Formation of single and double-headed streamers in sprite-halo events

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[1]   Sprite streamers initiate from electron inhomogeneities in the lower ionosphere and undergo significant acceleration and expansion growth before their optical emissions become observable. It is shown 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. The upward negative streamer heads start from the existing bright structures in the channel of previous downward streamers as observed by Cummer et al. (2006), McHarg et al. (2007), and Stenbaek-Nielsen and McHarg (2008) because at low altitudes, electron density enhancements associated with these channels are much stronger than in preexisting inhomogeneities in the ambient ionosphere. **Citation:** Qin, J., S. Celestin, and V. P. Pasko (2012), Formation of single and double-headed streamers in sprite-halo events, *Geophys. Res. Lett.*, *39*, L05810, doi:10.1029/2012GL051088.

1.   Introduction

[2]   Sprites [*Sentman et al.*, 1995] often exhibit a brief descending high-altitude diffuse glow, referred to as a sprite halo [e.g., *Barrington-Leigh et al.*, 2001], and develop into fine-structured filaments at lower altitudes [e.g., *Stanley et al.*, 1999; *Stenbaek-Nielsen et al.*, 2000] commonly referred to as sprite streamers [*Pasko et al.*, 1998]. *Barrington-Leigh et al.* [2001] identified that sprite halos are entirely produced by quasi-electrostatic fields induced by cloud-to-ground lightning discharges (CGs). The downward motion of sprite halos is mainly due to enhancement of mesospheric electric field by flowing lightning current in the underlying thundercloud, and is slightly affected by the space charge inside the halos [*Qin et al.*, 2011].

[3]   Since the first high-speed video observations of sprites, it has been noted by *Stanley et al.* [1999] and later confirmed by *Cummer et al.* [2006] that sprite streamers were primarily downward in some cases and both upward and downward with the upper region being more diffuse in other cases. More recently, sprite images recorded at 10,000 fps with 50 μs exposure time revealed significant sub-millisecond dynamics of the early stage of streamer formation [*McHarg et al.*, 2007; *Stenbaek-Nielsen and McHarg*, 2008]. *McHarg et al.* [2007] found that carrot sprites start as columnar sprites, but with subsequent upward propagating streamer heads, which, when present, always start later and from a lower altitude than that of the original downward propagating streamers, and appear to start from existing bright structures in the sprite body. *Stenbaek-Nielsen and McHarg* [2008] analyzed the same dataset and indicated that the delay between the downward and the upward propagating streamers appeared to be typically in the 0.5–2.0 ms range, and the onset altitude of the first downward propagating streamer head was ~80 km.

[4]   Sprites with extensive vertical structures are scaled analogs of streamers observed at atmospheric pressure in laboratory [*Pasko et al.*, 1998; *Liu and Pasko*, 2004]. *Qin et al.* [2011] studied the inception mechanism of streamers from sprite-halo events and pointed out that sprite streamers were initiated from competing electron inhomogeneities in the lower ionosphere under application of the lightning-induced electric field, whose altitude structuring and magnitude were determined by the lightning current waveform and the ambient electron density profile. Although it has been well established in previous model results that a single-headed streamer tends to form if the initial high electron density perturbation is placed adjacent to an electrode, and a double-headed streamer will develop if the initial perturbation is placed between two electrodes [e.g., *Vitello et al.*, 1994; *Liu and Pasko*, 2004], up to the present, there has been no successful explanation of the formation of single and double-headed sprite streamers. The goal of the present work is to provide quantitative modeling interpretation and explanation of some morphological characteristics of initial sprite streamers reported by *Cummer et al.* [2006], *McHarg et al.* [2007], and *Stenbaek-Nielsen and McHarg* [2008].

2.   Model

[5]   A two-dimensional (2D) cylindrically symmetric plasma fluid model is used to simulate the dynamics of a sprite halo and sprite streamers. In this model, the motion of charged species is simulated by solving the drift-diffusion equations for electrons and ions coupled with Poisson's equation [e.g., *Qin et al.*, 2011, equations (3)–(6)]. The charged species transport equations are solved using a flux-corrected transport (FCT) technique [*Zalesak*, 1979] that combines an eighth-order scheme for the high-order fluxes and a donor cell scheme for the low-order fluxes. Photoionization processes are included using the three-group SP$_3$ model developed by *Bourdon et al.* [2007], and the drift of ions is incorporated assuming the mobility of ions as a function of altitude $\mu_i \simeq 2.3 N_0/N$ cm^2/V/s [*Davies*, 1983].

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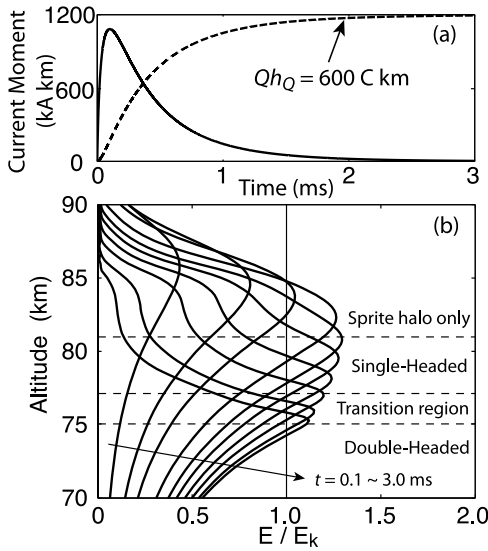
Figure 1. (a) Current waveform for a +CG of 600 C km. (b) Reduced electric field E_{halo}/E_k along the axis of symmetry at t = 0.1, 0.2, 0.3, 0.5, 0.7, 0.9, 1.2, 1.6, 2.3, 3.0 ms in the upper atmosphere produced by the +CG.

We assume that the electron density profile is [*Wait and Spies*, 1964]:

$$n_e(h) = 1.43 \times 10^{13} e^{-0.15h'} e^{(\beta - 0.15)(h-h')} \quad (1)$$

where h' = 85 km and β = 0.5 km^{-1}. The positive ion density equals the electron density at high altitudes where electron density is higher than 10^8 m^{-3}, and is 10^8 m^{-3} at low altitudes [e.g., *Narcisi*, 1973]. Negative ion density is then calculated based on charge neutrality.

[6] We divide the simulation of a sprite-halo event into two steps. In the first step, namely the sprite-halo modeling, the simulation domain extends from the ground up to 95 km, with a radius of 95 km. It is discretized using a numerical cylindrical grid (r, z) with 401 × 401 points corresponding to a spatial resolution of 237.5 m. Perfectly conducting boundaries of the simulation domain are used. We keep complete track of the electric field $\vec{E}_{halo}(r,z,t)$ in the upper atmosphere at this step. Then, in the second step, we use this field as an externally applied electric field in sprite streamer simulations. The simulation domain of sprite streamers extends 2 km vertically and has a radius of 0.25 km. The variation of air density with altitude is accounted for. For streamer simulations, we use open boundary conditions for the electric field [*Liu and Pasko*, 2006], and the domain is discretized using a cartesian grid of 5201 × 651 grid points, corresponding to a spatial resolution of ∼0.38 m in order to simulate accurately the streamer dynamics. The initial electron and ion densities in the streamer simulation domain are the same as these in the corresponding region in sprite-halo modeling.

[7] In order to monitor the possible streamer initiation, we place a Gaussian inhomogeneity with peak electron density of 2×10^9 m^{-3} and characteristic size of 30 m at different altitudes on the axis of the halo, and use a streamer model to simulate the evolution of this test inhomogeneity under application of $\vec{E}_{halo}(r,z,t)$. We chose the peak density to

be 2×10^9 m^{-3} because this inhomogeneity can transform into a double-headed streamer at low altitudes (∼75 km in this study). We kept parameters of inhomogeneity the same at all altitudes in order to simplify the discussion. Generally, if the size of the inhomogeneity is larger, a lower amplitude of the peak electron density is required for streamer initiation. We assume that during the initial stage of sprite streamer development, the mesospheric electric field $\vec{E}_{halo}(r,z,t)$ would not be significantly affected by the space charge effects of streamers.

3. Results

[8] Figure 1a shows the model current waveform used in this study that is adopted from *Cho and Rycroft* [1998]. The current moment is given by: $Ih_Q(t) = Qh_Q \frac{1}{12} \frac{1}{\tau_0} \left(\frac{t}{\tau_0}\right) \exp\left[-\left(\frac{t}{\tau_0}\right)^{1/2}\right]$ where the charge moment change is Qh_Q = 600 C km and τ_0 = 25 μs. Figure 1b shows the reduced electric field (i.e., E_{halo}/E_k) on the axis of the halo calculated in the sprite-halo modeling (i.e., during the first modeling step). Without considering streamer formation, the peak luminosity of the sprite halo in a horizontal line of sight is $\simeq 10^7$ R at 81 km at t = 0.9 ms. For convenience, in Figure 1b we mark the regions in which only sprite halo, single-headed streamers, both single and double-headed streamers (i.e., "transition region"), or double-headed streamers can be respectively produced. The exact division into different streamer initiation regions is determined by the lightning current waveform, electron density profile and strength of the electron inhomogeneity (see Discussion).

[9] Figure 2a shows the simulated emissions of the first positive band system of N_2 (1PN$_2$) for a streamer initiated from an inhomogeneity placed at 75.25 km. The acceleration and expansion dynamics of the downward positive streamer head is similar to that in previous observations and simulations [e.g., *Stenbaek-Nielsen et al.*, 2007; *Liu et al.*, 2009]. The luminosity of the sprite streamers in their early stage of development (∼10^8 R) is consistent with that of *Liu et al.* [2009]. *Liu et al.* [2009] demonstrate that the brightness of a sprite streamer head increases exponentially in time and can span more than 4 orders of magnitude in a very short period of about 1.25 ms, and the rate of increase depends on the magnitude of the applied electric field. Negative streamer head also appears, moving up towards the sprite halo, and its initiation is much slower than that of the positive head. Optical emissions near the upper boundary of the simulation domain are due to the sprite halo. We see that the halo emissions at t = 2.2 ms are still dim in this region, which is the lower edge of the halo (see Figure 1b).

[10] As shown in Figure 2b, in the case of an inhomogeneity placed at higher 77.25 km altitude, an intense negative streamer cannot develop. This results in a single-headed downward streamer. Halo emissions close to the upper boundary are already intense at $t \sim 1.5$ ms, which indicates that electron density in this region increases quickly and electric field relaxes fast (see Figure 1b). Within such a fast relaxation region, the negative streamer head can not survive (see Figure 2d).

[11] Figures 2c–2e show that the negative streamers are not stable if the inhomogeneities are placed at altitudes higher than 76.25 km. Figure 2f shows that the electron
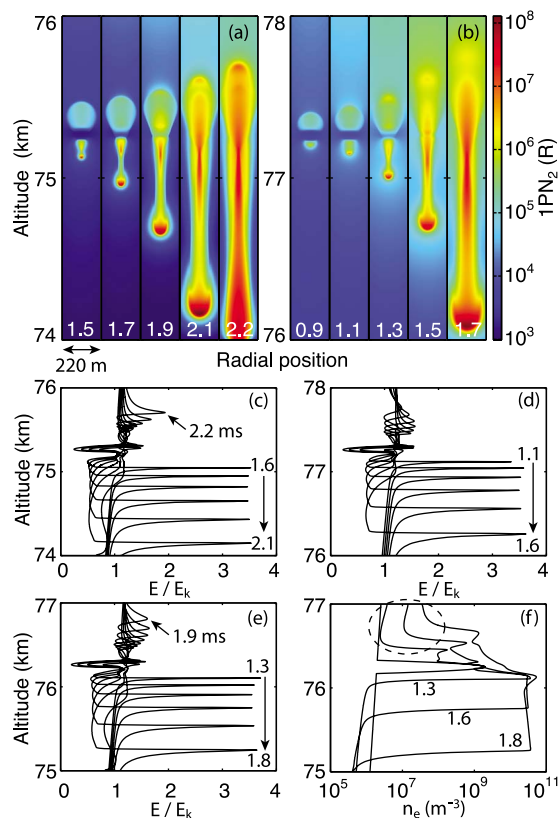
Figure 2. (a, b) Cross-sectional views of optical emissions produced by streamers initiated from inhomogeneities that are located at 75.25 and 77.25 km, respectively. (c, d) Electric field on the axis of symmetry for streamers initiated at 75.25 and 77.25 km, respectively. (e, f) Electric field and electron density on the axis of symmetry for a streamer initiated at 76.25 km. The dashed ellipse in Figure 2f highlights a region where ambient electron density increases rapidly due to sprite halo. Numerical values inside each panel are the moments of time in milliseconds.

density above/around the negative streamer head (highlighted with a dashed ellipse) increases rapidly due to the sprite halo. In the case of inhomogeneities placed at 77.25/75.25 km, the increase of ambient electron density above/around the upward head is faster/slower than that in Figure 2f (not shown in Figure 2). Rapid increase of electron density leads to fast screening of the lightning-induced electric field. We tested in our simulations that stronger inhomogeneity (i.e., higher amplitude of peak density and larger size), lower ambient electron density (e.g., $h' = 87$ km and $\beta = 0.5$ km^{-1}), and larger charge moment change, lead to easier formation of double-headed streamers.

4. Discussion

4.1. Formation of Single and Double-Headed Sprite Streamers

[12] In the modeled sprite-halo event, above $\sim$81 km (marked as "sprite halo only" in Figure 1b), the ambient electron density is higher than $\sim$10^7 m^{-3} and rapidly increases up to $\sim$4 $\times$ 10^7 m^{-3} within 2 ms, which is only two orders of magnitude lower than the electron density

inside a streamer body at 81 km ($\sim$10^{10} m^{-3}). The dielectric relaxation time $\tau \lesssim 1.0$ ms, and the sprite halo above $\sim$81 km quickly becomes equipotential effectively serving as lower ionospheric equipotential boundary. We tested in our simulations that even under conditions of introduction of an inhomogeneity with peak density of 2×10^{10} m^{-3} that is as high as that in a streamer body above $\sim$81 km, streamers cannot be triggered, due to fast relaxation of the electric field. The inhomogeneity merges into the sprite halo quickly and only leads to enhancement of the local luminosity. Between $\sim$77 and $\sim$81 km (marked as "single-headed" region in Figure 1b), single-headed downward positive streamers can develop if strong inhomogeneities are placed, as demonstrated in Figure 2b. In the "transition region" between 75 and 77 km (see Figure 1b), double-headed streamers can be initiated from strong inhomogeneities as shown in Figure 2a. Nevertheless, our simulations show that a relatively weak inhomogeneity (e.g., with peak electron density of 2×10^8 m^{-3}) will still lead to formation of a single-headed streamer in this region. Below $\sim$75 km is the "double-headed" region where sprite streamers are moving both downward and upward once initiated. We note that the electron density in the two lower regions decreases at the initial and increases at later moments of time, due to the slow establishment of mesospheric electric field as shown in Figure 1b. The attachment process that reduces ambient electron density is favorable for streamer initiation (see discussions by *Qin et al.* [2011]).

4.2. Interpretation of the Formation of Sprite Streamers in Different Regions of a Sprite Halo

[13] For a given combination of current waveform, which defines Ih_Q and Qh_Q, and electron density profile, the upper atmosphere can be divided into two regions: in the upper region where $E > E_k$, the ionization processes are dominant for a brief period, whereas in the lower region where $E < E_k$, the attachment processes are dominant all the time. Based on the discussion in Section 4.1, we conclude that the transition zone between these two altitude regions, where a region with $E \approx E_k$ persists (see Figure 1b and also *Qin et al.* [2011, Figure 4]), is the double-headed streamer initiation region SIR defined by *Qin et al.* [2011]). Larger charge moment change leads to lower altitudes for this transition zone. For altitudes far above the transition zone, high ambient conductivity and conductivity enhancement due to ionization processes lead to fast screening of the lightning-induced electric field, and thus impede the formation of upward streamer head. However, in the studied case, below $\sim$81 km, it is still possible to initiate downward positive streamer heads. The appearance of downward positive heads but absence of upward negative heads in the "single-headed" region is interpreted as following: (1) Below 81 km, ambient electron density ($\sim$10^6 m^{-3}) is lower and lightning-induced electric field persists longer ($\tau \lesssim 10$ ms) so that streamer initiation becomes possible. (2) During the lightning discharge in the process of charge removal from the thundercloud, the electric field is building up at low altitudes but relaxing at high altitudes, which leads to more favorable conditions for the initiation and propagation of downward streamer heads. (3) While propagating downwards, positive heads encounter decreasing ambient electron density, which is in contrast to the conditions encountered by upward negative heads that are

propagating towards the halo. (4) At higher altitudes, the electron density in a streamer channel is lower according to similarity laws [*Pasko et al.*, 1998]. At a given altitude, the electron density in a positive streamer channel is higher than that in a negative streamer channel [e.g., *Liu and Pasko*, 2004]. Therefore, upward propagating negative streamer heads more readily merge into the sprite halo.

4.3. Comparison With Recent High-Speed Video Observations

[14] The rationale for the absence of upward negative heads during the initial stage when only downward sprite streamers are observed [*McHarg et al.*, 2007; *Stenbaek-Nielsen and McHarg*, 2008] is that the inhomogeneities from which these downward streamers are initiated are adjacent to an "electrode", namely a highly conducting region. In the modeled sprite-halo event, the sprite halo above 81 km serves as this "electrode". Electron inhomogeneities that are placed adjacent to this "electrode" (i.e., placed in the "single-headed" region) could only lead to sprite onset that begins with development of a downward propagating streamer head. This is consistent with the observations of *McHarg et al.* [2007] and *Stenbaek-Nielsen and McHarg* [2008] showing that downward single-headed streamers are initiated always at higher altitudes than, if present, upward streamer heads. Further, these authors observed that the upward streamer heads start from a lower altitude and typically 0.5–2.0 ms later than downward streamers. This process corresponds to streamer initiation in the "transition region" or "double-headed" region. The time delay between the downward and the upward propagating streamers has also been demonstrated in Figure 2, and it strongly depends on the lightning current waveform and is mainly due to slower establishment of high electric field at lower altitudes by lightning current.

[15] We note that secondary upward streamers usually start from existing bright structures in the downward streamer channels [*McHarg et al.*, 2007; *Stenbaek-Nielsen and McHarg*, 2008]. We suggest that at high altitudes (i.e., "single-headed" region), single-headed streamers are initiated from ambient inhomogeneities. However, most likely, at low altitudes, the secondary upward streamer heads start from previous streamer channel, simply because the ambient electron density is low and, in most cases, it is expected that preexisting inhomogeneities are not as strong when compared to electron density in the channels of previous downward streamers. The upward streamer heads, if started from previous streamer channel, propagate in a direction that has an angle with respect to the previous channel, likely reflecting configuration of electric field lines in the region of their initiation [*Li and Cummer*, 2011]. The above analysis is consistent with the observations of *McHarg et al.* [2007] and *Stenbaek-Nielsen and McHarg* [2008].

[16] In this work, we make a distinction between the negative part of double-headed streamers that occur at the same time as downward positive streamers, and secondary upward streamers that initiate from previous streamer channel. In the case of secondary upward streamers initiating from previous streamer channel, there may be no companion downward propagating streamer because of the modification of mesospheric electric field and ambient conductivity by previous streamers. Otherwise the downward expansion may follow the initial downward streamer path as observed by

Cummer et al. [2006], and therefore will not be observed as an independent downward streamer. However, we emphasize that it is still possible that a double-headed streamer is initiated directly from an ambient inhomogeneity at low altitudes but not from previous streamer channels, as is possibly occurring in the work by *McHarg et al.* [2002, Figures 3 and 6] and *Moudry et al.* [2003, Figure 4]. We speculate that these large sprite events with bright halos were produced by impulsive +CGs associated with large charge moment changes. In such a case, the electron density in the halo body increases so fast that electric field is effectively screened out in a short time. Streamers cannot survive inside the halo and have to initiate at its lower edge or below it.

5. Conclusions

[17] Single-headed sprite streamers are initiated inside the main sprite halo region, which is characterized by fast relaxation of the lightning-induced electric field. The downward positive head is moving towards lower altitudes where electric field is building up due to lightning current, whereas the decaying negative head is propagating in a fast field relaxation and high electron density region. Double-headed streamers or secondary upward streamers are launched close to the lower edge of the sprite halo where a region with $E_{halo} \approx E_k$ persists significantly longer. Secondary upward streamers are initiated from previous channels of the downward streamers because electron density in these channels is much higher than that in preexisting inhomogeneities in the ambient ionosphere. The time delay between the downward streamers and the secondary upward streamers is mainly due to the slower establishment of high electric field at lower altitudes by the lightning current. We also predict that double-headed streamers may be able to initiate directly from preexisting inhomogeneities in the case of large +CG events.

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