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Formation Of Sprite Streamers At Subbreakdown Conditions From Ionospheric Inhomogeneities Resembling Observed Sprite Halo Structures

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Formation of sprite streamers at subbreakdown conditions from ionospheric inhomogeneities resembling observed sprite halo structures

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[1] Modeling results of sprite streamer formation from large ionospheric inhomogeneities or patches (several tens to hundreds of meter wide) indicate that positive streamers can be initiated at subbreakdown conditions from the inhomogeneities with a density comparable to sprite halo densities. For spherical patches with a given radius, the minimum density required for streamer initiation decreases with increasing ambient field. For a given density, the minimum size of the inhomogeneity decreases with increasing ambient field. The modeling results on the associated optical emissions show that a luminous spherical-like cap appears around the lower tip of the ionization patch before streamer initiation, and the streamer is initiated from the bottom of this cap, which appears to be similar to streamer initiation from luminous structures in the lower ionosphere recorded by recent high-speed videos. Our study suggests that if the sprite halo front is unstable, inhomogeneities developing from it can initiate sprite streamers at subbreakdown conditions. **Citation:** Kosar, B. C., N. Y. Liu, and H. K. Rassoul (2013), Formation of sprite streamers at subbreakdown conditions from ionospheric inhomogeneities resembling observed sprite halo structures, *Geophys. Res. Lett.*, *40*, 6282–6287, doi:10.1002/2013GL058294.

1. Introduction

[2] Sprites are finely structured, high-altitude electrical discharges driven by lightning quasi-electrostatic fields [*Pasko*, 2010; *Ebert et al.*, 2010; *Pasko et al.*, 2011]. The filamentary structures within sprites are known as streamers that are highly nonlinear ionization waves. A large amount of observational and modeling work has recently been conducted to understand how sprite streamers are initiated in the lower ionosphere. In high-speed videos, typical sprite streamers appear to either form out of dark background or be initiated from luminous structures at the bottom of sprite halos [e.g., *Cummer et al.*, 2006; *McHarg et al.*, 2007; *Stenbaek-Nielsen et al.*, 2007]. More recent high-speed video observations further show that the luminous structures descend downward with a decreasing speed, and sprite streamers are initiated when the speed of the structures is reduced so much that they appear to be stationary [*Stenbaek-Nielsen et al.*, 2011; *Takahashi et al.*, 2012]. The transverse size of those structures appears to be at least several times larger than the streamer head forming from them. Another important result regarding sprite streamer initiation is that they can be initiated in a lightning field below the conventional breakdown threshold field E_k [*Hu et al.*, 2007; *Li et al.*, 2008; *Gamerota et al.*, 2011].

[3] The sequence of sprite halo development and sprite streamer initiation has been the focus of several recent numerical studies [e.g., *Luque and Ebert*, 2009, 2010; *Qin et al.*, 2011, 2012, 2013]. It was concluded that sprite streamers are initiated as a result of the collapse of a sharpening halo front during its downward development, and preexisting inhomogeneities can facilitate the streamer initiation but are not necessary [*Luque and Ebert*, 2009, 2010]. However, *Qin et al.* [2011] noted that the theory of streamer initiation from a collapsing halo has difficulty explaining some features shown by the observations, such as the spatial and temporal offsets between the halo and sprite streamers, and initiation of sprite streamers by small charge moment changes. They proposed that preexisting inhomogeneities are critical for streamer initiation in the lower ionosphere. They also found that it is easier for sprite streamers to be initiated from the preexisting inhomogeneities located at the lower edge of the sprite halo where the conductivity is not significantly enhanced and strong electric field can last long enough to initiate streamers [*Qin et al.*, 2012, 2013]. The minimum density of the preexisting inhomogeneities used in their studies is 2×10^9 m^{-3}. In the above-mentioned modeling studies, the ambient electric field is generally greater than the conventional breakdown threshold field E_k, when streamers are forming. Streamer simulations reported in *Liu et al.* [2012] and *Kosar et al.* [2012] show that sprite streamers can be initiated in a subbreakdown field as low as $0.3E_k$ from columniform inhomogeneities, which are typically 10 m wide, 100 m long, and have a peak plasma density of $\sim 10^{10}$ m^{-3}. It was also shown that following the streamer initiation, the region around the streamer inception point brightens, which seems to agree with the observed brightening of the origin of the sprite streamers. In comparison, streamer initiation in the overbreakdown field depends on if the strong field lasts long enough for streamers to form. The duration of the field depends on the ambient conductivity, while the streamer formation time depends on both of the field and inhomogeneity magnitudes. For the streamer formation at subbreakdown conditions, not only are those factors important but also is if the inhomogeneities are dense and large enough so that the field will be at least moderately enhanced in a sufficiently large region due to the polarization of the inhomogeneities.

[4] However, it is unclear what the sources of those inhomogeneities in the lower ionosphere are. Some possible

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processes are briefly summarized in *Kosar et al.* [2012], and the candidates that are capable of generating high-density inhomogeneities are rather limited, including meteor-related processes, intense filamentary electrical discharges like streamers, etc. The purpose of this paper is to investigate if the density of the inhomogeneities for streamer initiation can be reduced. In view of the recent sprite halo modeling work of *Liu* [2012], a very sharp halo front (see electron density plot in Figure 5 in that paper) is formed as it descends downward with a decreasing speed. The halo front can be approximately viewed as a planar front to the spatial scale of the streamers or the observed luminous structures. It is known that a planar discharge wavefront tends to be unstable (see *Ebert et al.* [1997] for negative fronts and *Kyuregyan* [2012] for positive fronts). Of particular interest to the present study is the transverse instability of the positive discharge front theoretically studied by *Kyuregyan* [2012]. In that work, the positive front propagates in a background ionization density, and the author found that the front is unstable when subject to transverse perturbations with wavelengths in a range centered around the thickness of the front (the thickness of the space charge layer) [*Kyuregyan*, 2012]. With the ionization density growth in the lower ionosphere at subbreakdown conditions made possible by electron detachment process of O$^-$ [*Luque and Gordillo-Vázquez*, 2011; *Liu*, 2012; *Marshall*, 2012; *Neubert and Chanrion*, 2013], a typical ionospheric electron density profile is able to support the propagation of a positive halo front even though the peak electric field is smaller than E_k [*Liu*, 2012]. The speed of the front decreases quickly when its peak field becomes smaller than E_k at about 1 ms after the lightning [*Liu*, 2012]. The slowing-down front and electron density growth at subbreakdown conditions make it possible at the unstable halo front to grow structures from preexisting inhomogeneities, or background neutral or ionization density fluctuations. It is expected that those structures will have a transverse size on the order of the thickness of the sprite halo front.

[5] This study focuses on investigating if the inhomogeneities with a density close to the value obtained from halo modeling ($< 10^8$ m^{-3}) are able to initiate streamers at subbreakdown conditions. It is found that when large (tens to hundreds of meter wide) ionization patches are used, the required density can be significantly lowered, with the lowest value obtained being 9×10^7 m^{-3}. It is expected that this value may be further reduced if even larger patches are used. In addition, a brightening spherical-like cap of hundreds of meter wide can be formed around the lower edge of the patch before streamer initiation, which is similar to the observed optical signatures of the structures appearing at the bottom of sprite halos that lead to positive streamer formation. Our results suggest that if the halo front is unstable, the structures growing from preexisting inhomogeneities or background density fluctuations can initiate sprite streamers in subbreakdown electric fields.

2. Model

[6] The sprite streamer model used in the current study is a modified version of the one used in [*Liu and Pasko*, 2004, 2005; *Liu et al.*, 2006, 2009a, 2009b]. The dynamics of sprite streamers is described by electron and ion drift-diffusion equations coupled with Poisson's equation in a cylindrical coordinate system. The coefficients of the model are assumed to be a function of the local electric field and are obtained from the solution of the Boltzmann equation [*Moss et al.*, 2006]. The model uses the SP$_3$ method [*Bourdon et al.*, 2007; *Liu et al.*, 2007] to calculate the rate of electron-ion pair production by photoionization. The electron detachment from O$^-$ ions is not included in the model because it is ineffective on the short timescale of streamer formation considered here [*Liu*, 2012].

[7] The inhomogeneity is assumed to be spherically symmetric, and Meek's criteria for streamer initiation are used to estimate the required dimension and density, as shown below:

$$\int_a^{z_p} \frac{\nu_i - \nu_a}{\mu_e E} dz \simeq 18 - 22, \qquad (1)$$

where a is the radius of the spherical patch, z_p is the location where the field drops to E_k, ν_i is the ionization frequency, ν_a is the electron attachment frequency, μ_e is the absolute value of electron mobility, and E is the magnitude of the electric field. The electric field is the vector sum of ambient electric field $\vec{E}_0$ and space charge field arising due to polarization of the patch. To obtain this field, we approximate the polarized patch as a sphere containing only positive ions. Even though this approximation is inaccurate and unphysical for certain cases, it can establish a guideline on what values to be used for simulations. We also use a hyperbolic tangent profile for the density distribution of the patch, as shown below:

$$n_{e0}(r,z) = \frac{n_0}{2}\left[1 + \tanh\left(\frac{a - \sqrt{(z-z_0)^2 + r^2}}{\sigma}\right)\right], \qquad (2)$$

where a is the radius of the patch, σ controls the sharpness of its transition region, and n_0 is the peak plasma density. Compared to a spherically symmetric Gaussian profile that is commonly used to initiate streamer simulations, the hyperbolic tangent profile provides flexibility to change its size and sharpness separately. This turns out to be important for streamer initiation from large patches with a reduced density, because the Gaussian profile with a large radius may not result in a sufficiently enhanced field region at its tip to promote positive streamer formation.

3. Results and Discussion

[8] We note that an ambient density is not included in the simulations presented below, but a test simulation with an ambient density of 10^6 m^{-3} shows that the results do not vary significantly.

3.1. Dependence of Required Patch Parameters on Ambient Field

[9] In this section, we investigate the dependence of the required patch size or density on the ambient electric field when the other parameter is fixed. We first consider the minimum radius required for streamer initiation from a spherical patch with a given density of 4×10^8 m^{-3} in three different electric fields: 0.5, 0.6, and 0.8E_k. Figures 1 and 2 show the formation of a positive streamer from a spherical patch with $n_0 = 4 \times 10^8$ m^{-3}, $a = 65$ m, and $\sigma = 3$ m in a lightning field of $E_0 = 0.6E_k$. The direction of the electric field points vertically downward. The 2-D cross sections of electron density, electric field, and charge density distributions are shown in Figures 1a–1c, 1d–1f, and 1g–1i, respectively. Figure 1 shows three different stages of

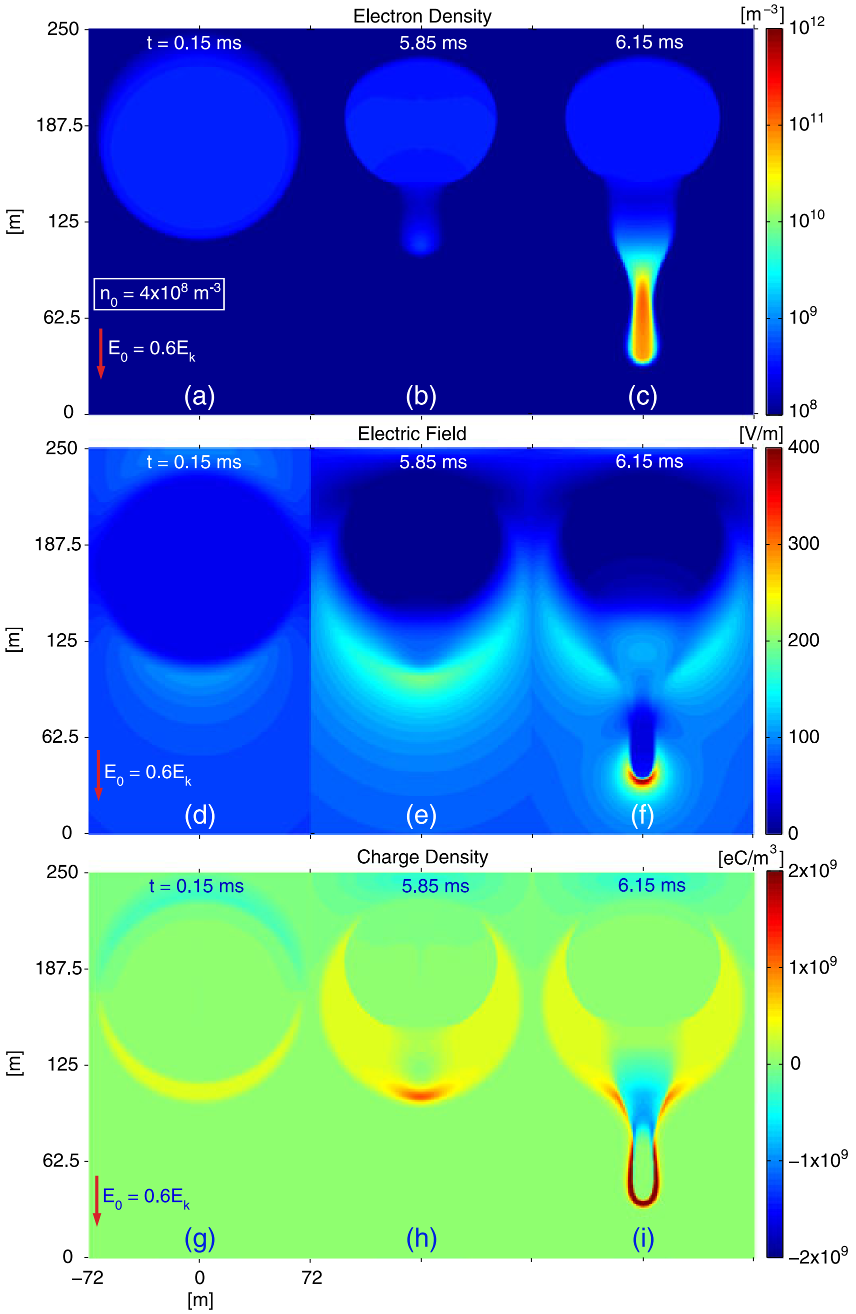

Figure 1. Cross sections of (a–c) electron density, (d–f) electric field, and (g–i) charge density distributions for a streamer forming from a spherical ionospheric inhomogeneity at 75 km altitude in $E_0 = 0.6E_k$. The spherical patch has a peak density of 4×10^8 m^{-3} and a radius of $a = 65$ m with $\sigma = 3$ m.

the streamer initiation process: (a) initial stage, (b) before streamer initiation, and (c) fully formed positive streamer, with each stage dominated by a different process. After the patch is placed into the field, electrons drift toward the upper tip in the opposite direction of the field, and positive ions are exposed in the lower tip. At 0.15 ms, the peak electric field is 103 V/m, slightly below E_k, and the two-body electron attachment time is 0.2 ms. The effects of both the electron impact ionization and two-body attachment are negligible. At this stage, the dominant process is electron drift. Figures 1b, 1e, and 1h correspond to the stage before streamer initiation. After the initial stage, electric field around the lower tip continuously increases, as more and more positive charge is exposed due to electron drift. As can be seen in Figure 2, the electric field becomes higher than E_k at ~0.3 ms shortly after the initial stage. As a result, the electron impact ionization becomes effective, increasing the electron density (Figure 2) around the lower tip. The electrons that are produced due to ionization also drift toward the upper tip, leaving more positive charge behind and therefore increasing the positive charge density around the lower tip (Figure 1h). Right behind the lower tip, a trail is formed around the symmetry axis with a positive charge density lower than the surrounding region that has a relatively uniform positive charge density. This low density trail forms due to the upward drift of the electrons produced by

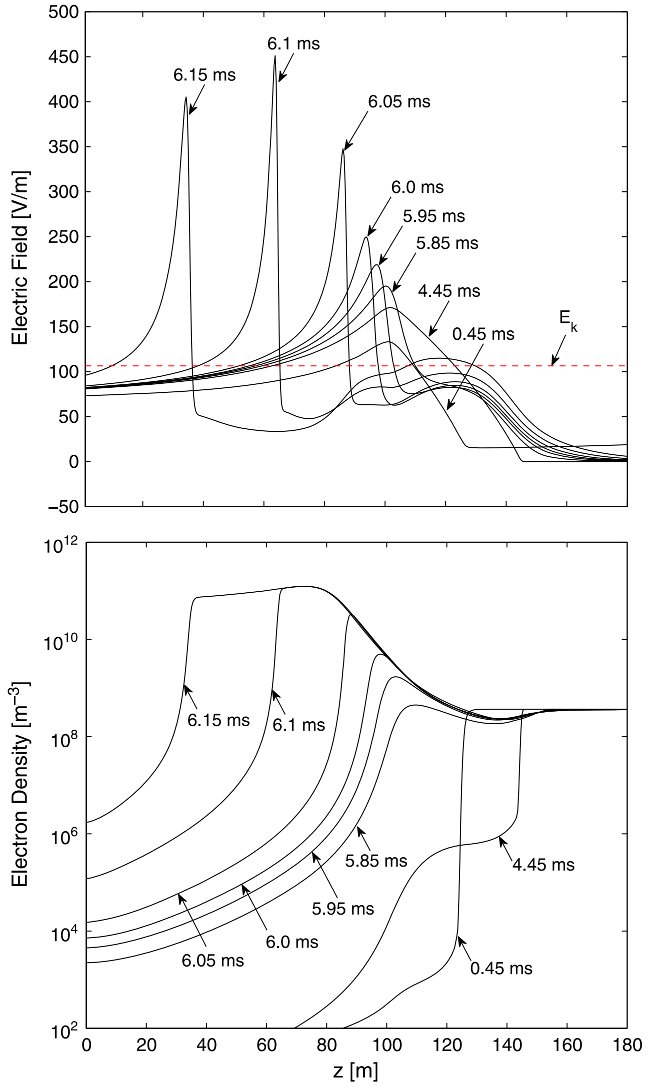

Figure 2. Electric field and electron density profiles along the symmetry axis for a streamer forming in $E_0 = 0.6E_k$ at 75 km altitude. The axial profiles show the detailed dynamics of streamer formation from an ionization patch.

the ionization that partially neutralize the positive charge in this region. At 5.95 ms (see Figure 2), the high field region starts to move forward, which represents the formation of a positive streamer. Figures 1c, 1f, and 1i correspond to the last stage and shows a fully formed positive streamer. Positive charge is confined in a thin layer around the streamer channel while the negative charge is deposited around the origin due to an increasing current drawn by the positive streamer [*Liu*, 2010; *Kosar et al.*, 2012].

[10] Table 1 summarizes the minimum radii of the initial spherical patches to initiate streamers in 0.5, 0.6, and $0.8E_k$ when its density is fixed at $n_0 = 4 \times 10^8$ m^{-3}. Table 2 summarizes the minimum densities of spherical patches to initiate streamers when the radius is fixed at 105 m. There is a difference between the results obtained from Meek's criteria and the simulations, suggesting that the fully polarized sphere approximation used for evaluating the integral in Meek's criteria does not accurately describe the polarization of the spherical patch. As shown, for a given density, the minimum size of the patch that can initiate a streamer decreases with increasing ambient field; for a given radius, the minimum density requirement decreases with increasing ambient field. The values obtained for the radius and density have ±10 m and $\pm 0.5 \times 10^8$ m^{-3} uncertainty associated with them, respectively. It should be noted that the results may change when different values of σ are used in the simulation. Although the lowest density presented in Table 2 is 2×10^8 m^{-3}, additional simulations show that streamers can be initiated from a larger patch (a = 500 m) with a density 9×10^7 m^{-3} in $E_0 = 0.8E_k$. This density may be lowered further, if an even larger patch is used. It can be concluded that sprite streamers can be initiated at subbreakdown conditions from large ionization patches of hundreds of meter wide with a density close to the sprite halo density.

Table 1. Minimum Radii Obtained From Meek's Criteria and the Streamer Simulations for $n_0 = 4 \times 10^8$ m^{-3} and σ = 3 m for Three Different Ambient Fields at 75 km Altitude

E_0/E_k	Meek's Criteria (m)	Streamer Simulations (m)
0.8	63 – 67	50
0.6	74 – 78	65
0.5	80 – 84	105

3.2. Optical Emissions Produced During Positive Streamer Formation From a Spherical Ionization Patch

[11] In this section, we present the optical emissions associated with the streamer initiation from a large spherical ionization patch. A patch with $n_0 = 2 \times 10^8$ m^{-3}, a = 330 m, σ = 70 m, and z_0 = 687 m is initially placed in an ambient field of $0.8E_k$ at 75 km altitude. The cross sections of electron density, electric field, and 1PN$_2$ intensity distributions for a positive streamer forming from this patch are shown in Figures 3a–3b, 3c–3d, and 3e–3f, respectively. The plots at t = 1.5 ms represent the stage before streamer initiation and those at t = 2.3 ms show that a positive streamer is formed from the patch. Initially, electrons continuously shift upward leaving the less mobile positive ions behind at the lower tip. When this field at the lower tip becomes greater than the breakdown threshold field E_k at t = 0.4 ms, electron impact ionization becomes effective, producing free electrons in that region. These electrons also move toward the upper tip, leaving more and more positive charge behind and hence enhancing the electric field in the lower tip further. The high field region starts to move at t = 1.8 ms, which indicates that the streamer is forming. Within the 1.4 ms time window, the electrons created due to the ionization travel ∼170 m and therefore are not able to bridge the gap between the lower tip of the initial patch and the shifted location of its electrons fully as seen in Figure 3a. Before the streamer initiation from the lower tip, the electric field is enhanced in a large region around the lower edge of the patch (Figure 3c). This electric

Table 2. Minimum Plasma Densities Obtained From Meek's Criteria and the Streamer Simulations for a = 105 m and σ = 3 m for Three Different Ambient Fields at 75 km Altitude

E_0/E_k	Meek's criteria (m^{-3})	Streamer simulations (m^{-3})
0.8	2.0×10^8	2.0×10^8
0.6	2.5×10^8	2.25×10^8
0.5	2.75×10^8	4.0×10^8

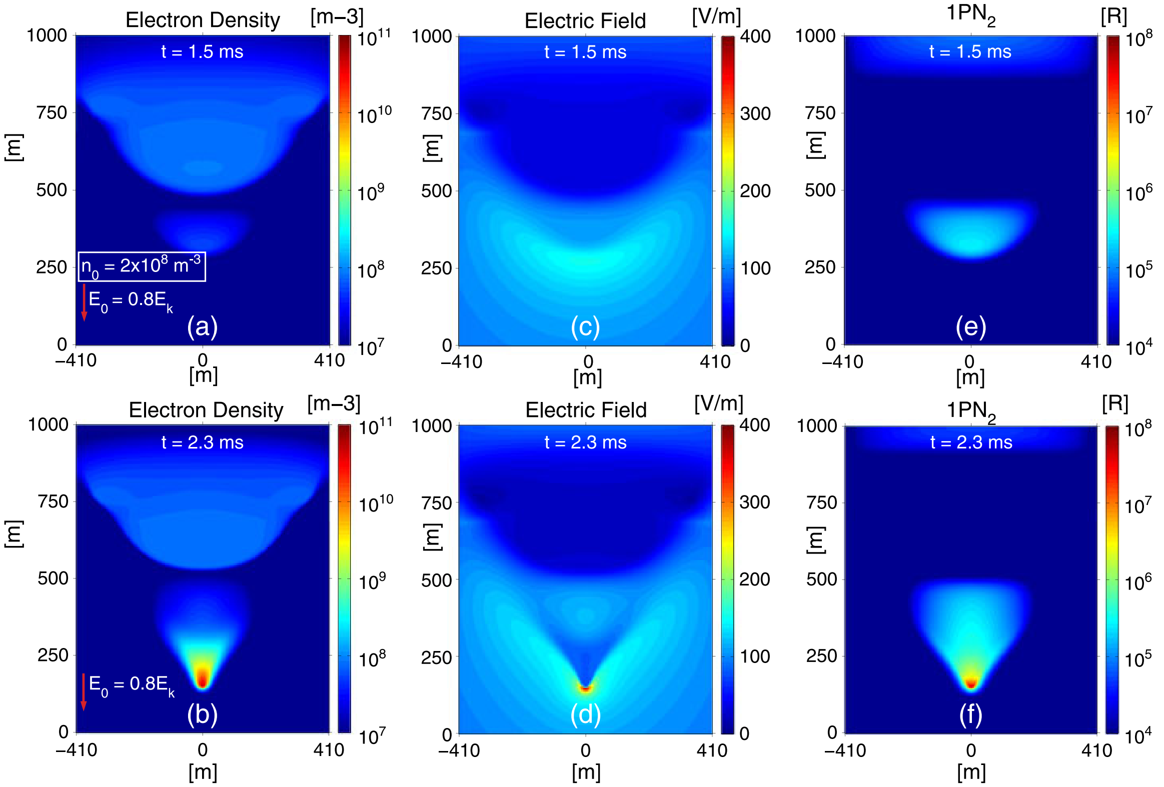

Figure 3. Cross sections of (a–b) electron density, (c–d) electric field, and (e–f) $1PN_2$ intensity distributions for a streamer forming from a spherical ionospheric inhomogeneity at 75 km altitude in $E_0 = 0.8E_k$. The spherical patch has a peak density of 2×10^8 m^{-3} and a radius of $a = 330$ m with $\sigma = 70$ m.

field enhancement results in an increasing intensity of $1PN_2$ emissions around the bottom edge of the patch. Figure 3e shows that the luminous region before streamer initiation looks like a spherical cap, and the transverse size of this region is ~200 m. It should be noted that the optical emissions are mainly produced by the free electrons generated by electron impact ionization not by the initial patch electrons. Although the size of the luminous region is relatively large, the positive streamer head emerging from it is compact, with a radius of ~20 m.

[12] The peak emission intensity from the spherical-cap structure in Figure 3e is ~3×10^5 R, which is 2 orders of magnitude smaller than the peak emission intensity of ~5×10^7 R from the streamer head in Figure 3f. Given that the luminous structure is stationary while the streamer head is fast moving, the apparent intensity of the structure may be comparable to the streamer head's in high-speed images. Therefore, the optical signatures from streamer formation from a large ionization patch at subbreakdown conditions appear to be consistent with the observations reported by *Stenbaek-Nielsen et al.* [2011] and *Takahashi et al.* [2012] in terms of the shape of the structure initiating streamers, the relative size between the structure and the sprite streamer head, and the relative brightness between the structure and the streamer head. This agreement suggests that streamer initiation from large inhomogeneities with a density close to the sprite halo density may explain the recorded sprite streamer initiation by high-speed videos. The size of the inhomogeneities must be significantly smaller than the transverse size of sprite halos so that they can strongly amplify the electric field of the halo. As discussed in section 1, a sharpening halo front may be unstable, and the instabilities have a spatial scale of the front thickness. It seems reasonable to speculate that the sharpening, unstable sprite halo front first produces structures of hundreds of meter wide due to preexisting inhomogeneities, and then sprite streamers are initiated from those structures. The sharpening of the sprite halo front is also emphasized by *Luque and Ebert* [2009]. However, it should be noted without electron density growth at subbreakdown condition allowed by electron detachment from O^- ions and preexisting inhomogeneities, both of which are not included in that work; it is hard to imagine how the sharpening front could produce structures of hundreds of meter wide to initiate streamers.

4. Conclusions

[13] Our simulations indicate that streamers can be initiated from hundred meter wide ionospheric inhomogeneities with a density comparable to the sprite halo density. The lowest density considered in this study is 9×10^7 m^{-3}, but it may be lowered further if even larger inhomogeneities are used in the simulation. It is also found that for a given density, the minimum size of the inhomogeneities that can initiate a streamer decreases with increasing ambient field, while for a given radius, the minimum density decreases with increasing ambient field. Our results suggest that if the halo front is unstable, the structures growing from preexisting inhomogeneities or background density fluctuations can initiate sprite streamers in subbreakdown electric fields.

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