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Study of streamers in gradient density air: Table top modeling of red sprites

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[1] Red sprites are large scale weakly ionized non-equilibrium electrical discharges that occur high above thunderstorm clouds, spanning the altitude range 50 kilometers to 90 kilometers above the Earth's surface. Their streamer-like nature has been pointed out by a number of groups. Streamer models used for the description of sprites are usually verified experimentally. However, sprites develop in a highly non-uniform air, where density changes by a factor of ~2.7 every 7.2 km, whereas streamer studies have been performed at different but uniform densities. In this paper we present the results of the first attempt to simulate sprites in laboratory by using streamer discharges in a gradient density air (the results of this paper were presented in 2009 Fall AGU meeting). The purpose of the experiments is to obtain data that could be used for validation of numerical and analytical models (the first results of a numerical study of red sprites (streamers) in a gradient density atmosphere were recently published by Luque and Ebert (2010)). **Citation:** Opaits, D. F., M. N. Shneider, P. J. Howard, R. B. Miles, and G. M. Milikh (2010), Study of streamers in gradient density air: Table top modeling of red sprites, *Geophys. Res. Lett.*, *37*, L14801, doi:10.1029/2010GL043996.

1. Introduction

[2] Following the discovery of sprites a continuous effort was made to improve the temporal and spatial resolution of their measurements. Indeed such improvements revealed new features, and improve our understanding of the physics of sprites. The first high speed images obtained by *Stanley et al.* [1999] showed streamer structure of sprites, including streamer branching. Later on *Stenbaek-Nielsen et al.* [2000], *Stenbaek-Nielsen and McHarg* [2008], and *Kanmae et al.* [2007] used high speed cameras, while *Gerken et al.* [2000] and *Marshall and Inan* [2005] developed telescope-based technique that dramatically improved both temporal and spatial resolution of the observed sprites.

[3] The streamer structure observed in red sprites is similar to that observed in laboratory experiments, although the streamers in the red sprites are scaled by reduced air density in the upper atmosphere [*Pasko et al.*, 1998; *Raizer et al.*, 1998]. The progress in sprites modeling is hindered by the fact that sprites develop in a highly non-uniform air, whereas streamer studies have been performed at different but uniform densities. In this paper we present the results of the first attempt to simulate sprites in laboratory by using streamer discharges in a gradient density air. The purpose of the experiments is to obtain data that could be used for validation of numerical and analytical models.

2. Experimental Setup

[4] We used a subsonic hot jet of air mixing with the ambient temperature room air to create the variable gas density at constant (atmospheric) pressure (Figure 1). A heat gun model HG-751 B by Master Appliance Corp. was used to produce the air jet with temperatures up to 500°C. The speed of the jet was around 10 m/s, and its diameter was equal to 25 mm at the nozzle exit. Mixing with the ambient room air leads to a formation of the temperature profile across the jet. Using the temperature profile and taking into account that the air pressure is constant, the density profile can be calculated. The temperature was monitored using a K-type thermocouple and is presented in Figure 2 along with the density calculated from the ideal gas law.

[5] Note that at the given conditions the mixing of the hot jet with cold room air was turbulent. Presence of eddies created temperature fluctuations across the flow. These fluctuations were observed by the thermocouple and are presented at Figure 2 by means of error bars.

[6] A high voltage pin electrode was placed in the center of the jet perpendicular to the direction of the flow. A copper plate served as the ground electrode and was placed 30 mm away from the pin just outside of the flow. A high voltage power supply was connected to the pin electrode through a fast high voltage switch, Behlke HTS 201-03-GSM, supplying 5.2 kV high voltage positive pulses. The radius of curvature of the pin electrode was 40 microns. A typical voltage pulse is shown in Figure 3. The rise time of the voltage pulse was approximately 50 ns. The pulse duration was 500 μs, much longer than the discharge propagation time, which is typically on the order of 10 ns.

[7] Images of the discharge were taken using an Andor iStar ICCD camera. The exposure time was equal to 1 msec, so it covered the duration of the entire pulse. Only one breakdown per pulse was registered at given experimental conditions. Typical images of the discharge are presented at Figure 4. First, images of breakdown in ambient room air were taken Figure 4a). These pictures show a streamer corona discharge spreading uniformly in all directions. Then the heat gun was turned on and pictures of the discharge in gradient density air were taken (Figure 4b). The streamers formed in this discharge are much longer than those at ambient pressure, and are directed along the density gradi-

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0094-8276/10/2010GL043996

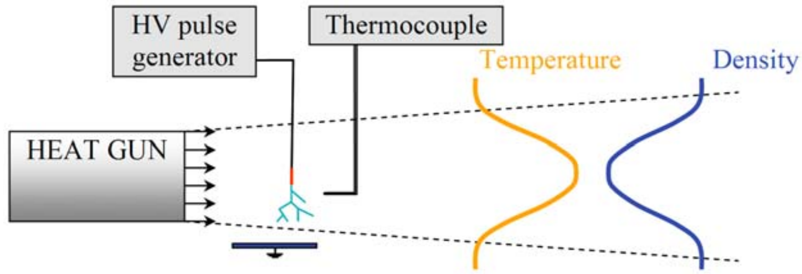

Figure 1. Experimental setup.

ent. In addition these streamers experience branching similar to the streamers in naturally occurring red sprites.

[8] The length of the streamers can be estimated based on the average value of the electric field in the streamer channels. The potential drop in a streamer channel is around E_0 = 5 kV/cm at atmospheric density ρ_0 [*Raizer et al.*, 1998]. In our model we consider the reduced electric field (E/N), and assume that that it is constant in the nonuniform atmosphere. Thus, given the applied voltage U, the length of a streamer L in a non-uniform density ρ(x) can be estimated from the following expression:

$$\int_0^L \frac{\rho(x)}{\rho_0} dx = \frac{U}{E_0} \quad (1)$$

Dash lines in Figure 4 show the expected length of the streamers calculated by equation (1).

3. Results and Discussion

[9] Streamer images in Figure 4 are very similar to sprite images presented in [*Cummer et al.*, 2006], which may be considered as one more experimental justification of the streamer nature of red sprites. However, how can we relate laboratory size streamers with the real size sprites? Many phenomena in gas discharges scale with ρ d-parameter (density times distance) [*Raizer et al.*, 1998; *Pasko*, 2007; *Ebert and Sentman*, 2008; *Raizer et al.*, 2010; *Ebert et al.*, 2010].

[10] As shown by *Raizer et al.* [1998] for a perfectly conducting cylinder with a hemispherical tip of radius r_m, the electric field near the streamer tip is $E_m \approx U/2r_m$. For our experiments with a potential U = 5 kV and a streamer radius r_m = 0.017 cm we obtain a reduced field at the streamer tip of $E_m/N \approx$ 580 Td (1Td=10^{-21} V m^2). We have previously described red sprites as downward streamers of varying cross section initiated from plasma patches in the lower ionosphere [*Raizer et al.*, 1998, 2010]. Good agreement between the observations of sprites by *Stenbaek-Nielsen and McHarg* [2008] and the model of *Raizer et al.* [1998, 2010] with a reduced field of ~600 Td was obtained. Our laboratory experiments are conducted under the reduced field values similar to those in observed red sprites.

[11] Under a constant applied voltage the radius of a streamer tip should reduce even in uniform gas, since a significant part of the applied voltage drop occurs in the streamer channel. According to *Bazelyan and Raizer* [1998] the field inside a channel is ~5 kV/cm at standard temperature and pressure. In order to maintain the required field for ionization in air near the streamer tip, the radius of the tip should decrease during the streamer propagation. The effect of the reducing tip radius becomes stronger if the streamer propagates in the direction of increasing density, as occurs in red sprites. However, when a streamer propagates under a high voltage its radial field will exceed the ionization threshold leading to an increase of the tip radius. Thus some models [e.g., *Kulikovsky*, 1997] as well as experiments conducted at over-voltage show radially expanding streamers.

[12] A similar relation between the radius of a streamer tip and the air density comes from analysis of the images pre-

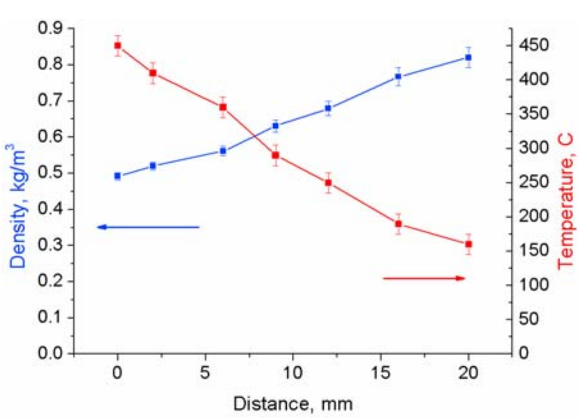

Figure 2. Temperature and density of air versus distance across the flow from the high-voltage pin electrode to the grounded plate electrode.

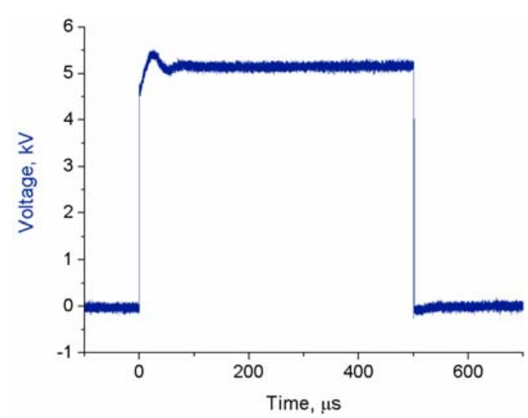

Figure 3. Voltage pulse profile. Streamers were originating, propagating and stopped at constant voltage in time much shorter than pulse duration.

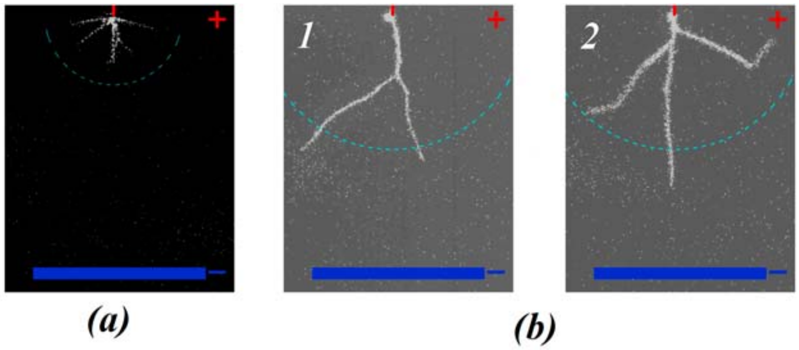

Figure 4. Typical images of the discharge. (a) In uniform density room air. (b) In gradient density air. Lowest density, on top near the pin electrode; highest density, on bottom near the plate electrode. Image size 32 × 40 mm. Note, that each image represents a separate discharge.

sented by *Cummer et al.* [2006] and *McHarg et al.* [2007]. However recent numerical simulations by *Luque and Ebert* [2010] show that the radius of a streamer propagating downward in the atmosphere grows instead of decreases. To resolve these inconsistencies some additional studies are needed. Therefore using our images we have measured streamer diameters along the trajectory. These measurements show that when propagating through air with increasing density the streamer diameter decreases (see Figure 5). Diameters of the streamers were measured using Streamer Width Analyzer v 1.0.7.20 by Sander Nijdam. The analyzer added the intensity profiles at different cross sections along 3 mm of the streamer channel, which had to be specified manually. Such procedure reduced the noise drastically and produced a relatively smooth bell shape profile. The full width at half maximum was taken as the diameter of the channel.

[13] The experiments in uniform density were performed at room temperature whereas in the experiments in gradient density air the gas temperature range was from 150C to 450C. Lower temperature corresponds to higher density, lower reduced filed E/N and therefore a smaller diameter of the streamer. The resolution of the camera used in the experiments was not sufficient to perform measurements of the streamer diameter with acceptable accuracy for the small diameter streamer which develops at uniform density.

[14] The error bars on Figure 5 were determined from the Streamer Analyzer Code. The X-error bar was defined by the length of the region along which the intensity profiles were averaged (3 mm), the Y-error bar was found by the code itself in result of measuring FWHM and was almost the same for all data points.

[15] It is interesting to note that the diameter of the first streamer is slightly bigger. It can be attributed to a fact that the first streamer propagates at an angle to the density gradient, meaning that at longer distances (length along the streamer channel) the air density is lower than that of the second streamer which propagates directly downwards into the region of a denser air.

[16] Note that some other methods can be applied to create controllable density gradients in air in laboratory conditions. One of them is to use quiescent air or slow air flows, so the pressure of the gas is constant in the entire test region and the density difference can be achieved through a non-uniform temperature distribution. In this case the density is inversely proportional to the temperature, and if proper heat insulation is used, the temperature will change linearly along the tube. The temperature profile can be shaped by adding additional heating/cooling elements in between. Another approach is to use a jet of hot air, as was done in this work. If the velocity of the jet is subsonic, the constant pressure assumption is generally valid. Close to the jet exit buoyancy effects do not have enough time to become important. And finally, strong density gradients can be achieved in supersonic flows. They can be created using supersonic nozzles, shock tubes, or combination of both. Advantages of these methods include possibility to create any desirable density profile by shaping the nozzle or cross section of the tube.

4. Conclusions

[17] In this work, a streamer discharge in a graded density air was studied in the laboratory. Such streamers simulate naturally occurring red sprites which span the altitude range between 30–50 km and 85 km. Pictures of the streamer discharge were obtained and their similarities to sprites, including branching structure, were pointed out. It was

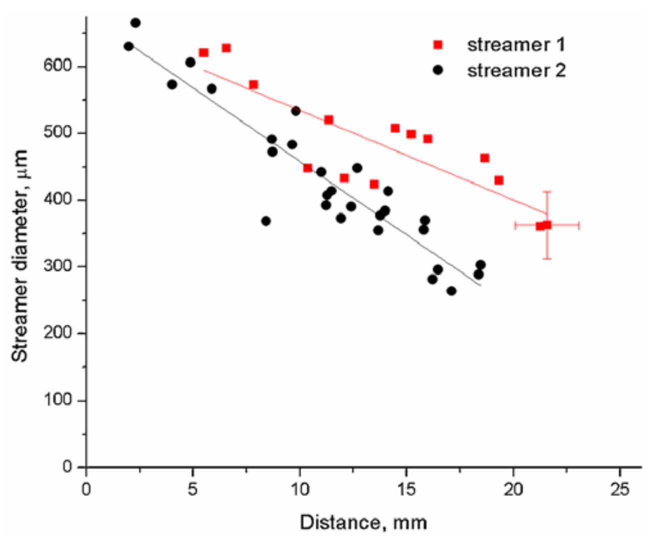

Figure 5. Diameter of streamer channel versus distance in gradient density air. The data taken for streamers presented in Figure 4b.

shown that the length of the streamers in a gradient density can be predicted using a simple empirical model. The experiments also revealed that when a streamer propagates inside the air with increasing density its diameter decreases.

[18] The presented study is a first attempt to investigate the development of streamers in a nonuniform medium. In the current experimental setup we are limited to a density ratio of two. We are planning to modify our experiment to extend the available density ratio. The results suggest further improvements to the experimental setup which will allow more detailed diagnostic of the discharge in a wider range of controllable parameters. In this study, the controlled gradient density in air was created using a mixing jet from a heat gun. Other methods of creating density gradients were also pointed out, such as supersonic nozzles, gas-filled tubes with controllable longitudinal thermal gradients.

[19] This paper studied streamer development from region with reduced density to higher gas density, in order to mimic red sprite conditions. It is possible however to conduct similar experiments, but with streamer development from high to low density regions. This will allow us to simulate the formation of Blue Jets, which are observed propagating upward from the top of thunderstorms.

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