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The Field Strength Necessary for the Formation of Blue Jets in the Middle Atmosphere

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Abstract—The formation of blue jets in air at low pressures is simulated using an apokamp discharge. The field strength is measured in the discharge channel. Assuming the applicability of similarity laws to gas discharges, the field strength in a storm cloud during the formation of blue jets is assessed to be from 6×10^{10} to 1.9×10^{9} V/m, which is much higher than the values characteristic of the development of cloud-to-ground lightning discharges. A hypothesis is suggested that excess magnitudes of characteristic fields is among features of high-voltage pulsed discharge within a cloud, which results in the formation of blue jets at altitudes of about 12–18 km.

Keywords: apokamp discharge, blue jets, electrical field strength, similarity laws in discharge, transient luminous events

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INTRODUCTION

In the past 20 years, significant progress was achieved in the study of transient luminous events, or transients. It is the name of large-scale optical phenomena occurring in the Earth's middle and upper atmosphere under conditions of high electrical activity characteristic of thunderstorms, storms, and hurricanes [1]. Transients include, in particular, blue jets and blue starters, which start from altitudes of 12–18 km and reach an altitude of 38 km (see references in [1]). Studies of transients commonly follow the path of both creating new tools for instrumental observation from aircrafts and from space [2–5] and constructing mathematical models (see references in [6, 7]).

In 2016, we discovered a new discharge type, which we called the "apokamp" discharge [8, 9]. This is a high-voltage pulsed discharge in air under normal conditions, where a high-voltage electrode has a positive polarity, and the current channel is at a floating potential and serves as a source of a visually observed plasma jet—the apokamp. Figure 1 shows the scheme of the apokamp formation and the characteristic geometric parameters of the apokamp and the discharge gap are marked. It can be seen that the spatial structure of the apokamp is nonhomogeneous: it consists of a bright branch and a faint glow region. The latter, as follows from high-speed photography [9], is formed by plasma bullets moving at speeds of ~200 km/s.

In terms of its morphological and spectral properties, an apokamp in air under different pressures is a convenient experimental model for studying atmospheric discharges in the middle and upper atmosphere [8–14]. In addition, a streamer model of the phenomenon was developed in [13].

The aim of this work is to assess the electric field strengths characteristic of the development of blue jets in the Earth's atmosphere in numerical experiments.

EXPERIMENTAL SETUP AND TECHNIQUES

A setup similar to that described in [10–14] is used in the work (see Fig. 1). It provides ignition of a high-voltage pulsed discharge between two steel tip electrodes with diameters of 0.195 cm, which form a discharge gap $d = 0.9$ cm. One electrode is connected to a generator of high-voltage positive-polarity pulses ($\tau = 1.5$ μs, $f = 53$ kHz, amplitude is up to 12 kV), and another electrode is at a floating potential. When voltage pulses are applied, an apokamp discharge is ignited between the electrodes. The electrodes are placed inside a quartz cylindrical sealed chamber 6.5 cm in diameter and 60 cm in height. The chamber is pumped out to pressures that correspond to the conditions for blue jet formation in the Earth's atmosphere, thus simulating the conditions of the Earth's middle atmosphere.

During the setup operation, the time behavior of the voltage is recorded at both electrodes using capac-

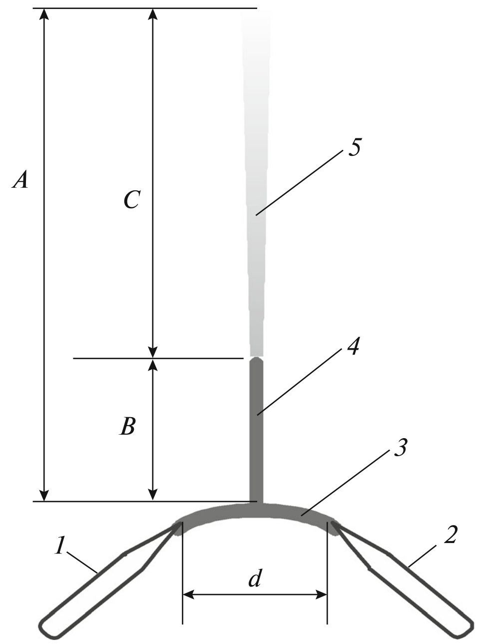

Fig. 1. Scheme of formation and geometric parameters of an apokamp discharge: high-voltage electrode (*1*); electrode at a floating potential (*2*); pulsed discharge current channel (*3*); bright branch of *B* in height (*4*); region of plasma bullets of *C* in height (*5*); discharge gap (*d*); apokamp height (*A*).

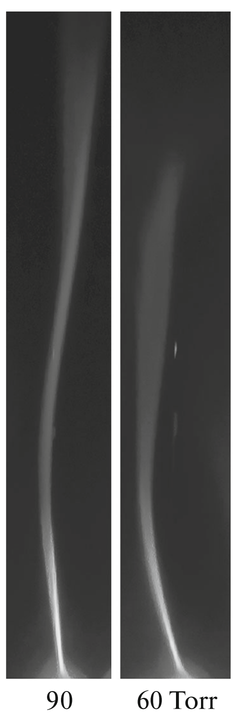

Fig. 2. Apokamp in air at different pressures; frame height is 25.5 cm.

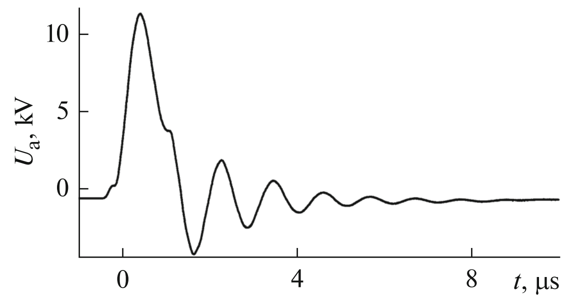

Fig. 3. Time variation in the voltage at the high-voltage electrode at an air pressure of 60 Torr.

itor voltage dividers; the results are transferred to a Tektronix TDS3034 oscilloscope. The discharge appearance is recorded by a Canon PowerShot SX60 HS camera in the time-lapse serial mode with an exposure 0.15 s and a frequency of ~6.4 frames per second.

The experimental procedure includes ignition of an apokamp discharge at low pressures and then attainment of the ratio between the total height of the apokamp and the branch $a = A/B \sim (2-4)$, characteristic of natural blue jets [2, 4], by means of variation in the voltage at the high-voltage electrode. Under these conditions, the peak electric field strengths E_a are measured at the high-voltage electrode (with averaging over 128 pulses) at a given air pressure p.

In our studies, we proceed from the similarity of an apokamp discharge and the pulsed discharge in a storm cloud, which initiates the appearance of blue jets (evidence of that was revealed in [10–14]). In this case, similarity laws should be obeyed between the conditions in the apokamp discharge and in a storm cloud [15]. In our case, the peak intensity of the electric field in a storm cloud $E_{bj} = E_a(l_{bj}/l_a) = E_a k$, where k is the similarity parameter, which is equal to the ratio of the characteristic length of a natural blue jet l_{bj} [2, 4] to the apokamp length l_a in the experiment.

EXPERIMENTAL RESULTS AND DISCUSSION

We know that natural blue jets start from altitudes of 12–18 km. Figure 2 shows the apokamp shape at two air pressure values. The pressure of 90 Torr approximately corresponds to an altitude of 15 km, and 60 Torr, to an altitude of 18 km. For them, the similarity parameter k, the peak field strength in the discharge gap E_a, and the field strength in a storm cloud E_{bj} have been calculated from the voltage oscillograms (see, for example, Fig. 3). The results are tabulated.

It is known that the electric field is highly inhomogeneous in the gap between the Earth's surface and the lower boundary of a storm cloud. Streamers (current channels) are formed at the electric field strengths $E \sim 5 \times 10^5 - 10^6$ V/m as a result of air ionization; they

Table 1. Apokamp discharge parameters

p, Torr	l_{bj}, m [Ref.]	l_a, m	k	E_a, V/cm	E_{bj}, V/m
90	20×10^3 [2]	0.19	10^5	1770	1.9×10^{10}
60	7.5×10^3 [4]	0.21	2.8×10^5	1570	6×10^9

move in steps of 1–60 m at a speed ~10^6 m/s, mainly in the cloud-to-Earth direction. The streamer motion represents the propagation of an ionization wave [16].

Let us compare the values of field strength in a storm cloud E with our estimates (Table 1). It is possible that the significantly overestimated strength in our experiments is a cause of streamer development upwards, but not downwards, which just results in the formation of blue jets at altitudes of ~12–18 km in nature.

Our estimates are reliable because we use data from both air and space observations of blue jets to determine the similarity parameter.

The approach suggested can probably be applied to the estimation of characteristic field strengths necessary for the formation of other transient luminous phenomena in the Earth's atmosphere.

CONCLUSIONS

A technique is suggested for the estimation of the field strength at altitudes that correspond to the development of blue jets in the Earth's middle atmosphere. It is based on the similarity law in a gas discharge. The experimental setup for producing an apokamp discharge at low air pressures is used in the work. The field strength estimates are $6 \cdot 10^9$–$1.9 \cdot 10^{10}$ V/m.

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REFERENCES

1. D. Siingh, R. P. Singh, S. Kumar, T. Dharmaraj, A. K. Singh, A. K. Singh, M. N. Patil, and S. Singh, "Lightning and middle atmospheric discharges in the atmosphere," J. Atmos. Sol.-Terr. Phys. **134** (10), 78–101 (2015).
2. E. M. Wescott, D. Sentman, H. C. Stenbaek-Nielsen, P. Huet, M. J. Heavner, and D. R. Moudry, "New evidence for the brightness and ionization of blue starters and blue jets," J. Geophys. Res., A **106** (10), 21549–21554 (2001).
3. T. Neubert, M. Rycroft, T. Farges, E. Blanc, O. Chanrion, E. Arnone, A. Odzimek, N. Arnold, C.-F. Enell, E. Turunen, N. Bosinger, A. Mika, C. Haldoupis, R. J. Steiner, O. van Der Velde, S. Soula, P. Berg, F. Boberg, P. Thejll, B. Christiansen, M. Ignaccolo, M. Fullekrug, P.T. Verronen, J. Montanya, and N. Crosby, "Recent results from studies of electric discharges in the mesosphere," Surv. Geophys. **29** (2), 71–137 (2008).
4. O. Chanrion, T. Neubert, A. Mogensen, Y. Yair, M. Stendel, R. Singh, and D. Siingh, "Profuse activity of blue electrical discharges at the tops of thunderstorms," Geophys. Rev. Lett. **44** (1), 496–503 (2017).
5. V. A. Sadovnichii, M. I. Panasyuk, A. M. Amelyushkin, V. V. Bogomolov, V. V. Benghin, G. K. Garipov, V. V. Kalegaev, P. A. Klimov, B. A. Khrenov, V. L. Petrov, S. A. Sharakin, S. A. Shirokov, S. I. Svertilov, M. Y. Zotov, I. V. Yashin, E. S. Gorbovskoy, V. M. Lipunov, I. H. Park, J. Lee, S. Jeong, M. B. Kim, H. M. Jeong, Y. Y. Shprits, V. Angelopoulos, S. T. Russell, A. Runov, D. Turner, R. J. Strangeway, R. Caron, S. Biktemerova, A. Grinyuk, M. Lavrova, L. Tkachev, A. Tkachenko, O. Martinez, H. Salazar, and E. Ponce, "“Lomonosov” satellite-space observatory to study extreme phenomena in space," Space Sci. Rev. **212** (3-4), 1705 (2017).
6. Y. P. Raizer, G. M. Milikh, and M. N. Shneider, "Streamer and leader-like processes in the upper atmosphere: Models of red sprites and blue jets," J. Geophys. Res.: Space Phys. **115** (A7), E42 (2010).
7. E. V. Mishin and G. M. Milikh, "Blue jets: Upward lightning," in *Planetary Atmospheric Electricity,* Ed. by F. Leblanc, K. L. Aplin, Y. Yair, R. G. Harrison, J. P. Lebreton, and M. Blanc (Springer Science + Business Media, New York, 2008).
8. V. S. Skakun, V. A. Panarin, D. S. Pechenitsin, E. A. Sosnin, and V. F. Tarasenko, "Formation of an apokampic discharge under atmospheric pressure conditions," Rus. Phys. J. **59** (5), 701–711 (2016).
9. E. A. Sosnin, V. S. Skakun, V. A. Panarin, D. S. Pechenitsin, V. F. Tarasenko, and E. Kh. Baksht, "Phenomenon of Apocamp Discharge," JETF Letters. **103** (12), 761–764 (2016).
10. E. A. Sosnin, V. A. Panarin, V. S. Skakun, and V. F. Tarasenko, "Blue jets and starters laboratory modeling by underpressure apokamp," Opt. Atmos. Okeana **29** (10), 855–868 (2016).
11. V. A. Panarin, V. S. Skakun, E. A. Sosnin, and V. F. Tarasenko, "Laboratory simulation of blue and red diffuse minijets in air environment," Opt. Atmos. Okeana **30** (3), 243–253 (2017).
12. E. A. Sosnin, E. Kh. Baksht, V. A. Panarin, V. S. Skakun, and V. F. Tarasenko, "Ministarters and Mini Blue Jets in Air and Nitrogen at a Pulse-Periodic Discharge in a Laboratory Experiment," JETP Lett. **105** (10), 641–645 (2017).
13. E. A. Sosnin, G. V. Naidis, V. F. Tarasenko, V. S. Skakun, V. A. Panarin, and N. Yu. Babaeva, "On the Physical Nature of Apokampic Discharge," JETP. **125** (5), 920–925 (2017).
14. V. F. Tarasenko, V. A. Panarin, V. S. Skakun, and E. A. Sosnin, "Laboratory demonstration in the air red and blue mini-jets," J. Phys.: Conf. Ser. **927**, 012062 (2017).
15. G. A. Mesyats, "Similarity laws for pulsed gas discharges," **49** (10), 1045–1065 (2006).
16. V. A. Donchenko, M. V. Kabanov, B. V. Kaul', P. M. Nagorskii, and I. V. Samokhvalov, *Electrooptical Phenomena in the Atmosphere* (NTL, Tomsk, 2015) [in Russian].

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