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Inception and growth of an electrodeless atmospheric double-headed streamerS. Iseni,^{1,*} G. B. Sretenović,² V. V. Kovačević,² N. Bonifaci,³ C. Pichard,⁴ C. Cachoncinlle,¹ and A. Khacef¹¹*GREMI (Groupe de Recherches sur l'Énergétique des Milieux Ionisés)—UMR7344 CNRS / Université d'Orléans, 14 rue d'Issoudun, BP6744, 45067 Orléans, France*²*Faculty of Physics, University of Belgrade, PO Box 44, 11000 Belgrade, Republic of Serbia*³*G2Elab (Laboratoire de Génie Électrique de Grenoble)—UMR5269 CNRS / Grenoble INP / Université Grenoble Alpes, 21 rue des Martyrs, 38042 Grenoble, France*⁴*Polytech Orléans, Université d'Orléans, Site Galilée, 12 rue de Blois, 45067 Orléans, France*

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Gas discharge physics is particularly helpful to study many spectacular aspects of atmospheric electricity, e.g., lightning and sprite streamers. However, the observations of double-headed streamers (DHS) in nature—formed after the breakdown—remain an open question. Considering that the topic of DHS has been studied exclusively through theoretical and numerical models, this Letter presents the very first experimental model of DHS. Here, a primary plasma jet device operated at ground pressure is used to ignite a DHS in laboratory-scale experiments. This fundamental experimental model employs a noble gas flow (helium or neon) that expands freely and mixes with ambient air. The growth of the positive and the negative head was observed to originate from an isolated ionized column, directly confirming the previously published theoretical study. The high predictability and stability of the discharge allow advanced characterization diagnostics such as the Stark effect from which the electric field was measured along the discharge axis. This investigation indicates that a DHS can ignite in subbreakdown conditions and reveals the crucial role of the preionization phase. The consistency of these findings with some modeling studies on the topic will shed light on fundamental elementary processes in atmospheric electricity.

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Introduction. Among natural phenomena, *atmospheric electricity* has always been a fascinating topic, especially with the spectacular creation of lightning [1]. It is mainly with the knowledge of gas discharges [2] that the physics of lightning (e.g., sprites) was partly unveiled. Unlike mesospheric transient diffuse glow, i.e., sprite halo, *sprite streamers* essentially consist of self-organized ionization waves [3]. These filamentary plasma channels occur at lower ionospheric altitudes. However, the underlying mechanisms are not fully understood and, to date, remain a partial mystery since the first observations in the late 1990s. Recent remarkable advances using numerical simulation techniques provided some explanations of the formation of single- and double-headed—*sprite—streamers* (DHS) [1,3,4]. However, up to the present, the absence of a repeatable *experimental model of DHS* could not validate the results of the computational models. Prior to this finding, the theory of streamers was indeed supported by various numerical models describing the dynamics of streamers with different discharge conditions [4–7]. Interestingly, DHS was already investigated in the first numerical works, in the early 1990s [8,9]. This was merely to model positive and negative streamers in a single—computationally demanding—simulation. Ultimately, DHS could be considered as a pure numerical simulation concept before being revealed by the pioneer observation in nature [10]. But it is

worth noting the absence of experimental work in the DHS literature while the fundamental question on how double-headed sprite streamers ignite is still open.

Decades of consistent measurements of electric field (EF) in thunderclouds report values well below the critical breakdown field (E_k), i.e., when the insulating property of air fails. Two hypotheses are regularly discussed in the community of atmospheric sciences to explain the ignition of DHS. On the one hand, the existence of a solid conducting object featuring sharp tips (e.g., hydrometeors [6,11]) and placed in an EF much weaker than E_k could greatly enhance the local EF. On the other hand, DHS is also hypothesized to ignite from ionization patches exposed to the same EF conditions. Lately, Liu *et al.* [4] have proposed a modeling approach to investigate the latter assumption, showing promising results in this direction.

This work may be seen as an experimental attempt of the concept proposed within the theoretical study by Liu *et al.* [4] on the formation of DHS discharges from an isolated ionization column under subbreakdown conditions. Unlike large-scale electric discharges in the middle atmosphere, this laboratory experiment focuses on the ignition of DHS from a conducting object using a preionization column operating at ground pressure in the macroscopic scale.

Concept and experimental approach. The idea to ignite the formation of streamers—at subbreakdown conditions—from an isolated ionization column requires the use of an *electrodeless* plasma source to prevent any electrical connection with the external circuit as discussed by Liu *et al.* [4]. This means the absence of solid metal electrodes in the inception

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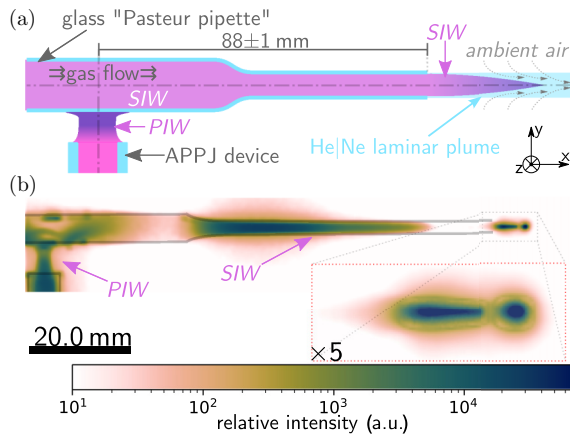


FIG. 1. Experimental setup showing the region of interest of the EASII-jet plasma source [13]. Only the electrodeless part with the transfer from the PIW to the SIW is shown. (a) Schematic of the setup, the Pasteur pipette fed with helium or neon gas and forming a laminar plume in ambient air. (b) iCCD image showing the neon SIW propagating within the Pasteur pipette as well as the *isolated* double-headed streamers ignited in the laminar plume of noble gas in ambient air. iCCD gate width: 5 ns; averaging: 10^4 triggered shots; spectral range: 590–850 nm).

region of the DHS, which would lead to depositing additional charges with the rise of the current and thus influencing the natural development from an ionizing electron avalanche to streamer growth. The use of a solid electrode—as small as it might be—would greatly enhance the EF to satisfy the growth of the avalanche [11]. For instance, this mechanism can take place in the natural environment with the presence of hydrometeors [6], which is not the approach considered here. To experimentally satisfy the hypothesis proposed by Liu *et al.* [4], i.e., having an initial ionized column of free charges prior to the breakdown at ground pressure, a plain and original plasma source was designed. Based on a typical atmospheric pressure plasma jet (APPJ) device [12], the electrodeless atmospheric secondary induced ionization jet (EASII-jet) was recently introduced [13]. Figure 1(a) presents the central part of the EASII-jet, leaving aside the main segment of a typical APPJ, electrically powered with a HV generator producing squared pulses with an adjustable width (w_{pulse}). The system is fed with 0.7 slm (standard liter per minute) helium or neon (see Ref. [13] for more details). At the first edge of the HV pulse, the APPJ produces the primary ionization wave (PIW) which propagates within its glass tube. At the outlet, the PIW will ignite a secondary induced IW (SIW) inside the pipette which propagates along its own axis before expanding into the laminar flow to form a plasma plume in free space [13]. This sequence of events also occurs on the second edge of the HV pulse to return to 0 V. In other words, *each* HV pulse produces two separate PIWs, and then SIWs, which are delayed by w_{pulse} [13]. It is worth noting that the pipette is *electrically isolated* and is supplied with 0.3 slm noble gas flow, *creating at its own exit a laminar plume*—of helium or neon—*surrounded by ambient humid air* at ground pressure. The use of noble gases mixed with in-diffusing air molecules facilitates the ignition and the reproducibility of

the discharge. To some extent, this approach was successfully demonstrated in Ref. [14], where the streamer physics in air could be thoroughly investigated using an APPJ device. Air molecules also diffuse into the noble gas plume, as shown in Fig. 1(a). In fact, the fraction of air molecules in the plume is not negligible. It typically ranges from a few tenths to a few percent in APPJ-like sources [12]. A dedicated work on guided streamer in noble gases surrounded by air has experimentally demonstrated the crucial role of in-diffusing air molecules on streamer dynamics [15]. The small volume of gas at the outlet of the pipette will be the region of interest in this study as it can have a preionization level distributed along a gas column axis similar to the numerical work of Liu *et al.* [4]. Figure 1(b) shows an image when the PIW—from the APPJ—efficiently induces a SIW that remotely ignites an *isolated and asymmetric discharge* outside the pipette; the latter resembles a DHS [3,4,7,16]. The EASII-jet features several operating modes evidencing different dynamics of the SIW propagation [13]. In the following, helium and neon gases will be used independently in order to demonstrate the comprehensiveness of the underlying elementary processes of the DHS inception.

To seed with free charges the laminar plume expanding from the pipette outlet, a PIW is ignited and then transferred to form a SIW. With the absence of an electrode in the pipette, the SIW is not able to last longer than a couple of hundreds of nanoseconds. From the SIW trail, a column remains, seeded with free charges distributed along the laminar noble gas flow [12]. To avoid changing the effective first Townsend coefficient by modifying the air entrainment in the gas plume, the constant flow rate is monitored [17,18].

How is an isolated streamer remotely ignited within this transient preionized column? This is possible by timely launching the *new* SIW within the pipette. Practically, the succeeding SIW is triggered while setting the voltage potential of the APPJ back to 0 V, i.e., the second edge of the HV square pulse powering the APPJ, as reported in Ref. [13]. The timing between the discharge used to preionize the column and the subsequent SIW, which serves to impose a high potential to remotely ignite the DHS, corresponds to w_{pulse} of the APPJ's electrical excitation. It can be tuned while keeping the HV amplitude constant with typical rise and fall times of 33 ± 2 ns. In addition, by varying w_{pulse} at a constant high-voltage pulse amplitude, it is possible to vary the preionization while maintaining a constant driving electric field.

Results. In essence, the mechanism of streamer formation is conceivable as long as the *local* EF of the space charge created at the breakdown time reaches a value of at least the order of the external field (E_0). E_0 is typically of 30 kV/cm in dry air. It is expected to be three times lower in helium containing air impurities [2]. In the present experiment, neither the externally applied field strength (E_0) nor the gap width (d) can be determined with absolute certainty *a priori*. However, it is certain that the critical local EF strength is reached within the gap between the electric potential of the SIW confined within the pipette and a lower, floating potential outside.

Meek's number $M = \alpha(E_0)d$, with α^{-1} the ionization length, is a well-established and convenient quantity to describe the breakdown conditions for streamer discharges [19]. Values of $M = 18\text{--}21$ refer to the Raether-Meek criterion

required for a streamer to grow, which corresponds to the number of free charges $N_e \approx 10^8\text{--}10^9$ [2].

Despite the inherent difficulty in experimentally determining the value of M , it is possible to identify conditions in space and time that lead to the creation of a critical local EF opposite to the E_0 direction and of comparable magnitude, thereby initiating streamer inception. In helium, w_{pulse} ranging from $1.9\text{--}(2.4 \pm 0.1)\ \mu\text{s}$ with the streamer inception is located at $(2.4 \pm 0.2)\ \text{mm}$ downstream from the pipette outlet. Figure 2 reports the same situation but in neon for w_{pulse} values between $0.8\text{--}(1.5 \pm 0.1)\ \mu\text{s}$. The figure presents the electrodeless DHS dynamics growing in the opposite directions along the x axis. To overcome the inherent low light emission at the early breakdown time, the data are shown in logarithmic scale using a perceptually uniform color palette to properly resolve the intensity gradients [20]. The very first moment of the DHS inception is captured in Fig. 2(a). Acquired over hundreds of triggered shots, the tiny luminous spot—revealing the exact position of the DHS starting point—shows a remarkable space and time repeatability. It is located about $(6.5 \pm 0.2)\ \text{mm}$ from the pipette outlet. In the following, the breakdown spot will be conveniently set to the origin for both gases, i.e., $x = 0$. As a matter of fact, Figs. 2(a)–2(e) reveal a significant asymmetrical propagation of the discharge originating from the breakdown location and following a straight line. This favorable direction corresponds to the preionized laminar plume of neon, which has a significantly higher ionization rate than air [2]. In a timescale as short as 25 ns, the light emission comes from the excitation of atoms—and possible molecular impurities—by nonelastic collisions (mostly direct excitation by electron impact). Thus, the emission is often assumed to resemble the ionization source term in streamer simulations [21]. Consequently, one can infer that the mechanism of the streamer growth into the right direction is different from the processes involved in the streamer growing into the counter-direction (toward the pipette outlet).

The morphology of each side of the discharge is consistent with the description suggested by the theory of positive and negative streamers [2,5,21–23]. In fact, a negative streamer front is formed by an overabundance of mobile electrons drifting outward from the ionized body, creating the space charge. Electrons drifting in the lateral (radial) direction tend to shape a diffuse space charge, producing a lower EF enhancement at the front. This is clearly visible in Figs. 2(f)–2(k) where the streamer directed toward the pipette outlet becomes wider and wider as it is growing. Thus, the emission of the surrounding excited air species (mainly N_2) is due to the drift of the lateral electron cloud, resembling the pinkish glow in Figs. 2(f)–2(k). In the next frames, the negative streamer growth mechanism will progressively turn into an external-field-driven electron by the drift process before vanishing by attachment and recombination.

Fundamentally, the identification of an electrodeless negative streamer implies that the discharge propagating in its counterdirection (right side of $x = 0$) must be a *positive* streamer [4,5,7,16]. Theoretically, the latter grows from electrons drifting inward toward its head and forming a charge layer by an excess of immobile positive ions. This leads to an efficient enhancement of the EF ahead of the streamer, yielding a rather compact ionization front compared to

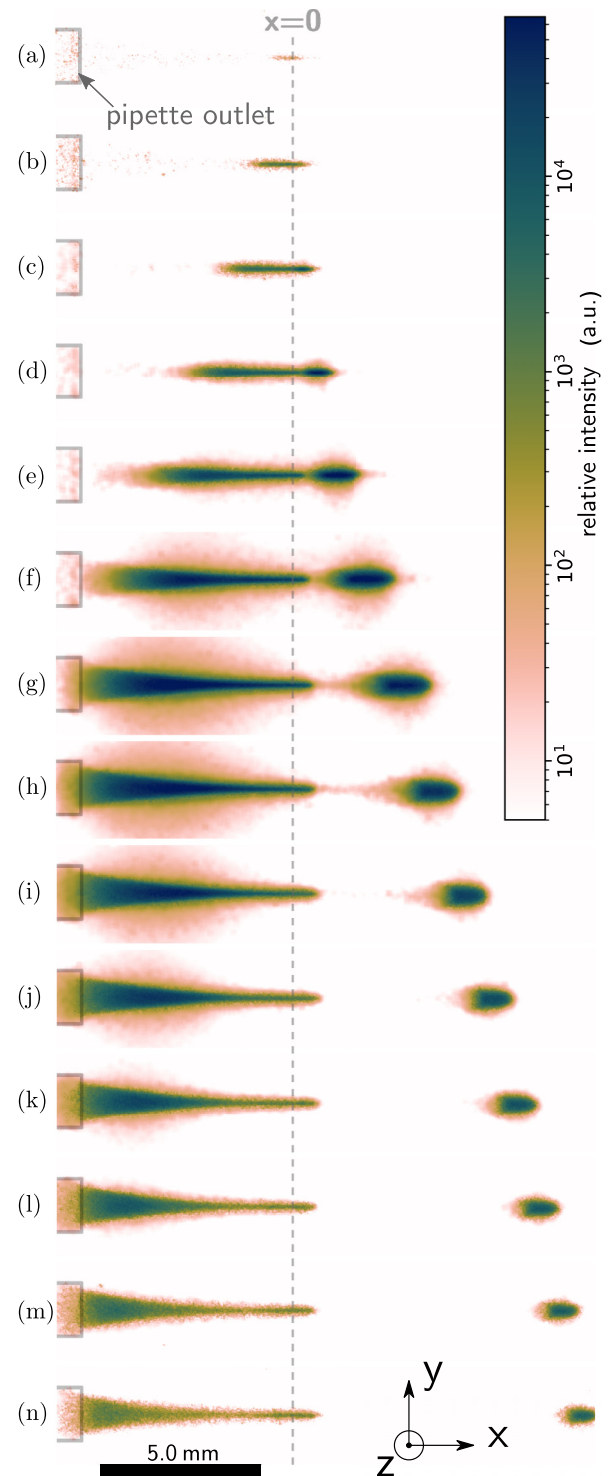


FIG. 2. Successive iCCD images showing the *isolated* DHS growth in the preionized column in noble gas surrounded by ambient air. The position $x = 0$ corresponds to the on-axis location of the DHS inception. (iCCD gate width: 25 ns; delay between each frame: 25 ns; averaging: 800 triggered shots; spectral range: 240–900 nm).

negative streamers. This is observed in Fig. 2 with the growth into the right direction of a dense and localized luminous ionizing front. To sustain the positive streamer growth, the photoionization process—involving in-diffused

TABLE I. Ionization front velocities of double-headed streamers in helium and neon (10^6 cm/s).

Helium		Neon	
Positive	Negative	Positive	Negative
0.72 ± 0.15	0.57 ± 0.15	2.8 ± 0.9	1.6 ± 0.7

air molecules—is essential to produce free energetic electrons ahead of the front [2,7,16]. As a nonlocal ionization mechanism, it is extremely difficult to investigate this elementary process experimentally. However, Figs. 2(a)–2(e) show that the growth of the negative streamer occurs *before* its positive counterpart. This time delay could be attributed to the lack of a yet efficient photoionization process—of air impurities—as argued in Ref. [5]. Indeed, advanced numerical simulations have shown that the positive discharge side remains at rest until the photoionization mechanism has built up a sufficient electron density for the streamer front to grow. This fact supports the identification of a negative streamer, while an electron drift wave would be expected to develop slower than the counter positive streamer. Furthermore, it would raise questions regarding the source of electrons to contribute to the electron drift wave.

Experimentally, it is convenient to characterize streamers with their radius and growth velocity. On the one hand, the DHS is guided in the neon or helium laminar plume which tends to bound the front radius expansion. On the other hand, velocities were measured for both gases by means of averaged gated images. Values are presented in Table I and are in agreement with the recurrent literature [12,13,22]. Nevertheless, streamer velocities can be found in a much larger range of values. Despite the earlier growth of the negative streamer, the positive front is faster for both gases. It results from a more focused and a more intense EF at the head of positive streamers compared to the more extensive negative streamer shape. The order of magnitude of the current can be estimated from the velocity in helium compared to the data reported in Ref. [24]. The best agreement gives a corresponding current in the order of (350 ± 50) μ A.

To support the previous argumentation, the EF along the x axis of the DHS was experimentally investigated. Measurements of EF in transient plasmas still remain challenging. As a method of choice, optical emission spectroscopy (OES), as an inherently noninvasive approach, allows for measuring some discharge properties. Using the same diagnostic setup as documented in Ref. [13], the EF strength is investigated by means of the Stark effect. Practically, the EF is measured with the emission line profile analysis of the π -polarized Stark splitting and shifting of the allowed transition ($4d^1D \rightarrow 2p^1P^0$) and the forbidden transition ($4f^1F \rightarrow 2p^1P^0$) of He I at 492.19 nm [14]. As demonstrated in Ref. [17], high-resolution space-resolved EF measurements are achieved with time-integrated OES emission recorded during the streamer growth. The results—in helium—are plotted in Fig. 3 presenting the local EF strength within the streamer head along the x axis. At first glance, the measurements exhibit a peculiar longitudinal EF profile. Indeed, the curve describes a shape with an inflection point at $x = 0$ mm, exactly where the DHS is

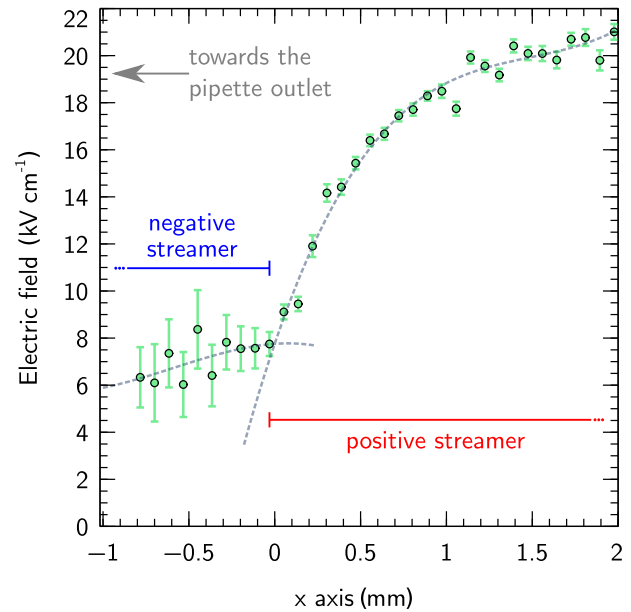


FIG. 3. Local electric field values (maximum of the streamer head field), along the x axis of the DHS in helium. The measurements are shown with circle markers and error bars. Dash curves are trend lines taking into account the measurement uncertainties. The streamer inception—as shown in neon in Fig. 2(a)—is located at $x = 0$ mm.

ignited. Consequently, two parts of the curve can be identified and—fairly—emphasized by the two trend lines. Again, this reveals that the elementary processes governing each side of the discharge are indeed of different nature.

The EF evolution of the helium DHS is perfectly in line with the previous findings reported in neon. The positive streamer grows from $x = 0$ mm toward the right direction with a fast rise of its EF at the front up to 22 kV cm^{-1} . This value is in excellent alignment with theoretical, numerical, and experimental studies from the literature [12,24]. Regarding the negative streamer, EF stays relatively high in the trail in order to maintain the discharge, which explains the slow decay as long as the streamer grows. It is also a requisite to report on EF measurements in negative helium streamers at ground pressure. The latter are fully consistent with the theory of negative streamers and with numerical works [2,16,21,23]. Lately, experimental values of EF in negative streamers were measured using the electric-field-induced second harmonic (E-FISH) method [25]. The authors report a EF strength of 8 kV cm^{-1} in a negative IW front for relatively slow transient time of the applied HV. Although the EF may seem relatively low for streamer discharges, the characteristic time of E_0 also plays a role in the streamer properties. This was also investigated with numerical modeling in air [26] and in rare gases [27].

A major fact revealed in Fig. 3 would certainly be the EF magnitude where the streamer breakdown criterion ($M = 18$ – 21) is most likely met in a limited volume, i.e., at $x = 0$ mm. The local EF at this precise position is $7.8(2)$ kV cm^{-1} , while in helium the conventional breakdown threshold field at ground pressure is typically $E_k = 10$ kV cm^{-1} [2]. Consequently, this result would suggest that

the remote DHS can ignite at *subbreakdown conditions*. This would bring a substantial experimental argument to support the numerical study by Liu *et al.* on the formation of sprites [4]. It also corroborates a part of the discussion proposed in Ref. [28].

An estimation of the minimum electron density of the preionized column (n_{e_0}) is possible assuming a cylindrical conductor in a uniform field E_0 . At the inception position x_0 it reads

$$n_{e_0} = \frac{\lambda(x_0)}{\pi e(D/2)^2}, \quad (1)$$

with $l \approx 5$ mm the length and $D = 0.5$ mm the diameter of the preionized column; e is the absolute value of electron charge and $\lambda(x)$ the linear charge density analog conductor [4]. This leads, for helium, to a preionization in the order of $1.5 \times 10^{11} \text{ cm}^{-3}$ before the DHS inception. This value is in agreement with another estimation approach taken from the theory of streamers, $n_e = (\epsilon_0/e)\alpha(E)E$, [24,29]. With $E_{x=0 \text{ mm}}$ taken from Fig. 3, n_{e_0} is found to be around $2(1) \times 10^{11} \text{ cm}^{-3}$.

Concluding remarks. In summary, this paper successfully demonstrates the possibility to create the as yet poorly understood natural atmospheric phenomenon of DHS in a laboratory-scale experiment at ground pressure. This experimental model is one of a kind to reproduce the inception of an *electrodeless* DHS resembling several phenomenological observations by the atmospheric electricity community. The use of guided ionization waves originating from an APPJ device offered an excellent reproducibility and predictability to trigger the DHS inception. Furthermore, this experimental approach could provide suitable conditions to realistically produce most of the assumptions proposed by Liu *et al.* [4], i.e., maintaining an initial preionized column of free charges prior to the breakdown. This fundamental experimental model remarkably resembles a large set of simulation results found in modeling publications. The positive streamer could be identified distinctly from the negative one, evidencing a

simultaneous counterpropagation of each front in the opposite directions from the breakdown location. The high stability of the discharge allows for applying advanced diagnostics such as time- and spaceresolved optical emission spectroscopy. Thus, the first measurements of velocity growth, gas temperature, and electric field of a DHS could be carried out. The EF values diagnosed in the DHS confirmed the identification of the positive and the negative streamers. The latter seem to develop within a highly preionized column resulting in relatively lower values of EF, which are consistent with the published literature. Furthermore, it is worth noting that the electric field diagnostic revealed the capability of a DHS to ignite at subbreakdown conditions. The latter results from the preionization of the gas volume being essential for the formation of the DHS. These findings support the theory proposed by Liu *et al.* [4] based on the excellent agreement of the simulations and our experimental results. In other words, this work brings out the main elementary processes favorable to the DHS creation, which is extended to more than a single gas. Indeed, the cases of helium and neon mixing with ambient air showed similar results which tend to generalize the existence of DHS in air. In all likelihood, there should not be a unique elementary process leading to the growth of DHS. While more work is needed to fully understand the underlying mechanisms, the results open the door to deeper investigations—with an affordable laboratory-scale experiment—into the physics involved in the early step of sprite discharges and other poorly understood phenomena in atmospheric electricity.

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