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Influence of solar activity on red sprites and on vertical coupling in the system stratosphere–mesosphere

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ABSTRACT

The positive downward propagating streamers of sprites are considered as factors of vertical coupling in middle atmosphere. Sprites are initiated in the lower ionosphere (at 75–85 km) and their streamers propagate in the mesosphere and upper stratosphere where the solar activity (SA) can have significant influence. The problem considered by us is whether sprites are sensitive to the solar activity. Different possible ways of such influence are considered. They concern: i) relations between solar activity and the occurrence of sprite-producing lightning discharges; ii) sensitivity of streamer inception to solar variability; iii) 11-year variations of conductivity in the night-time mesosphere and stratosphere during solar cycle due to modulation of the galactic cosmic ray flux by solar activity, which can lead to changes in sprite-driving electric fields, and therefore, in sprites. Accounting for the effects of sprites on minor constituents (in particular NO_x), a link between SA level and the che^mical balance in the mesosphere and stratosphere is considered, as well. With respect to this we study by modeling the response of the sprite-driving electric fields to SA variations with the account to a complex of parameters of sprite-producing lightning discharges and atmospheric conductivity. The lightning-driven electric fields needed for streamer propagation show minor dependence on conductivity changes caused by variations in cosmic ray flux during a solar cycle. The long-term changes in sprite's lower boundary by different parameters of lightning discharges and atmospheric conductivity parameters are estimated. During solar minimum, of the vertical dimension of sprites increases by up to 1.5 km than those during solar maximum. We estimate also the effect of the reduction of conductivity in thunderclouds with respect to the adjacent air. Reduction of cloud conductivity by a factor of 5–10 leads to larger vertical dimension of sprites due to descending of the sprite lower boundary by up to 5 km related to the case of unmodified cloud conductivity. The solar variability has significantly bigger effect on the sprite vertical dimension by larger charge moment change of the parental lightning discharge and by large reduction of the cloud conductivity.

1. Introduction

Sprites are transient luminous events which occur in the height interval from ~90 down to ~40 km above nighttime thunderstorms (Sentman et al., 1995). These events are driven by strong quasi-static (QS) electric fields generated in this region usually after positive (typically) cloud-to-ground (+CG) lightning discharges. The mechanisms of sprites and their role in the planetary atmosphere have been intensively studied since their discovery in 1989 (Pasko et al., 1997, 2012, 2013; Rycroft, 2006; Pasko, 2006; Surkov and Hayakawa, 2012). Sometimes sprites appear as sequence of two events: a sprite-halo (a descending structure of weak diffuse glow) at altitudes 85–90 km whose duration is about one millisecond, followed by the essential sprite streamer phase initiated in the region at ~75–85 km and below. In this phase a net structure of positive (propagating downwards) and, sometimes (in carrot sprites) also negative (propagating upwards) streamers is formed. The sprite streamers are first observed by Gerken and Inan (2003). These originate from a single (or several initial) streamer by branching. The initial streamers are usually positive, but they may be also double-headed ones (of both polarities) (Qin et al., 2013). Sprite-halos and sprite streamer are closely interrelated, as both are driven by quasi-static electric fields produced by lightning. According to Qin et al. (2013), the absence of an observable halo preceding a sprite does not mean actually that there is no halo: it may be sub-visual.

The interrelations between the sprite-halo and sprite streamers form the background of mechanisms of inception of sprite streamers which are not fully understood yet (Pasko et al., 2013). The problems of the onset and development of sprite streamers are

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Notation

$E_k(z)$, E_{k0} Breakdown electric field at altitude z and at the ground level
$E_{cr}^{\pm}(z)$, $E_{cr0}^{\pm}$ Threshold field of positive/negative streamer propagation at altitude z and at ground level
$N(z)$, N_o Atmospheric neutral density at altitudes z and at ground level
z_T Streamer termination height
$\Delta z_T = z_{Tmax} - z_{Tmin}$ Change of streamer termination height by transition from minimum to maximum SA
q_{max}, q_{min} Ionization rate during SA maximum and minimum
σ_{max}, σ_{min} Conductivity during SA maximum and minimum
Q_0, $Q(t)$ Initial cloud charge; the remained charge during lightning discharge at time t
z_Q Altitude of the charge
$Q_0 z_Q$ Charge moment change of a cloud-to-ground lightning discharge
$\rho_Q(r)$ Distribution of the cloud charge density at the surface $z = z_Q$ (C m^{-2})
ρ Density of the spatial charges
τ_L Lightning discharge time
h_{tran} Altitude at which the distance between electrons is equal to the radius of an electron avalanche at the moment of avalanche-to-streamer transition
$\mathbf{E}$, E Vector of the electric field from lightning; vertical electric field above the discharge by absolute value
$\boldsymbol{E_{peak}(z)}$ The peak magnitude reached by time by the electric field E at altitude z
j, j_D, j_M Densities of: electric current; displacement current; Maxwell's current
(r, φ, z) Cylindrical coordinates used in modeling
τ_R Relaxation time of a free electric charge (s)
$C_E = E_{max}/E_{min}$ Relative change of the peak electric field by transition from minimum to maximum SA.
H_E, H_{Ecr} Scale heights of $E_{peak}(z)$ and of $E_{cr}^{+}(z)$
H_σ Average scale height of conductivity profile between the altitude z_Q of the charge in the cloud and a reference altitude Z (km)
$\sigma_{exp}(z)$ Exponential conductivity profile with scale height H_σ (m)
R_B, R_A Columnar resistances in intervals $[0, z_Q]$ and $[z_Q$, 60 km$]$ when the conductivity profile is $\sigma(z)$
R_{Bexp}, R_{Aexp} Columnar resistances in intervals $[0, z_Q]$ and $[z_Q$, 60 km$]$ when the conductivity profile is $\sigma_{exp}(z)$
C_c Correction coefficient to E_{peak} for the inaccuracy introduced to the total free negative charge above the charge Q_0 by changing conductivity profile $\sigma(z)$ with the approximate profile $\sigma_{exp}(z)$
ζ Scaled altitude $= z/H_S$ (dimensionless)
ζ_Q Scaled altitude of the charge in the cloud $= z_Q/H_S$ (dimensionless)
ζ_L Scaled lightning discharge time $\zeta_L = \ln(\tau_{R0}/\tau_L)$ where τ_{R0} is the charge relaxation time at ground level $z = 0$ with conductivity profile $\sigma_{exp}(z)$
P Scaled E_{peak} depending on the scaled parameters ζ, ζ_Q, ζ_L
H_P Scale height of $P(z)$ profile (dimensionless)

considered in a series of publications, e.g. Luque and Ebert (2009), Qin et al. (2011), Liu (2012), da Silva and Sao Sabbas (2013), Qin and Pasko (2015) discussed later in this paper.

The role of sprites in the atmospheric processes is not thoroughly revealed by now. Sprites are considered as elements of the global atmospheric electric circuit (Rycroft et al., 2007, 2008, 2012). It is suggested, as well, that sprites may affect the chemical balance in the mesosphere and the upper stratosphere locally or even on regional scales (Sentman et al., 2008; Arnone et al., 2008; Hiraki et al., 2008; Enel et al., 2008), accounting for their global rate (1–3 per minute), the volume of a single sprite (thousands of cubic kilometers), and their specific irregular distribution over the planet (Chern et al., 2003; Chen et al., 2008; Ignacollo et al., 2006). Sentman et al. (2008) conducted the first comprehensive study of the chemical effects produced by the head of a sprite streamer at an altitude of 70 km considering more than 80 species and 800 reactions. According to Sentman et al. (2008), a single streamer can produce 5×10^{19} NO molecules. On the basis of an electron kinetics model with the account to the intense electric field and high electron density at the streamer head, Hiraki et al. (2008) find that the passage of a sprite streamer initiates a cascade of reactions and causes perturbation of the densities of minor species through ion-neutral reactions. The authors show that the streamer causes pronounced (several orders of magnitude) increase of NO and NO_2 densities which persist for 1 h around 60 km altitude. Large increase of O_3, H, and OH (several times) is revealed, as well. Hiraki et al. (2008) conclude that sprites can have at least local impact on nighttime chemistry. Statistically significant enhancement of NO_2 in the lower mesosphere in the regions of high lightning activity at nighttime compared to the background NO_2 density is also detected from experimental data on a scale of hundreds of kilometers (Arnone et al., 2008). On the basis of nighttime observations of NO_2 Rodger et al. (2008) find no significant variations in NO_x due to sprites on regional scales or beyond, and conclude that such variations may take place at most on local scales.

The frequency occurrence rate and other sprite parameters could be sensitive to the solar activity (SA) on the solar cycle timescale. The mesosphere and upper stratosphere, where the sprites act, respond to SA by long-term variations of the ionization rate (Usoskin et al., 2010; Velinov and Mateev, 1990a,b) and thus, by related changes in the electron and ion densities and conductivity. It is, therefore, reasonable to consider the problem of possible long-term (11-year) changes of conditions which can be responsible for sprite initiation and variations of the sprite streamer parameters due to the SA variations, and of the level of effects of these changes (if any) on the atmospheric chemistry. If significant dependences take place, they would constitute a link between the solar activity and the chemical state of the mesosphere and upper stratosphere.

The night-time electron and ion densities and conductivity at altitudes 40–70 km at nighttime are formed mainly by the galactic cosmic ray (GCR) flux (Velinov et al., 1974; Heaps, 1978; Usoskin et al., 2009, 2010), and are thus modulated by SA. The ionization rate by GCR flux at these altitudes during solar minimum is much larger than by solar maxiumum by a factor which is a function of the latitude and altitude: it is close to 100% above 50–55° latitude, and is only several percent at the equator. This difference in the ionization rate leads to significant long-term variations of electron-ion densities and conductivity: it can be tens of percent bigger during solar minimum than during solar maximum (Velinov and Mateev, 1990a,b).

The purpose of this work is to clarify the question whether (and how much) sprites are influenced by SA variations on the solar