *ii*). Two different phases are distinguished. In the first phase (resp., ~8 and ~2.5 hours from the SPE onset) the average AEF E_{za} is much bigger than the average E_z before the SPE arrival; also, E_z demonstrates large and fast jumps between its minimum and maximum values (from 120 to 540 V/m for SPE *ii*, and from 115 to 840 V/m for SPE *iii*). In the second phase jumps between E_z minimums and maximums are large, as well (from −20 to 160–170 V/m for these both SPEs), however the average value E_{za} is much smaller than before SPEs. Another peculiarity in the second phase is that sometimes AEF changes its direction from a downward (which is typical in fair-weather regions) to an upward (E_z becomes negative) for a time period which can be longer than the relaxation time constant for GEC (7 min). For SPE *i*) (15.04.2001) [1] similarly AEF E_z reaches untypically large positive ~+600 V/m in its first phase and large negative ~– 900 V/m values in the second phase. However, in this SPE an extra peculiarity occurs: before the SPE arrival E_z initially rapidly increases to 500 V/m, then abruptly jumps to extremely large negative value of −1 kV/m.

It should be noted that some similarity exists between the discussed peculiarities for AEF E_z with variations of the vertical electric current J_z in Antarctic stratosphere (at ~32 km altitude) observed at a balloon platform during GLE on 20.01.2005 [2, 3]. For this last event J_z is directed downwards, as usual, however, much larger than its pre-SPE average value J_{za} during initial 5 hours, in spite of the large increase of conductivity. In contrary, during the last eight hours of SPE J_z reverses to upward, yet has large value: $|J_z| > 2J_{za}$.

A series of measurements of AEF E_z during SPEs (with GLE) have been performed at low latitudes, as well: at CASLEO, Argentina (31.8°S, 69.3°W), 2552 m altitude a.s.l. [4]. Typical features, which differ in the first and succeeding periods of SPEs can be observed at these latitudes, as well, however they differ from those observed at high latitudes, when compare AEF Ez with its average value E_{za} found for quiet conditions. A typical example is for SPE on 17 May 2012. Fig. 2 shows time variations of E_z (pure line) and E_{za} (line with confidential intervals added). At the first phase (for more than 3 hours after SPE arrival) E_z is significantly (up to 17%) smaller than E_{za}. During succeeding >6 hours considerable increase (up to 38 %) of E_z occurs above the average E_{za}. Statistical analysis of eight major SPEs have shown that thus demonstrated features are common for measurements in CASLEO [4].

It is thus demonstrated that the variations of Ez around its average E_{za} are of opposite sign at high and at low latitudes: while at initial phase of SPEs $E_z \gg E_{za}$ at high latitudes, and $E_z < E_{za}$, at low latitudes, in a later phase $E_z \ll E_{za}$ at high, and $E_z > E_{za}$, at low latitudes.

Finally, for a comparative analysis, we consider respective results at middle latitudes. Variations of AEF E_z at sea level during SPE on 11 April 2013 from measurements performed in Reading, United Kingdom (51.45°N, 0.97°W) are commented [5]. It is useful to note, for our goals, the peculiar effect which has occurred within a period of 10 minutes with the arrival of SPE: AEF E_z has changed three times its direction from the typical downward to upward; each time it has reached ~−200 V/m - much larger than its average before SPE.

Further we propose 1D modeling based on an ‘equivalent electric circuit’ in order to clarify the discussed peculiar effects of variations of AEF E_z during SPE when extra electric currents are formed in GEC. It should be noted that the previous models [7] cannot predict such variations in GEC.

1D model representation of GEC during SPE

We represent GEC in a single hemisphere (under assumption for ‘symmetry between hemispheres’) by an ‘equivalent electric circuit’ (Fig. 3) under quasi-static conditions with account of the capacitive atmosphere. Here three links for electric currents between the well conducting ionosphere at $z = Z_I = 80$ km (upper horizontal line) and earth (lower horizontal line) are included. These represent regions of: a) thunderstorms which generate current into the ionosphere (R_{TS}); b) fair-weather regions at all sub-high geomagnetic latitudes < 65° (R_{LL}); c) fair-weather regions at high latitudes > 65° (R_{HL}). Each region R is characterized by a its own profile of conductivity $\sigma_R(z)$, $0 < z < 80$ km. These profiles are adopted from [6] for R_{LL} and R_{TS} and from [3] for R_{TS} for SPE conditions. The source continuity equation $\nabla\cdot(\mathbf{J} + \mathbf{J}_{Src}) = 0$ is used, where **J** is the Maxwell current density, $\mathbf{J}_{Src}$ is the common electric current source of from the tropospheric electric generators (J_{TSrc}= const), and that created by SPE (J_{PSrc}). This source equation leads to the following system of three equations in 1D presentation, for each region R_{TS}, R_{LL}, and R_{HL} (respective characteristics are noted in italics):

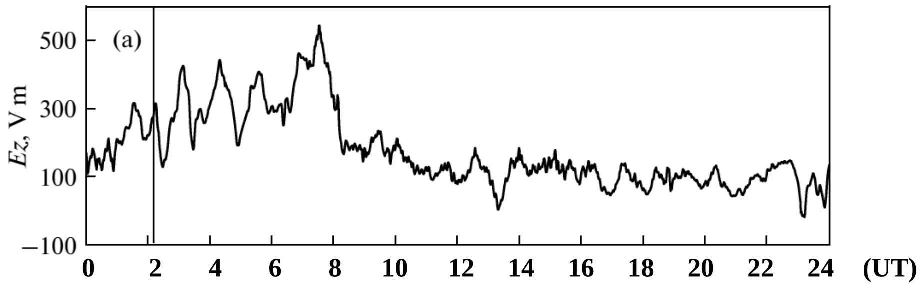

Fig. 1. Atmospheric electric field E_z in Apatity (67.3°N, 33.2°E) during SPE (*ii*) on 18.04.2001

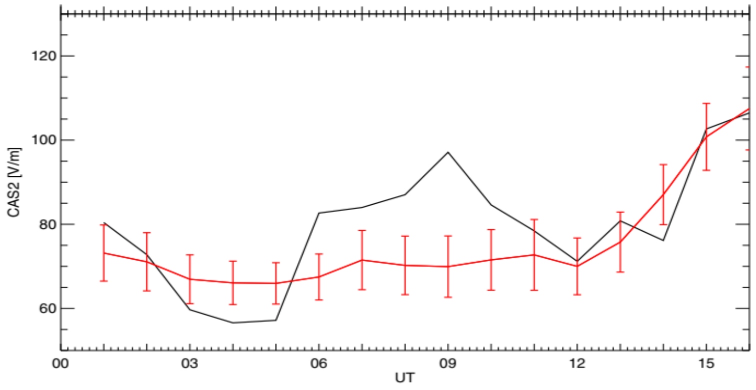

Fig. 2. AEF E_z in CASLEO (31.8°S, 69.3°W) during SPE on 17.05.2012 (pure line) compared with the average AEF E_{za} (line with hourly error bars of one standard deviation added)

(1) $$d(\sigma_R E_R)/dz + \varepsilon_0 (d^2 E_R/dz\,dt) = dJ_{R\,Src}/dz \ ,$$

where the index R relates to region *R*, $J_{RSrc}(z,t)$ – source current in region *R*. The system (1) of equations for R_{TS}, R_{LL} and R_{HL} is solved under conditions:

(2) $$J_{TS}(t, z{=}0) + J_{LL}(t, z{=}0) + J_{HL}(t, z{=}0) = 0;$$

(3) $$V_{TS}(t) = V_{LL}(t) = V_{HL}(t) = V(t).$$

Here $J_R(t,z)$ is the total Maxwell current from ionosphere to surface, and $V_R(t)$ is the ionospheric-surface potential difference for *R*-th region. This last is computed as follows:

(4) $$V_R(t) = \int_0^{Z_B} J_R(t,z) / \left(\sigma_R(z) A_R\right) dz$$

$V_R(t)$ should be the same for each region *R*. We assume J_{TSrc} = *const* by time. The initial condition at $t = 0$ is given by the steady-state characteristics E_R, J_R before arrival of SPE when $J_{PSrc} = 0$. Each region *R* is characterized by a unified profile of atmospheric conductivity $\sigma_R(z)$. For region R_{HL} the profile $\sigma_{HL}(z)$ is adopted from [3] for conditions of SPE (GLE) on 20.01.2005. Conductivity profile of σ_{HL} of region R_{LL} is adopted from [6] for low latitudes, and $\sigma_{TS} = \sigma_{HL}$ above $z = Z_{CT} = 6.5$ km accepted as average cloud top altitude. Between the average cloud bottom altitude $Z_{CB} = 2.5$ km and Z_{CT} $\sigma_{TS} = \sigma_{HL}/3$ to take account of reduced conductivity in clouds. Below 2.5 km $\sigma_{TS} = 2\sigma_{HL}$, to present the role of lightning discharges.

Model results

For a estimation (in terms of our simplified model) of the GEC response to SPE in its initial period of the proton flux increase up to its maximum F_{max} in time t_{max} we accept rather simplified assumptions for the flux of protons of energies >1 MeV which penetrate to the upper model atmospheric boundary of 80 km averaged for region R_{HL}, and for the current density profile $J_p(t,z)$ by termalized protons below 80 km. The respective expressions are given below.

(5) $J_p(t,z) = q_e f_p(t,z) A_{HL}$

where q_e is elementary charge. $f_p(t,z)$ is assumed to be an exponential profile, as follows:

(6) $f_p(t,z) = C_p \exp(z/H_p)$

which is determined on the height interval between z_L= 25 km and z_U = 78 km from conditions:

a) The ratio $f_p(t,z_U)$ / $f_p(t,z_L)$ is equal to the average ratio between fluxes of protons of energies >1 MeV and > 100 MeV at model top boundary, z = 80 km.

b) The total proton flux $F(t)$ at time t (integrated over the height interval $[z_L,z_B]$) is assumed here (for simplicity) to be a linear function of time: $F(t) = F_{max}t/t_{max}$. We determine it here for $F_{max}=10^2$ $cm^{-2}s^{-1}$, t_{max}=20 min, to have accordance with events *i-iii* considered above.

The scale height H_p is determined from condition *a*) as $H_p= (z_U - z_L)/\ln [f_p(t,z_U)/f_p(t,z_L)]$. Here we accept that the ratio $f_p(t,z_U)/f_p(t,z_L)$ averaged by time is = 200, to have accordance with SPE *i*)-*iii*), and obtain H_p= 8.590 km. The constant C_p is determined from condition *b*) so that the flux f_p integrated by height to be equal to the total flux $F(t)$.

The first results from the model obtained with the proposed assumptions and parameters give the next estimations for the relative maximum change (RMC, in percent) of AEF E_z at surface at both high (RMC_H) and all lower (RMC_L) latitudes, for two values of F_{max}:

F_{max}, $cm^{-2}s^{-1}$	50	100
RMC_H, %	25.3	51.4
RMC_L, %	–2.6	–5.1

These values obtained with rather idealized assumptions show that in the first SPE period of increase of the proton flux AEF significantly increases at high latitudes, and has a decrease at lower latitudes which is about one order of magnitude smaller than at high latitudes, but, nevertheless, cannot be neglected. This estimation is in accordance by the type with AEF variations observed at both latitudes at the first SPE phase. The modeled variations are much smaller than the observed ones, possibly, due to oversimplification of the model. Nevertheless, the estimations are much closer than the predictions in [7].

Understanding the global GEC response to SPEs is important for clarification links between SPEs and weather formation revealed in [8].

Conclusions:

- Synchronism between variations of atmospheric electric field E_z observed during major solar proton events at high and low latitudes takes place. While in first case E_z has initially positive changes, and then negative, opposite sign of variations takes place in the second case.
- A simple 1D model of global electric circuit based on continuity equation for electric current density is proposed to explain variations of E_z.
- The first model estimations predicts the synchronism between E_z variations at high and low latitudes, but the magnitude of variations is smaller. Development of more adequate model may be needed in order to obtain better predictions.

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