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ON FRACTAL DIMENSION SPECTRUM OF NEW LIGHTNING DISCHARGE TYPES IN IONOSPHERE: ELVES, JETS AND SPRITES

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Starting from the middle of nineties of XX a new phenomenon became the focus of physicists' interest – lightning electric discharge in the middle atmosphere at attitudes from 20 to 100 kilometers which are above the absolute majority of clouds. It results in rise of absolutely new classes of discharge phenomena. Physical properties of elves, jets and sprites which are the most interesting types of the high-attitude discharges in the atmosphere are considered in the work. The results of researches of its fractal characteristics are presented. The obtained results give grounds for a deeper insight of development, relaxation of such atmosphere processes and taking into account of action of such kind of strays on functioning of radio systems.

Keywords: fractal dimension, lightning discharge, ionosphere, noise

Introduction

Since the mid 90-ies of XX century a new phenomenon has become the focus of physicists' interest. It is a lightning electrical discharge in the middle atmosphere at altitudes from 20 to 100 km, lying above the absolute majority of the clouds. This leads to a few completely new classes of discharge phenomena called elves, jets and sprites.

Physical models of sprites, elves and jets are still a subject of intense debate [1, 2]. Although the data accumulation phase, characterizing the morphology of these phenomena is not completed, it is already possible go to the study of finer features of the structure and dynamics of high-altitude discharges and their role in the global electric circuit and the balance of minor components of the atmosphere. Methods of study of nonlinear dynamics of high-altitude lightning discharge rely mainly on classical statistical processing of the obtained data. However, the rapid development of fractal scaling methods of signal and image processing makes it possible to expand and refine the obtained data. In particular, the fractal processing provides an opportunity to study topology of the discharges in space and time.

The paper presents the results of experimental studies of fractal characteristics of the new types of atmospheric disturbances such as high-altitude lightning discharges. The concept of a global atmospheric electrical circuit is defined. The obtained data may be of interest when considering the problems of immunity space radiocommunication and radiolocation to interferences, as well as in the evaluation of potential threats to the existing spacecraft and probes.

1. A global atmospheric electric circuit

A global electric circuit or GEC (Fig. 1) is a current distribution loop, which is "closed" by electrically conductive atmosphere [1, 2]. GEC consists of a combination of solid and plasma gas shells united by the continuity of the electric current density, with lightning generators as the main sources of electromotive forces and undisturbed regions of the free atmosphere as return current areas. The physical reason for the formation of GEC in the atmosphere is a sharp increase in the conductivity of the air with increasing altitude.

Near the Earth's surface the conductivity of the air is very low and amounts to $(2\div3)\times10^{-14}$ cm/m, which corresponds to the concentration of light ions of about 10^3 cm^{-3}. With increasing altitude, due to rise in ionization level, which up to 40 km altitude results from galactic cosmic rays, and above – from ultraviolet and X-ray radiation of the Sun, the conductivity increases almost exponentially with a characteristic scale of 6 km. As high as at the altitude *H* of the ionosphere layer (about 80 km), it increases by more than 10 orders of magnitude compared to the troposphere. The conductivity of the earth in the surface layer (and particularly that of ocean water) is also higher than the conductivity of the atmospheric boundary layer by 10 ... 12 orders.

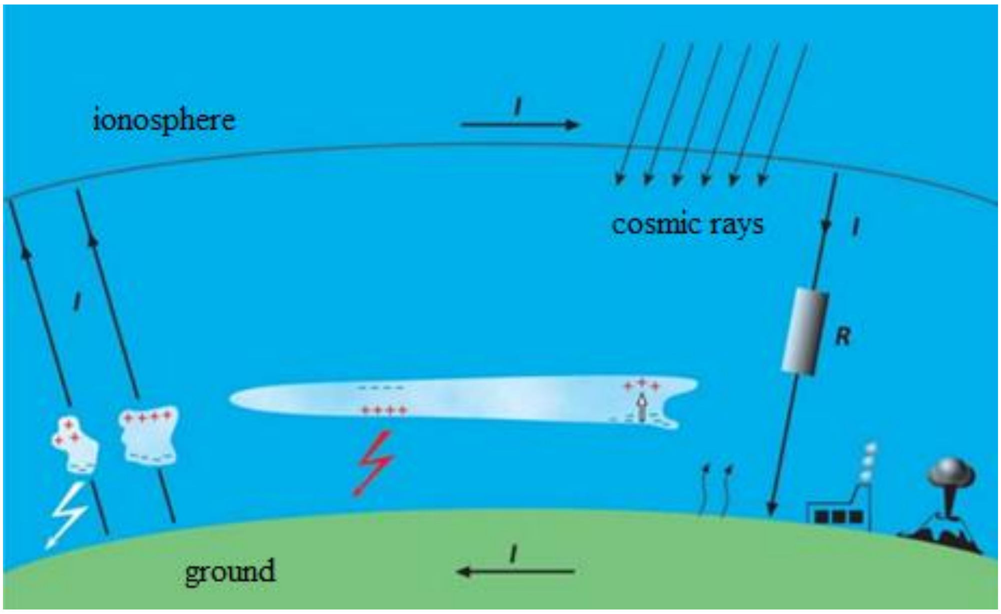


Fig.1. Diagram of the global atmospheric electrical circuit.

To simplify the GEC description, the earth surface and the lower boundary of the ionosphere (about 60-70 km) are often considered as coatings of a giant spherical capacitor, which discharges in areas of fair weather and charges in areas of thunderstorm activity. In these conditions, quasi-stationary charging currents are not completely closed to the ground near thunderclouds, but partly "dragged" into the overlying area of high conductivity and spread over the ionosphere. It is believed that primarily quasi-stationary currents, "bear responsibility" for the maintenance of the potential difference ≈350 kV between the ionosphere and the ground. Since the upper part of most thunderstorm clouds has a positive charge, the potential of the ionosphere is also positive, and in the areas of fair weather the electric field is directed downward, in that way causing conduction currents, closing GEC. If the action of the generators stopped, the potential difference between the Earth surface and the ionosphere would disappear in about 8 minutes.

According to the hypothesis of Wilson, tropospheric lightning generators provide charging the spherical Earth-ionosphere capacitor and determine the quasi-stationary electric state of the undisturbed atmospheric regions [3]. The potential difference between the huge plates of the spherical capacitor is 300...400 kV. Under this voltage, electric current of about 1,000 amperes passes through the air to the ground. This figure may seem huge, but the current is distributed over the entire surface of the planet, so that only a couple of microamps is accounted for by every square kilometer of water or land, and the entire power of the atmospheric circuit is comparable to a turbine of a large hydroelectric power plant. That's why the idea (which goes back to Nikola Tesla) to use atmospheric potential differences to produce energy is untenable.

2. A brief history of the discovery of new dynamic natural structures in the ionosphere and a their brief characteristics

Every twenty-four hours the sky is traced by 4 million lightnings, about 50 ones per every second. And over the gunmetal grey thunderstorm fronts, in the upper layers of the atmosphere a light show of "spectral lightnings" is set: blue jets, red-purple sprites, red rings of elves soaring in the sky. Those are very high energy discharges, which are not directed to the ground but to the ionosphere. Thus, high-altitude electrical discharges (20...100 km) are divided into several basic types: elves, jets, sprites, halos, etc. – Fig. 2.

The story of their discovery was as follows. On the night of 5 July 1989, an important event happened in the history of the study of the Earth. John Randolph Winkler, a retired professor, 73-year-old NASA veteran focused a high-sensitivity camera on thunderstorm clouds. Then, thoroughly looking through the record, he found two bright flashes, which, unlike the lightning did not go down to the ground but went up, to the ionosphere. In that way *sprites*, the largest of high-altitude discharges in the Earth's atmosphere, were discovered. They clearly confirmed the existence of GEC on the planet and gave new opportunities for its research. His articles literally caused a shock among experts on astronomy, atmospheric electricity, radio physics, atmospheric acoustics, gas discharge physics and aerospace safety.

The shortest-lived high-altitude discharges, *elves* occur in the lower ionosphere at heights of 80...100 km. Having originated in the center, the glow expands to 300...400 km in less than a millisecond, and then quenches. Elves emerge in 300 microseconds after a strong lightning having stricken the ground from a thunderstorm cloud. The channel of the lightning becomes a "transmitting antenna", from which a powerful spherical electromagnetic wave of very low frequency rate "starts" at light speed. In 300 microseconds it reaches a height of 100 km, where it "sets in" a red glow of nitrogen molecules.

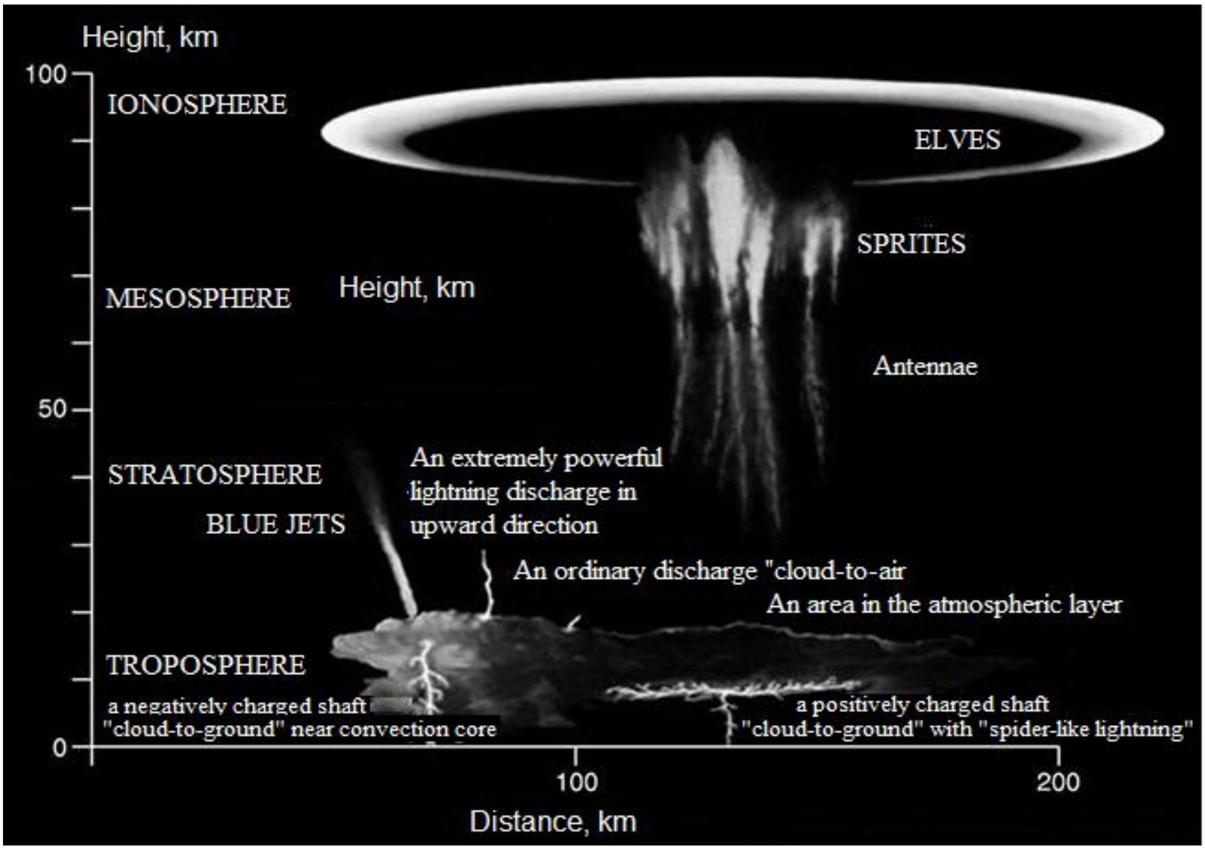


Fig.2. Dynamic fractal structures in the atmosphere.

The most mysterious high-altitude discharges are blue jets; they are also a glow of nitrogen molecules in the ultraviolet-blue spectrum. They look like a narrow blue inverted cone, "starting" from the upper boundary of a thundercloud. Sometimes jets reach a height of 40 km, their extension rate is 10 to 100 km/s. Their emergency is not always caused by lightning discharges. Besides blue jets, "blue starters" (they extend to a height of ≤ 25 km) and the "gigantic jets" (extending to the lower ionosphere heights of about 70 km) are differed.

Sprites are very bright three-dimensional flashes with duration on the order of milliseconds, occurring at an altitude of 70-90 km and descend down to 30-40 km. Their top width reaches tens of kilometers. Sprites flare up in the mesosphere in about a hundredth of a second after the discharge of powerful lightning "cloud-to-ground", sometimes at a distance of several tens of kilometers horizontally from the lightning channel.

The red-purple color of sprites, as well as that of elves, is attributed to atmospheric nitrogen. The frequency of sprites occurrence is on the order of several thousands of events per day around the globe. The fine structure of the bottom of sprites is characterized by a plurality of luminous channels with transverse dimensions ranging from tens to hundreds of meters – Fig.1. The emergence of sprites is associated with the formation of a high dipole moment of the uncompensated charge, after particularly powerful lightning discharges cloud-to-ground, usually of positive polarity.

Halo is a uniform reddish-purple glow at an altitude of about 80 kilometers. Halo is a luminous disc in the mesosphere just above the area of tropospheric discharge. The reason for the discharge is probably the same as that of the top of sprites, but unlike them, halo always originates just above the "cloud-to-ground" flash of lightning.

It is a mystery for scientists that discharges in the ionosphere are fairly numerous; they appear not only where there are thunderstorm clouds occur, and not over the entire surface of the Earth. They are not visible above Siberia, oceans and deserts. But a large number of them are recorded over Australia, Africa and Latin America. It is difficult to register high-altitude discharges and diagnose their characteristics due to their short lifetime.

3. Some approaches to the modeling of ionospheric structures

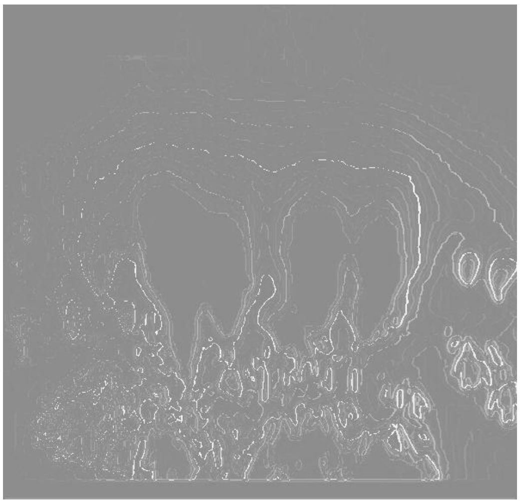
Development of physical and mathematical models of sprites, elves and jets is an urgent task of researchers. Dynamic spatiotemporal characteristics and morphology of sprites may be explained, in particular, by fractal geometry of discharges and percolation. [1, 2, 4 – 14].We have here another example of self-organized criticality when the dynamics of the system (in this case, of a high-altitude discharge) results from reaching the threshold of the so-called directed percolation, which features the formation of branched (fractal) conducting channels that cover the entire length of the sprite.

4. The results of fractal processing of a sprite and a jet in the ionosphere

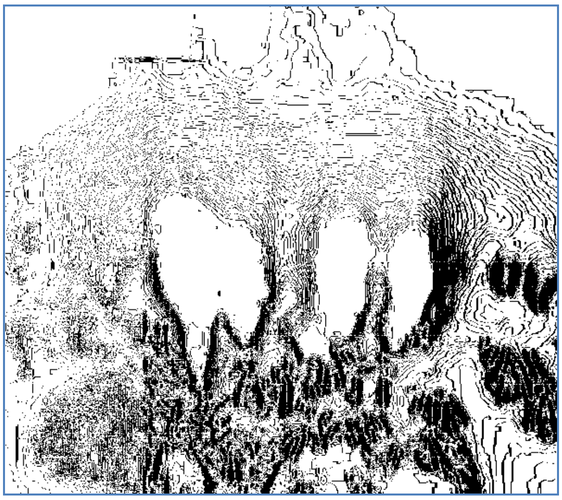
The situation is quite different with the matters of statistical data processing. In this case, classical methods are traditionally used. They *do not make it possible* to obtain all the information about these new atmospheric structures. In other words, in [6-16] the author shows that the use of the mathematical theory of fractional measure and fractals opens up a whole range of new methodological principles for physicists and experimenters – for examples, see Fig. 3 and Fig. 4. There are clearly visible numerous branches and channels in the structures of sprites and jets.

Apropos, these are *the first in the world* results of fractal processing of such structures (the initial processing was carried out at the beginning of 2013, the final processing – in 2014). In such cases it is possible to apply simulation based on fractal mazes, which reflect the physics and morphology of those ionospheric structures quite well [14, 15].

a)

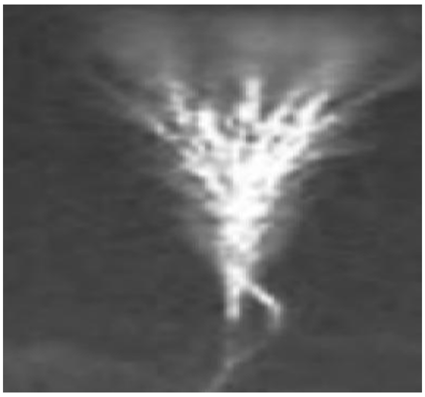


b)

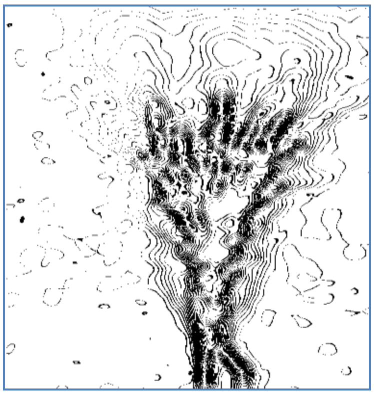


c)

Fig. 3. The results of fractal filtering of a sprite image:
(*a*) – an initial sprite image (US, NASA [17]),
(*b*) – a fractal dimension estimate chart with the average value of the fractal dimension
$D = 2.43$,
(*c*) – the section of the chart on the value of
$D = D - 0.05$.
(External, basic and hyperfine sprite structures clearly differ).



a)



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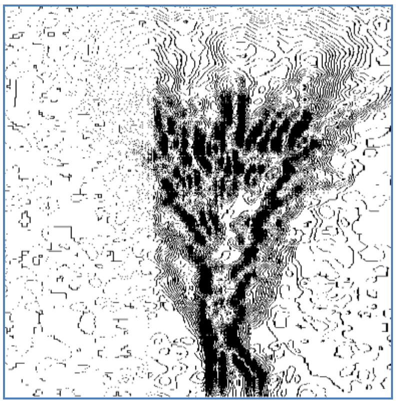

c)

Fig. 4. The results of the fractal filtering of a gigantic jet image (photographed in China, 12 August 2010): (a) –the jet image [18], (b) and (c) – the sections of D fractal dimension

A complete series of fractal filtering results of an instant frame sprite image based on initial data from [17] is shown in Fig. 5.

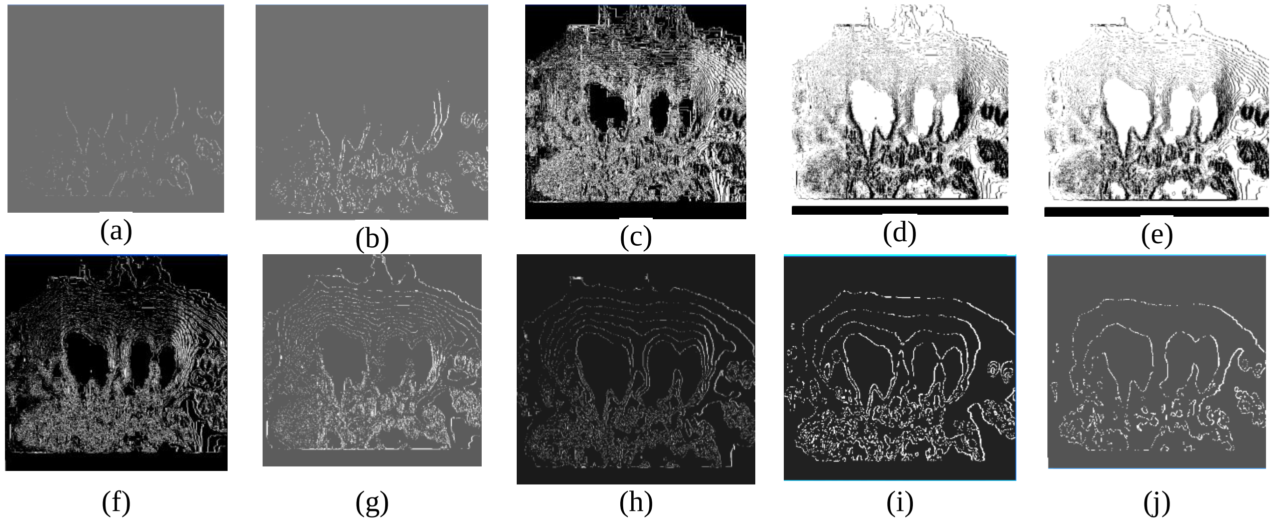

Fig. 5. A complete series of the results of the sprite image fractal filtering:
(a) – a chart of the fractal dimension with the mean value of D = 2.1; (b) – 2.2;
(c) – 2.3; (d) – 2.4; e) – 2.5; (f) – 2.6; (g) – 2.7; (h) – 2.8; (i) – 2.9; (j) – 3.0.

Conclusion

One of new types of high-power pulse interferences are recently discovered specific discharges of atmospheric electricity. Fractal scaling methodology applied to describe the morphology of jets, sprites and elves can be successfully used to evaluate their performance and development dynamics. This evaluation will be overall and objective as it is based on quantitative estimates of D fractal dimensions at contouring of related structures; and it is operational since the data processing is easily performed by computers. Then problems of mathematical physics are solved.

The results obtained in this work provide a basis for more profound effect of interferences of this kind on the functioning of modern ground and space radio systems. Here are some characteristics of sprites [4, 5]: typical space $30\times30\times30$ km; the spatial extent of irregularities – the external structure on the order of 10 km, the basic structures on the order of 1 km, the hyperfine structure less than 100 m; the electron density N_e~10^4 cm^{-3}, the flash duration τ_s ~10 ms; relaxation time of the electron density τ_r ~1...10s; the electron temperature T_e~2 eV at the flash and T_e~0.02eV during the relaxation period; total current momentum in the discharge p_s~100 $kA\times km$.

The obtained results in this paper confirm that the common point of nonlinear electrodynamics of GEC and the developed global fractal-scaling method has been found [6-16, 19].

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