POSSIBLE EXPLANATION OF REVERSAL OF IONOSPHERE-EARTH ELECTRIC CURRENT OBSERVED IN HIGH-LATITUDE STRATOSPHERE DURING SOLAR PROTON EVENT ON 20.01.2005

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Abstract: *Results of balloon-borne measurements in Antarctic stratosphere, namely, the electric characteristics (the conductivity and the electric field) are considered during the solar proton event (SPE) on 20 January 2005. A well-expressed peculiarity in these results is the reversal of direction of the vertical electric field Ez (and, thus, of the ionosphere-earth current Jz) from downward to upward for several hours in the later phase of SPE; yet, the absolute value of Jz in this period remains much larger than its typical value ~2 pA/m*^{2}*. A possible explanation is given here of this quite untypical behavior of the current Jz. We suggest as factors for such behavior the increase of contribution of FAC system in the global atmospheric electrical circuit (GEC) at high latitudes, and the geomagnetic sub-storm occurring in the time period of interest. Our interpretation is supported by results of dc model in which continuity equation is used for electric currents in GEC originated by FAC.*

ВЪЗМОЖНО ОБЯСНЕНИЕ НА ОБРЪЩАНЕТО НА ЕЛЕКТРИЧЕСКИЯ ТОК ЙОНОСФЕРА-ЗЕМЯ НАБЛЮДАВАНО В СТРАТОСФЕРАТА НА ВИСОКИ ШИРИНИ ПРИ СЛЪНЧЕВОТО ПРОТОННО СЪБИТИЕ НА 20.01.2005 Г.

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Резюме: *Разгледани са резултати от балонни измервания за електрическите характеристики (проводимост и електрическо поле) в антарктическата стратосфера по време на слънчевото протонно събитие (СПС) на 20 януари 2005 г. Силна особеност на тези резултати представлява обръщането на посоката на вертикалното електрическо поле Ez (и, следователно, на тока Jz йоносфера-земя) от насочено надолу към сочещо нагоре, и то в продължение на няколко часа в късна фаза на СПС; също, Jz по абсолютна стойност в този период е много по-голям от типичната му стойност ~2 pA/m*^{2}*. Тук е дадено възможно обяснение на това нетипично поведение на тока Jz. Като обуславящи фактори тук се предлагат поява на съществен принос на системата на системата от надлъжни токове в глобалната атмосферна електрическа верига (ГЕВ) на високи ширини по време на това СПС и възникването на геомагнитна суб-буря в интересуващия ни период. Интерпретацията е подкрепена с резултатите от dc модел използващ уравнението на непрекъснатост за електрическите токове в ГЕВ породени от надлъжните токове.*

Introduction

The solar proton event (SPE) on 20 January 2005 is one of the most powerful – the strongest GLE since 1956 occurred. Simultaneously during 20 January, measurements of electric conductivity σ and the electric field **E** are supported in the Antarctic stratosphere (MINIS balloon campaign) [1]. During the day of SPE the balloon position changes from (70.9°S, 10.9°W) at 30.9 km altitude, to (71.4°S, 21.5°W) at 33.2 km altitude. The enhanced ionization causes enormous increase of conductivity. The vertical electric current J_z is computed from σ and E_z by Ohm's law. It demonstrates a peculiarity:

although in a fair-weather region, J_z reverses to upward direction for several hours. We interpret this peculiarity as related to an increase of the coupling of FAC with the global atmospheric electric circuit (GEC) at high latitudes during SPE and test our interpretation by means of modeling.

Phenomenon of Jz reversal and our interpretation

The measurements at MINIS [1] of interest are demonstrated in Fig. 1. Panel (a) shows the variations of conductivity σ due to enhanced ionization: ~20 times increase in the initial phase of SPE which begins at 06:51 UT, and several times later. Panel (b) is for the vertical component of the electric field E_z. The vertical component J_z of the electric current density (panel c) is computed from the Ohm's law, $J_z = \sigma E_z$. Since no electrical activity took place in the underlying troposphere (thunderstorms are untypical in Antarctica), J_z must represent the ionosphere-earth current in GEC which flows downwardly and is close to 2 pA/m^2. This current typically varies slightly and slowly, otherwise, short transients can occur (< 10 min). However, after the arrival of SPE the behavior of current *Jz* become untypical. Its most striking feature is after 15:56 UT: *Jz* reverses its direction from a downward to an upward for several hours, yet it rises up to 5 pA/m^2 by absolute value.

Here we suggest a possible explanation of this phenomenon. Since J_z remains reversed for time much longer than the relaxation constant for GEC (below 10 min), an outer, with respect to GEC, electric source takes part. At auroral latitudes these can be field-aligned currents (FAC). Principally, FAC do not penetrate lower than 90 km; their closure occurs above this height. However, FAC can possibly be extended down to the neutral atmosphere: a very small part $\mathbf{J}_{IS}$ of them which can be many orders of magnitude smaller than the ionospheric FAC of the order of μV/m^2. This suggestion is supported, for example, by experimental results in [2]. Such small current $\mathbf{J}_{IS}$ will be negligible with respect to the FAC system, but even if it is ~10^{-6} of the peak FAC ~10^{-6} V/m, it cannot be ignored with respect to GEC where typical currents are of order of 10^{-12} A/m^2, We hypothesize that during strong SPE larger currents $\mathbf{J}_{IS}$ can penetrate into GEC at high latitudes, due to the increase of conductivity, so that their contribution can become comparable to or even larger than the ionosphere-earth current J_{TS}~2 pA/m^2 whose source is the global tropospheric electric activity. The total current **J** in the neutral atmosphere thus is to be represented as follows:

(1) $\mathbf{J} = \mathbf{J}_{TS} + \mathbf{J}_{IS}$

Respectively, only for the vertical components of these currents we have $J_z = J_{TSz} + J_{ISz}$. We adopt the upward direction as positive. In region closer to the dawn sector with downward FAC dominating one has, $J_{TS\,z} < 0$, and $J_{ISz} < 0$. In region closer to the dusk sector (where FAC are upward) $J_{ISz} > 0$. The reversal of the vertical electric current Jz (and of the related field Ez) becomes in this last region when $J_{ISz} > 0$ and $|J_{ISz}| > |J_{TSz}|$. The satisfaction of these conditions is verified further by means of modeling by developing results of [3].

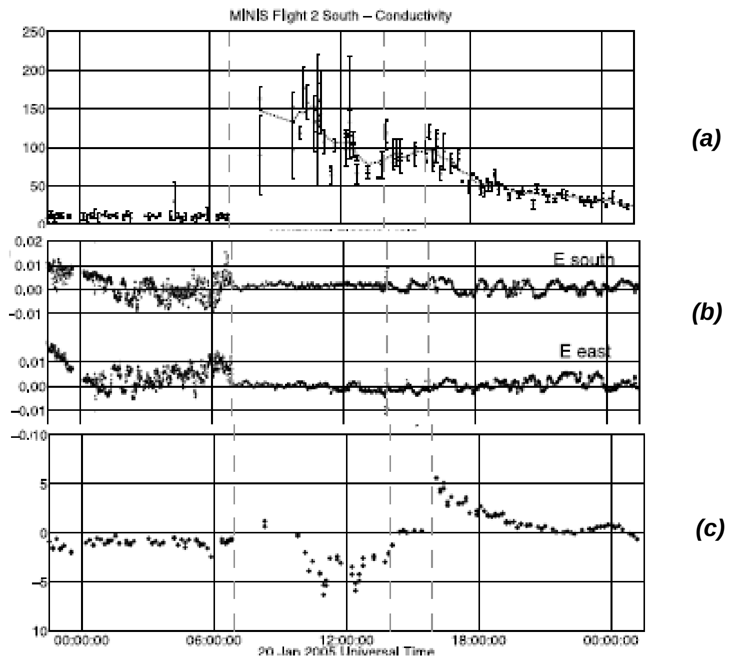

Fig. 1. (a) Electric conductivity σ in $10^{-12}\Omega^{-1}m^{-1}$ (b) vertical electric field E_z in Vm^{-1}; (c) vertical electric current J_z in pA/m^2 from balloon-borne measurements in Antarctic stratosphere simultaneous with SPE on 05 January 2005

The model

The continuity equation for the density of electric current $\mathbf{J}_{IS}$ by FAC origin is solved:

(2) div $\mathbf{J}_{IS} = 0$

under steady-state conditions (transients are on time-scale < 10 min, and are neglected). The model region comprises altitudes 0–150 km, $\mathbf{J}_{IS} = [\sigma]\mathbf{E}$ where $\mathbf{E}$ is the electric field vector, $\mathbf{E} = -\nabla u$, u is its potential. $[\sigma]$ is the conductivity (it is tensor, in general; below ~65 km it is a scalar σ). Tensor $[\sigma]$ is function of orientation of geomagnetic field $\mathbf{B}$ which depends on geomagnetic latitude. The extension of FAC down the ionosphere becomes principally at high latitudes, where the magnetic field $\mathbf{B}$ is close to vertical, so we assume here vertically oriented $\mathbf{B}$. At the upper boundary Z_B = 150 km FAC flow vertically and are presented by their distribution at geomagnetic latitudes >50° adopted here from [4]. Linearity of Eq.(2) allows to present the electric current $\mathbf{J}_{IS}$ as superposition from a series of elementary sources j_i of sample distribution of FAC at 150 km with a maximum j_{imax} at given coordinates represented as:

(3) $j_i(r) = j_{imax}\exp(-r/r_i)$,

where r is the horizontal distance from the source center, r_i is the characteristic radius of the source. The total current from all elementary sources integrated over the upper boundary Z_B should be zero. The simplest representation of picture of FAC distribution is by two balanced sample sources: of the dawn downward (j_{1max}<0), and the dusk upward (j_{2max} > 0) currents; it is used further in estimations.

Here assumption for flat ground is adopted. Eq. (2) is solved separately for each elementary FAC source; the final solution is obtained as superposition of these solutions. Cylindrical coordinates (r,φ,z) are used with respect to the elementary FAC source: z is altitude above ground; r = 0 relates to the sample source center. Eq. (2) is written for the electric potential u as:

(4) $$1/r\,\partial/\partial r\left(r\sigma_P\,\partial u/\partial r\right)+\partial/\partial z\left(\sigma_0\,\partial u/\partial z\right)=0\,.$$

Here σ_0 and σ_P are the field-aligned and the Pedersen conductivities.

The boundary conditions for the equation with the i-th elementary FAC source are given; i) at the upper boundary Z_B=150 km, $J_{ISz}= j_i$ where j_i satisfies distribution (3); ii) at ground level u≡0.

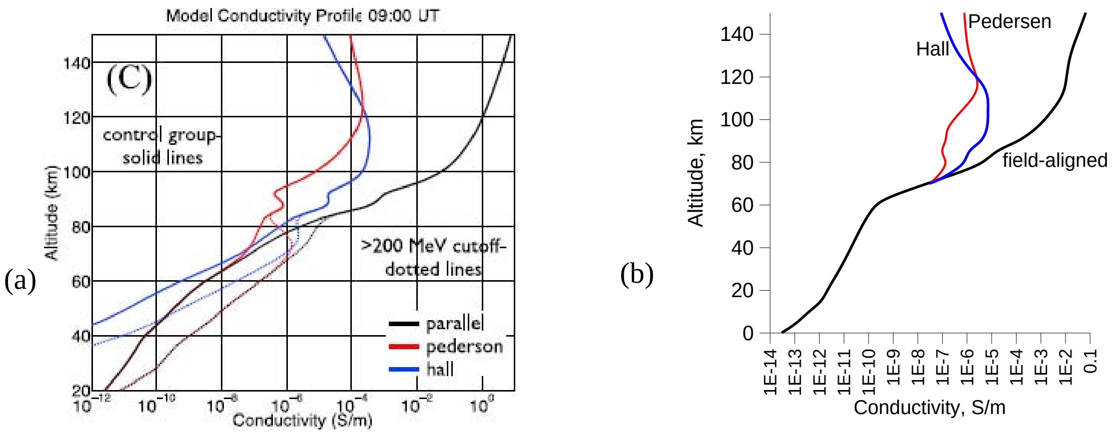

Fig. 2. Conductivity profiles: (a) for high latitudes (adopted from [5]) and (b) for any lower latitudes

To take into account the ionization effects of SPE above 20 km, the conductivity profiles are represented as depending on the distance r from the elementary FAC source. In order to solve 2D problem, the profiles of σ_0 and σ_P are adopted from Fig. 2a in some surrounding, $r \le r_B$= 2500 km they are computed in [5], and from Fig. 2b (typical for lower latitudes) outside it, r>r_B.

To obtain the distribution of potential u analytically, a step-wise representations of profiles of conductivities σ_0 and σ_P are used: the region 0-150 km is separated into N = 100 layers $z_{i-1}\le z < z_i$, with $\sigma_0 = \sigma_{0i}$ = const, $\sigma_P = \sigma_{Pi}$ = const in i-th layer. The general solution to Eq.(4) in i-th layer is:

a) for r ≤ r_B

(4) $$u^-(z_{i-1}\le z<z_i)=\int_0^\infty J_0(rk)\left[F_i(k,z)+G_i(k,z)\right]dk\,;$$

b) for r > r_B

(5) $$u+(z_{i-1}\le z<z_i)=\int_0^\infty J_0(rk)\left[f_i(k,z)+g_i(k,z)\right]+Y_0(rk)\left[p_i(k,z)+q_i(k,z)\right]dk$$

The upper indices –/+ relate here to inner ($r\le r_B$) and outer ($r>r_B$) regions; J_0 and Y_0 are the Bessel functions of first and second type of 0-th order. Also,

(5a) $F_i = A_i e^{-kz}$; (5b) $G_i = B_i e^{kz}$,

where A_i, B_i are arbitrary constants. f_i, p_i are similar to (6a) but with constants a_i, and c_i; g_i, q_i are similar to (6b) but with constants b_i, d_i. These 6*N* constants are determined from a system of 6N linear equations formed according to the boundary conditions *i*) and *ii*), and to the following requirements.

1) For $r\le r_B$ continuity is needed of the potential u^- and of the vertical electric current j_z^- between layers $z = z_i$, i.e. $F_i = F_{i-1}$ and $dF_i / dz = dF_{i-1}/ dz$ at $z = z_i$

2) For $r>r_B$ continuity of the respective mean values is needed, i.e.:

- at $z=z_i$, for u^+ and j^+: $\int_{r_B}^{\infty}\left[u_i^+(r,z_i)-u_{i-1}^+(r,z_i)\right]dr=0$; $\int_{r_B}^{\infty}\left[j_{zi}^+(r,z_i)-j_{zi-1}^+(r,z_i)\right]dr=0$;
- at $r=r_B$, for $z_{i-1}< z < z_i$: $\int_{z_{i-1}}^{z_i}\left[u_i^+(r,z)-u_i^-(r,z)\right]dr=0$; $\int_{z_{i-1}}^{z_i}\left[j_r^+(r,z)-j_r^-(r,z)\right]dr=0$.

Estimations of current J_{ISz}

We estimate the electric current from FAC J_{ISz} at 16:00 UT at the balloon when the observed total current J_z (1) is upward, i.e. $J_z > 0$. This will be valid if $J_{IS\,z} > 2$ pA/m^2. In order to estimate current J_{ISz} Eq. (2) is solved. The Weimer model [4] is used to determine distribution of FAC at $Z_B = 150$ km with the account to a sub-storm (auroral geomagnetic index AL at this time is AL = 1100 nT). For simplicity, we represent approximately FAC at 150 km only by two elementary FAC sources of distributions (3) with $r_{1,2} = 300$ km, $j_{1,2\,max} = \pm 1.2$ μA/m^2. The balloon is much closer to the first source (the horizontal distance is $r = 400$ km than to the second one (at distance $r = 2800$ km). In this example $r_B = 3000$ km. The contribution of the first and the second elementary FAC sources to J_{ISz} as determined from the model, is 4.84 pA/m^2 and –0.65 pA/m^2, respectively, so that $J_{ISz} = 4.19$ pA/m^2. This value is larger by absolute value than J_{TSz}, i.e. the total current (1) is directed to upward. Possibly, the obtained value J_{ISz} is underestimated due to the assumption for flat ground.

Conclusions

- The problem is considered of the reversal of the ionosphere-earth electric current in upward direction one on high latitudes observed during the solar proton event on 20.01.2005.
- It is suggested that field-aligned currents have contribution in GEC at high latitudes which is not negligible during strong solar proton events due to increase of conductivity in middle atmosphere.
- The simplest model estimations show that during SPE on 20 January 2005 remaining of field-aligned currents in stratosphere can exceed the ionosphere-earth current (its reversal occurs).

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