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HYPOTHETICAL MESOSPHERIC MODIFICATIONS DURING SEP EVENTS PROVIDING CONSISTENCY WITH ATMOSPHERIC ELECTRICAL RESPONSE

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Abstract: *The experimentally documented electrical response in stratosphere and at surface at high latitudes during major SEP events demonstrates significant inconsistency with theory of global atmospheric electrical circuit (GEC). In particular, such is represented by non-transient variations of the atmospheric electric field (AEF)* E_z *at surface with unusually large amplitude. These variations indicate for accumulation of spatial electric charges in specific atmospheric layers which could form electric currents superimposed to fair-weather current* J_z *in GEC. Such case can be caused by hypothetical (and paradoxical) occurrence of dramatic decrease of conductivity in these layers during SEP. A hypothetical mechanism of such conductivity modification at high latitudes in mesosphere and higher altitudes is proposed and discussed here as result of major SEP. This mechanism is based on creation and growth of multi-charged aerosol particles during SEP. Experimental evidence for dramatic decrease of conductivity in strato/mesosphere during major SEP is also demonstrated.*

ХИПОТЕТИЧНИ МЕЗОСФЕРНИ МОДИФИКАЦИИ ПРИ СЛЪНЧЕВИ ПРОТОННИ СЪБИТИЯ СЪГЛАСУВАНИ С ОТКЛИКА НА АТМОСФЕРНОТО ЕЛЕКТРИЧЕСТВО

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Ключови думи: *Аерозоли, атмосферна проводимост, пространствени електрически заряди, електрически ток при ясно време.*

Резюме: *Експериментално документираният електрически отклик в стратосферата и на земната повърхност на високи ширини по време на големи слънчеви протонни събития (СПС) демонстрира несъответствие с теорията на глобалната атмосферна електрическа верига (ГЕВ). По-специално, атмосферното електрическо поле Ez на повърхността при ясно време има нетранзиентни вариции с необичайно голяма амплитуда. Това показва, че има натрупване на пространствени заряди в опредерени атмосферни слоеве, които могат да предизвикат протичането на допълнителни електрически токове в ГЕВ. Подобен случай е възможно да възникне при парадоксално силно снижаване на проводимостта в тези слоеве. Предложен и дискутиран е хипотетичен механизъм за такава модификация на проводимостта в мезосферата и над нея на високи ширини, причинена от СПС, която се основава на образуването и растежа на електрозаредени аерозолни частици. Съществува експериментално доказателство, че по време на голямо СПС проводимостта в мезо/стратосферата може силно да намалее.*

Introduction

The response of the global atmospheric electrical circuit (GEC) to major solar proton events (SPE) has well expressed typical peculiarities which cannot be explained in terms of GEC theory. The accent in this paper is put on unusually large atmospheric electric field (AEF) E_z experimentally observed at surface at high latitudes which persists for long time period indicating for non-transient behavior. Such periods of excessive disturbance of the atmospheric electric field (AEF) E_z at ground level are met actually in all experiments during SPE/GLE (on its first phase) at high latitudes [1]. We consider hypothetical changes in upper atmosphere up to ~150 km caused by SPE which could lead to the observed response of GEC. We assume that uncompensated positive spatial electric charge (UC) is accumulated in mesosphere and above it at polar latitudes due to creation and growth of aerosol in these regions during SPE. Principal mechanism of processes is described below.

AEF behavior at high latitudes during SEP – an example of contradiction with theory

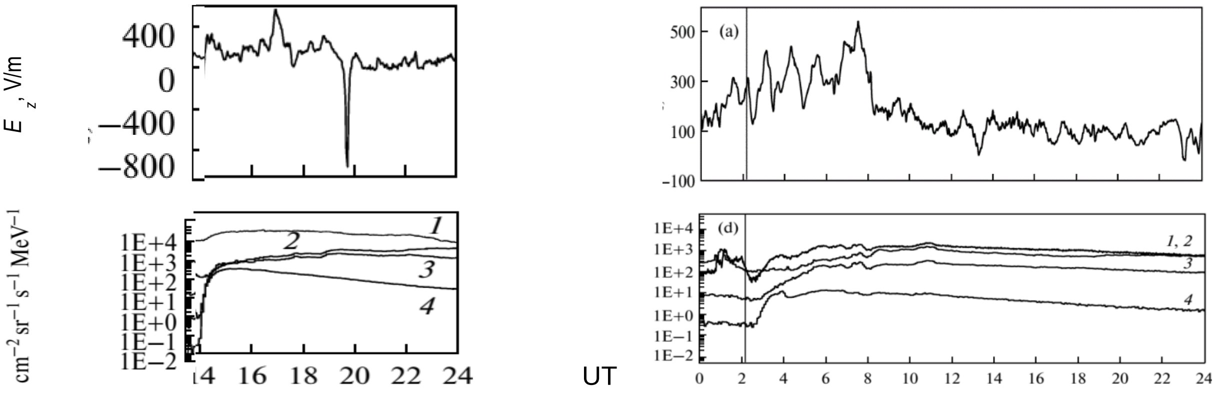
We study experimentally demonstrated peculiarities of variations of atmospheric electric field E_z at high latitudes (Apatity, Russia, geomagnetic latitude 63.3°) during major SPEs accompanied by ground level enhancement (SPE/GLE) obtained in [1]. Two cases of SPE/GLE are considered here, respectively, on: *a*) 15.04.2001; *b*) 18.04.2001. For these cases variations of AEF E_z at high latitudes obtained by Shumilov et al. (2016) are presented in Figs.1, 2 (upper panels), respectively. Lower panels show the integrated proton flux from GOES-10 data. AEF E_z reach unusually large values exceeding usual E_z values by several times for time intervals well longer than the relaxation time in GEC (τ_R~8 min). Such time intervals are: in (a) from 1630 until 1710 UT; in (b) from 02:20 to 0800 UT.

Therefore, the relative electric current J_z to the surface during these time intervals is not a result only of the inner source of GEC (thunderstorms and electrified clouds on the globe), but also an external source is needed. J_z can be represented as follows:

(1)

$$J_z = J_{FW} + J_{UC}$$

In Eq.(1) J_z is superposition of fair-weather current J_{FW} and an additional current J_{UC} which is caused by an outer source. We note that J_{UC} is not a result of ionospheric transpolar (dawn-to-dusk) potential difference - mapping of polar cap ionospheric potential distribution downwards to surface is ineffective.



(**a**) (**b**)

Fig. 1. AEF E_z measured at surface at high latitudes (Apatity, geomagnetic latitude 63.3°) during two SPE / GLE in 2001: on 15 April (**a**), and 18 April (**b**) [1]. Upper graphics show E_z variations during SPE. Lower ones are for integral fluxes of E>2 MeV electrons (curve 1) and protons of energies E>1 MeV, >10 MeV, and E>100 MeV (curves 2-4, respectively) from GOES-10 data.

Hypothetical assumptions [2, 3]

We assume that the outer source which generates the electric current J_{UC} is represented by uncompensated positive elementary electric charges (UC) injected into the atmosphere by solar protons where they can be accumulated within up to few hours or more (the time can be comparable to that of SPE). Electric current J_{UC} is a result of re-distribution (slow) of these charges in GEC in supporting global charge balance. The following requirements take place in our hypothesis:

1) For accumulation of large spatial uncompensated charge (UC) Q_{UC} at altitudes where energetic solar protons of different energies E>~0.2 MeV stop (mostly, in mesosphere and above up to 150 km at polar and high latitudes which could persist for about one or few hours. This can take place if the charge relaxation time $\tau_R=\varepsilon_0/\sigma$ is respectively large (ε_0 = 8.85x10^{-12} Fm^{-1} is the dielectric constant). This means that conductivity should be extremely low: σ~10^{-15} S/m. At first glance, this is a paradox:

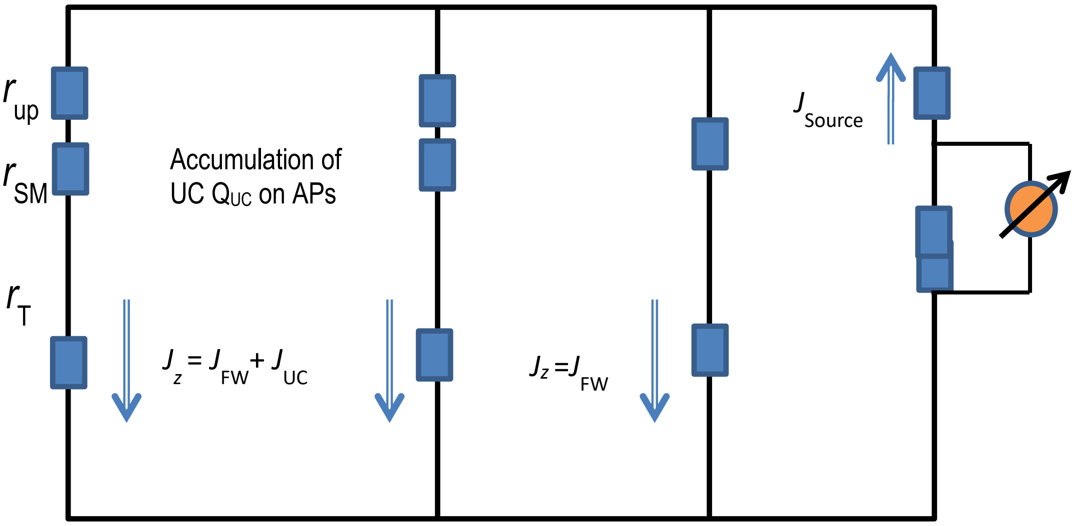


Fig. 3. Equivalent electrical circuit used. Vertical links 1 - 3 correspond to polar, high, and lower latitudes; 4 is for the region of tropospheric electric source to GEC. Columnar resistances r_T are for height interval 0 - 20 km; r_{SM} and r_{up} are for strato/mesosphere and higher, respectively. Usually r_{SM} and r_{up} are negligible compared with r_T; during SPE they can strongly increase with corresponding reciprocal decrease of σ due to formation and growth of aerosol particles and the accumulation of the spatial electric charges on them.

in mesosphere and above since conductivity σ exceeds 10^{-8} S/m under quiet conditions; yet, during SPE σ is expected to be even much larger due to enhanced ionization. Here we consider possible mechanism which explains dramatic decrease of conductivity during SPE with the key role of formation and growth of charged aerosol particles (AP). This assumption is indirectly supported experimentally: AP increase has been observed in stratosphere one day after SPE [4].

2) Gradual expansion of area of accumulated spatial charge Q_{UC} from polar to high latitudes will take place by electric current of positively charged aerosol particles J_{AP} driven by horizontal equator-ward electric field E_{AP} generated by UC Q_{UC}.

Qualitative study of hypothetical conductivity changes during SPE

AP is characterized by number k of charges carried by it: $k>0$ for positively, $k<0$ for negatively charged AP; $k=0$ for a neutral AP. Presence of APs under quiet conditions has been experimentally demonstrated []. In such case the total electric conductivity σ in these regions is:

$$\sigma = \sigma_e + \sigma_i^- + \sigma_i^+ + \sigma_{AP}^- + \sigma_{AP}^+ \tag{2}$$

Terms in right hand of Eq.(2) represent conductivities due to electrons, negative and positive ions, and negatively and positively charged aerosol particles, respectively. Conductivity of type m σ_m is $\sigma_m = q_m \mu_m n_m$ where μ_m is the mobility of respective particles, n_m is their density, and q_m is the mean electric charge carried by a particle. The mobility μ_m is reciprocal to the mean mass of the particles. The last two terms in Eq.(2) are usually negligible since the mass of an AP is much bigger than those of electrons and ions; yet, their density S is small. Above ~80 km the first term σ_e dominates over σ_i. We assume here that SPE causes creation and succeeding growth of APs to which elementary charges are transferred from electrons and ions by recombination and attachment. This transfer leads to a decrease of electron n_e and positive n_i^+ and negative n_i^- ion densities, hence to a decrease of first three terms in Eq.(2), and thus of total conductivity σ. We hypothesize further that SPE can cause a gradual increase of APs density S and their mass in mesosphere and above, and increased transfer of electric charges to APs as consequence leading to gradual decrease of the first three terms in Eq.(2). If they become comparable with last two terms, dramatic decrease of total conductivity σ is the result.

We consider principal way of realization such situation. [5] and other authors demonstrate presence of aerosol particles in summer mesopuse by quiet conditions in order to explain phenomena as noctilucent clouds (NLC) in mesopause at high latitudes, and polar mesospheric summer echoes (PMSE). In a rocket experiment [5] show dramatic (about five orders of magnitude) decrease of conductivity σ in NLC and assume presence of aerosol particles to explain related electron-ion density changes. Ice crystals in summer mesopause and cosmic dust can play role of nuclei used by APs.

Hence, structures of large density of multi-charged APs (regions R_{AP}) can exist in mesosphere before SPE onset. We show that SPE can initialize processes of aerosol multiplication and growth which start in (or close to) mesopause at polar latitudes from such structures, so that their characteristics determine dramatic diminishing of conductivity to similar values. Later during SPE these processes can be extended to alternative altitudes and lower latitudes, as well.

There is big variety of reactions between different particles (electrons, ions, neutral molecules, and APs - neutral or charged) when AP exist. While recombination, attachment, detachment between electrons, ions and neutral molecules and their parameters are described relatively well, reactions of small particles with APs and their rates are still not completely known: we note that these last parameters are function of many additional characteristics, such as the AP size and mass, as well as the number k and sign of elementary charges carried by it. These reactions are determinative for variations of electron and ion densities during SPE which are of main interest here. In order to examine the initial changes in a region R_{AP} we analyze the following equation for balance between densities of electrons, ions and APs written in its simplest form which is used for qualitative analysis:

(3) $$dn^{\pm}/dt = q - n^{+}\alpha_{eff}n^{-} - \beta_{e}n_{e} - (n^{\pm}\beta^{\pm}_{eff} + n\beta_{eff})S$$

This equation is for densities of positive ions n^{+} and n^{-} for electrons and negative ions. Here q is the ionization rate; for simplicity we assume that $q = const$ during the time period of interest; α_{eff} is the effective recombination rates of positive ions with both negative ions and electrons. S is the total density of aerosol particles; $\beta^{\pm}_{eff}$ is the effective coefficient of attachment of positive and negative ions to AP, and $\beta^{\pm}_{eff}$ is the effective coefficient of attachment. Each AP is characterized by its radius r_{AP} and also by number k of elementary electric charges carried by it: $k>0$ by positive charges; $k<0$ by negative charges, and $k=0$ corresponds to a neutral AP. The interplay between second and third terms in Eq.(3) is of key importance for variations of $n^{\pm}$ in our case.

It is important to note that initial conditions to Eq.(3) at the SPE onset t_0 strongly differ in dependence of the region in which Eq.(3) is considered. In a region R_{AP} the last terms is not negligible and it is significant for the type of solution, in contrast to other regions where this is not the case.

One should note that coefficients β_{eff} of attachment to APs are functions of AP parameters r and k. According to [6,7] in the upper stratosphere $\beta^{\pm}_{eff}$ depends linearly on the AP's radius r_{AP} for r_{AP} >10 nm which is usually the case in R_{AP}. Actually, for large enough r_{AP} $\beta^{\pm}_{eff} \sim 4.36\times10^{-11} r_{AP}$, i.e. it increases proportionally with r_{AP}. For the mesopause we assume that this dependence is even of the more common form $\beta^{\pm}_{eff} \sim c^{\pm} (r_{AP})^{\gamma}$ where γ can be larger than 1. For example, $\gamma = 2$ if attachment rate is proportional to the surface. The effective coefficient of attachment of neutral particle to an AP β_{eff} assumingly depends on radius r_{AP} in similar way. The dependence of the rate of attachment to AP on r_{AP} determines the growth of an individual AP with time t while detachment from AP or its destruction determine the term of losses L; this last is assumed to be small compared to AP growth. If neglect L, the increase of the volume V_{AP} of an individual AP with time can be principally represented as dependent on the total effective coefficient β (for electrons, ions and neutral particles) by the following equation 'in average':

(4) $$dV_{AP}/dt = c_{AP}\beta N$$

Here N is the total density of particles which take part in the AP's building by attachment, c_{AP} = const. If $\beta = c\,(r_{AP})^{\gamma}$, r_{AP} can be obtained from the solution to Eq.(4) as function of time t which depends on γ.

1) For $\gamma = 1$ $r_{AP} = C_1 \ln(t)$;
2) For $\gamma > 1$ $r_{AP} = C_2\, t^{\gamma-1}$;

where C_i = const. These dependences demonstrate that the AP growth in R_{AP} can accelerate in time. Another important factor is the transfer of elementary electric charges to APs. An individual AP is characterized by the number k of charges k on it, where $k>0$ if these are positive, and vice-versa. Because of the presence of positive uncompensated spatial charge, the mean charge k_m carried by APs is positive, $k_m>0$. Since larger APs can accept larger number of charges (assumingly, proportional to their mass), k_m increases in time, as well as the maximum number of charges k_{max}.

We assume that when k_{max} reaches a critical value, the respective AP splits to two or more smaller APs due to the enhanced inner electric field. Initially this splitting occurs when the AP reaches also critical radius r_{AP} which allows transfer of bigger charge to this AP. If the result of splitting is presented by two AP's successors, they are also big enough to have large speed of growth, as follows by solution to Eq.(4). Hence, they will grow themselves to critical size in relatively short time t_G when they also can undergo splitting. Such mechanism of APs multiplication can be effective initially for quasi-exponential increase of AP's density S: in time $10t_S$ S can increase by three orders of magnitude. This increase is limited by the density of positive UC in region R_{AP}. Initially this multiplication is limited to a region R_{AP}.

The quasi-exponential increase of S in region R_{AP}, as well as increase of the mean r_{AP} leads to change of significance of terms in Eq.(3): gradually the last term becomes dominant. This changes the form of solution for ion-electron densities $n^{\pm}$. Initially, under steady-state conditions, the derivatives in left parts tend to zero, and $n^{\pm}$ tend to positive constant values. On the other hand, when the last term in right side becomes dominant, $n^{\pm}$ tends to zero. This solution determines fast decrease of conductivities σ_e, $\sigma^{\pm}_i$ in Eq.(2) which means also dramatic drop of the total conductivity σ.

Another important process during SPE is driven by the electric field $\mathbf{E}_{UC}$ generated by positive UC situated on APs. This electric field causes distribution of positively charged APs to regions R out of R_{AP}. This transmission determines transformation of Eq.(3) in R to such where its last term become significant. Hence, in region R the mechanism of aerosol enhancement and decrease of conductivity can be repeated. In this way the region of decreased conductivity comprises alternative altitudes and lower latitudes.

Conclusion

- The observed peculiar persisting of unusually large atmospheric electric field (AEF) at high latitudes during SPE/GLE are explained hypothetically as result of accumulation of uncompensated positive charge in polar and high-latitudinal mesosphere and above originated from injected protons.
- Such accumulation of uncompensated positive charge can occur due to creation, quasi-exponential density increase and growth of aerosol particles during SPE which become principal charge carriers.
- These hypothetical processes give consistent explanation of unusually large AEF reached for times longer than the charge relaxation time.

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