Experimental modelling of apokamp discharge formation under outer electric field

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Abstract. A laboratory setup has been created for modeling certain aspects of the initiation process of blue jets in the Earth’s atmosphere. With its help, the influence of an electric field on the apokamp discharge in air at pressures of 180–260 Torr was established. It is shown that the formation of a negatively charged zone located above the channel of a pulse-periodic discharge with a positive potential leads to both initiation and lengthening of the apokamps starting from the channel, and also reduces the voltage amplitude necessary for their formation.

1. Introduction

In 2016, an unusual form of discharge was obtained under laboratory conditions in atmospheric pressure air [1, 2]. It is a luminous structure, which is formed on the bend of the pulse discharge channel, and propagates almost perpendicular to the channel bend. This structure was called the apokamp (from Greek από “off” and καμπή “bend”), and the discharge mode, respectively, was apokampic.

It was shown in the works [3–5] that the apokamp is a positive streamer, the head of which moves at a speed of 100 to 220 km/s. Comparison of experimental data and simulations suggests that the apokamp is a streamer formed due to the discharge gap closure by the conducting channel and heating of the gas near the channel.

In a series of works [6–10], it was shown that in air, at low pressures, the apokamp has the signs of transient light phenomena of the middle atmosphere - blue starters and jets [11, 12]. Both phenomena: observed in the pressure range (90–150 Torr); are formed only with a positive polarity of the voltage pulse; have similar (in the range (λ ~ 280-800 nm) and maximum structure) luminescence spectra; have a similar morphology; the average propagation velocity values of ionization waves in the apokamp (180 km/s) coincide in order of magnitude with the propagation velocity of blue jets in the Earth’s atmosphere.

It should be noted that the conditions for the formation of blue jets and starters do not repeat laboratory conditions in everything. Nevertheless, laboratory modeling of atmospheric phenomena is of undoubted interest as a way to identify physical mechanisms and conditions responsible for their appearance [13, 14].

It is known that the maximum ionization of the atmosphere at altitudes of 12–18 km (starting altitudes for blue jets and starters) is provided by cosmic rays [15]. However, experimental data on the electric field influence on the formation of blue jets and starters are not available.
The purpose of the work is to experimentally reveal the electric field effect on apokampic discharge. To this end, it was proposed to ignite the apokampic discharge at pressures approximately corresponding to the magnitudes of the appearance of blue jets in the Earth’s atmosphere, and to change the magnitude of the electric field above the apokamp.

2. Experimental setup

The experimental setup is shown in Figure 1. The discharge was ignited between the tip electrodes 1 and 2 made of stainless steel (diameter 2 mm, radius 80 mm) with an interelectrode distance of 8 mm.

![Figure 1](image)

**Figure 1.** 1, 2 – tip electrodes; 3 – discharge gap; 4 – quartz chamber; 5 – high voltage pulse source; 6 – constant voltage source; 7 – voltage divider

The electrodes were located at an angle of 140° relative to each other and were placed in a quartz tube 4 with an inner diameter of 5.9 cm and a height of 65 cm. The air pressure in the tube was regulated. In the course of experiment, high-voltage pulses of positive polarity with amplitudes 5 < \( U_p < 12 \) kV and repetition rates of 27 < \( f < 50 \) kHz were applied to electrode 1 from source 5. The appearance of the resulting discharge was recorded with a Canon PowerShot SX 60 HS camera with various shutter speeds, exposure, and photosensitivity.

The time course of voltage \( U_1(t) \) at electrode 1 was recorded using a capacitive divider \((C_2 = 1.65 \text{ nF}, C_3 = 1.65 \text{ pF})\), and the time course of current \( I_1(t) \) between electrodes 1 and 2 was shunted \((R_1 = 1 \text{ Ohm})\). Signals from the dividers and the shunt were fed to a TDS-3034 oscilloscope (Tektronics, Inc.).

To study the effect of external electric field on the initiation of the apokamp, a capacitor with one removed electrode \( C_5 \) (K15-4) was placed over the electrodes 1 and 2 at a distance of 5 < \( d_g < 20 \) cm. It was made from a container with two electrodes 4700 pF with a diameter of 46 mm or 1000 pF with a diameter of 41 mm. The end of the capacitor connected to the power source 6 had an electrode, and the other was with a metal electrode removed. This ceramic end was turned towards the electrodes 1 and 2. A high voltage was supplied from the source 6 to the electrode of the modified capacitor through the resistor \( R_2 = 18 \text{ M\ohms} \) \(+3.5 < U < +30 \text{ kV}\). The voltage value was recorded by a divider 7 (AKTAKOM ACA-6039, CJSC SPE «Eliks»). Capacitor \( C_7 \) (720 pF) ensured the smoothing of voltage ripples from source 6 and a slow voltage drop across the metal electrode of the modified capacitor \( C_5 \).

The order of the experiments was as follows:

1. A high-voltage pulse discharge was ignited between electrodes 1 and 2, selecting the voltage amplitude \( U_p \) so as to obtain a regular periodic-periodic discharge without an apokamp in the form of a bended channel.
2. From source 6, voltage was applied to capacitor $C_5$. As a result, due to a low-current discharge, electrons could collect on the ceramic end of the capacitor directed toward the electrodes and the capacitor was partially charged.

3. The source 6 was turned off, which led to the grounding of the electrode of the capacitor $C_4$ through resistance $R_2$ and the resistance of the voltage divider 7. At the same time, the capacitor $C_4$ was discharged, and the voltage on the metal electrode of the capacitor $C_5$ was also reduced. The discharge rate was determined by the constant RC-circuit. At the moment the source was turned off, the recording of $U_2(t)$ was started and the discharge was photographed with various delays. Before each experiment, the distance $d_g$ between the electrodes 1 and 2 and the capacitor 6 was varied, as well as the value of the capacitor $C_5$.

3. Results

Figure 2 shows how the discharge of the capacitor $C_4$ and the decrease in voltage on the metal electrode of the capacitor $C_5$ affect on the discharge form and the voltage time course.

![Figure 2](image_url)

Figure 2. Demonstration of starting the apokamp (a), the time course of the voltage across the capacitor $C_5$ with the apokamp (b) and without it (c). $U_p = 5.4$ kV, $p = 180$ Torr, $f = 50$ kHz, $d_g = 8.8$ cm, $C_5 = 1000$ pF

It was found that after turning off source 6, a pulsed discharge between electrodes 1, 2 can turn into an apokampic one (Figure 2a, II, and III), namely: at the place of bending, an apokamp is formed that covers (partially or completely) the gap $d_g$ between the electrodes 1, 2 and the ceramic end of the capacitor $C_5$. Then the apokamp shortens and disappears. According to the presented photographs, the lifetime of the apokamps, taking into account the exposure (0.125 s), can be estimated approximately as 0.3 s. It should be noted that since a pulsed discharge is ignited at a frequency of 50 kHz, ~ 15,000 apokamps are formed during the indicated period of time.

In Figures 2b, c shows how the discharge of the capacitor $C_4$ occurs in the apokamp mode and without it. Without the apokamp, we have an almost exponential dependence (Figure 2c) characterizing the discharge of the capacitor $U_2(t) \sim \exp(-t/\tau)$, where $\tau \sim 2$ is the discharge time constant. When the apokamp was initiated, the discharge was interrupted by a voltage surge, as shown in Figure 2b. This occurs due to the streamers formation in the interval $d_g$. In rare cases, surges could be two or three. The time constant for surges is $\tau \sim 0.5$ s, i.e. a decrease in the magnitude of $U_2(t)$ in surges by $e$ times occurs approximately 4 times faster. This, in turn, means that the apokamp - a positive streamer - serves as a source of recharging the capacitor $C_4$ and increases the voltage at the metal electrode of the capacitor $C_5$. It should also be noted that the typical amplitude of the voltage pulses $U_p$, necessary for the transition
from a pulsed discharge to an apokampic one, is usually 7–8 kV. But with the described initiation of the apokamp, it decreases to 5.5–6 kV. This can be explained by the accumulation of electrons on the ceramic surface of the capacitor $C_5$.

Voltage path $U_2(t)$ with Figure 2b on enlarged scale is shown in Figure 3. It is seen that the voltage surge is accompanied by 37 small pulses, the average amplitude of which is 0.7 kV. The first impulse always has a maximum amplitude. In the described case, it was 4.64 kV. The front of each pulse is 1 ms, and the half-amplitude duration is ~ 3 ms. Taking into account the ignition frequency of a pulsed discharge between electrodes 1 and 2 – 15 apokamps are formed during the indicated period of time.

![Figure 3](image_url)

**Figure 3.** The time course of the voltage across the capacitor $C_5$ in the first peak. $U_p = 5.4$ kV, $p = 180$ Torr, $f = 50$ kHz, $d_g = 8.8$ cm, $C_5 = 1000$ pF

The effect of turning off the source 6 on the apokamp already formed in the gap is illustrated in Figure 4. In this case, the typical dependence $U_2(t)$ has several surges corresponding to overlapping by the streamers of the gap $d_g$. As before, the first impulse in each surge always has a maximum amplitude.

![Figure 4](image_url)

**Figure 4.** Demonstration of apokamp extension (a) and time course of voltage across capacitor $C_5$ (b). $U_p = 8$ kV, $p = 240$ Torr, $f = 50$ kHz, $d_g = 8.8$ cm, $C_5 = 1000$ pF

4. Summary

We have seen that discharging $C_4$ and decreasing the voltage across the metal electrode $C_5$ leads to both initiation and lengthening of the apokamps. In addition, each apokamp - a positive streamer - compensates for leakage of the charge through the voltage divider and resistor $R_2$, making up for the discharge of the capacitor $C_4$. In this case, it is important not only the electron charge on the ceramic end of the capacitor, but also the voltage gradient when the source 6 is turned off. The shutdown initiates the start of apokamps, and the electrons accumulated on the ceramic end affect the propagation height of the apokamps on the $C_5$ metal electrode.
The decrease in voltage on the top plate of the capacitor $C_5$ and the increase in the negative potential at the ceramic end in our circuit is caused by the discharge of the capacitor $C_1$ through the voltage divider and resistor $R_2$ after turning off the power source 6. Does this process have an analog in the Earth’s atmosphere? It is known that during thunderstorms under the influence of an electric field, free electrons move from the Earth’s ionosphere (> 60 km) to the top of the clouds. At various heights, they acquire different energies and are able to reach the upper limit of cloud cover. This leads to a local increase in the negative charge above the clouds. And since the upper part of the cloud (at the stage of its development) is a dielectric dipole with a negative space charge at the bottom and positive at the top, this facilitates the initiation and upward movement of the positive streamer. The above experiments were carried out in the range of air pressures corresponding to the altitudes at which blue jets form in the Earth’s atmosphere. When the pressure increases to 340 Torr and higher (which corresponds to heights of ~ 7 km and lower), the apokamp initiation effect does not appear. Probably, in nature, the initiation of blue jets requires a combination of several conditions: the separation of charges in a thundercloud and the jump-like reaching by high-energy charged particles of the boundary of upper clouds. Then it becomes possible to initiate both a wide air rainfall and blue jets [16].

Thus, in this work, we created a laboratory setup for modeling individual aspects of the process of initiation of blue jets in the Earth’s atmosphere. It is shown that the formation of a negatively charged zone (ceramic end of the processed capacitor) located above the channel of a pulse-periodic discharge with a positive potential leads to both initiation and lengthening of the apokamps, and also reduces the voltage amplitude necessary for their formation.

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