**Workshop Solar Influences
on the Magnetosphere, Ionosphere and Atmosphere**
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Detecting Common Origin of Atmospheric Electric Responses during SEP

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Evidence for strong and peculiar response of atmospheric electricity to SPE

Many experimental measurements for several decades demonstrate too strong & unusual response of the atmospheric electrodynamics during major solar proton events (SPE).

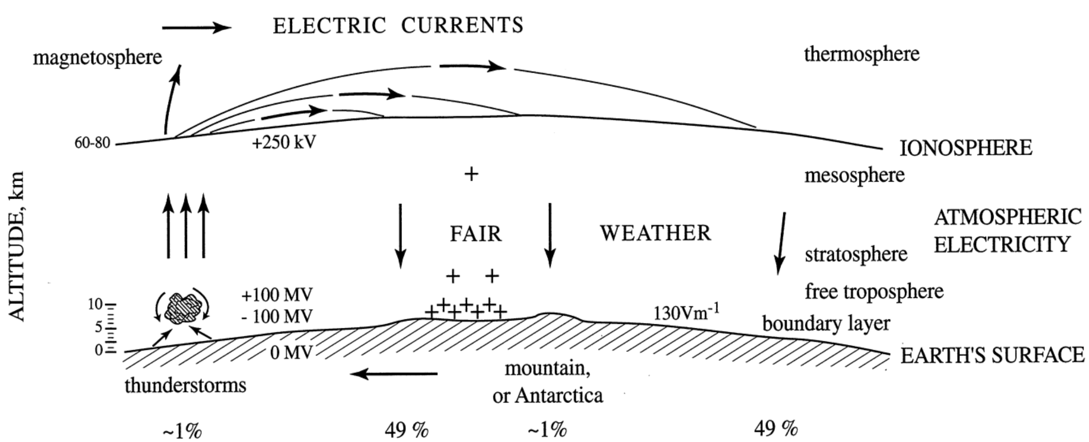
- *At different latitudes*: high, middle, and low
- *In different atmospheric regions*: in mesosphere (rocket-borne data); stratosphere (balloon-borne or rocket-borne data); and at ground level

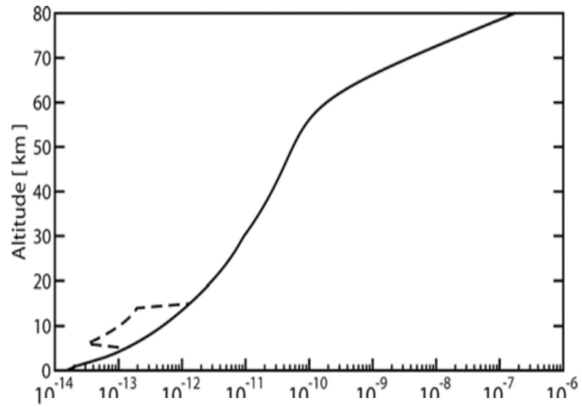
Basic characteristics of interest: *i*) Conductivity σ; *ii*) Vertical electric field *Ez* & current *Jz*

Peculiar features (unexplained for the majority of experiments):

- Extremely large and unusual non-transient, as well as transient, variations of Ez & Jz;
- Reversals of electric field Ez and related current Jz for hours (i.e. non-transient).

Global atmospheric electric circuit (GEC) - simple representation





Electric conductivity, S/m

El. current J_{fw} ~ 2-3 pA/m² from ionosphere down to the surface in fair-weather regions.

Hypothesis: *The variations observed in each experimental case represent the response of GEC to the processes in mesosphere at high & auroral latitudes driven by SPE.*

<u>I.1. In mesosphere and upper stratosphere</u>: during major SPE 19-22 October 1989

Rocket-borne data was obtained on 21.10.1989 at 19.31 UT, at latitude 58.5°S (Zadorozhny et al., 1998). SPE (one of those with biggest fluence for E<10 MeV) is accompanied by major geomagnetic storm on 20-21.10 (on 21.10 index Kp reached 8+; Kp=8 during rocket launch).

Vertical electric field Ez reaches <u>extremely high values in mesosphere</u> (unexplained)

Ez = +12.2 V/m at altitude z=58 km, and -9.7 V/m at z= 46 km

For comparison, for usual conductivities 2-6 x10^{-11} S/m and fair-weather current –2 pA/m^2 E_z should be about -100 mV/m i.e. smaller at least by two orders of magnitude; and well below that, as result of enhanced conductivity σ due to strong impact ionization during SPE.

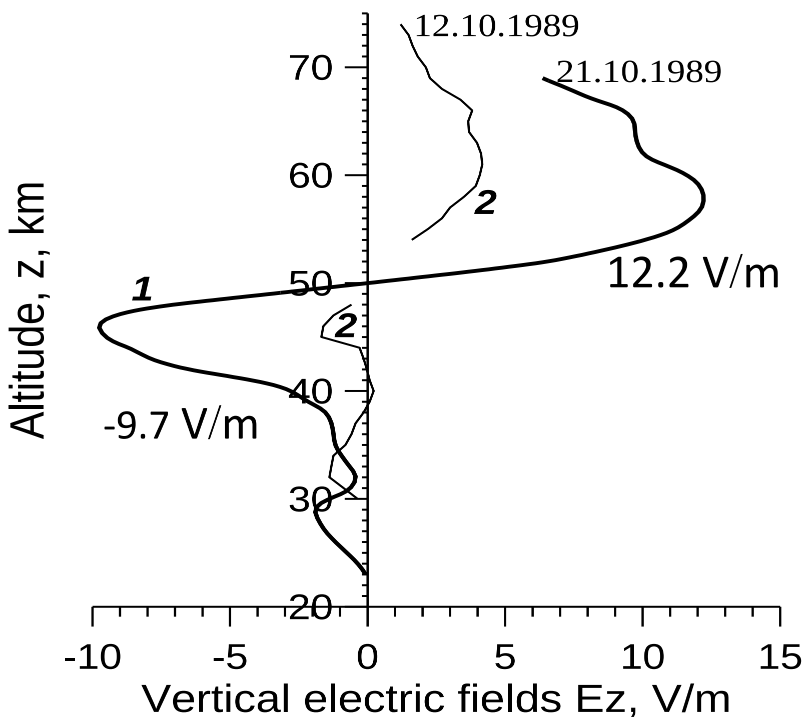


Fig.1. Profile of vertical electric field Ez from rocket-borne data at latitude 58.5 ° (South Indian Ocean) on 21.10.1989, 19:31 UT during major SPE of GLE event type, and major geomagnetic storm (Kp=8): thick line. Peak values of Ez are the largest ever measured in mesosphere; much bigger than those in case of second largest peaks measured on 12.10.1989 (thin line).

Series of measurements in different locations in mesosphere for decades show, for most of the cases, unusually large (and still unexplained) vertical electric fields of the order of magnitude of 1 V/m, but never that large.

Essential of the experimental results: **I**.2 High and auroral latitudes, stratosphere -2-

Balloon-born measurements took place in *Antarctic middle stratosphere* at 31-33 km during SPE on 20 January 2005 (with very hard spectrum: GLE'69) (*Kokorowski et al., 2006*).

Balloon coordinates: from (70.9°S, 10.9°W) to (71.4°S, 21.5°W).

Geomagnetic conditions: a) From SPE onset at 06:51 UT until 14:00 UT – quiet;

b) Increased geomagnetic activity from 14:00 UT until the end of day;

c) Strong geomagnetic substorm after 15:54 UT.

Main features of vertical electric field Ez and current Jz

i) Non-transient large variations; *ii*) Jz reaches more than twice larger values than usual; *iii*) Ez changes its direction for many hours; *iv*) Ez has two jumps coinciding with SW changes.

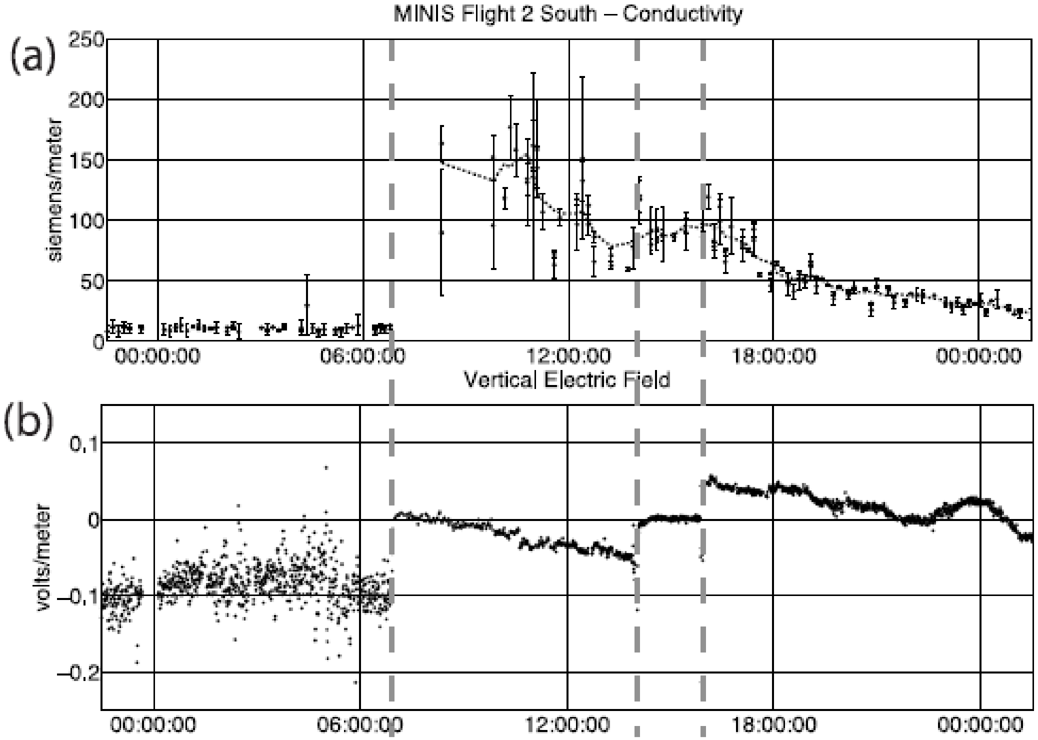


Fig.2. Time variations of: a) conductivity σ; b) vertical electric field Ez.

Unexplained features:

i)Typical moderate variations of related current density Jz~2 pA/m^2 are strongly impaired here.

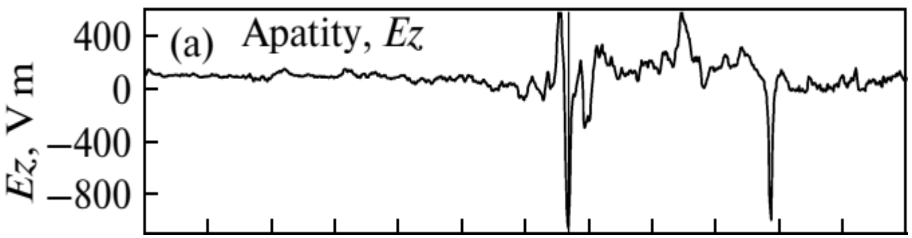
ii) Too large integrated el. current across the balloon altitude for each of two time periods ~08:30-14:00 UT and from 16:00 UT on. The origin of the large amount of the transited electric charge is unknown.

<u>*Ez* at ground level:</u> during three SPE of GLE type in 2001, on 14.04, 18.04, 04.11

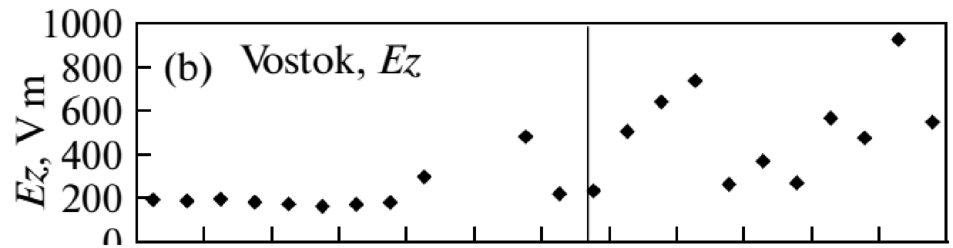
<u>*Measurements of Ez in*</u>: i) Apatity, Russia (67.3°N, 33.2°E), geomag. latitude +63.8°; and ii) Vostok station, Antarctica (geomag.lat. -89.3°) on 14.04, *Shumilov et al., (2015)*.

<u>*Variations of Ez*</u> observed are **between about -1 and +1 kV/m** (typically, Ez~100 V/m)

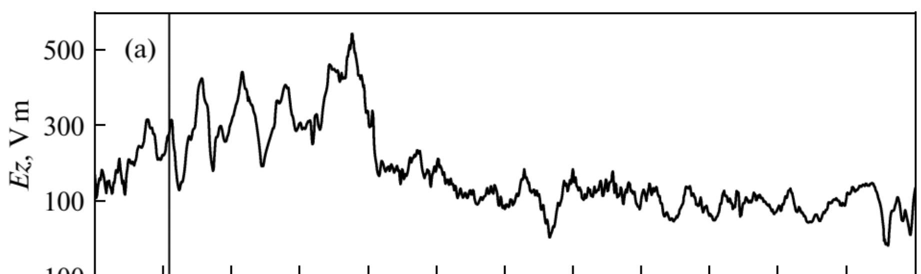
<u>*Unexplained Peculiarities:*</u> *i)* Unusually large variations; *ii*) non-transient reversals of Ez.



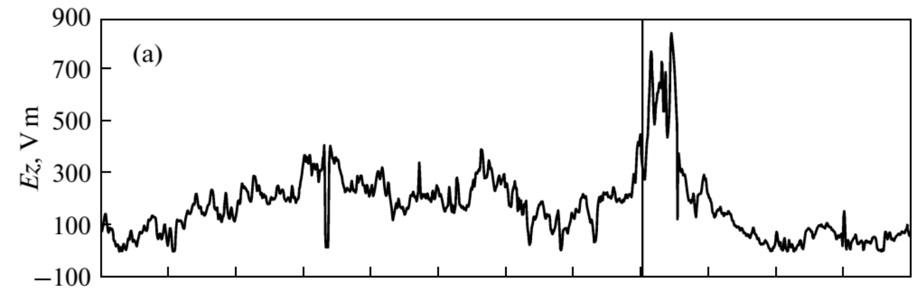
14 April 2001, Apatity



14 April 2001, Vostok station



18 April 2001, Apatity



4 November 2001, Apatity

Fig.3. Time variations of vertical electric field Ez (>0 for downward; <0 for upward direction) at Apatity and Vostok during three SPEs. Vertical lines indicate respective solar flares.

We have examined several hypothetic mechanisms to explain these data - no success!

<u>*The new idea is that the observed variations of Ez & Jz are mutually consistent via GEC*</u>

Essential of the experimental results. **II**.1. Low latitudes, ground-level

Measurements of atmospheric electric field Ez at surface in CASLEO, Argentine (31.8°S, 69.3°W), at 2552 m altitude, for 15 major SPEs, Tacza (2018).

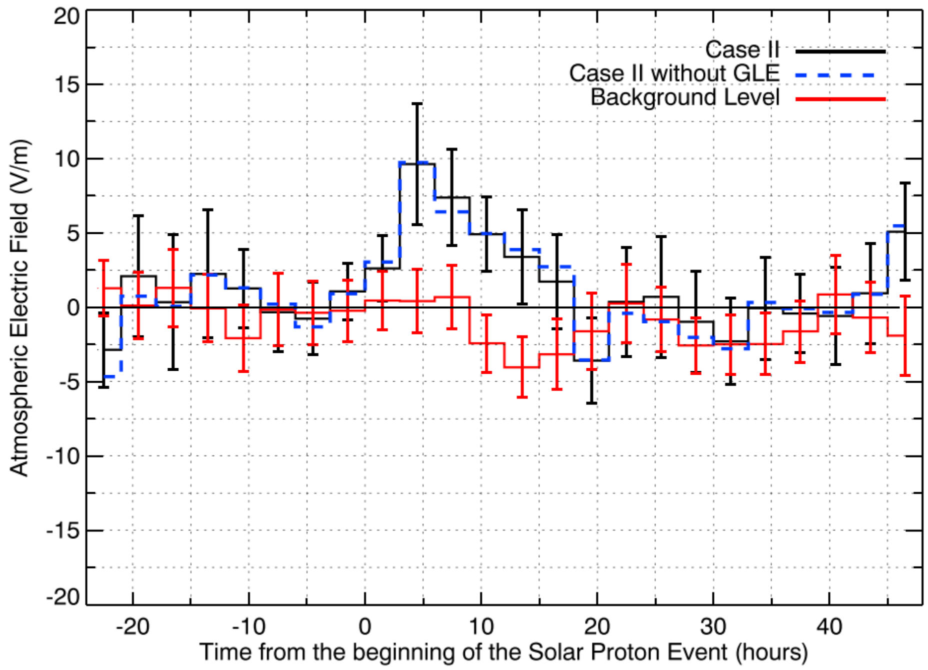


Fig.4. Results for atmospheric electric fields (AEF) during 15 major SPEs.

The average absolute deviation (in V/m) of AEF Ez from mean diurnal curve for Ez is shown.

Unambiguously, SPEs lead to significant deviations of Ez from its mean value.

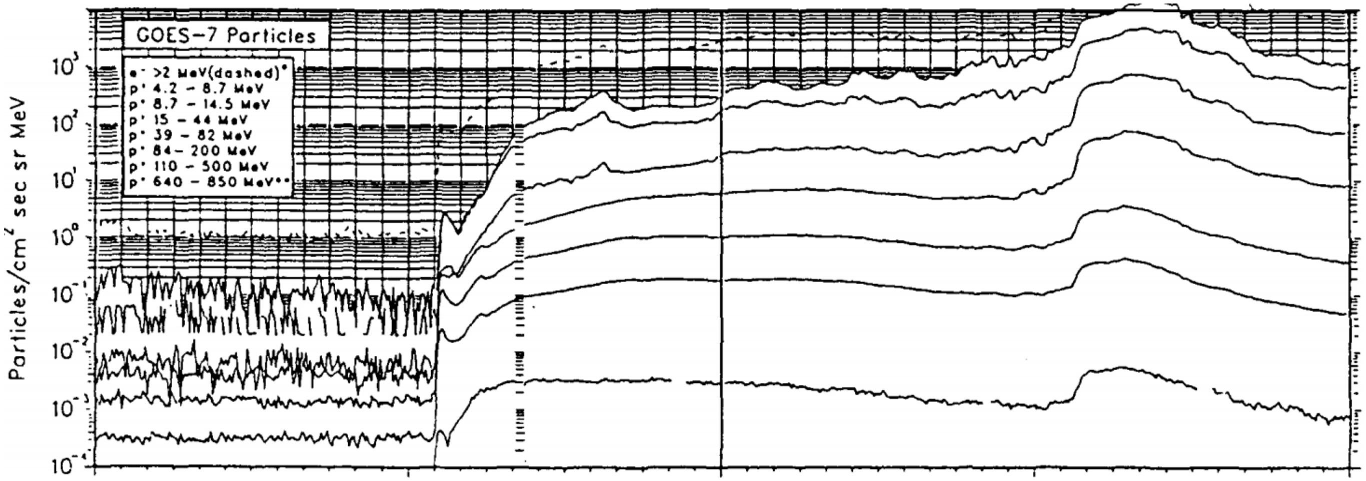
The cutoff rigidity is 9.8 GV. Hence, the deviation hardly can be explained by a direct effect of energetic proton flux.

II.2. Middle latitudes, ground level

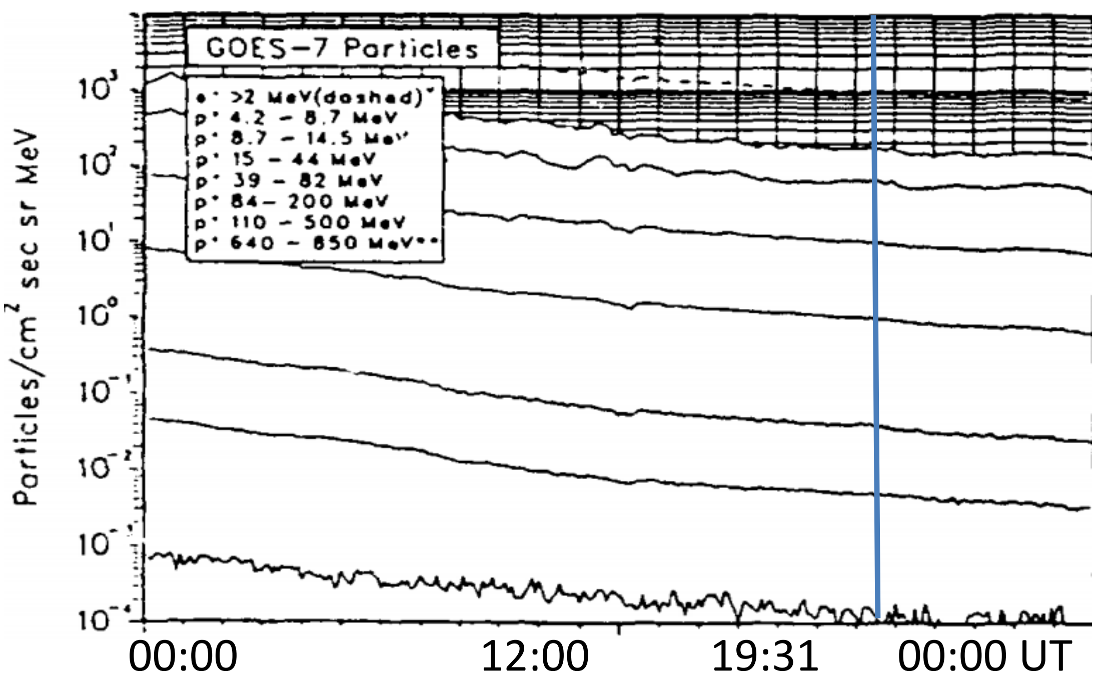
Similar results have been obtained at low (Cobb, 1967) and middle (Reiter, 1978) latitudes

According to our point of view, the observed deviations in electric field Ez represent the response of GEC to SPE, or, more precisely, its response to effects of SPE in mesosphere at high and auroral latitudes

Energetic proton flux spectrum for SPE 19-22.10.1989, Marvin & Gorney (1992)



19-20 Oct. 1989

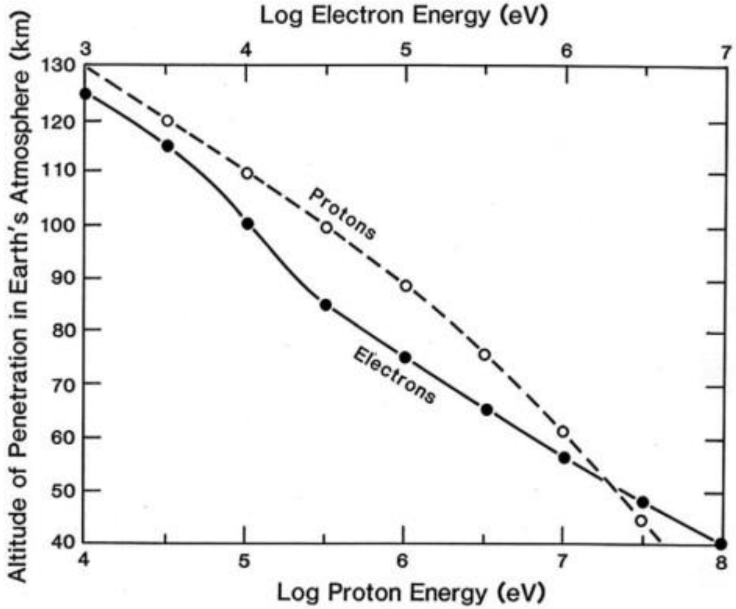


21 Oct 1989

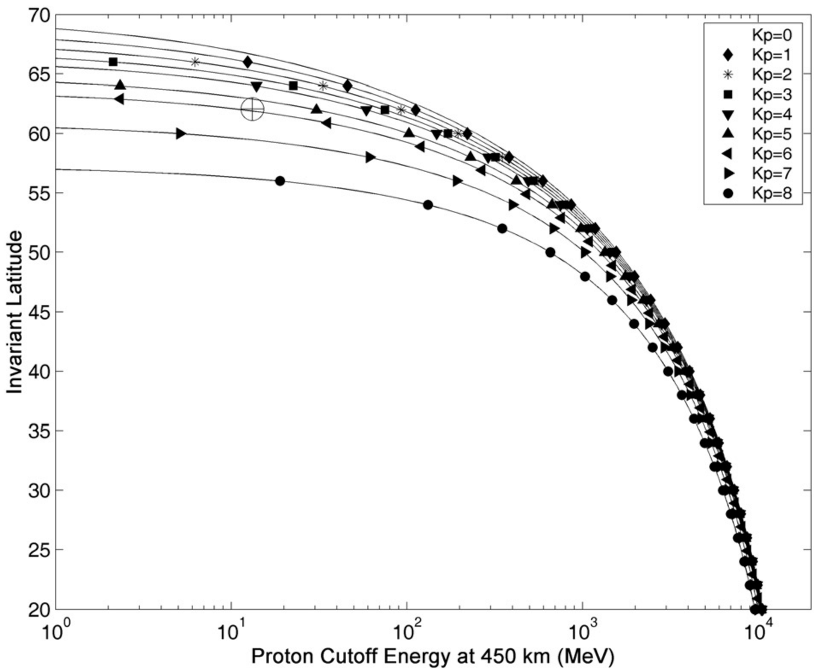
Fig.5 GOES-7 data on 19-21.10.1989. Proton channels: 1) 4.2-8.7; 2) 8.7-14.5; 3) 15-44; 4) 39-82; 5) 84-200; 6) 110-500; 7) 640-850 MeV (Dashed curve is for electrons >2 MeV. Vertical line indicates launch time 19:31 UT.

Proton fluence for energies 1-10 MeV is among the highest ever observed.

Factors determining height distribution of relaxed protons in atmosphere



Stopping altitudes of energetic protons (dashed line) and electrons (solid line) as function of their energy.



Proton cutoff rigidity at 450 km by different values of Kp index, Rodgers et al.(2006)

- Each energetic proton that penetrates into atmosphere enters also an extra elementary positive charge $q_e=1.6\times10^{-19}$ into it.
- This extra charge cannot enter back the magnetosphere due to low energy of its (any) carrier
- Hence, uncompensated positive spatial charge $Q_{PT}= q_e n$ is being accumulated below about 150 km during SPE where n is the number of penetrated protons.
- Its neutralization can occur by precipitatied electrons of same quantity from magnetosphere.

Integral Fluence for 19-31.10 (cm^{-2}); & Equivalent positive charge Q_{PT}

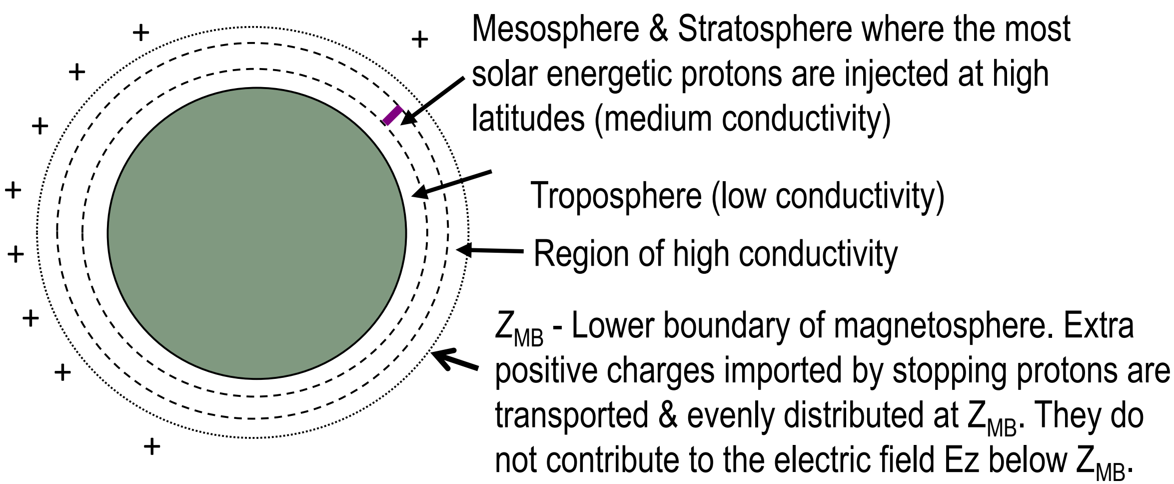
	>1 MeV	>5 MeV	>10 MeV	>30 MeV	>60 MeV	>100 MeV
pfu	1.03×10^{11}	3.89×10^{10}	1.92×10^{10}	4.26×10^{9}	1.23×10^{9}	4.65×10^{8}
Q_{PT}, C/m^2	1.65×10^{-4}	6.24×10^{-5}	3.07×10^{-5}	6.82×10^{-6}	1.97×10^{-6}	7.44×10^{-7}

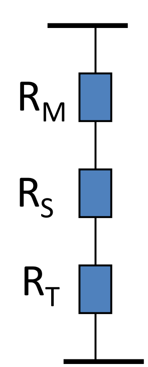
Even if very small part of this charge enters the atmosphere, it would be yet much larger than the charge in GEC from tropospheric sources evenly distributed at the globe: ~10^{-10} C/m^2

Hence, the uncompensated charge injected into atmosphere should be taken into account!

The problem of redistribution of elecric charges in the atmosphere thus arises.

Oversimplified model: Uncompensated electric positive charges injected at the stopping altitude corresponding to protons initial energy, are transported then upwards towards increasing conductivity to the base of magnetosphere at ~150 km altitude. But the uniformly distributed charges at this altitude would have no effect on GEC below!





Equivalent electric link between surface and ionosphere. R_T, R_S, R_M are column resistances for troposphere, stratosphere & mesosphere, $R_T \gg R_S \gg R_M$. A newly injected elementary charge is carried upwards.

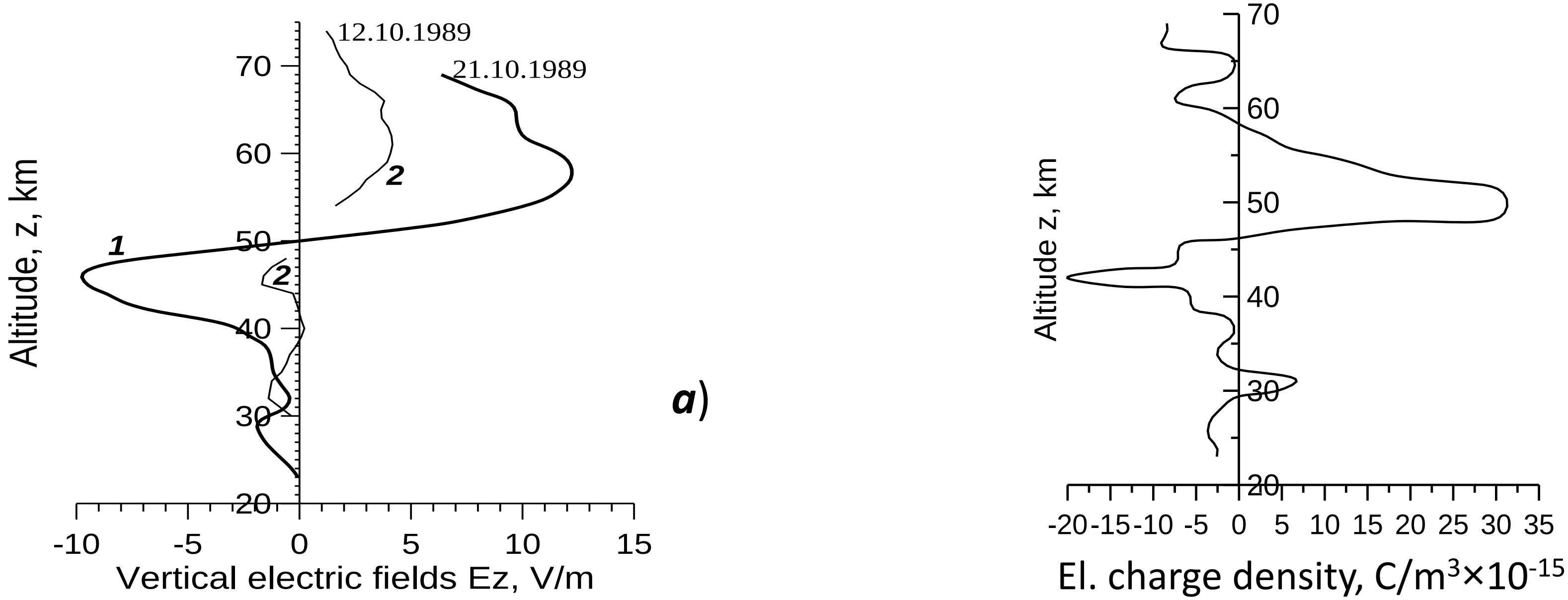


Fig.6. From the profile of vertical electric field Ez at the time of rocket launch time (***a***) we derive the profile of electric charge density ρ (***b***) from Gauss's law div**E**=ρ/ε_0, ε_0=8.85x10^{-12} F/m is permittivity.

- We analyze the main layer L_P of positive charge around 50 km and the total positive charge Q_{LP} in it. This layer is hypothetically fed by the uncompensated positive charges injected during SPE. Any precipitation of protons from magnetosphere have no significant contribution to layer L_P
- Layer L_P is in quasi-steady state at the flight time since the decay of proton flux is very slow (~7% per hour), and no other sources affect it. The conductivity σ in L_P satisfies then:

$$Q_{LP} / t_P = J_P \quad (1)$$

where $J_P(z) = F_P(z) q_e$ is the source current of newly injected uncompensated positive charges; $F_P(z)$ is the proton flux reaching altitude z), and t_P is the relaxation time, $t_P = \varepsilon_0 / \sigma$.

The source current J_P is derived from the proton flux parameters (*Fig.5*) by assumption that at the top of atmosphere (~100 km) the same flux as that measured at Lagrange point (such approximation has been used also by other authors).

With columnar charge density in L_P Q_{LP}~10^{-10} Cm^{-2} and J_P~10^{-14} Am^{-2} for the layer L_P, a rough approximation of conductivity σ_{LP} in the layer L_p around 50 km yields:

$$\sigma_{LP} = J_P \varepsilon_0 / Q_{LP} \sim 10^{-15} \text{ S/m} \quad (2)$$

This incredibly low conductivity is necessary to avoid fast relaxation of the charge Q_{LP}.

Such paradoxically low conductivity, if only relevant, could be due to presence of aerosol particles. Similar conclusion is made by Zadorozhny (2001), Holzworth and Goldberg (2004).

Similar large reduction of conductivity by several orders of magntude has been derived from measurements of Ez in NLC in mesopause by Holzworth and Goldberg (2004) (***Fig.7***). They obtained for conductivity there ~4×10^{-13} S/m, i.e. decreased by several orders of magnitude.

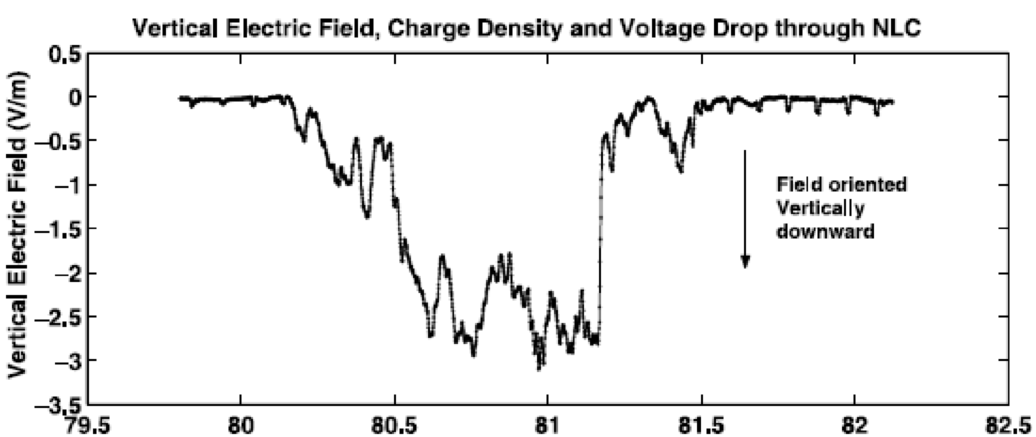
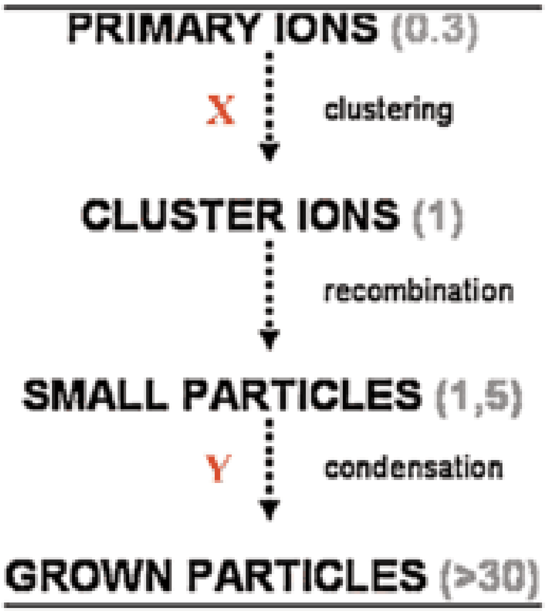


Fig.7. Vertical electric field measured in a noctilucent cloud around ~81 km altitude (Holzworth and Goldberg, 2004). Conductivity is decreased by several orders of magnitude, which is due to aerosol particles, according to authors.

Creation, growth, and charging of aerosol particles



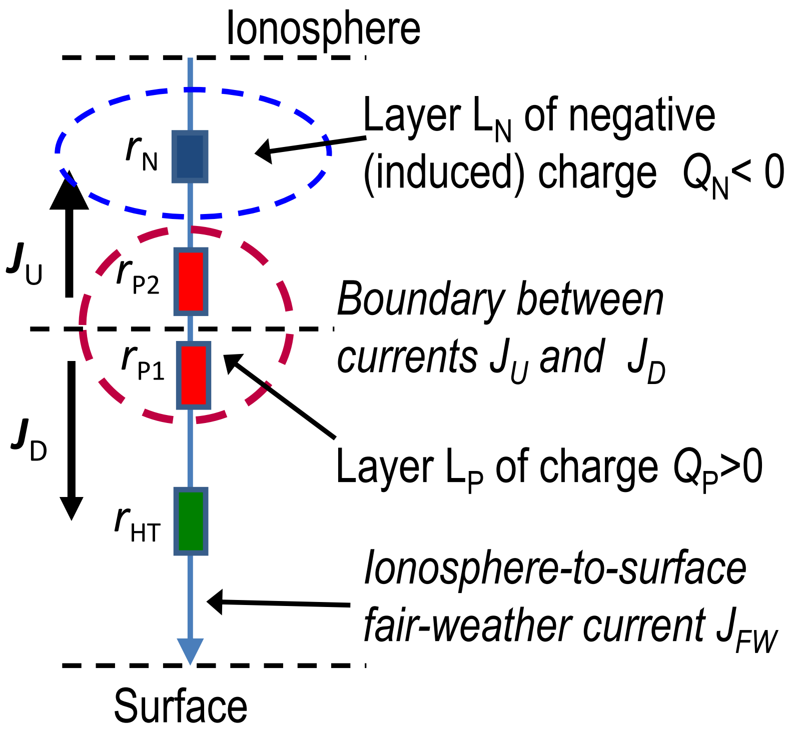
Main phases of creation and growth of aerosol particles. We suppose that during major SPE aerosol particles (APs) are being created and grow to larger particles; they also can carry multiple electric charge (up to 10?).

Physics of aerosol in stratosphere and mesosphere is not well developed yet.

<u>Presumed properties of layer of aerosol particles (APs) during strong SPE</u>

- Growth and multi-charging of APs during SPE;
- Grown up APs are stable and their mobility is very low;
- APs control mesospheric and stratospheric conductivities during SPE: these decrease strongly in time: hence, columnar resistance within an aerosol layer would increase;
- A significant portion of the uncompensated positive charge is being accumulated in the middle atmosphere forming a layer LP of positive charge which is descending in time.

Hypothetic model of redistribution of unsatisfied electric charges (when no EEP takes place)



r_{HT} ~ const is tropospheric columnar resistance; r_{P1}, r_{P2} & r_N. are strongly varying columnar resistances.

Fig.8. Representation of link in GEC between ionosphere and surface at high & auroral latitudes during SPE.

- Columnar resistances in the upper stratosphere, mesosphere and mesopause increase during SPE.
- Layer L_P of uncompensated positive charge is built and developed together with the gradual increase of columnar resistances $r_{P1} + r_{P2}$ and r_N. Layer L_N of negative charge is induced above layer L_P due to the conductivity gradient.
- Relaxation of the charge Q_P occurs through the upward J_U and downward J_D currents. J_U and J_D are superimposed to fair-weather current J_{FW};
- If $r_{P2} + r_N >\sim r_{HT} + r_{P1}$, the downward current J_D is significant;
- J_{FW} decreases with increase of resistances.

<u>For large downward electric field Ez in stratosphere and lower the requirements are</u>:

1) The columnar charge density Q_{LP} is large enough;
2) $r_{P2} + r_N >\sim r_{HT} + r_{P1}$.

Analysis of measurements in Antarctic stratosphere on 20.01.2005 (*Kokorowski et al., 2006*), first phase: t_0=06:51 – t_2=14:00 UT (quiet geomagnetic conditions) -1-

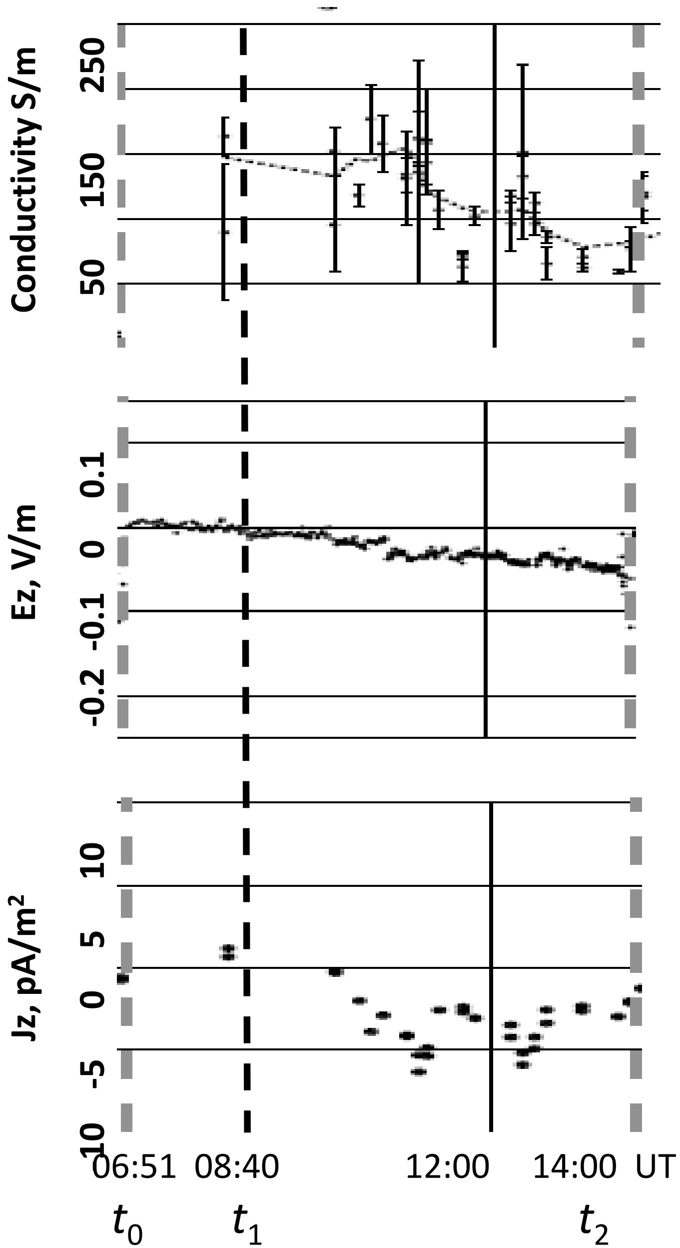
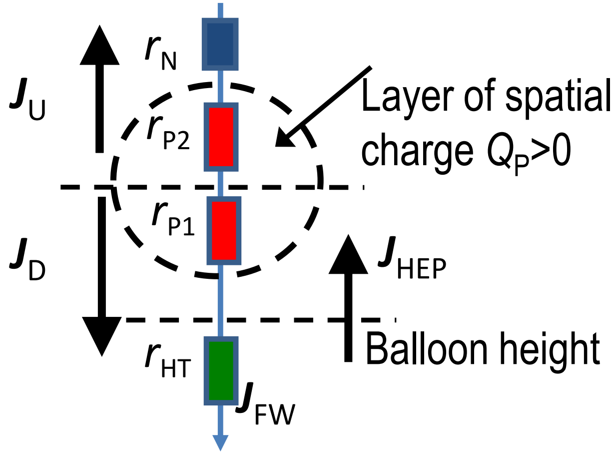


Fig.8. Data during first phase, 06:51-14:00 UT

- From t_0=06:51 until t_1=08:40 UT the vertical electric field Ez is small and mostly positive. The inverse direction of Ez is result of protons of energies >~100 MeV which penetrate below the balloon whose charges then form an upward current J_{HEP} which is larger than the decreased fair-weather current J_{FW}.
- At time period t_1 - t_2 the downward current J_D enlarges and $J_{FW} << J_D$ due to the enhanced charge Q_{LP} and increased columnar resistances r_{P2} and r_N.



Link between surface & ionosphere in GEC at high latitudes. Increase of current J_D begins at t_1

Analysis of measurements in Antarctic stratosphere (Kokorowski et al,2006), second phase after 14:00 UT (geomagnetically disturbed) - 2 -

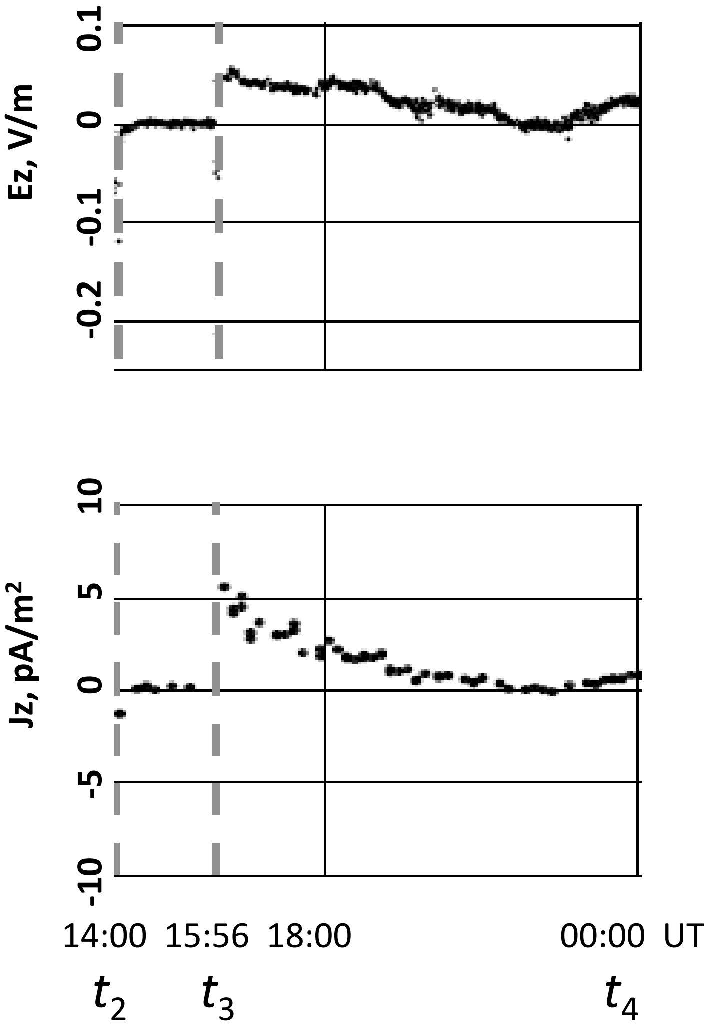
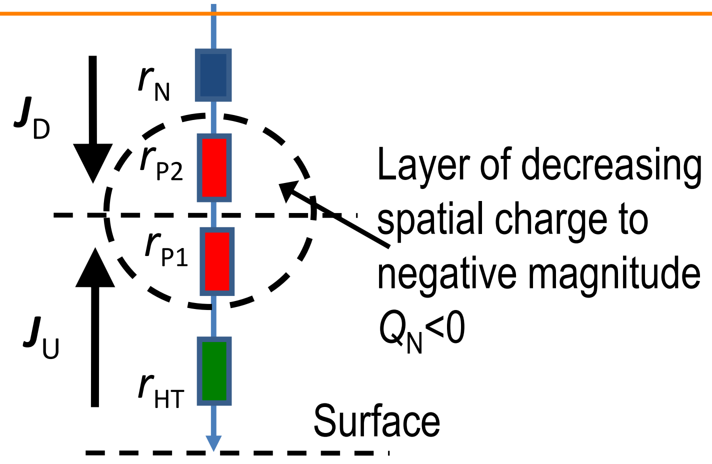


Fig.9. Second phase: 14:00 – 00:00 UT

- With the increase of geomagnetic activity at t2=14:00 UT the vertical electric field Ez jumps from extremely large negative values to almost zero, possibly, due to weak electron precipitation which imports negative charge descending towards layer L_P.

- The second jump at t3 = 15:56 UT (the substorm onset) is caused, possibly, by stronger EEP. Layer L_P is filled with negative charges Q_N which increases and descends quickly. Aerosol particles are controlling charge carriers. Before 15:56 UT the current J_U below L_P is small yet, and compensated by the fair-weather current. At 15:56 UT intensified recharging of layer L_P occurs, and an upward current J_U>0 surface-to-stratosphere is quickly generated.



Interpretation of AEF Ez variations at surface for SPE 14.04.2001 (*Shumilov, 2015*)

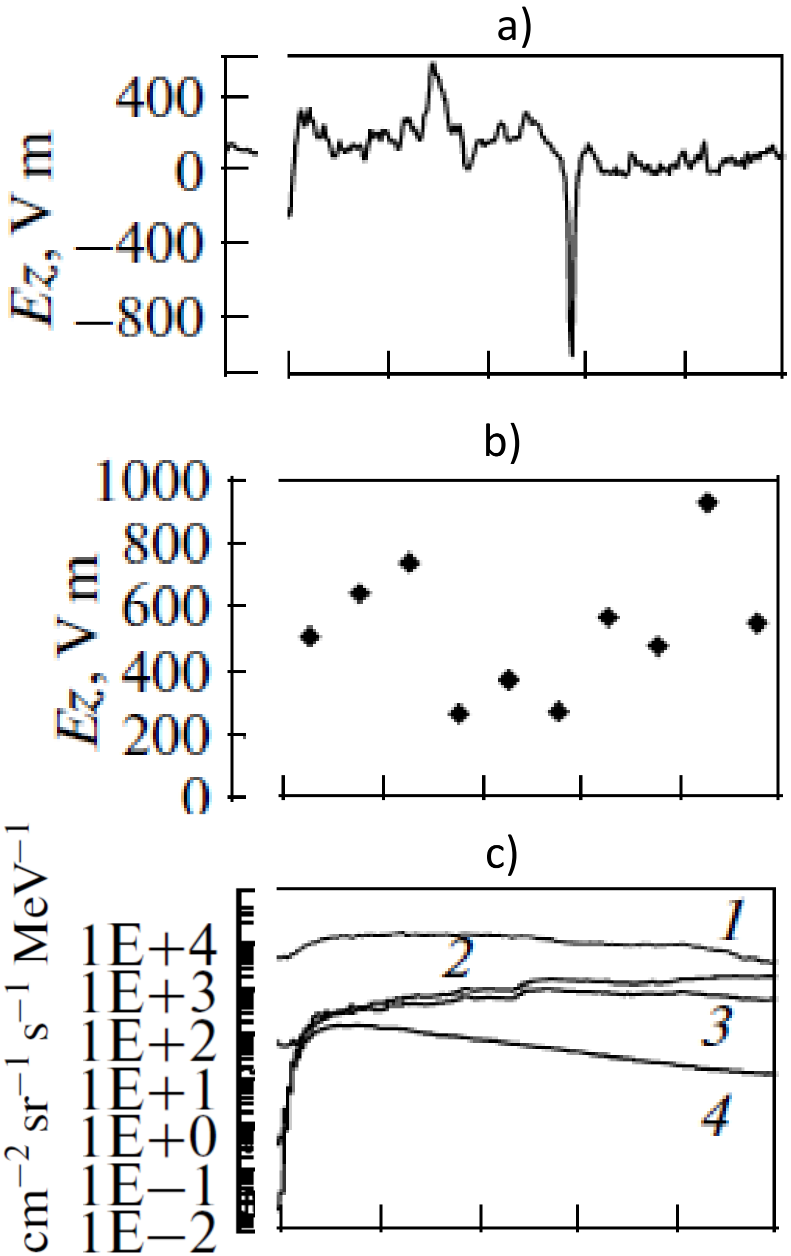


Fig.10. Ground-level electric field Ez in: a) Apatity (Λ=+63.8 °) on 14.04.2001 and b) Vostok, Antarctica (Λ=-89.8°); c) GOES-10 integral fluxes: 1) electrons >2 MeV; 2)-4): protons >1 MeV, >10 MeV, >100 MeV.

Ez behavior resembles that in stratosphere Figs.8-9

- Relatively small Ez for the first two hours is due to initial gradual growth and charging of APs in stratosphere and mesosphere;
- After that, increase of Ez to untypically large values is due to increase of downward current JD from the upper stratosphere to surface, as in Fig.8;
- Transient reversal of Ez reaching ~ -1 kV/m, could be due to EEP or REP, similarly to Fig.9.
- The increase of Ez up to almost +1 kV/m at Vostok station possibly represents the GEC response to effects of EEP at auroral latitudes.

Explaining deviations of Ez at surface at low latitudes during 15 SPE: (*Tacza et al. 2018)*

Coordinates: (31.8°S, 69.3°W); altitude: 2552 m asl.

List of 15 Solar Proton Events Examined

	Solar Proton Event (≥100 MeV)	
Year	Start Date/Time (UT)	Proton Fluence (protons/cm^2 day sr)
2011	21 March/04:00	8.4e + 03
2011	23 September/02:00	7.7e + 03
2012	27 January/18:00	1.6e + 05
2012	17 May/02:00	3.2e + 05
2012	12 July/17:00	3.7e + 03
2012	19 July/07:00	1.9e + 04
2012	23 July/07:00	2.9e + 04
2012	28 September/01:00	5.0e + 03
2013	11 April/08:00	7.0e + 04
2013	15 May/12:00	2.8e + 03
2013	22 May/14:00	9.4e + 04
2013	30 September/02:00	6.5e + 03
2014	06 January/08:00	9.4e + 04
2014	07 January/19:00	6.1e + 04
2014	18 April/13:00	1.3e + 04

Picked up is the SPE on 17.05.2012; it has the larges fluence

Average deviation of AEF Ez for 14 SPE (without marked one) from diurnal curve

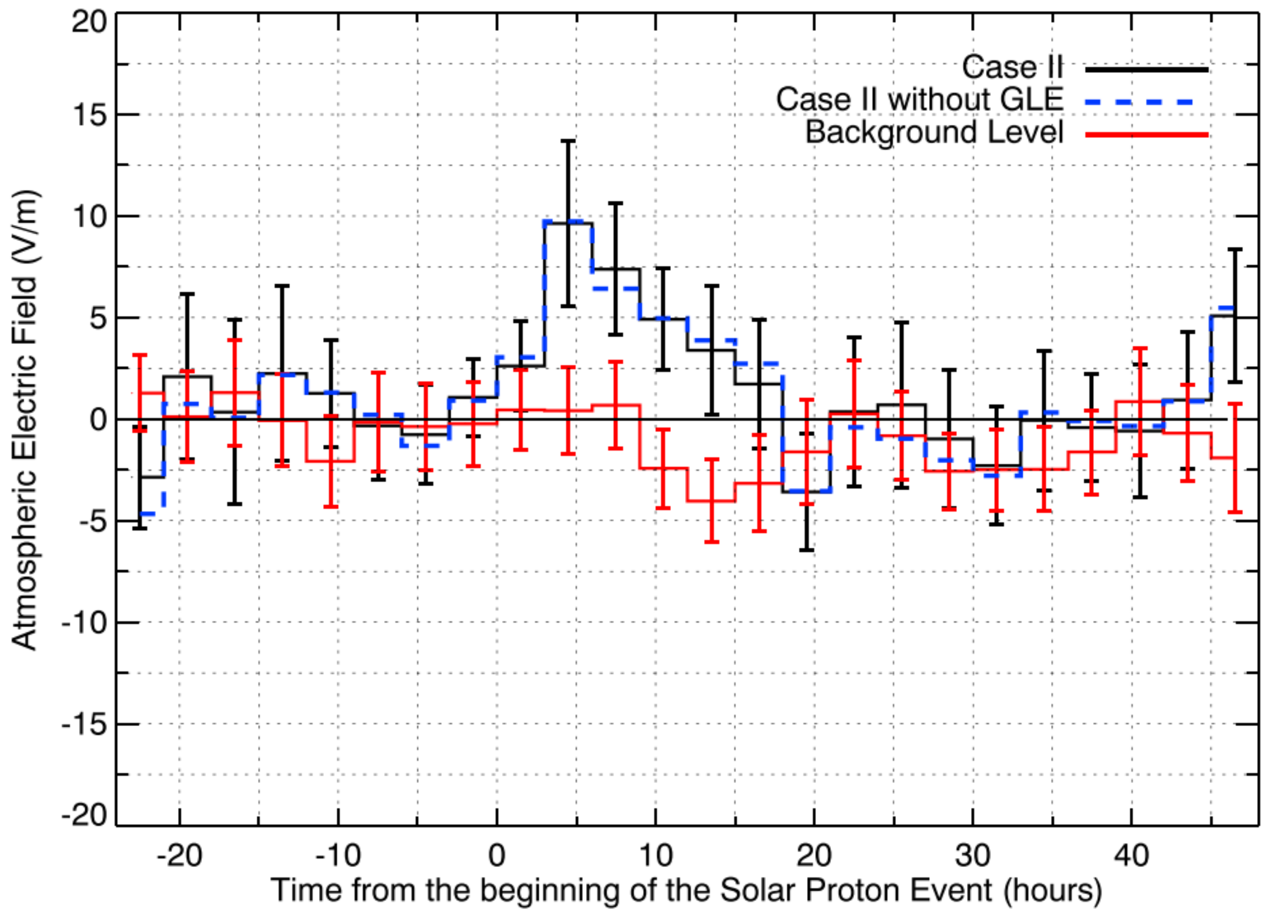


Fig.11a. Absolute average deviation ΔEz (in V/m) of Ez from the mean diurnal curve for Ez for the 14 unmarked SPEs (shown by blue dashed line).

Features: Increase of ΔEz (up to 15%) for the first ~17 hours from the beginning of SPE. Then, only slight (~5%) and short (~3 hours) decrease can be seen.

Deviations of atmos. el. Field Ez at CASLEO during SPE 17 May 2012 (*Tacza et al. 2018)*

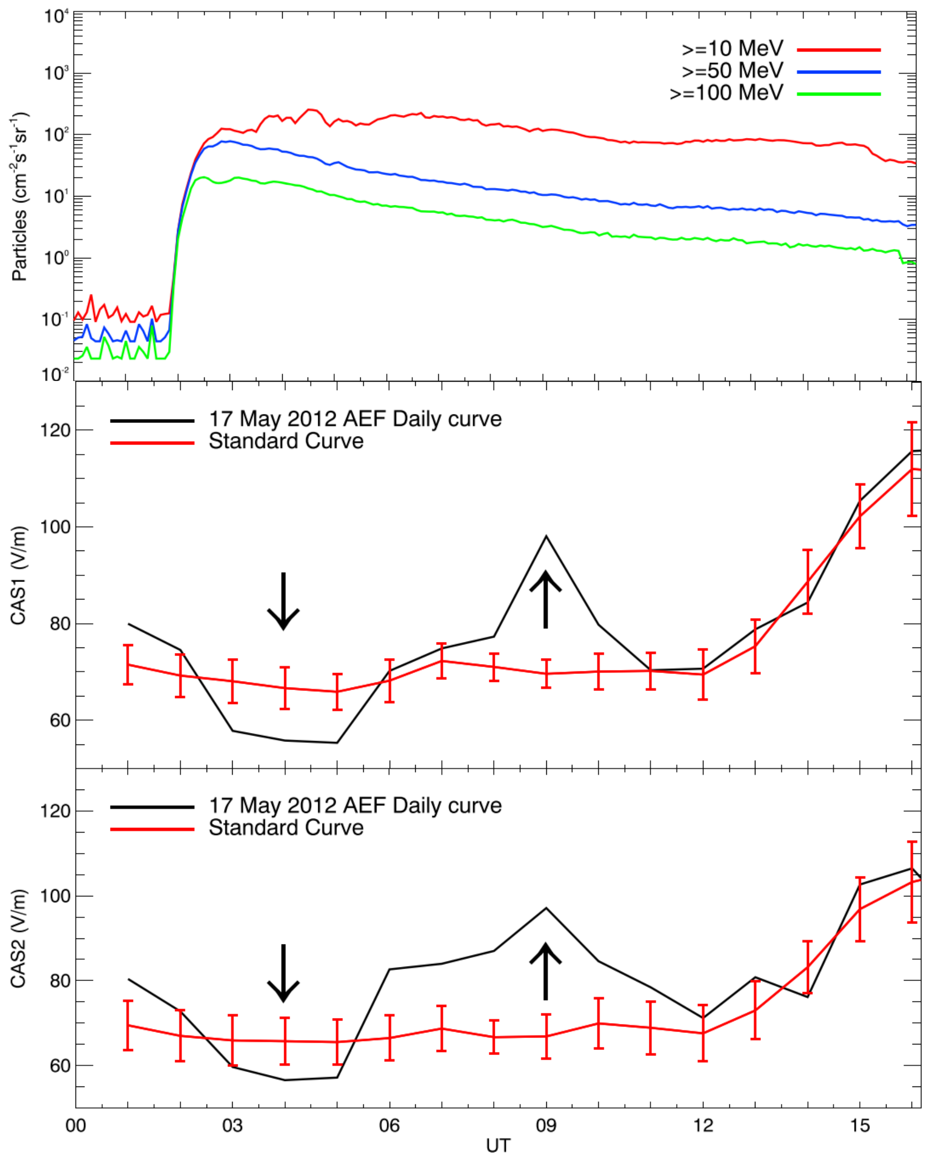


Fig.11b.

- Energetic proton flux for protons >10 MeV, >50 MeV, and <100 MeV from GOES-11 measurement data (upper panel).

- Atmospheric electric field Ez at ground level; data is from stations CAS1, CAS2 at altitude 2552 m asl. (two lower panels). The mean diurnal curve of Ez is shown in red, and Ez during during SPE – in black.

<u>Properties</u>: As opposed to previous case, Ez has first a negative deviation from the standard diurnal curve up to ~15% for 4.5 hours, then a positive deviation increase (up to ~40%) for next 7 hours.

Interpretation of electric field Ez deviations as response of GEC to SPE

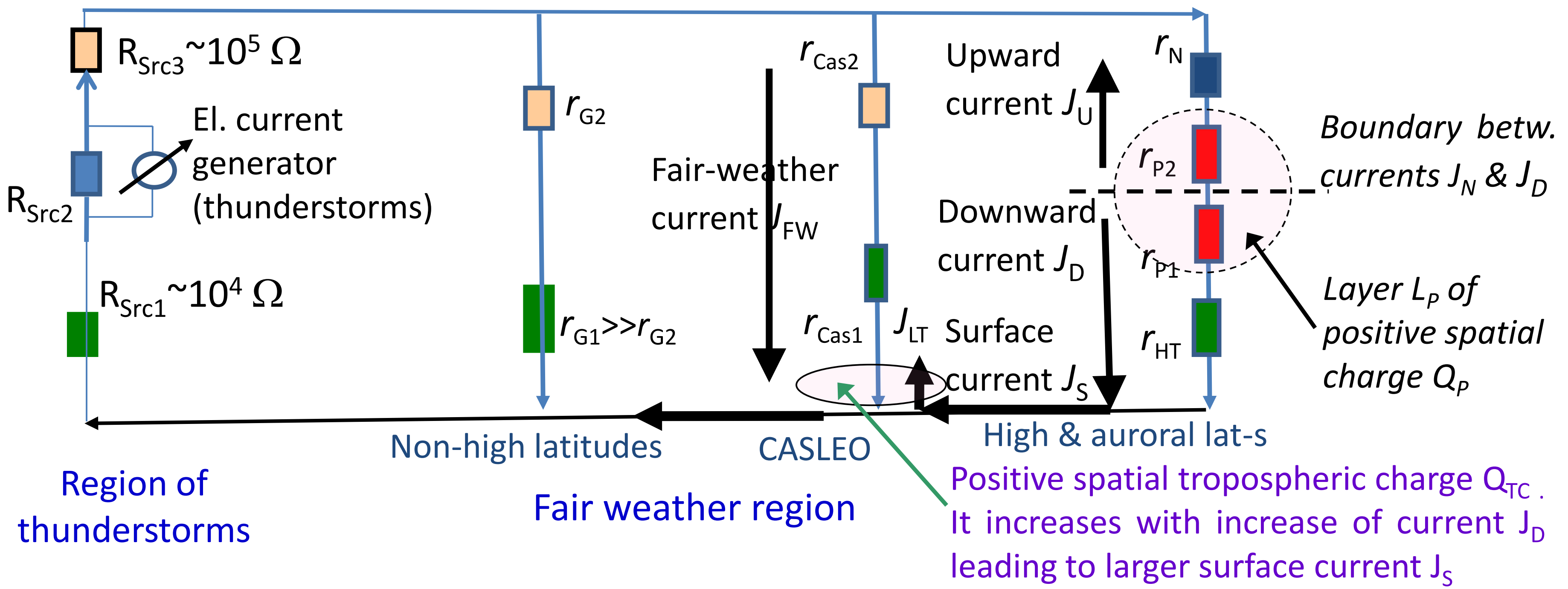


Fig.12. Model representation of GEC. The uncompensated positive charge in layer L_P at high latitudes is redistributed to lower latitudes by currents J_D (downward, at high latitudes), J_S (through surface) and J_{LT} (upward, at lower latitudes) which contribute at lower latitudes to induced tropospheric spatial charge Q_{TC}. Key characteristics are the positive charge Q_P and resistances r_{P1}, r_{P2}, r_N which increase in time during SPE. They determine the upward current J_{LT}. For weaker SPEs J_{LT} at low latitudes is less than the enhancemnt of J_{FW} due to the increase of ionospheric potential; the result is increase of Jz and Ez. Stronger SPEs cause first, in opposite, an increase of Jz and of charge Q_{TC}. At later phase Q_{TC} is relaxed partially and contributes for the increase of Jz.

CONCLUSIONS

- Large electric fields ~10 V/m measured in mesosphere at auroral latitudes during major SPE are hypothetically considered as result of development of aerosol layers in which the electric conductivity gradually decreases to very low values.
- During major SPE significant uncompensated positive electric charge can be accumulated in mesosphere and stratosphere. As result, downward current J_D to the surface can arise.
- Unexpectedly large and quite untypical non-transient variations of the vertical electric field E_z and related current J_z in the middle stratosphere at auroral latitudes during major SPE can be result of the downward current J_D when no EEP occurs.
- Four phases detected in electric field variations in Antarctic stratosphere during GLE69 are consistent with the hypothetically predicted processes in mesosphere.
- Electric field variations at surface at auroral latitudes can be explained in similar way.
- Experimentally observed large and untypical variations of the electric field and current in different atmospheric regions and at different latitudes represent GEC response to processes in high-latitude mesosphere driven by SEP.
- SEP-driven hypothetical processes of aerosol creation and growth in mesosphere and upper stratosphere at high and auroral latitudes, is important factor in physico-chemical atmospheric processes, particularly concerned to small constituents.
- Large variations of electric currents in the troposphere possibly affect weather formation.
- The presented hypothetic considerations indicate GEC as effective mediator between sun and atmospheric physico-chemical processes.

THANK YOU