Toward better understanding of sprite streamers: initiation, morphology and polarity asymmetry

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The goal of this tutorial talk is to provide an introduction to physics of gas discharges as relevant to interpretation of morphological features observed in large scale electrical discharges termed sprites and sprite halos that are produced at mesospheric and lower ionospheric altitudes in the Earth's atmosphere by lightning. We will introduce parameters typically used for quantitative description of electron avalanches and discuss importance of space charge effects on different spatial scales, including sprite halos (exhibiting 10s of km transverse extents) and sprite streamers (requiring sub-meter resolution for accurate description). The special emphasis will be placed on interpretation of initiation and development of sprite streamers observed in high-speed video observations and critical review of the most recent modeling efforts related to these observations.

1. Introduction

Sprites are large-scale transient luminous events that are produced at altitudes ~40-90 km by lightning discharges [1]. They consist of a large number of vertically oriented filamentary plasma structures referred to as sprite streamers [2]. Initially sprites also often exhibit a brief descending diffuse glow with an upwardly concave shape, referred to as sprite halo [3]. In the next section we include representative examples of outstanding issues in sprite theory. An extensive recent review of literature published on sprites can be found in [4].

2. Outstanding issues in sprite modeling

The charge moment change Qh_Q (i.e., charge removed by lightning Q times the altitude from which it was removed h_Q) represents the key parameter, which is used to measure the strength of lightning in terms of sprite production potential [5]. The impulsiveness of charge transfer by lightning (i.e., during first 2 ms) as well as the follow up charge transferred by a lightning continuing current on time scales of 10s of ms, both significantly affect large scale dynamics of electric field at high altitudes, and sprite initiation processes [5]. The lightning-driven electric fields not only initiate sprite streamers at high altitudes but also control their propagation to lower altitudes until termination [6]. The charge moment change dynamics derived from electromagnetic remote sensing of lightning can be used to infer the background lightning-driven electric fields during the full extent of downward propagation of sprite streamers [6]. Recent work also indicates a possible importance of electron detachment processes for initiation of long-delayed sprites [7] and in definition of time dynamics of sprite halo [8], in particular suggesting that additional downward progression of sprite halo due to the electron detachment may explain initiation of some sprites at altitudes as low as 65-70 km [8].

Streamers are needle-shaped filaments of ionization embedded in originally cold (near room temperature) air and driven by strong electric fields due to charge separation in their heads. In this tutorial we will provide a review of various properties of streamers, including fields required for their initiation and propagation, and similarity relationships allowing scaling of streamer parameters as a function of gas pressure for the purposes of interpretation of sprite discharges.

Luque and Ebert [9] have recently reported a high resolution modeling of inception of sprite streamers as a result of sharpening and collapse of screening-ionization wave associated with sprite halo. The streamer emerged as a result of halo dynamics on the axis of symmetry in a two-dimensional axisymmetric plasma fluid model that employed a non-uniform, dynamically adapted computational grid [9]. The transverse dimension of the modeled streamer was on the order of 1 km, and its time dynamics was resolved on a fine grid with ≥ 3 m spatial resolution [9]. This result is qualitatively similar to the dynamics reported in early low resolution sprite modeling in which columns of ionization with transverse extent on the order of 10 km were observed to emerge from upwardly concave regions of sprites and to propagate down to altitudes ~45 km [10]. We note that although the upwardly concave regions of luminosity forming during sprite development were fully resolved and quantitatively described in early papers [e.g., 11], the name sprite halo was introduced several years later when these events, driven primarily by quasistatic electric fields, were discovered, clearly identified and separated from elves phenomenon using comparisons of high-speed video observations and fully electromagnetic modeling (see discussion in [3]). A difficulty of both the early [10] and more recent [9] modeling is that streamers appear in these models as a continuous process of halo development, while in many existing high resolution photometric and video records the sprite streamers exhibit significant spatial (both vertical and horizontal) as well as temporal separations with respect to position and timing of the sprite halo (see [12] and references therein]). The asymmetry in initiation of sprite streamers by cloud-to-ground lightning discharges (CGs) with different polarities, and sprite streamers triggered by cloud-to-ground lightning with very low charge moment changes are also not reproduced in [9,10]. Additionally, Qin et al. [12] recently indicated that the collapse of sprite halo reported in [9,10] is due to numerical instability, that can be somewhat postponed but not eliminated by increasing resolution of numerical grid.

In order to monitor the inception of sprite streamers, Qin et al. [12] have used an improved avalanche-to-streamer transition criterion, and have investigated the response of the lower ionosphere to the charge moment changes induced by lightning discharges as a system of avalanches. An analysis of the origin of polarity asymmetry between positive (+CG) and negative (-CG) lightning discharges in triggering of sprite streamers indicated that the vertical extent of streamer initiation region (SIR) created by a -CG was smaller than the SIR created by the opposite +CG that corresponded to the same charge moment change [12]. Qin et al. [12] also demonstrated as part of the asymmetry study that the triggering of long-delayed sprites is a unique property of halos produced by +CGs due to the formation of a long-lasting high field region, that can be significantly enlarged by the lightning continuing current. Qin et al. [12] demonstrated importance of initial electron inhomogeneities in the lower ionosphere for initiation of sprite streamers. The initial inhomogeneities were discussed in many early papers on sprite modeling (see list in [4]). The approach of Qin et al. [12] is different as it considers the seed electrons in the framework of competition of many avalanches in which only a perturbation with a larger number of initial electrons reaches the avalanche-to-streamer transition, becomes dominant in defining the macroscopic electric field, and also eventually becomes observable.

The sprite streamers initiate from electron inhomogeneities in the lower ionosphere and undergo significant acceleration and expansion growth before their optical emissions become observable. Qin et al. [13] demonstrated recently that electron inhomogeneities located at high altitudes in the region of sprite halo, which may be sub-visual, only transform into single-headed downward streamers, and corresponding upward streamers quickly merge into the sprite halo due to fast relaxation of lightning induced electric field. In contrast, the inhomogeneities located at and below the lower edge of the sprite halo, where a high field region persists significantly longer, can transform into double-headed streamers [13].

The above-mentioned exponential expansion and acceleration of streamers is also an important effect that is accompanied by exponential growth of electric potential differences in the streamer heads [14]. These differences have significant implications for the energy that thermal runaway electrons can gain once created and quantitative results presented in [14] indicate that under realistic conditions associated with lightning leaders, streamers can create ~100 keV electrons that are capable of further accelerating to several MeVs energies needed for explanation of terrestrial gamma ray flashes in the Earth's atmosphere (see [15] and references therein).

3. References

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