# Mechanisms of Sprite Initiation, Morphology, and Lightning Polarity Asymmetry

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## Abstract

Sprites are spectacular optical emissions in the mesosphere induced by transient lightning electric fields above thunderstorms. Recently, significant efforts have been devoted to the understanding of the inception mechanism of sprite streamers, the origin of different sprite morphologies, and the lightning polarity asymmetry in producing sprites. In this paper, we present a combination of observational and modeling results explaining the physical parameters and processes that are important for the resolution of these outstanding issues. We first emphasize the presence of plasma inhomogeneities in the lower ionosphere as a necessary condition for the initiation of sprite streamers. Then we explain the relation between sprite morphology and the characteristics of the causative lightning discharges using plasma fluid modeling results in comparison with optical and radio observations. Finally, we discuss the critical factors that account for the lightning polarity asymmetry in producing sprites.

## 1. Introduction

Sprites are large-scale mesospheric gas discharges produced by intense cloud-to-ground lightning discharges (CGs) in the underlying thunderstorms. These luminous discharges often exhibit a brief descending high-altitude diffuse glow in the shape of a pancake with diameters up to about 80 km near 75 km altitude, referred to as a sprite halo, and develop into fine-structured filaments with diameters up to several hundred meters in the altitude range of about 40 to 90 km, commonly referred to as sprite streamers [1, 2]. Since the first video documentation, sprites have attracted extensive research interest in the last two decades, primarily due to their potential as natural resources for the study of streamer physics, their potential impact on the chemistry in the upper atmosphere, and their ability to perturb the sub-ionospheric radio signals [3, 4].

In recent years, high-speed video observations of sprites have revealed significant sub-millisecond dynamics of streamers, providing excellent experimental data that could be used in comparison with modeling results to resolve many outstanding issues in sprite research [4, 5]. In this paper, the first issue to be investigated is the inception mechanism of sprite streamers. Although the streamer nature of sprites has been generally accepted, how these filamentary plasmas are initiated in the lower ionosphere has not been well understood, as many spatial and temporal features of sprites in their initial stage of development remain to be explained. The second issue is the origin of different sprite morphologies documented in large amount of video observations [2, 3]. In high-speed video observations, the morphological complexity of sprites is manifested as the significant variation of halo luminosity, the absence or presence of upward negative streamers, and the complicated initiation sequence of downward and upward streamers. Generally, sprites are classified into column sprites, which contain predominantly vertical downward streamers, and carrot sprites, that exhibit both upward and downward propagating streamers. Simultaneous observations of sprites and ELF/VLF sferics have suggested that the morphological features of sprites are closely related to the characteristics of their causative lightning discharges [3]. Contrary to extensive experimental studies in the existing literature, theoretical understanding of sprite morphology is still in a preliminary stage [4, 5]. Modeling results in comparison with sprite

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observations will be presented for achieving a quantitative interpretation of the dependence of sprite morphology on lightning characteristics. Another well-known puzzle in sprite research is that sprites are almost exclusively produced by positive could-to-ground lightning discharges (+CGs), and that negative sprites (produced by -CGs) are extremely rare, with only nine events documented in the existing literature compared to thousands of their positive counterparts [6]. It was expected from previous modeling studies that the ability of lightning discharges in producing sprites is independent of the lightning polarity [7]. However, recent modeling results demonstrate that positive sprites (produced by +CGs) are easier to produce than negative sprites, which is one major factor accounting for the lightning polarity asymmetry in producing sprites. Other major factors, including charge moment contrast of +CGs and –CGs [6, 8], and different observability of positive and negative sprites will also be discussed.

## 2. Inception Mechanism of Sprite Streamers

In early sprite research, neutral density or plasma density perturbations in the lower ionosphere have been conjectured to be a possible factor for the initiation of sprite streamers. Recent modeling studies demonstrated that the presence of plasma inhomogeneities, previously thought not to be indispensable, is in fact necessary for the initiation of sprite streamers [7]. This is due to fast relaxation of the lightning electric field and overlapping of electron avalanches in the lower ionosphere that disable initiation of streamers from single seed electrons [7]. Between two electrodes in laboratory where ambient electron density is negligible, the electric field can be sustained above $E>E_k$ for as long time as external high voltage is being applied, such that a single seed electron could have sufficient time to develop and transform into a streamer. Note that $E_k$ is the conventional breakdown field defined by the equality of the ionization and dissociative attachment frequencies. On the contrary, at high altitudes in the lower ionosphere where ambient electrons are abundant, the lightning electric field $E>E_k$ raises the electron density rapidly and leads to fast dielectric relaxation. Larger lightning electric fields $E$ lead to quicker electron density enhancement so that the electric field relaxes more rapidly, which means that larger lightning electric fields are not necessarily more favorable for sprite initiation [4]. Since the lightning electric field could only be sustained above $E_k$ for such a short period of time that single seed electrons could not transform into streamers before the field relaxes, plasma inhomogeneities are necessary to enhance locally the electric field and thus shorten the time required for streamer initiation [8].

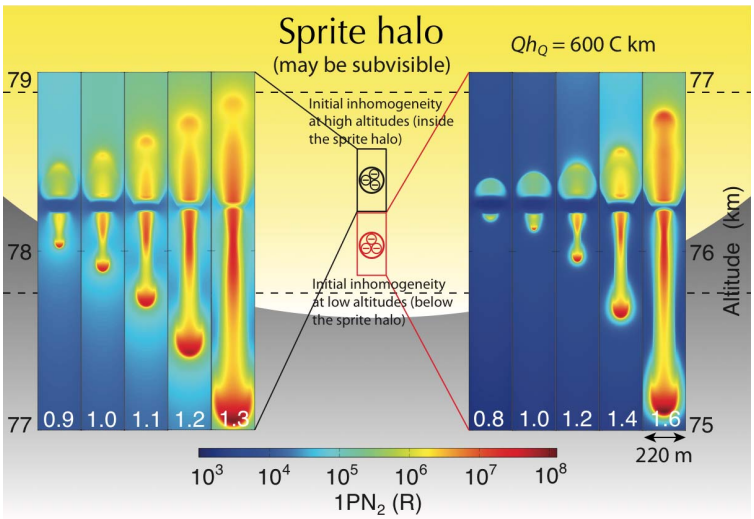


**Fig. 1. Cross-sectional views of optical emissions of the first positive band system of $N_2$ in Rayleighs produced by streamers initiation from plasma inhomogeneities at different locations [9].**

The location of the pre-existing plasma inhomogeneities with respect to the sprite halo has significant impact on the initiation of positive and negative streamers in sprites [9]. It is demonstrated recently that plasma inhomogeneities located inside the region of sprite halo with significant electron density enhancement only transform into single-headed downward positive streamers, and upward negative streamers could not initiate due to fast relaxation of the lightning electric field. Only at the lower edge of the sprite halo where the lightning electric field is approximately equal to $E_k$, the electron density is not significantly enhanced such that the electric field could persist for sufficient time to initiate upward negative streamers [9]. Fig. 1 is one example of simulations showing the difference of the initiation of upward negative streamers at different locations with respect to the halo. It appears that the inhomogeneity located at lower altitude (76 km) can develop into a bright negative streamer but the one at 78 km decays rapidly.

## 3. Complexity of Sprite Morphology

Difference between the requirements for the initiation of positive and negative streamers is one of the most important factors leading to the complexity of sprite morphology [4, 5]. According to plasma fluid modeling, positive streamers can be initiated in lightning electric fields that last for about 1 ms above $0.8E_k$, or in electric fields that persist for a few milliseconds at values from $0.5E_k$ to $0.8E_k$. On the other hand, the initiation of negative streamers requires the persistence of lightning electric field above $0.8E_k$ for longer than 2 ms [4]. The more stringent requirements for the initiation of negative streamers lead to the fact that lightning discharges associated with small charge moment changes (CMC) could only produce column sprites that are formed by downward positive streamers. Simulations also show that those lightning discharges associated with large CMC tend to produce carrot sprites with the presence of a mesospheric region where the electric fields exceed the value $0.8E_k$ and persist for longer than 2 ms [4]. Fig. 2 shows the simulation results of the initiation of streamers, respectively, in a column sprite event and in a carrot sprite event using experimentally observed lightning current waveforms [5]. In the simulations, upward negative streamers could only be initiated in the carrot sprite event, in agreement with the optical observations of the two sprite events [5].

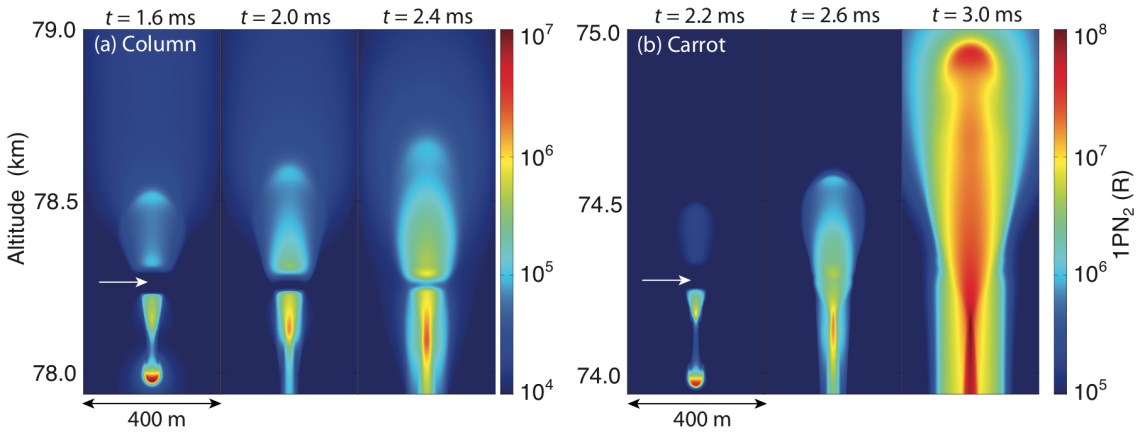


**Fig. 2. Cross-sectional view of optical emissions of a streamer produced (a) in a column sprite event and (b) in a carrot sprite event using experimentally observed lightning current waveforms [5].**

Another important factor is the complexity of lightning current waveforms. According to modeling results, for a sufficiently large CMC capable of producing carrot sprites, the time dynamics of the CMC determines the specific shape of the carrot sprites [4]. In the case when the sufficiently large CMC is produced mainly by an impulsive return stroke, strong electric field is produced at high altitudes and manifests as a bright halo. The conductivity enhancement in the bright halo leads to fast decay and termination of the upper diffuse region of carrot sprites because it effectively screens out the electric field at high altitudes. One the contrary, if the sufficiently large CMC is produced over a relatively long period of time (i.e., produced by a weak return stroke followed by intense continuing current), the lightning electric field at high altitudes persists at a level comparable to $E_k$, and thereby an extensive upper diffuse region can develop. Moreover, the polarity of the causative lightning discharges has significant impact on sprite morphology. It is demonstrated that negative sprites are necessarily carrot sprites, as in the negative cases upward positive streamers are always easier to be initiated that downward negative streamers [4, 10]. It is also expected from simulations that the upper region of negative sprites should be brighter than their lower part, in agreement with recent observations of negative sprites [10]. Sprite morphology is also dependent on the upper atmospheric ambient conditions. Lower ambient conductivity leads to smaller CMC required for the production of carrot sprites. Therefore, geographical, short-term, and long-term variations of the upper atmospheric conductivity, which, along with the seasonal variations of thunderstorm activity that lead to different lightning characteristics in the troposphere, may account for the differences of sprite morphologies observed in different campaigns [4].

## 4. Lightning Polarity Asymmetry in Producing Sprites

A global survey of CMC associated with -CGs indicates that there is a small, but non-negligible number of -CGs that have magnitudes of CMC as large as those that are known to produce sprites in the case of +CGs [6]. It is estimated that the number of -CGs possessing these properties is approximately 10% of the related +CG population worldwide. However, observations show that negative sprites are extremely rare (much less that 10% of total number of positive sprite events). In our numerical simulations, it is found that the significant differences in the development of sprite

streamers in the case of +CGs and -CGs are the most important factor for understanding why sprite produced by -CGs are so rare [4]. The key factors for the understanding of the lightning polarity asymmetry in producing sprites are as follows: (1) According to modeling and experimental results, the threshold CMC of negative sprites are larger than those of positive sprites, which are, respectively, 500 and 320 C km under typical nighttime conditions [4, 10]; (2) A factor of 3 lower minimum electric field required for the propagation of positive streamers in comparison with negative streamers [4]. This leads to better observability of positive sprites since streamers in sprites need to go through a significant growth before they become observable [10, 11]; (3) +CGs much more frequently produce large CMC [6, 8].

## 5. Conclusions

We present a discussion of basic physical mechanisms and parameters needed for the understanding of sprite initiation, morphology, and lightning polarity asymmetry. The roles of plasma inhomogeneities, lightning current waveforms, and lightning polarity have been emphasized. Numerical results have been analyzed in comparison with observations to achieve a quantitative understanding of the addressed outstanding issues in sprite research.

## 6. Acknowledgments

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