Sixth International Conference

Solar Influences on the Magnetosphere, Ionosphere and Atmosphere

Sunny Beach, Bulgaria *26-30 May 2014*

Red sprites as possible factor in the link between solar activity and conditions in strato/mesosphere

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The problem considered

Question concerned: whether there are effective links between ***Solar Activity*** (**SA**) and the status of ***Meso- and Stratosphere*** realized ***by global atmospheric electric circuit*** (**GEC**). Such links, if present, would play a role in relationships between ***SA*** and ***climate***.

What the possible mechanisms could be?

One of mechanisms which involves GEC as a factor in SA-climate links is proposed ***by B.A. Tinsley***. Variations of fair-weather ionosphere-ground electric currents (due to) are thought to play role in formation of weather & climate through controlling processes in clouds.

Here we consider the phenomenon of ***red sprite*** as a possible candidate by which links between SA and the status of meso- & stratosphere can be realized. Sprite is a GEC phenomenon (transient luminous event) realized at altitudes 90 - 45 km above thunderstorms.

Possible scenario - specific features:

1. **Red sprites** essentially consist of **electric streamers** generated in lower ionosphere (**at 80-85 km**) and propagating downward to the stratosphere. The initiation and characteristics of these streamers (and of the sprites, as a whole) may be sensitive to the solar activity, since an expressed response of lower ionosphere to SA exists. Such sensitivity can depend on actual mechanism of streamers generation.

2. The streamers of sprites (actually, in their lower portion below 70 km) presumably play a role in the chemical balance and thermal status in meso- and stratosphere. With the account of 1., there will be a link between solar activity and the meso- and stratosphere characteristics.

3. The significance of such hypothetical link in global scale depends on the rate of sprites over the globe and on the contribution of separate sprites (actually, of their streamers) to meso/stratosphere.

Thus, sprites are considered here as possible ‘transmitters’ of solar activity influences from lower ionosphere (at 80-85 km) to stratosphere.

Sprites [1]

A sprite (Fig.1) is typically created in the middle atmosphere at night after a positive cloud-ground (CG+) lightning discharge in troposphere below.

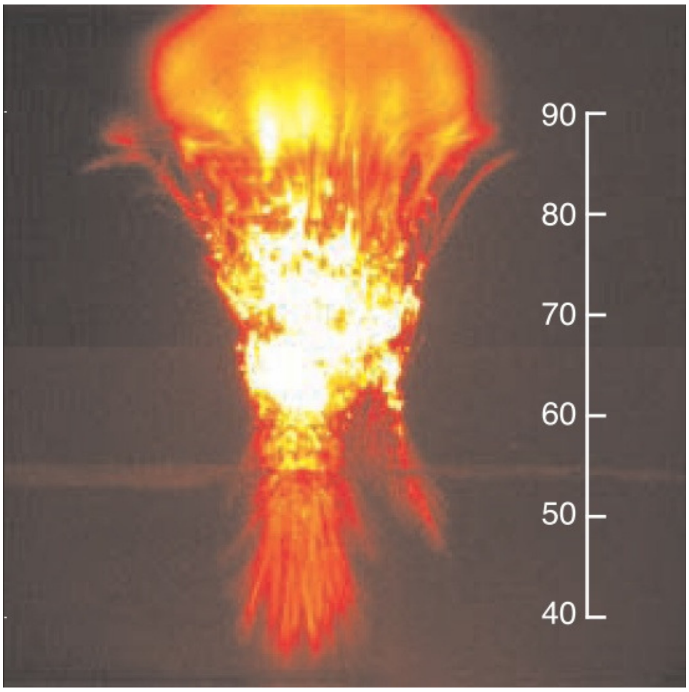


Fig.1. *Photo of a sprite [1]*

Parameters:

Onset: 2-4 ms after the causative lightning

Duration: from few milliseconds to tens (or even hundreds) ms.

Cause: Large post-lightning quasi-electrostatic fields

Main parts: 1. Halo, formed at 85-90 km ~1 ms after the causative lightning discharge; 2) Body (consists of streamers) – generated 2-4 ms after lightning at ~80-45 km.

Spatial dimensions:

- from ~90 down to ~45 км by altitudes;
- transverse size up to 40-50 km;

Luminosity: within 4 orders of magnitude.

The sprite body is presented by a set of positive and negative streamers created and driven by post-lightning quasi-electrostatic fields (QSF).

Typically, sprites occur at night, after a +CG lightning characterized by large charge moment change (>500 C.km) and is accompanied by intense continuous currents.

A sprite begins with a short-living halo formed for ~1 millisecond at 85-90 km. Then positive streamers are generated (within or below the halo - at 75-85 km) and propagate downward due to the strong QSF. When positive streamers reach ~70 km altitude, often upward negative streamers originate from them.

As descend downward, the positive streamers develop by thickness, brightness, etc. They branch to give a hierarchy of numerous downward streamers. Similar (not identical) is the case with negative streamers. The streamers move downward to ~45 km.

Mechanism of sprite generation

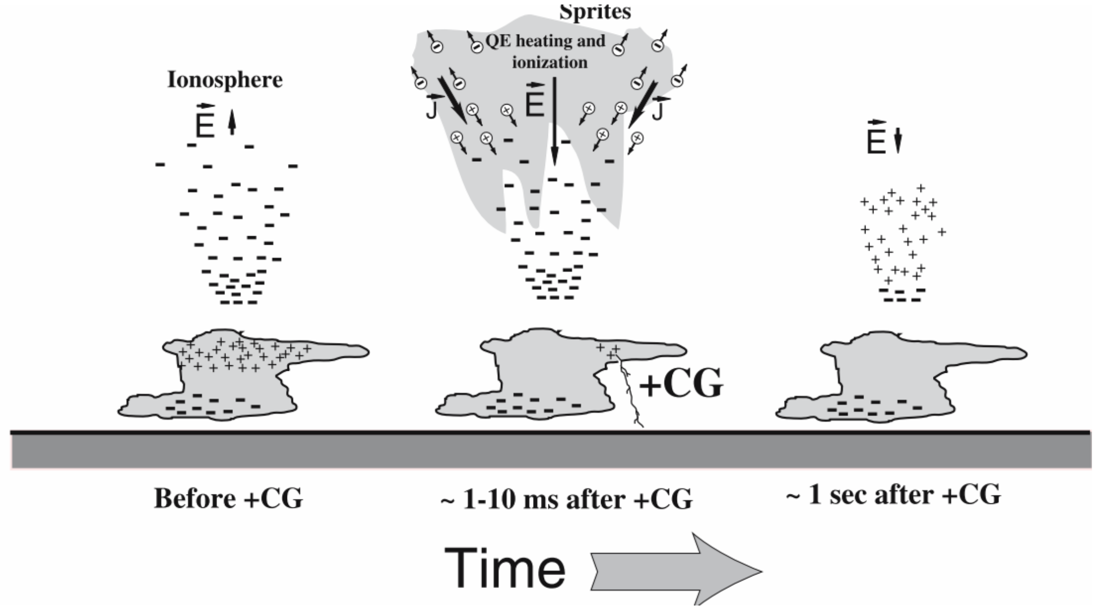


Fig.2. *A sketch of the mechanism of sprite generation in three stages: a) spatial charges distribution before a +CG lightning discharge; b) formation of strong QSF due to re-arangement of charges 1-10 ms after the removal of positive charge from the cloud by +CG lightning; c) spatial charges reach new balance ~1 s after the +CG lightning discharge.*

After a CG+ lightning discharge strong downward transient QSF are created above the thunderstorm due to re-arrangement of spatial electric charges (leading to formation of strong displacement currents). These charges are formed before the lightning discharge due to the conductivity gradient. Large QSF are generated first at higher altitudes (in lower ionosphere), where they produce halo and then positive streamers. The downward propagation of a positive streamer

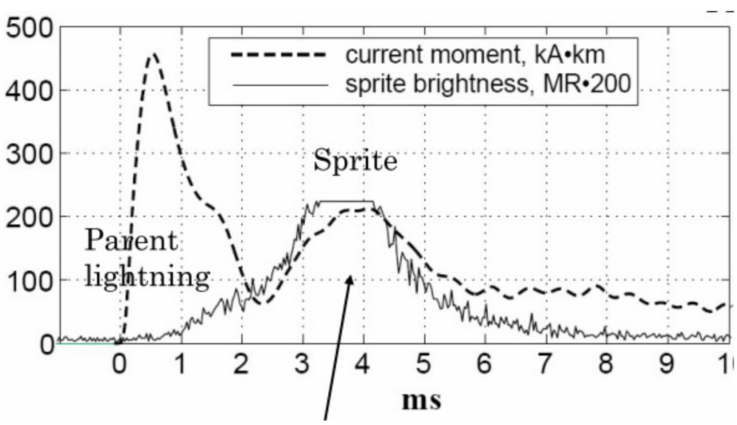


Fig.3. *Comparison of the lightning current moment with the brightness of a sprite generated. Accordance between curves confirms that sprites are produced due to lightning discharges*

Streamers

The streamer is a thin filament of plasma driven as a nonlinear wave of spatial charges in strong electric field E_0. Fig.4a shows a positive streamer: its head has large positive charge of high density (its channel is filled with electrons). Fig.4b describes a streamer as a wave of charges. When the electric field generated in front of the head becomes E_H>~E_0, ionization and photoionization takes place [5] An area of net positive charge remains close before the head after polarization and becomes part of it, thus realizing propagation of streamer along E_0. E_H can rise up to 4 - 7×E_κ (E_κ is the threshold field of the conventional electric breakdown) [7]. Negative streamers are similar but with negative polarity of their heads.

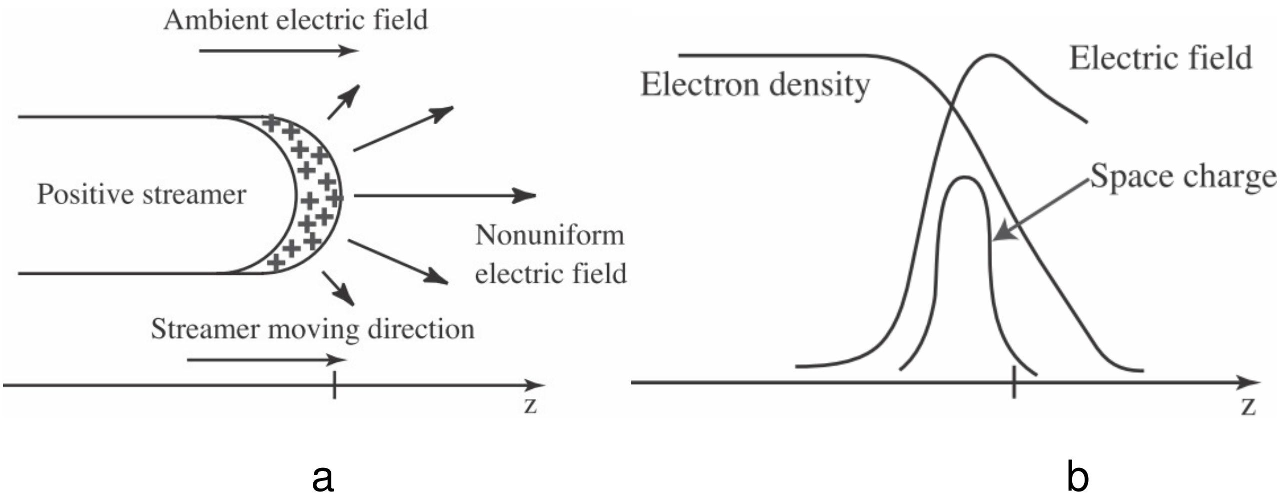


Fig.4. Positive streamer (a); propagation as a non-linear wave of charges (b)

Conditions for propagation of streamers and parameters

A threshold electric field E_{cr} is required for the propagation of streamers (E_{cr+} for a positive and E_{cr-} for a negative streamer). At see level E_{cr+}=440 kV/m, E_{cr-}=1250 kV/m. At higher altitudes E_{cr} decreases as $E_{cr} \propto N$ where N is the atmosphere density. Since E_{cr} decreases with height faster than the peak value of the QSF E, there is an altitude in the lower ionosphere above which the QSF by lightning exceeds the streamer threshold (Fig.5). The condition $E > E_{cr}$ is not sufficient for creation of a streamer. The results for the the QSF E after a +CG lightning obtained by [3] are shown in Fig.5.

The velocity *V* of propagation of streamers can reach ~10% of the speed of light in bright sprites (2 - 3$\times$10^{7} m/s). By these high velocities streamers branch. Initially they accelerate (above 70-65 km) with 0.5 - 1$\times$10^{10} m.s^{-2}, then decelerate. There are also slow streamers (*V* is smaller by one order), In this case they are dim, thinner and do not branch. Streamers are unobservable when initiatiated. A separate streamer, as well as sprites as a whole, may remain obscured [6].

The main streamer characteristics are: the dimensions (transverse size and length); luminosity (depends on transverse size); velocity, acceleration and deceleration; electron & ion density distributions; electric characteristics; branching parameters; residual luminosity.

The number of streamers simultaneously propagating in a sprite within a sprite is typically from hundreds to thousand or more.

Model study of QSF E responsible for sprites [3]

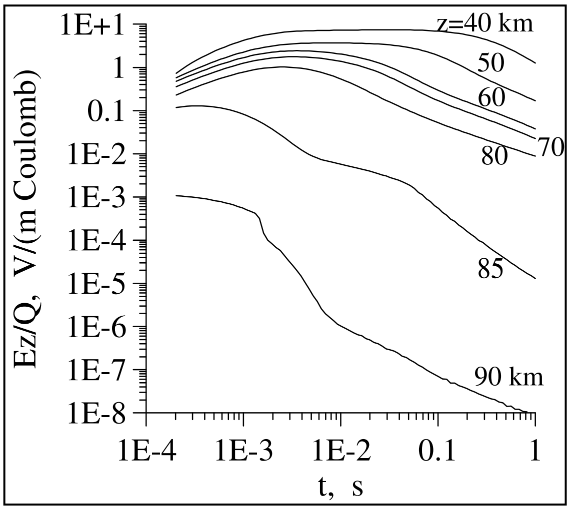
To distributions of QSF **E** after +CG lightning, we solve the equation of continuity of the Maxwell (full) current $\mathbf{j_M} = \mathbf{j_C} + \mathbf{j_D}$, where $\mathbf{j_C}$ and $\mathbf{j_D}$ are the densities of the conduction and displacement currents:

$$\mathbf{div\ (j + j_D) = 0}\ ,$$

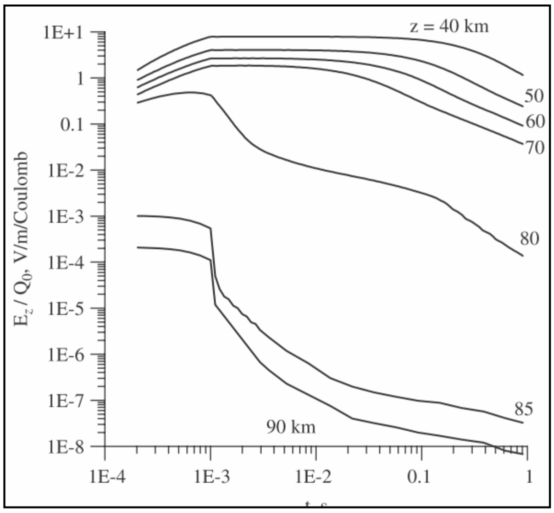
by appropriate boundary conditions. The complex dependence on parameters of both lightning and conductivity is obtained in [3].

Fig.5a,b show variations of QSF E at altitudes 40-90 km as function of time *t* after the lightning discharge beginning by two shown in Fig.6.

Time variations of QSF by two different conductivity profiles



a



b

Fig.5. Time variations of the vertical electric field at altitudes 40 - 90 km above thunderstorm after a +CG lightning discharge for time 1 ms (a, b) by two different conductivity profiles (Fig.5c) [3]. Results are normalized to 1 C of the removed charge.

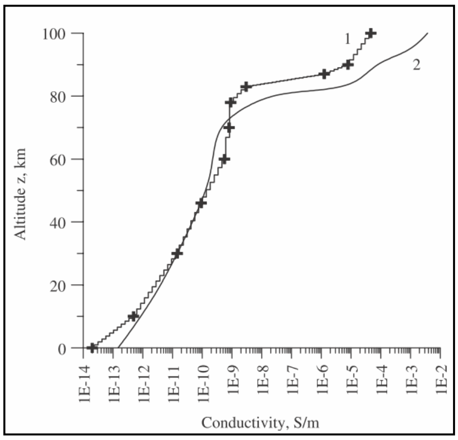


Fig.5c. Conductivity profiles used in Fig.5a,b [3].

Effects of streamers in meso- and stratosphere

As an ionization wave, streamers can have influence in the lower portion of a sprite (at 70 - 40 km). They can have effects to:

1. *The chemistry – the effects are mainly on NO_x and HO_x, and also on the ozone O_3 which is controlled by them. It can also cause increase of the electron density;*
2. *Heating.*

Chemical reactions are realized by streamers at night. They are related to the electric field in the streamer's head.

By $E > 0.5\ E_k$ we have large increase of the density of the constituents considered with the increase of QSF *E*.

Chemical reactions take place in the streamer trace showing residual luminosity 0 these are much continuous in time and influence most of all densities of NO_x и HO_x. The following key reactions take part at night:

1) $N_2 + e \rightarrow N + N^- + e$ (the nitric atom is in basic or in ^2D state);

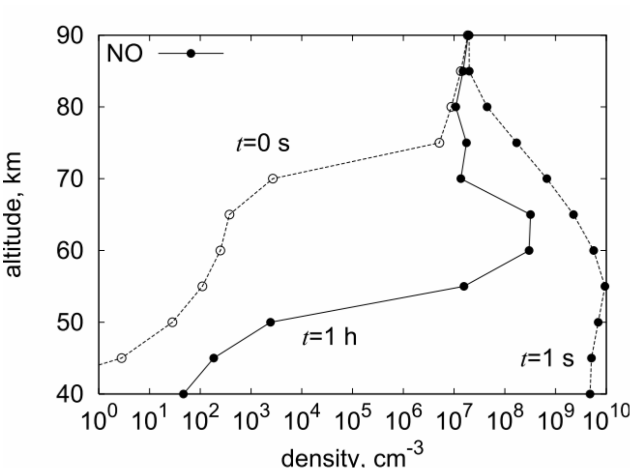
2) $N(2D) + O_2 \rightarrow NO + O$ (after 1): O is in basic, or1D състояние

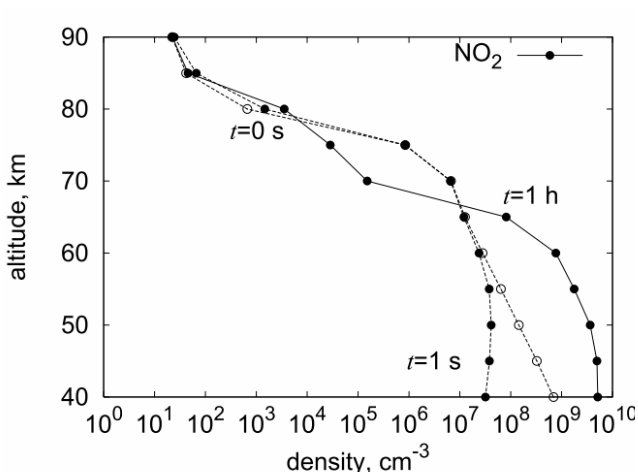
NO is destroyed slowly (in 10^2 - 10^3 s) and can be transported on big distances. At night NO yields NO_2 for hours.

Some theoretical results

• Hiraki, Fukunishi, et al. (2008) [8] report for variations of densities of NO_x, HO_x, O_3 by the effecf of a streamer derived by modeling. The variations caused to NO, NO_2 and O_3 in the time period from t =1 s after initiation of a streamer in a sprite are shown in Fig.6a, b, c (by dashed lines with solid circles) till t =1 hour (solid line). The results at moment t = 0 are shown with dashed line with empty circles.

NO, NO_2, O_3, H_2O_2 in the region 40-70 km have big (8 orders for NO and H, several orders for the rest) and continuouis (~ 1 h) changes. By a transport without losses these large variations will cause significant change in continental scales (for example, for Africa). These estimations are much larger than of other authors (e.g. Enel et al., 2008) due to different boundary conditions used.





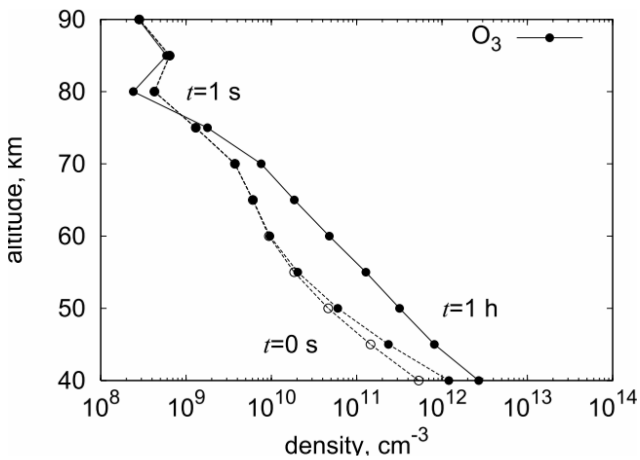
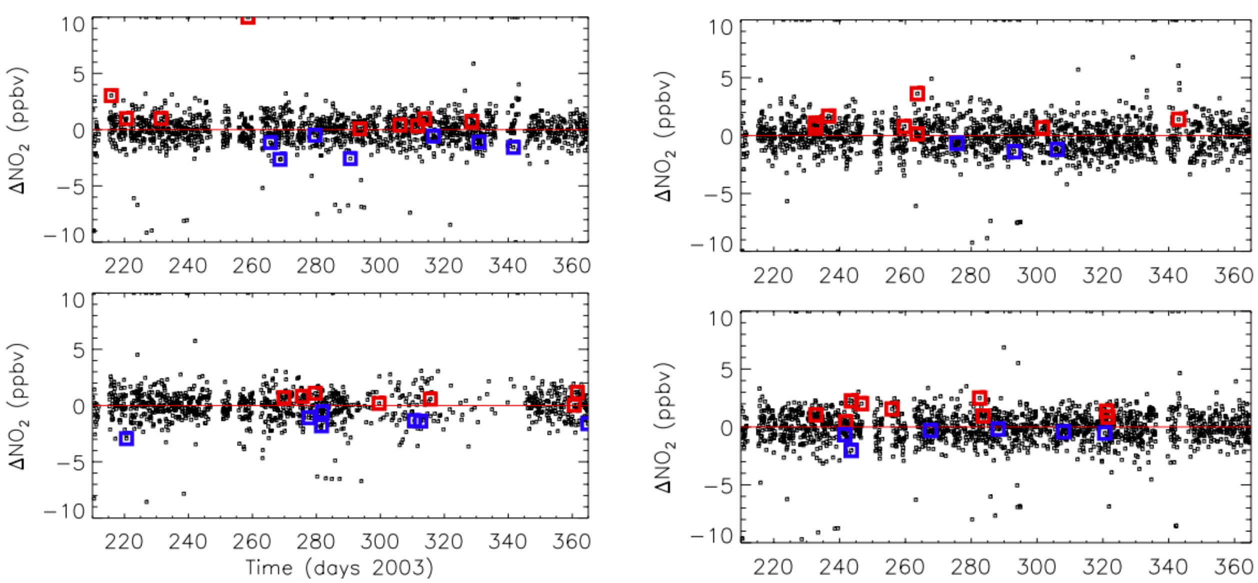


Fig.6. Density profiles of NO (a), NO2 (b), and O3 at times *t* = 0 s, 1 s, and 1 hour after the streamer initiation [8].

Experimental estimations

Arnone et al., (2008) [9] by satellite data from MIPAS/ENVISAT by measurements of NO_2 in the regions of sprite occurrence (by data from WWLLN), for the period from August to December 2003 (graphics below).

Increases of ~10% take place at altitude ~50 km and tens % at 60 km after thundercloud activity (in the summer, predominantly due to tropical regions at 5◦N - 20◦N).



Time series from MIPAS for ΔNO_2 at night (black = background ΔNO_2, color = ΔNO_2 by lightning activity according to WWLLN: red for $\Delta > 0$, blue for $\Delta < 0$) in 5◦ latitudinal intervals at altitude 52 km. The panels correspond to latitude bands from 20◦N–15◦N, 10◦N–5◦N, 5◦N–Equator and Equator–5◦ (top to bottom).

Global rate of sprites

The global rate of sprites on the Earth is estimated to one per minute from the data obtained by instrumental ISUAL onboard the FORMOSAT-2 satellite in period July 2004 - June 2008 [1]. It can be compared to the global lightning rate: 50 per second, by which +CG lightning are few (one or two) per second.

Having in mind the relatively high global rate of sprites and studies on their chemical effects in the meso- and stratosphere, it is reasonable to stay the following question:

Is there a link between solar activity and meso- & stratosphere realized by sprites and streamers?

Two possible ways by which streamers could depend on SA are discussed

A. Influences realized by changes in conductivity in middle atmosphere

- Galactic cosmic rays (GCR) of energies ~10 MeV are modulated by SA. They influence conductivity σ in middle atmosphere below 90 km at night. Thus, long-term variations of conductivity σ with the 11-year solar cycle will take place.

- Since conductivity σ controls the penetration of QSF **E** after lightning and its peak magnitude $\mathbf{E}_{peak}$, its variations will control the onset of sprites under similar conditions concerning QSF sources. Therefore, variations of the global rate of sprites will take place during an 11-year solar cycle, which will lead to small variations of modifications of meso- and stratospheric chemical characteristics.

An estimation of the 11-year changes of conductivity σ at night is obtained by the Ionospheric conductivity model of the World center of geomagnetic data (Kyoto) (above 80 km). These changes are negligible, as seen from the model data for the field-aligned conductivity σ_0 on 1 July in two years: 2001 (of solar maximum) and 2008 (solar minimum).

The conductivity variations at 50-70 km (where streamers branch and have maximum effect) during an 11-year solar cycle are important for streamer propagation. These variations at middle latitudes can be more significant (by few tens of percent or even more). The streamer propagation and branching depend on such variations (streamer branching is a key characteristic of a sprite's lower portion, and is more intense by larger electric fields applied). The mesospheric conductivity depends on the GCR flux, and thus will be larger by solar minimum than by solar maximum. Therefore, the branching and developing of streamers, and, hence, their effects in the meso- and stratosphere will be expressed better by solar maximum than by solar minimum. At this stage of investigation it is difficult to give a correct quantitative estimation of the dependencies considered. Their precise study needs further complex investigations.

2. Forbush decreases can lead to short-period (few days) diminishing of the meso- and stratospheric conductivity. As in 1., enhancement of the rate of sprites, streamers and of their effects can be expected.

Velinov et al. (1974) estimated the relative decrease $\delta q / q$ of the electron production rate during big Forbush decreases not accompanied by strong geomagnetic storms in 1959 and 1960 (during solar activity decrease short after the highest maximum of solar activity in 1958). In four such periods $\delta q / q$ is between 45% and 70%. This means that a significant decrease of meso- and stratospheric conductivity (~tens of percent) will take place. Thus larger QSF will penetrate and streamer propagation will be easier. However, it is difficult to say what will be the effect on the streamer onset.

3. Significant increases of the middle atmosphere conductivity take place during intense solar proton events. The conductivity at 50 - 70 km can increase by several times for many hours (possibly, few days). In such case the peak QSF $\mathbf{E}_{peak}$ at altitudes of interest will be at least several times smaller than in quiet conditions. Production or, at least, propagation of streamers will not be able due to the effective screening of post-lightning electric fields.

B. Possible direct influence of galactic and solar cosmic rays

Such influence would take part if the initiation of streamers involves the role of cosmic rays. This problem is considered in [10].

References

[1] Sentman, D. D., E. M. Wescott, D. L. Osborne, D. L. Hampton, and M. J. Heavner (1995), Geophys. Res. Lett., 22, 1205-1208.

[2] Liu, N., V.P. Pasko, J. Geophys. Res., 109, A04301, doi:10.1029/2003JA010064, 2004.

[3] Tonev, P.T. and P.I.Y. Velinov, J. Atmos. Sol-Terr. Phys, 69, (2007), 2510-2522.

[4] Chen, A. B., Kuo, C.-L., et al., J. Geophys. Res., 113, A08306, doi:10.1029/2008JA013101, 2008.

[5] Li, J., S. and A. Cummer, 2009, Geophys. res. lett., 36, L10812, 2009.

[6] Pasko, V.P., et al., Surv Geophys (2013) 34:797-830

[7] Vitello, P. A., B. M. Penetrante, etc. Phys. Rev. E, 49, 5574-5598, 1994.

[8] Hiraki, Y., Y. Kasai, and H. Fukunishi, Atmos. Chem. Phys., 8, 3919–3928, 2008.

[9] Arnone, E., P. Berg, et al., Adv. Geosci., 13, 37–43, 2008.

[10] Tonev, P.T., Conditions for initiation and propagation of electric streamers in lower ionosphere above thunderstorms at night, Rep. on 6-th Int. Conference ‘Solar Influences on the Magnetosphere, Ionosphere and Atmosphere’, Sunny Beach, Bulgaria 26-30 May 2014.