

Unusual plasma formations produced by positive streamers entering the cloud of negatively charged water droplets

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Abstract. Kostinskiy et al. (2015a), using a high-speed infrared (2.5-5.5 μm) camera, discovered the so-called unusual plasma formations (UPFs) in artificial clouds of charged water droplets. UPFs had complex morphology including both streamer-like regions and hot channel segments. They were observed both in the presence and in the absence of hot leader channels developing from the grounded plane toward the cloud. In this paper, which is aimed at revealing the genesis of UPFs, we present two UPFs that occurred inside the initial corona streamer burst of positive polarity emitted from the grounded plane, prior to the formation (or in the absence) of associated hot leader channel. These streamer bursts developed at speeds of 5 to 7 $\times 10^5$ m/s over 1 to 1.5 m in apparently clear air before entering the negatively-charged cloud and producing UPFs at its periphery. Hot channel segments within UPFs were formed in very short times of the order of 1 μs or less. It is not clear if the UPFs were caused solely by the enhanced electric field near the charged cloud boundary or other factors also played a role. Occurrence of UPFs may be a necessary component of any lightning initiation mechanism (Kostinskiy et al., 2020; Iudin et al., 2021).

Key Points:

1. Unusual plasma formations (UPFs) can occur inside the initial corona streamer burst, before the development (or in the absence) of hot leader channel
2. UPFs contain hot channel segments that are formed, possibly via thermal-ionizational instability, on a time scale of the order of 1 μs or less
3. UPFs tend to occur in the vicinity of cloud boundary, where the electric field is highest, as this boundary is penetrated by the streamer burst

Introduction

Kostinskiy et al. (2015a,b), using a framing camera operating in the infrared (IR) range of 2.5-5.5 μm , have discovered a new class of electric discharges within artificial clouds of charged water droplets and termed them unusual plasma formations (UPFs). In the IR images, some UPF segments had similar or even greater brightness than the positive upward leader channel imaged in the same frame, suggesting that the temperature of those UPF segments is comparable to that of upward positive leaders. The upward positive leaders were preceded by initial positive corona streamer bursts, both originating from the grounded plane and propagating over 1 m or so toward the negatively charged cloud. The relatively long exposure time, 2-3 ms, of the infrared camera used by Kostinskiy et al. (2015a) did not allow them to

resolve the dynamics of UPFs and draw any conclusions about the mechanism of their initiation and development.

The goal of this work was to examine the genesis of UPFs; that is, processes that trigger their occurrence. In order to accomplish this, an experimental setup used by Kostinskiy et al. (2015a), was supplemented by microwave diagnostics (Bogatov et al., 2020), which, together with other devices, provided experimental data that allowed us to reveal a possible mechanism of the occurrence of UPFs.

In this article, we use the term “long streamers” in referring to streamers that have essentially lost their galvanic (electrical) connection with their origin. Streamer is a cold plasma formation composed of a brighter head and a much fainter tail. Part of the tail, which is closer to the head, contains a significant number of free electrons and therefore is conducting. The characteristic length of the conducting part of streamer tail can be estimated based on the speed of movement of streamer head v_{str} and the electron attachment time τ_a in the streamer channel behind the head: $L_{str} \approx v_{str}\tau_a = 2 - 10 \cdot 10^7 \frac{cm}{s} \cdot 10^{-7} s \approx 2 - 10 \text{ cm}$ (Bazelyan & Raizer, 1998; Kossyi et al., 1992). Thus, streamers whose heads moved farther than 1 – 10 cm from their origin are considered here as long streamers.

Experimental setup

The experiments were performed at the High-Voltage Research Center of the Zababakhin All-Russian Scientific Research Institute of Technical Physics, Istra, (<http://www.ckp-rf.ru/usu/73578/>). The experimental setup used in this study (Fig. 1) was similar to the one used in previous studies and described in detail by Kostinskiy et al. (2015a,b; 2016). Charged cloud (1) was created by steam generator (2.1) and high-voltage source (2.2) coupled with the corona-producing sharp point (needle). The latter was located in the nozzle (2.3) which the steam-air jet was passing through. The steam in the nozzle had a temperature of about 100-120 °C and a pressure in the range of 0.2–0.6 MPa. The steam moved at an initial speed of about 400-420 m/s with an aperture angle of 28°, forming a submerged turbulent jet. The nozzle with the needle was located in the center of a grounded plane (3) with a diameter of 2 m. As a result of rapid cooling, the vapor condensed into water droplets with an average radius of about 0.5 μm. Ions produced by corona discharge between the tip of the needle and the nozzle (2.3) served to charge the water droplets. The corona-producing needle was energized by a 10–20 kV DC voltage source. The current carried by the charged aerosol jet was in the range from 60 to 150 μA. When the total charge accumulated in the cloud reached ~60 μC, meter-scale sparks spontaneously appeared between the nearby grounded objects and the cloud. In the case of negatively-charged cloud, the sparks usually occurred as a sequence of an initial positive corona streamer burst and a positive leader, both developing from the grounded metal sphere (4) toward the cloud (1). The metal sphere had a diameter of 5 cm and was located at a distance of 0.85 m from the center of the grounded plane (3). The top point of the sphere was 12 cm above the plane. Initial positive corona streamer bursts and positive leaders, originating from the metal sphere, propagated essentially perpendicular to the direction of the diagnostic microwave beam (9.5).

Currents of initial corona streamer bursts and upward positive leaders were measured by a low-inductance 1-Ω shunt, inserted between the metal sphere (4) and ground, and a digitizing oscilloscope (5). Once the current exceeds a preset threshold value, the oscilloscope (5) records (a) the current through the shunt, (b) the discharge luminosity signal from the photomultiplier tube (PMT) (8), and (c) the signal from the 50-cm diameter metal sphere (10), used for monitoring the variation of cloud charge. The oscilloscope also outputs a trigger signal for the pulse generator (11) which forms a TTL pulse triggering high-speed cameras 4Picos (6) and FLIR SC7700M (7), as well as a second oscilloscope (9.7) recording microwave radiation (9.5) that passed through the cloud (1). The infrared framing camera FLIR SC7700M

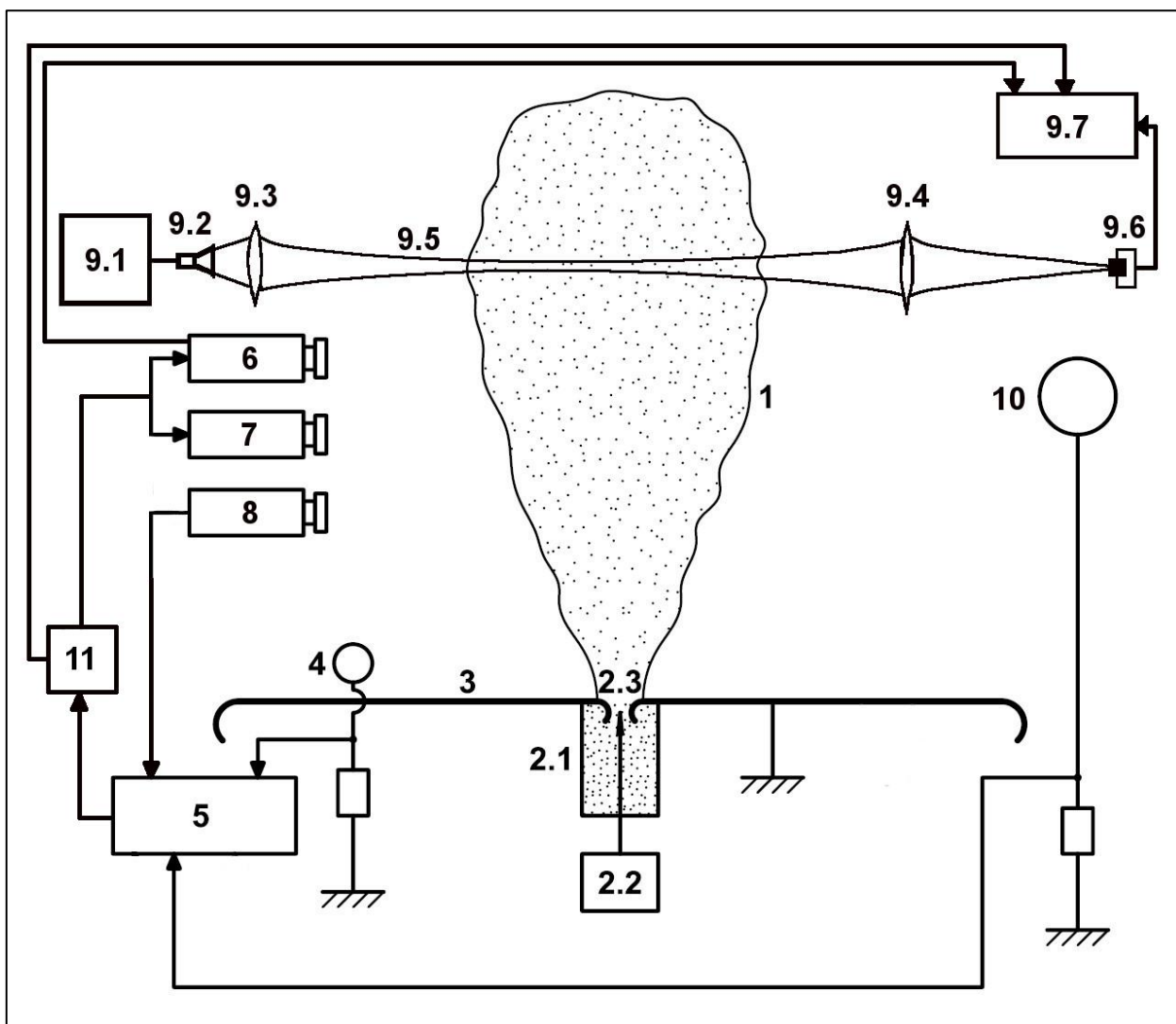


Figure 1. Experimental setup: 1 — cloud of negatively charged water droplets, 2.1 — steam generator, 2.2 — high-voltage source with corona-producing sharp point, 2.3 — nozzle, 3 — grounded metal plane, 4 — 5-cm sphere connected to ground via current-measuring shunt, 5 — oscilloscope, 6 — visible-range high-speed framing camera 4Picos, 7 — infrared high-speed framing camera FLIR-7700, 8 — photomultiplier, 9.1 — microwave generator G4-91, 9.2 — horn antenna, 9.3 and 9.4 — dielectric lenses, 9.5 — microwave beam, 9.6 —receiving waveguide, microwave amplifier, and a microwave diode, 9.7 — oscilloscope, 10 — 50-cm sphere for monitoring variations of cloud charge, 11 — pulse generator.

($\lambda \approx 2.5\text{--}5.5\ \mu\text{m}$) operated at 412 frames per second (exposure time was 2.4 ms), with the image size on the matrix being 320×256 pixels. The IR-camera was equipped with a germanium lens with a focal length of 50 mm and an aperture of $f/2$. The 4Picos high-speed visible-range (actually it includes a portion of the UV range; $\lambda = 315\text{--}850\ \text{nm}$) camera with image amplification (optical gain was 10^4) captured images on a 1360×1024 -pixel matrix with exposure time from 50 ns to 10 μs . It can produce only two frames with selectable interframe interval of 500 ns or more. The 4Picos camera was equipped with a glass lens with a focal length of 50 mm and an aperture of $f/0.95$. The cameras were installed at a distance of 8.5 m from the nozzle, which forms the aerosol cloud (2.3) in the direction of the propagation axis of the microwave beam. The viewing angle (directional diagram) of the photomultiplier was $\sim 10^\circ$, and the size of the photomultiplier's field of view at the location of the cloud was $\sim 1\ \text{m}^2$. The photomultiplier tube was aimed at the upper half of the cloud, at a height of about 0.8–1 m above the plane. The time constant of the PMT was several milliseconds, but still it could fairly accurately record the onset of luminosity in its field of view.

The source of microwave radiation was a G4-91 generator (9.1). The generator output power was 5 mW, and the radiation frequency was 35 GHz ($\lambda = 8.5\ \text{mm}$). The generator was operating in continuous mode. A converging microwave beam with a Gaussian profile was formed by a horn antenna (9.2) and dielectric lenses (9.3 and 9.4). The waist of the microwave beam (9.5) was located on the axis of the cloud. The angle between the axis of the microwave beam and the axis of the cloud was $85\text{--}87^\circ$. The diameter of the microwave beam in the waist region was $\sim 10\ \text{cm}$ (in the studied region, the beam was almost cylindrical, and in the region of the visible edge of the aerosol cloud it was only 3% wider than at its center). The distance from the axis of the microwave beam to the grounded plane was $\sim 1\ \text{m}$. The polarization of microwave radiation was linear (vertical). Microwave radiation transmitted through the cloud was focused by a dielectric lens (9.4) into the open end of the receiving waveguide, amplified with a 20 dB microwave amplifier, and detected with a microwave diode (9.6). The output level of the signal from the microwave diode was recorded with an oscilloscope (9.7). The relative attenuation of microwave radiation passing through the cloud was determined by the ratio of the value of the output signal level from the diode to the unperturbed level (in the absence of the cloud). The main source of noise that determines the sensitivity of microwave diagnostics in general was the instability of the output power of the microwave generator, which was $\sim 10^{-3}$; the latter value determined the minimum relative attenuation of the probing microwave radiation that we could register. An uncharged cloud and a charged cloud in the intervals between in-cloud events did not noticeably attenuate the probing microwave radiation. The equipment was installed in three electromagnetically shielded structures/enclosures, of which two smaller ones (housing the high-speed cameras 6 and 7 and the receiving part of the microwave diagnostics setup 9.6; see Fig. 1) had autonomous power supply.

Experimental results

Presented in Fig. 2 is a sequence of two 4Picos frames separated by a time interval of 1 μs . The first frame (labeled I; exposure time of 2 μs) shows the initial corona streamer burst that originated from the grounded sphere in the lower left corner and entered the negatively-charged cloud in the upper right corner. Also seen in the first frame is a UPF containing three bright channel segments, which are similar to those reported by Kostinskiy et al. (2015a) and inferred by them to be hot (having gas temperature similar to that of leader channels; it is in this sense that we refer to those segments being “hot”). The second frame (labeled II; exposure time of 10 μs) shows the upward positive leader composed of a relatively short, branched hot channel and a relatively large streamer zone which enters the cloud in the upper right corner. Clearly, the UPF occurred inside the initial corona streamer burst, before the

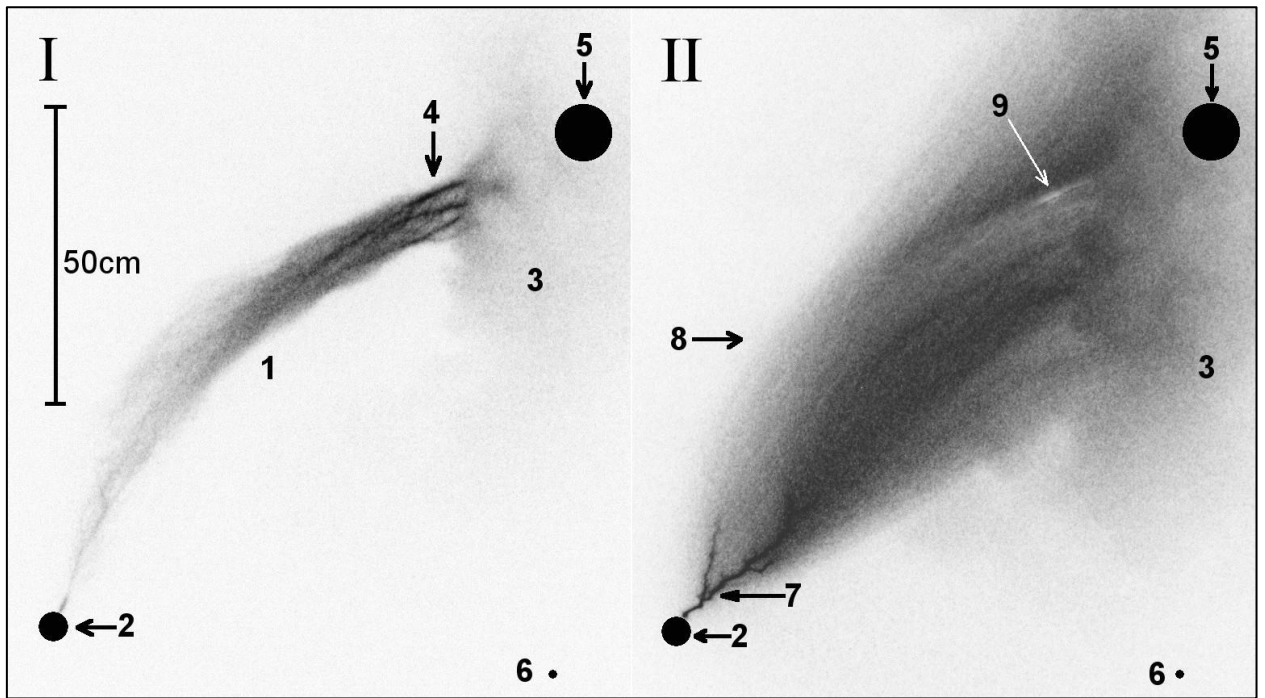


Figure 2. Two consecutive frames of event 2015-12-04_03 obtained with a visible-range 4Picos camera with image enhancement. Frames I and II had 2- μ s and 10 μ s exposure times, respectively, and the time interval between frames was 1 μ s. Both frames are inverted. 1, the initial positive corona streamer burst converted to UPF; 2, 5-cm grounded sphere equipped with a current-measuring shunt; 3, cloud of negatively charged water droplets; 4, hot channel segments embedded in UPF; 5, the region of passage of the microwave beam; 6, the center of the grounded plane where the nozzle (see Fig. 1) is located; 7, channel of upward positive leader; 8, streamer zone of the upward positive leader; and 9 - light stripe, which is an image artifact.

development of hot leader channel from the grounded sphere. Further, it occurred in the vicinity of the visible cloud boundary, where the electric field is expected to be highest, as that boundary was penetrated by the streamer burst. It is logical to assume that the streamer burst entering the cloud experienced some kind of instability (for example, thermal-ionizational instability (Nighan, 1977; Raizer, 1991, pp. 222-226; Bychkov et al., 2007; Zhong et al., 2019; Wolf et al., 2020)) that led to its conversion to UPF. In the following, we will use the entirety of our experimental data (see Figs. 3 and 4) to estimate the time needed for conversion of streamer burst to UPF seen in Fig. 2. An additional example of such conversion is presented in Figs. 5a and b.

The initial corona streamer burst precedes the formation of hot leader channel (this is why it is referred to as initial), although sometimes no following leader is formed. Current associated with those two processes in the first event we are going to present exhibits the initial pulse labeled 1 Fig. 3b followed by a time interval with very low current level and then by a much larger in amplitude and longer in duration current waveform with multiple peaks or superimposed pulses (the overall current waveform is best seen in Fig. 3a), the first three of which are labeled 2, 3, and 4 in Fig. 3b. Current pulse 1 occurred before the first 4Picos frame and current peaks 2 and 3 occurred during that frame, which shows no leader channel. Therefore, we attribute current pulse 1 and current peaks 2 and 3 to the initial corona streamer burst, while current peak 4 and the following part of the large current waveform could be formed in the presence of leader channel. It is likely that the UPF was associated with current pulse 1. Note that there is a small pulse during the low-current interval, which appears to coincide with the onset of the photomultiplier signal originating from the upper part of the cloud. It is not clear if it was just a minor variation of the low-level current or it was somehow related to the streamer burst to UPF conversion process. Interestingly, the small current pulse seems to be coincident with the beginning of appreciable cloud-charge variation (not shown here), detected with 50-cm sphere 10 (see Fig. 1).

One can see in Fig. 2(I) those streamers of the initial corona streamer burst (1), once they entered the cloud (3), were moving toward the microwave beam (5). The fact that the streamers did reach the position of microwave beam is evidenced by a pronounced microwave absorption pulse with an FWHM of about 135 ns and its peak being within the exposure time of the first 4Picos frame (left frame labeled I in Fig. 2), approximately 0.85 μ s before the end of exposure of that frame. It is worth noting that corona streamers in long sparks cause stronger absorption of microwave radiation than leader channels (Bogatov et al., 2020). The streamer heads traversed an arc-like trajectory between the grounded sphere (2) and the region of the microwave beam (5) in the cloud (3). The length of that trajectory was about $S_{st} \approx 1.2$ m and the streamer-head travel time was about $\tau_{st} \approx 1.7$ μ s (estimated as the time interval between the peak of the current pulse 1 (see Fig. 3b), associated with the onset of the initial corona streamer burst at the grounded sphere, and the onset of microwave absorption signal. Thus, the average 2D speed of streamers of the initial corona streamer burst was about $v_{st} \approx S_{st}/\tau_{st} \approx 7 \cdot 10^5$ m/s.

Also seen in Fig. 2(I) is a UPF with three bright channel segments (4), which are partially outside of the optically opaque part of the cloud and are similar to those recorded in previous experiments by Kostinskiy et al. (2015a) and inferred by them to be relatively hot. Since the bright segments of UPFs are located at a distance of about 1 m from the origin of the initial corona streamer burst (grounded sphere), and the average velocity of streamer propagation is about 7×10^5 m/s, the process of transition of streamer burst to UPF began approximately 1.4 μ s ($1 \text{ m} / 7 \times 10^5 \text{ m/s}$) or more after the start of the initial corona streamer burst. The time interval between the onset of the initial corona streamer burst (current pulse labeled 1 in Fig. 3b) and the end of exposure of the first frame of 4Picos was 2.5 μ s. Since the UPF was formed before the end of the exposure of this frame, its formation process took no more than 1.1 μ s ($2.5 \mu\text{s} - 1.4 \mu\text{s}$).

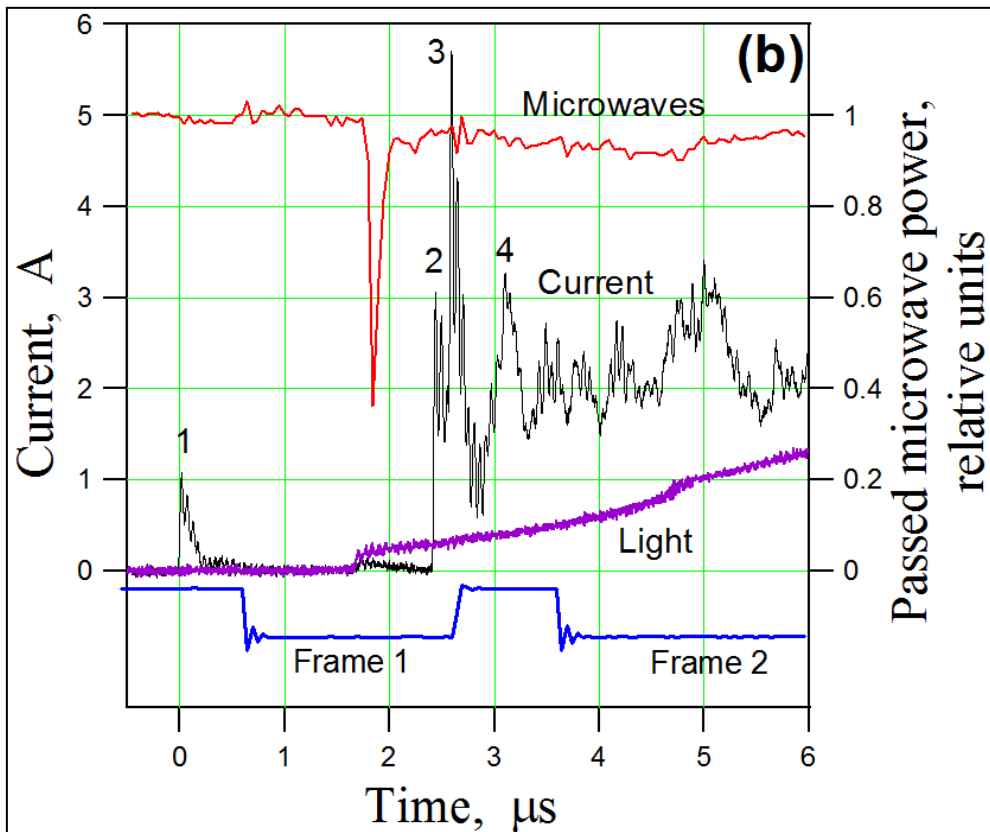
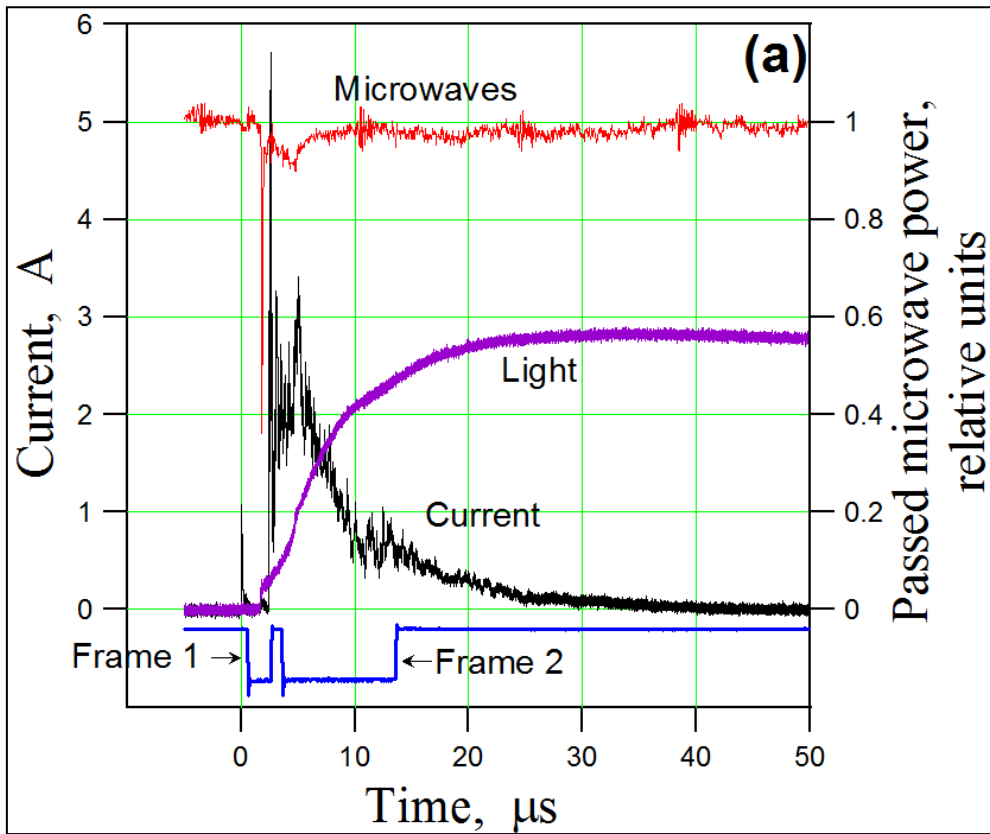


Figure 3 (event 2015-12-04_03). (a) Current measured at the grounded sphere (shown in black); absorption of microwave radiation that passes through the cloud (shown in red and labeled “Microwaves”); photomultiplier signal (shown in purple and labeled “Light”), and exposure times of 4Picos Frames 1 and 2 (shown in blue and labeled I and II in Fig. 2). (b) Same as (a), but shown on an expanded time scale. The first four major current pulses are numbered in (b).

In the second frame of 4Picos (right frame labeled II in Fig. 2), the channel of upward positive leader (7) and its streamer zone (8) are clearly visible. The maximum 2D extent of the leader channel, measured from its origin on the grounded sphere (2) to its most distant point is about 29 ± 2 cm. It was found from the corresponding infrared images (discussed later in this paper), captured with much longer (2.4 ms) exposure time, that the total leader channel length was 42 ± 1 cm; that is, it did not enter the cloud.

As noted above, current pulse 1 associated with the beginning of the initial corona streamer burst was followed, after a time interval of $2.4 \mu\text{s}$, by a multi-peak current waveform. Light emissions of streamers associated with the first two peaks of that current waveform (labeled 2 and 3 in Fig. 3b) were likely imaged in the first frame of 4Picos (see Fig. 2(I)). We argue that the UPF occurred before those two subsequent streamer bursts, because the onset of signal from the photomultiplier (viewing the upper part of the cloud, with the region within about 0.5 m of the grounded sphere being outside of its field of view) was $\sim 1.7 \mu\text{s}$ after the current pulse 1 and $1.9 \mu\text{s}$ before the current pulse 2. Further, the light intensity of a discharge near the grounded sphere after being scattered by the cloud was below the sensitivity threshold of the photomultiplier. Thus, current measured at the grounded sphere must precede (not follow) the light emission detected by the photomultiplier, which means that the UPF seen in Fig. 2(I) was caused by the streamer burst associated with current pulse 1 (see Fig. 3b), as stated above.

Characteristics of current pulses 1 through 4 (see Fig. 3b) are summarized in Table 1.

Table 1. Characteristics of current pulses 1 through 4 labeled in Fig. 3b.

	Peak current, A	Rise Time, ns	FWHM, ns	Fall Time, ns	Interpulse interval relative to pulse 1, μs
Pulse 1	1.1	30 ± 5 ns	90 ± 10	147 ± 10	—
Pulse 2	3.14	30 ± 5 ns	—	—	2.42
Pulse 3	5.8	30 ± 5 ns	130 ± 10	180 ± 20	2.58
Pulse 4	3.3	195 ± 10	180 ± 10	210 ± 10	3.08

Rise time of current pulse 4 is considerably larger than that of the preceding three pulses, which might be indicative of the streamer-to-leader transition (Bazelyan and Raizer, 1998) around the time of pulse 4. With an uncertainty less than $0.2 \mu\text{s}$, the microwave absorption peak occurred $1.75 \mu\text{s}$ after current pulse 1 (associated with the streamer burst, within which the UPF was formed (see Fig. 2(I)), $0.56 \mu\text{s}$ before the beginning of pulse 2, and $0.71 \mu\text{s}$ before pulse 3, after which the upward positive leader was initiated from the grounded sphere (see Fig. 2(II)).

The total positive charge transferred to the cloud by the initial corona streamer burst in its entirety and by the following upward leader, estimated by integrating the current waveform from 0 to $50 \mu\text{s}$, was $15 \mu\text{C}$, which is about a quarter of the typical total (negative) cloud charge.

The upward positive leader is clearly imaged during the $10\text{-}\mu\text{s}$ exposure time of the second 4Picos frame (see Fig. 2(II)). For the first couple of microseconds, when the leader current was 2-3 A, some of the streamers apparently reached the region of passage of the microwave beam (labeled 5 in Fig. 2(II)), as evidenced by the small absorption of microwave radiation seen in Fig. 3. Interestingly, the absorption is smaller for current pulse 3, whose peak is appreciably larger (5.8 A). The latter observation may indicate that most of the streamers did not reach the microwave beam.

Fig. 4(I) shows an infrared (IR) image of the event whose visible-range image is shown in Fig. 2. In Fig. 4(I), the image size is 320 x 256 pixels, and frame exposure time is 2.4 ms). To improve contrast, the presented IR image was obtained by subtracting the previous frame from this one and inverted. With the exposure time of 2.4 ms, almost all discharge processes are imaged (integrated) in the presented single (differential) frame. The relatively hot channel (4) of the branching upward positive leader and its streamer zone (5) reaching the cloud are superimposed on the image of the preceding initial corona streamer burst/UPF (6) with relatively hot channel segments (7). Overall, the IR image is similar to its visible-range counterpart, seen in Fig. 2(I), but with poorer spatial resolution. Also, the infrared image presented in Fig. 4(I) has a lower spatial resolution and brightness compared to the infrared images reported previously by Kostinskiy et al. (2015 a,b). This is because in the present study images were taken from 2.5 times greater distance, resultant images had 4 times fewer pixels, and frame exposure time was 3-4 times longer (with the same lens). Nevertheless, all the main features of the discharge are visible in infrared image shown in Fig. 4(I).

The IR brightness (which represents the energy input to gas) of the channel segments within UPF is similar to that on the channel of upward positive leader, as evidenced by IR brightness profiles shown in Fig. 4(II) for two cross-sections labeled [1] and [2] in Fig. 4(I). The 2D length of the leader channel without taking into account the branching in the IR image from the starting point on the grounded sphere to the most distant point was about 42 ± 1 cm, which, given the 2.4-ms exposure time, is the total leader channel length for this event. It is longer than 29 ± 2 cm in the visible-range image by 10 cm or so.

We now present an additional event for which the current, light (photomultiplier signal), and microwave absorption were recorded (see Fig. 5a) along with a UPF image (see Fig. 5b). In contrast with the event presented in Figs. 2-4, no leader channel was formed after the initial corona streamer burst. In this case, 40 μ s before the initial corona streamer burst and 160 μ s after it, microwave absorption and current measured at the grounded sphere do not indicate any discharge activity. The current signature of the initial corona streamer burst is a single submicrosecond-scale pulse labeled 1 in Fig. 5a. Fig. 5b shows part of the streamer burst (1) that originated on the grounded sphere (2) and propagated to the visible edge of the cloud (3), entered the cloud, and approached almost perpendicularly the region of passage of the microwave beam (5). The streamer heads propagated from the grounded sphere (2) to the microwave beam (5) along an arc distance of about $S_{st} \approx 1.2$ m in about $\tau_{st} \approx 2.4$ μ s (measurement accuracy ± 50 ns). The streamer movement inside the cloud is confirmed by the microwave absorption pulse labeled 2 in Fig. 5a. The microwave absorption pulse duration (FWHM) was slightly longer than in Fig. 3b and was equal to 160 ± 20 ns. The absorption pulse peak was very close to the end of exposure of the 4Picos frame shown in Fig. 5b. The average 2D speed of streamers in this case was slightly lower than in Fig. 2 and was equal to $v_{st} \approx S_{st}/\tau_{st} \approx 5 \times 10^5$ m/s. In Fig. 5b, bright channel segments (labeled 4 in Fig. 5b) are seen within the UPF, near the edge of the cloud. The exposure of the first frame of 4Picos (see Fig. 5b) started about 600 ns after the onset of the initial corona streamer burst (see current pulse 1 and the leading edge of the exposure pulse corresponding to Frame 1 in Fig. 5a); that is, the beginning of the streamer burst was not captured by the 4Picos camera. This is why the lower part of the streamer burst (corresponding to the first 600 ns of its development) appears to be missing in Fig. 5b. Note that in Fig. 2(I), the image of streamer burst corresponds to three current pulses labeled 1, 2, and 3 in Fig. 3b.

The current pulse 1 (see Fig. 5a) associated with the streamer burst has a peak of about 1.5 A (the rise time of the current pulse is 35 ± 5 ns, the duration of the current pulse at half maximum (FWHM) is 100 ± 10 ns, and the fall time is 190 ± 10 ns). The total charge of the initial corona streamer burst (estimated by integration of measured current) was about 0.3 μ C, very small compared to the expected cloud charge of about 60 μ C. Relatively hot segments within the UPF in Fig. 5b do not look as bright as those in Fig. 2(I),

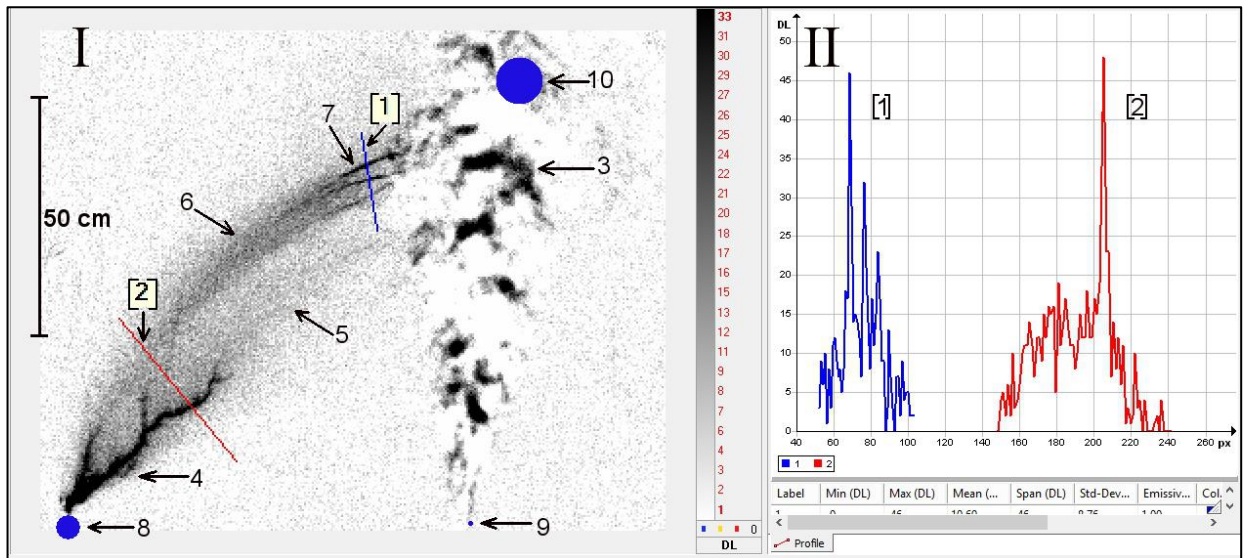


Figure 4. I (left panel) - One frame of event 2015-12-04_03 obtained with an infrared (FLIR) camera (wavelength range - 2.5-5.5 μm , image size 320x256 pixels, pixel size 14x15 μm , image depth - 14 bit, frame exposure - 2.4 ms, lens focal length - 50 mm, f/2). This infrared image was obtained by subtracting the previous frame from this frame and inverting the differential image; II (right panel) - The IR brightness profiles for hot channel segments within UPF (shown in blue and labeled [1]) and upward positive leader channel (shown in red and labeled [2]), with the corresponding cross-sections being shown in I (left panel). Numbered in I (left panel) are: 3 — negatively charged cloud; 4 — upward positive leader; 5 — streamer zone of the upward positive leader; 6 — initial corona streamer burst converted to UPF; 7 — hot channel segments within UPF; 8 — grounded metal sphere (drawn to scale); 9 — center of the grounded plane, where the nozzle (see Fig. 1) is located; 10 — the region of passage of the microwave beam (drawn to scale).

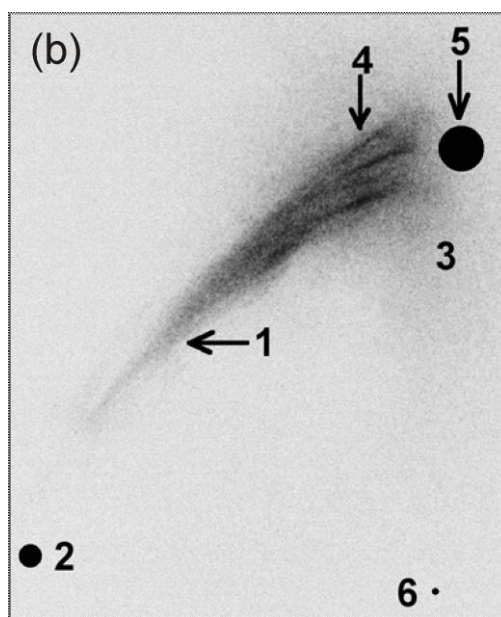
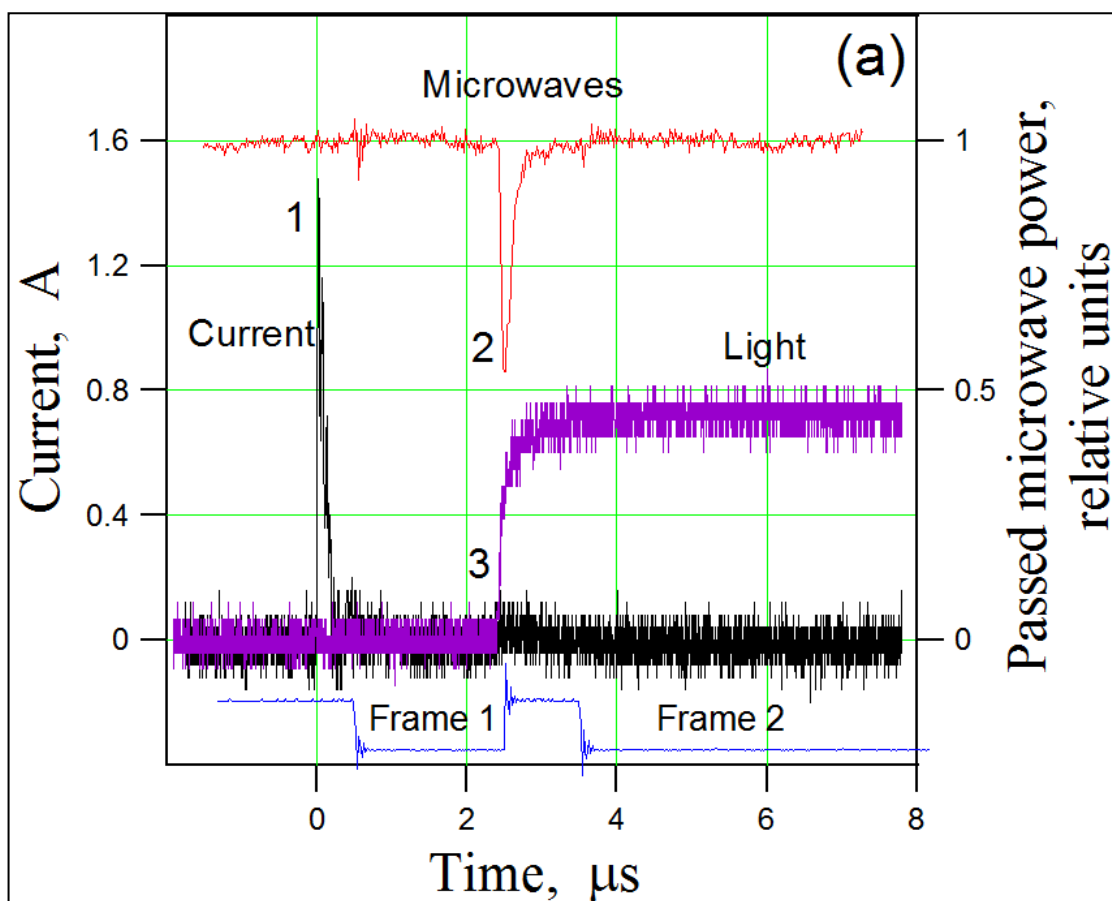


Figure 5 (event 14_2015-12-04). (a) Current measured at the grounded sphere (shown in black); absorption of microwave radiation that passes through the cloud (shown in red and labeled “Microwaves”); photomultiplier signal (shown in purple and labeled “Light”), and exposure times of 4Picos Frames 1 and 2 (shown in blue), (b) 4Picos Frame 1 (there is no image in Frame 2). 1 – initial corona streamer burst converted to UPF; 2 - grounded metal sphere (drawn to scale); 3 - visible boundary of the cloud of negatively charged water droplets; 4 – hot channel segments within UPF; 5 - the region of passage of the microwave beam (drawn to scale); 6 - center of the grounded plane, where the nozzle (see Fig. 1) is located.

because they were formed at the end of exposure of the 4Picos frame, as evidenced by the photomultiplier and microwave absorption signals, labeled 3 and 2 in Fig. 5a, respectively.

Discussion and Summary

We observed that UPFs, first reported by Kostinskiy et al. (2015a), occurred when the initial (positive) corona streamer burst, initiated from the small grounded sphere, approached and entered the cloud of negatively charged water droplets. In contrast with ordinary streamer formations (e.g., initial corona streamer burst), UPFs contain presumably hot channel segments that are as bright as leader channels in our infrared records and persist for milliseconds (it is in this sense that we refer to them as “hot”; their temperature is actually not known). Importantly, the UPFs occurred prior to the formation (or in the absence) of associated hot leader channel. From this observational fact, we conclude that some kind of streamer-to-leader transition within the initial corona streamer burst is one of the mechanisms behind UPFs. The estimated electric field strength near the cloud boundary was in the range of 500-1000 kV/(m·atm). It is presently not clear if the UPFs were caused solely by the enhanced electric field near the charged cloud boundary or other factors also played a role. Within 40 μ s prior to the onset of the initial corona streamer burst, no events that could give rise to UPFs were detected. We infer that the streamer burst entering the cloud experienced some kind of instability (for example, thermal-ionizational instability (Nighan, 1977; Raizer, 1991, pp. 222-226; Bychkov et al., 2007; Zhong et al., 2019; Wolf et al., 2020)) that led to its conversion to UPF.

Using current and low-light recordings in conjunction with the microwave sounding of the cloud, we found that hot channel segments within UPFs were formed in very short times of the order of 1 μ s or less. These times are consistent with the characteristic time of development of the streamer-to-leader transition in air at atmospheric pressure (Bazelyan et al., 2007; Popov, 2009). Note also that Suzuki (1971) found, from laboratory experiments with discharges in 1- to 4-cm positive point-to-plane gaps, that thermalization (streamer-to-arc transition) occurred in several hundred nanoseconds, provided that overvoltage exceeded 30%.

In this work, we observed hot channel segments embedded in UPFs, which in part were outside the cloud boundary seen with the visible-range camera. It is likely that the space charge is present not only inside, but also outside of the visible cloud, which can explain those observations. It is worth noting that the hot channel segments within UPF always appear in groups, which probably implies that the occurrence of one such segment creates conditions facilitating the occurrence of additional ones.

The main findings can be summarized as follows:

1. Unusual plasma formations (UPFs) can occur inside the initial corona streamer burst, before the development (or in the absence) of hot leader channel.
2. UPFs contain hot channel segments that are formed, possibly via thermal-ionizational instability, on a time scale of the order of 1 μ s or less.
3. UPFs tend to occur in the vicinity of cloud boundary, where the electric field is highest, as this boundary is penetrated by the streamer burst.

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