Whether and how the vapors of Al, Cu, Fe, and W influence the dynamics of apokamps

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Abstract. The recent hypothesis about the initiation of red sprites in the Earth atmosphere in presence of metal atoms was verified. We have tested this hypothesis using Al, Cu, Fe, and W electrodes in laboratory apokamp discharges in air at a pressure of 45 and 760 Torr. Our experiments show that the electrode material does influence the apokamp dynamics. However, for Fe and W, compared to Al and Cu, the start voltage of an apokamp in pulse-repetition mode is higher and its length is shorter. The emission spectrum of apokamp discharges reveals lines of their metal electrodes. Thus, the experiments confirm the hypothesis on the contribution of metal vapors from burnt meteors to the initiation of red sprites in the Earth atmosphere.

1. Introduction

Recently, considerable study has been given to discharges in the upper atmosphere and particularly to red sprites at altitudes of tens of kilometers [1–9]. It is thought that red sprites develop as positive streamers toward the Earth [7–9], but their cause is still poorly understood. In ambient air, the electric field sufficient for the start of a positive streamer is 4.5–5 kV/cm, and its propagation via ionization needs at least 25 kV/cm [10] and a rather high density of primary electrons ahead of its front [11]. In thunderstorms, the electric field increases but dissipates in going higher such that its average value at tens of kilometers above sea level is low [12]. Theorists suggest different factors favorable for sprites. Some studies show that this can be electric field amplification at sharp edges of different particles [13], e.g., ice particles [14]. Other studies consider that the generation of sprites can be facilitated by ultraviolet and vacuum ultraviolet ionization of metal atoms at nitrogen and oxygen transitions [15, 16]. Such metal atoms in air can increase the electron density ahead of a streamer front, thus favoring its motion. Atoms of different metals and other elements are left at high altitudes mainly by burnt meteors, and their presence in the Earth atmosphere is reported in many studies (see, e.g., [17, 18]).

Here, using laboratory apokamp discharges [19–25], we test whether and how the presence of metal atoms influences the initiation and motion of positive streamers. Apokamp discharges are a high-voltage pulsed discharge in ambient air with an extended luminous structure (apokamp) streaming upward or downward from its bent channel when the channel and both electrodes are at a potential of several kilovolts with respect to ground [19, 20]. It is for the streamer starting from its bent channel, rather than...
from its high-voltage electrode, that this type of discharge is termed *apokamp* (from Greek από and καμπή: off and bend).

The apokamp comprises a bright offshoot from which a streamer escapes in the direction of maximum electric field and normally perpendicular to its parent discharge channel. The apokamp color depends on the air pressure. At atmospheric pressure, the apokamp is blue like blue jets, and bands of the second positive system of nitrogen dominate its spectrum [19]. As the pressure is decreased, it becomes red due to a change in the intensity ratio of the first and second positive systems of nitrogen [24]. The apokamp can be directed both up and down with respect to the ground surface, depending on the electric field direction [25], and its downward motion corresponds to that of sprites in the Earth atmosphere. As noted above, the apokamp starts from the bend of its parent discharge channel spanning between two metal electrodes, but some conditions can provide its start from the electrodes [19–26].

It should also be noted that the metal electrodes of a repetitive pulsed discharge are sputtered and their vapors get in the discharge gap and surrounding region, which is evidenced by the presence of metal lines at a distance of several centimeters from different metal electrodes [27, 28].

2. Experimental setup and measuring equipment

Our laboratory experiments were performed on two setups to form an apokamp discharge in ambient air and in a quartz bulb of inner diameter 60 mm and length 600 mm at variable air pressure. The second setup is shown in Figure 1.

![Figure 1. Block diagram of experimental setup with quartz bulb: 1 – voltage generator, 2 – high-voltage electrode of positive polarity, 3 – electrode capacitively decoupled from ground (C₁ = 5 pF), 4 – discharge channel, 5 – offshoot, 6 – streamer, 7 – cylindrical quartz bulb, 8 – collimator, 9 – optical fiber, 10 – spectrophotometer, 11 – camera. U₂, U₃ – voltages from electrodes 2 and 3, respectively. I – current from electrode 3.](image)

Generator 1 produces voltage pulses of positive polarity, which are applied to electrode 2, spaced from electrode 3 by 7.8 mm. At a voltage amplitude of several kilovolts, the gap is broken down and a discharge is ignited between two sharp-ended electrodes 2, 3. In two-three seconds, the discharge is stabilized showing a diffuse glow (halo) around its channel 4 due to convectively expelled hot gases [22]. Almost immediately, the discharge channel starts to bend, and the point of maximum bending gives rise to an apokamp: offshoot 5 with streamer 6 escaping from it. Note that to produce an apokamp, voltage pulses of positive polarity should be applied to electrode 2 and capacitive decoupling (C₁) should necessarily be present between electrode 3 and ground.
In idle mode, the generator provided output voltage pulses of positive polarity with a frequency of 4 < f < 60 kHz, duration of 1.5 µs, and amplitude of up to 15 kV. Both electrodes had the same shape with a tip angle of 25° and curvature radius of 60 µm, and the material of both was either aluminum, copper, iron, or tungsten.

The equipment for spectral measurements included collimator 8 (focal length 30 mm), optical fiber 9 (known bandwidth), and spectrometer 10 (Ocean Optics HR2000+ES, Sony ILX511B array, wavelength 200–1100 nm, instrument function halfwidth ~1.33 nm). The apokamp dynamics was captured in frame-by-frame mode with camera 11 (Canon PowerShot SX 60 HS).

3. Results

The influence of the electrode material on the apokamp start voltage was studied in air at atmospheric pressure. During steady-state operation with a high (kilohertz) repetition frequency, each voltage pulse provided stable formation of an apokamp, allowing its easy observation, photographing, and recording of its emission spectra. Table 1 demonstrates how the electrode material influences the average apokamp start voltage \(<U_a>\) at f = 60 kHz.

| Electrode material | Cu  | Al  | Fe  | W  |
|--------------------|-----|-----|-----|----|
| \(<U_a>\), kV      | 7.1 | 7.2 | 7.5 | 7.7 |

It is seen that the apokamp start voltage in atmospheric pressure air is highest for W and decreases successively for Fe, Al, and Cu, which correlates with experimental data on breakdowns and runaway electron generation with different sharp-ended cathodes [29, 30]. In our experiments, like in those reported earlier [29], the gap is bridged by an ionization wave which consists of a single or several parallel streamers [31]. Breakdown of the gap at the first voltage pulses after a break, sufficient for metal vapor to escape from the gap, occurred at a significantly higher voltage. Note that the breakdown voltage in this case was also affected by a decrease in the concentration of air molecules due to its heating in a pulse-periodic mode.

Figure 2 shows the apokamp start voltage and length at frequency f = 4.47 kHz versus the voltage across the high-voltage electrode at an air pressure of 45 Torr for different electrode materials.

![Figure 2](image)

**Figure 2.** Apokamp length for different electrode materials in air at 45 Torr vs voltage across electrode 2. Frequency \(f = 4.47\) kHz
Start voltage of apokamp is the lowest points in Figure 2. No measurements were taken at lower pressures because the apokamp touched the bulb walls. It is seen that at 45 Torr, compared to atmospheric pressure, the apokamp start voltage decreases (the lowest points on the curves in Figure 2) and that its value for Fe and W is higher than for Al and Cu, like in atmospheric pressure air. Besides, at the same electrode voltage, the apokamp length for Al and Cu is larger than the length for Fe and W.

Figure 3 shows the apokamps at frequency $f = 4.47$ kHz with Cu and Fe electrodes in air at 45 Torr and 4.6 kV.

The apokamp shape is similar to that observed earlier [19–26]. The apokamp length, being dependent on the pressure, voltage, repetition frequency, and gap width, is largest for Cu electrodes. With the quartz bulb turned through 180° (with the electrodes at the top), the apokamp moves downward [25].

Figure 4 shows the electrode voltages $U_2, U_3$ and discharge current $I$ (Figure 1) for apokamps 70 and 40 mm long.

**Figure 3.** Apokamps in air at 45 Torr and 4.6 kV with Cu (a) and Fe electrodes (b). Frequency $f = 4.47$ kHz

**Figure 4.** Electrode voltages $U_2, U_3$ and discharge current $I$ in air at 45 Torr for Cu electrodes, apokamp length 70 mm (a) and for Fe electrodes, apokamp length 40 mm (b). Frequency $f = 4.47$ kHz
It is seen that both voltages and the discharge current for Cu and Fe are similar. Compared to the discharge current, the apokamp current in these conditions is low, and its measurement fails.

The intensity of metal lines in discharge emission spectra was maximal for Cu electrodes. It is seen from Figure 5 that along with the second positive system of nitrogen and NO, the emission spectrum for Cu electrodes reveals Cu lines at a wavelength of 324.7 nm, 327.3 nm, 510.6 nm, 515.3 nm, and 521.8 nm.

![Discharge emission spectrum for Cu electrodes in air at 45 Torr and f = 4.47 kHz](image)

**Figure 5.** Discharge emission spectrum for Cu electrodes in air at 45 Torr and $f = 4.47$ kHz

4. Discussion
The ignition voltage of pulsed discharges depends on the electrode material and gas kind [10]. For an apokamp to arise in a pulsed discharge, the discharge should get diffuse after its initial spark, and this needs a large number of applied voltage pulses [22]: the first hundred to thousand pulses result in a thin channel between two electrodes, and the next pulses in an apokamp discharge. When the apokamp discharge gets steady, the air temperature in the gap at atmospheric pressure goes above 1000 °C [26], and thus, it is hardly possible to avoid metal vapors in the discharge region and its surroundings. Hence, they are inevitable in all our measurements.

The fact that the vapors of metal electrodes do occur at up to several centimeters away from them is confirmed by the spectral data presented here and by our previous studies of repetitive pulsed discharges in an inhomogeneous electric field [27, 28]. By varying the electrode material, we can determine whether its work function and ionization potential influence the apokamp start voltage and apokamp length.

Our experimental data suggest that the electrode material does influence the apokamp start voltage and length. The lowest start voltage of apokamps and their largest length are found for metals whose breakdown voltage in an inhomogeneous electric field is low [29–32]. Such an effect can be explained by the difference of metals (Al, Cu, Fe, W in our case) in electron emission threshold, ionization potential, and work function. Note that the work function of a metal strongly depends not only on its type but also on its purity and experimental conditions [33, 34]. For example, the work function of pure metals in high vacuum differs from their work function in poor vacuum [34]. Besides, the emission of electrons is largely influenced by the presence of nanoparticles [35] and dielectric films [36]. Likely, it is these factors that show up when using Cu electrodes whose work function in high vacuum differs little from the work function of Fe. At the same time, the highest average start voltage of apokamps falls on W, featuring the highest work function among the materials studied [33, 34].

Thus, there is reason to think that the metal vapors in air in our experiments served as an easily ionized agent. It can be concluded that the use of electrodes with low average breakdown voltages
facilitates the start of an apokamp and increases its length and that Al and Cu likely provide the highest density of primary electrons among the electrode materials studied.

5. Conclusion
Our apokamp experiments confirm the hypothesis on the contribution of metal vapors from burnt meteors to the initiation of sprites in the upper atmosphere [15, 16]. The presence of metal vapors facilitates the initial breakdown, the formation of a dense plasma with electric field amplification at its boundary, and the motion of a positive streamer. The apokamp type of discharge, being a streamer discharge [19–22], needs simple equipment, allows visual observation and reliable recording of its streamer dynamics, and provides a very convenient way to study atmospheric discharges occurring at high altitudes. We also note that during the formation of sprites, one can expect the generation of runaway electrons, which are recorded during laboratory discharges [30, 31, 37, 38].

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