HYPOTHETIC INTERPRETATION OF ATMOSPHERIC ELECTRIC FIELDS AND CURRENTS AT HIGH LATITUDES MEASURED DURING SEP

Peter Tonev

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

Keywords: *middle atmosphere electrodynamics, aerosols, atmospheric conductivity, spatial electric charges.*

Abstract: *The electric response in mesosphere, stratosphere and at ground level at high latitudes during major SEP events observed by experimental measurements during decades is characterized by systematically peculiar and extremely large variations of the electric fields and currents. The experimental case considered demonstrates vertical electric fields ~10 V/m in mesosphere at latitude 58.5°S during major SEP event began from 19 October 1989 and very strong geomagnetic storm (Kp reaches 8+) on 21 October (the experimental day). We show that the profile of vertical electric field indicates for severely reduced conductivity in the mesosphere and upper stratosphere, and for capability of generation of extra downward electric currents below the mesosphere during major SEP events. These last can give a key for explanation of the peculiar behavior of electric fields measured in the stratosphere at auroral latitudes during GLE69.*

ХИПОТЕТИЧНА ИНТЕРПРЕТАЦИЯ НА АТМОСФЕРНИТЕ ЕЛЕКТРИЧЕСКИ ПОЛЕТА И ТОКОВЕ НА ВИСОКИ ШИРИНИ ИЗМЕРЕНИ ПО ВРЕМЕ НА СЛЪНЧЕВИ ПРОТОННИ СЪБИТИЯ

Петър Тонев

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

Ключови думи: *електродинамика на средната атмосфера, аерозоли, атмосферна проводимост, пространствени електрически заряди.*

Резюме: *Електрическият отклик на големи слънчеви протонни събития (СПС) в мезосферата, стратосферата и на повърхността на високи ширини, наблюдаван чрез експериментални измервания в продължение на десетилетия, се характеризира системно със странни и екстремно високи вариации на елекрическите полета и токове. Разглежда се ракетен експеримент проведен на 21.10.1989 г. на географска ширина 58.5°S, в който по време на СПС с начало 19.10.1989 г. и силна геомагнитна буря (Kp достига 8+) е измерено вертикално електрическо поле Ez~10 V/m в мезосферата. Тук се показва, че профилът на Ez е индикатор за силно намалена проводимост в мезосферата и високата стратосфера, а също за възможността под мезосферата да се генерират допълнителни низходящи токове по време на големи СПС. Това може да даде обяснение за странното поведение на измерените в средната стратосфера електрически полета по време на СПС на 20.01.2005 г.*

Two experiments demonstrating effects of SEP on atmospheric electric characteristics

In this paper is given hypothetical explanation of the effects of major solar proton events (SPEs) on atmospheric electrical characteristics in different atmospheric regions (mesosphere, stratosphere, and at ground level) which have being experimentally observed during several decades. From these two experiments at high and auroral latitudes during strong SPEs are studied here: *i*) a rocket-borne measurements at latitude 58.5°S which yield profile of the vertical electric field E_z from 20 to 70 km [1]; and *ii*) a balloon-borne measurements in Antarctic middle stratosphere [2]. They demonstrate extremely strong and unusual electric response. A short description follows:

The rocket experiment. During SPE on 19-22 October 1989 at latitude 58.5°S over Southern Indian Ocean the profile of vertical electric field E_z has been obtained in a rocket experiment [1]. The experimental rocket flight is on 21 October at 19:31 UT when also strong geomagnetic storm takes place with planetary geomagnetic index Kp=8 at the time of flight (during this day Kp reaches 8+). The profile of E_z is shown in Fig.1 by thick line. E_z reaches extremely high values in mesosphere and upper stratosphere: E_z=+12.2 V/m at altitude z=58 km, and E_z= −9.7 V/m at z=46 km. A striking fact is also the change of sign of E_z: the electric field is upward above 50 km, and downward below that altitude. There is no satisfying explanation of these features. For comparison, by usual conductivities close to 50 km, 2 - 6 $\times 10^{-11}$ S/m, and by fair-weather current J_{fw}=−2 pA/m^2 Ez should be about −100 mV/m, i.e. at least by two orders of magnitude smaller, or even well below that value if conductivity σ is enhanced due to strong impact ionization during SPE. It should be noted that the E_z peak values $E_{z\text{peak}}$ found are the biggest ever measured in many tens or more similar rocket-borne experiments [1].

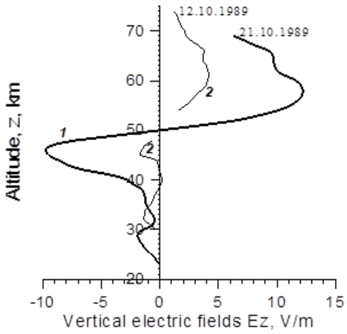

Fig. 1. Profile of vertical electric field E_z (curve 1) at latitude 58.5° (South Indian Ocean) on 21.10.1989, at 19:31 UT during major SPE (GLE event) and strong geomagnetic storm [1]

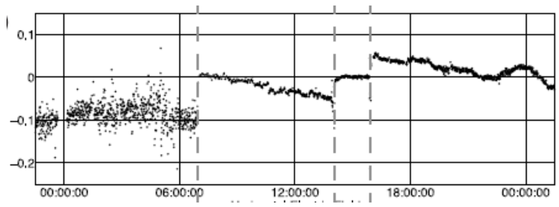

Fig. 2. Time variations of the vertical electric field E_z at 31-33 km altitude during GLE 69 [2]. Dashed vertical lines correspond to times: t_0=06:51 of SPE onset, t_1=14:00 UT, and t_2=15:54 UT.

The balloon-borne experiment. Measurements in Antarctic middle stratosphere (31-33 km) carried out on 20 January 2005 coincide with a SPE of very hard spectrum (GLE 69) [2]. Balloon coordinates change from (70.9°S, 10.9°W) to (71.4°S, 21.5°W) during the day. The geomagnetic conditions are: *i*) quiet from the SPE onset at t_0=06:51 UT until t_1=14:00 UT; *ii*) from 14:00 UT until the end of day the geomagnetic activity is increased; *iii*) after t_2=15:54 UT strong geomagnetic substorm takes place. Also, at times t_1 and t_2 the protons of energies <5 MeV have sudden increase, according to GOES-10 data for the proton flux (*Kokorowski et al.,* 2006). The observed variations of vertical electric field E_z are shown in Fig.2. For the first ~1.5 hours after t_0 E_z is close to zero. Then, until time t_1 E_z<0 becomes unusually large, so that the related current J_z exceeds the nominal fair-weather current J_{fw} more than three times. At time t_1 E_z has a jump to about zero and remains such until time t_2. At t_2 the electric field E_z has another sudden jump to large positive values such that J_z becomes well larger than J_{fw}, but now it is upward until the end of the day. These features remain unexplained.

Interpretation of rocket measurements

The stopping altitude z_{ps} of energetic protons entering the atmosphere depends approximately by logarithmic law on their initial energy E_p, as shown below:

E_p, MeV	0.3	1	5	10	30	50	100
z_{ps}, km	100	89	72	63	48	39	30

Any proton penetrating into the atmosphere injects an elementary positive charge q_e=1.6×10^{-19} C there which cannot abandon the atmosphere since their carriers have no sufficient energy to enter the magnetosphere. Thus, uncompensated positive spatial charges injected during SPE are being accumulated in the atmosphere. They remain uncompensated until precipitation of electrons of the same quantity which neutralize the atmosphere. Redistribution of these uncompensated positive charges within the atmosphere takes place before neutralization. If conductivity is undisturbed, these charges run upwards to the base of the magnetosphere (~150 km) and are being distributed evenly there, with no contribution to atmospheric electrical characteristics. However, we show here that this is not always the case, because of the strong disturbance of conductivity in middle atmosphere related to formation and growth of aerosol particles.

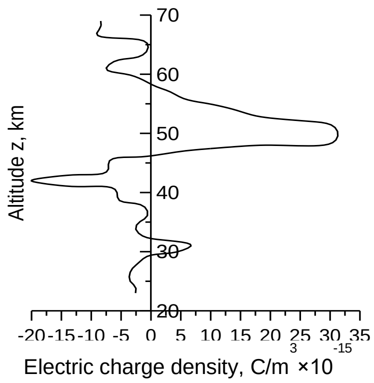

Fig. 3. Profile of the electric charge density ρ (z) derived from Ez profile by the use of Gauss's law

The specific E_z profile in Fig.1 indicates for presence of layers of positive, as well as negative spatial charges of large density ρ. These last are estimated here from the Gauss's law $\mathrm{div}\mathbf{E}=\rho/\varepsilon_0$, where **E** is the electric field, $\varepsilon_0=8.85\times10^{-12}$ F/m is permittivity. In $\mathrm{div}\mathbf{E}$ dE_z/dz is the only significant term, hence, the charge density ρ is determined as

$$(1) \qquad \rho = \varepsilon_0\, dE_z/dz.$$

Fig. 1b demonstrates the profile of ρ obtained from the profile of E_z shown in Fig.1a. Further, we analyze the main layer L_P of positive charge around 50 km and the columnar positive charge Q_{LP} in it. Layer L_P is hypothetically fed by uncompensated positive charges injected together with energetic protons during SPE. This layer is assumed to be in quasi-steady state at time of the experiment, since: i) any precipitations of protons or electrons from the magnetosphere ±1 hour to the launch time would not have contribution to L_P; *ii*) the decay of proton flux is slow for many hours before and after the experiment, only ~7% per hour, as follows from data for energetic proton flux obtained at GOES-7 [3]. Under quasi-steady conditions the conductivity in layer L_P satisfies the equation:

$$(2) \qquad Q_{LP}/t_R = J_{prot}\,,$$

where $J_{prot}(z) = q_e F_{prot}(z)$ is the source current into L_P formed by the newly injected uncompensated positive charges; $F_{prot}(z)$ is the flux of protons whose stopping altitude is z, and $t_R(z)$ is the charge relaxation time at z, $t_R(z) = \varepsilon_0/\sigma(z)$. The source current J_{prot} into the layer is obtained here from GOES-7 data for the energetic proton flux [3] assuming identity between proton flux at the top of atmosphere (~100 km) and that measured at GOES-7 (this assumption is used also by other authors). We take into account [4] which show that during strong geomagnetic storm with Kp = 8 all protons of energies >0.5 MeV enter the atmosphere at geomagnetic latitude Λ=–62.7° of the experiment.

With columnar charge density in layer L_P Q_{LP}~10^{-10} Cm^{-2} and J_{prot}~10^{-14} Am^{-2} from protons with stopping altitude in L_P, roughly estimated conductivity σ_{LP} at L_P (47-58 km) is:

$$(3) \qquad \sigma_{LP} = J_{prot}\varepsilon_0 / Q_{LP} \sim 10^{-15}\ \mathrm{S/m}$$

This is extremely low conductivity, but it is necessary to avoid fast relaxation of the charge Q_{LP}. Hypothetically, such low conductivity could realize in presence of aerosol particles, if their parameters, such as density and size, are suitable. Similarly, extreme reduction of conductivity, but in noctilucent clouds in summer mesopause, is determined in different experiments although without SPE. [5] show that SPEs produce aerosol particles in stratosphere.

The estimation of columnar resistance r_L of the layer L_P 47-58 km of thickness Δz=11 km yields $r_{LP} = \Delta z/\sigma_{LP} \sim 10^{19}\ \Omega m^2$ - more than one order of magnitude larger than the columnar resistance r_0 of the region 0 - 20 km. We should note that under quiet conditions only r_0 is significant.

These results demonstrate that the following structure of the electrical link in middle atmosphere at high and auroral latitudes has been formed during SPE with onset on 19 October 1989. Main layer L_P of positive spatial charge ~ ±5 km has been formed around the altitude z_B=50 km which is a boundary separating regions of upward vertical electric field E_z above z_B, and downward E_z below z_B. Layer L_P contains large uncompensated positive spatial electric charge Q_{LP} fed by the elementary charges of arriving protons which is relaxing through the electric currents J_U above z_B (upward), and J_L below z_B (downward). Another boundary z_{PN} above z_B separates layer L_P and an upper located layer L_N of induced negative spatial charge due to the conductivity gradient (here z_{PN}=58 km).

Electric currents J_U and J_D are superimposed to the downward fair-weather current J_{fw} which is ~2 pA.m^{-2} under quiet conditions, and during SPE is strongly diminished due to decreased conductivity σ_M in the middle atmosphere. The reduction of conductivity σ_M leads to increase of columnar resistances r_{PL} below altitude z_B of the region where conductivity is affected by aerosol particles, r_{PU} between boundaries z_B and z_{PN}, and r_N above z_{PN}.

Current $J_z = J_D + J_{fw}$ is of interest since it determines the electric field variations in stratosphere and down to surface, as well. At the time of the rocket experiment resistances r_{PL} and r_{PU} become extremely large, corresponding to the very late phase of SPE (54.5 hours from its onset). This determines that current J_D is very small. At earlier phases of SPE these resistances would be smaller, but yet large enough to affect current J_D which depends also on the charge Q_{LP}, and on separating boundary z_B which, at earlier phases, would be located at higher altitude.

Interpretation of balloon measurements on 20 January 2005

From time t_0=06:51 until 08:40 UT the electric field E_z is close to zero since resistances r_{PL}, r_{PU} and r_N are too small to affect it, and J_{fw} is reduced since σ is increased by 10-20 times. At time period t_1-t_2 the charge Q_{LP}, the resistances r_{PL} and r_{PU}, and current J_D enlarge, while $J_{fw} \ll J_D$. This determines large currents J_D and $J_z \sim J_D$. The jump of E_z from extremely large negative values to almost zero with the geomagnetic activity increase at time t_2=14:00 UT is possibly due to sudden enlargement of resistance $r_{PU} + r_N$. The second jump at t_3=15:56 UT (the substorm onset) is caused, possibly, by strong EEP which causes eventually a change of polarity of layer L_P and of current J_D.

Conclusion

- Extremely large electric fields (exceeding 10 V/m) observed in mesosphere at auroral latitudes during major SEP could be caused by development of aerosol layers and injection of uncompensated positive electric charge.
- Creation and growth of aerosol particles in mesosphere and upper stratosphere at high latitudes are driven by SEP; they cause dramatic decrease of conductivity and thus control the redistribution of uncompensated positive charges within the atmosphere.
- These processes determine effective electrical coupling between mesosphere and stratosphere at high latitudes which appears as consistency of electric field behavior in these regions.

References:

1. Zadorozhny, A. M., A. A. Tyutin (1998). Effects of geomagnetic activity on the mesospheric electric fields, Ann. Geophys. 16, 1544–1551, 1998.
2. Kokorowski, M., Sample, J.G., et al. (2006). Rapid fluctuations of stratospheric electric field following a solar energetic particle event, Geophys. Res. Lett., 33, L20105.
3. Marvin, D. C., D. J. Gorney. Solar Proton Events of 1989: Effects on Spacecraft Solar Arrays, Aerospace Report No. TR-0091(6945-01)-2, 1992.
4. Rodger, C. J., M. A. Clilverd, et al. Dynamic geomagnetic rigidity cutoff variations during asolar proton event, J. Geophys. Res., 111, A04222, 2006, doi:10.1029/2005JA011395.
5. Shumilov, O. I., E. A. Kasatkina, K. Henriksen, E. V. Vashenyuk (1996). Enhancement of stratospheric aerosols after solar proton event, Ann. Geophysicae 14, 1119–1123, 1996).