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Similarity analysis of the streamer zone of Blue jets

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ABSTRACT

Multiple observations of Blue Jets (BJ) and Gigantic Blue Jets (GBJ) show that BJ and GBJ emits a fan of streamers similar to a laboratory leader. Moreover, in the exponential atmosphere those long streamers grow preferentially upward, producing a narrow cone confined by the aperture angle. It was also noticed that BJ are similar to the streamer zone of a leader (streamer corona) and the modeling studies based on the streamers fractal structure were conducted. Objective of this paper is to study the fractal dimension of the bunch of streamer channels emitted by BJ and GBJ, at different altitude and under the varying electric field. This similarity analysis has been done in three steps: first we described the dendritic structure of streamers in corona discharge applying the fractal theory. Then using this model and the data from existing laboratory experiments we obtained the fractal dimension of the branching streamer channels. Finally the model was validated by the observations of BJ available from the literature.

1. Introduction

About two decades ago, researchers discovered upward-propagating collimated flashes of light originating above thunderstorms (Wescott et al., 1995). Due to their distinctive, principally, blue color, they were termed "blue jets" (BJ). They resemble tall trees with quasi-vertical trunk and filamentary branches. (Pasko et al., 2002) discovered the so-called gigantic blue jets (GBJ), propagating into the lower ionosphere. Number of GBJ observations were made since (Su et al., 2003; Kuo et al., 2009; Cummer et al., 2009; Chou et al., 2011; Neubert et al., 2011; Soula et al. 2011; Liu et al., 2015).

Multiple observations of BJ show that they emits a streamers similar to the streamers of corona discharge of a laboratory leader. Streamers in corona discharge are self-similar plasma structures termed fractals (Wiesmann and Pietronero, 1986; Pasko et al., 2000; Pasko et al., 2002; Popov, 2002). According to the current understanding the streamer propagates due to the formation of electron avalanches in the strong electric field E of the space charge near the streamer tip. The propagation direction of those avalanches is determined by the shape of the streamer's electric field. The probability of streamer propagation in a given direction is determined by the spatial distribution of the electric field near the streamer tip.

In the case of BJs the leader trunk barely exits the cloud and we only see the streamer zone (Raizer et al., 2006) and (da Silva and Pasko, 2013). Contrary to BJs GBJs lightning leaders escape the thundercloud upwards and propagate through the stratosphere. An interesting hypothesis (da Silva and Pasko, 2013) stated that when GBJ reach *the jump altitude when the streamer zone length is longer than the scale height of the atmospheric air density profile, the* streamer zone reaches the ionosphere.

Note that we focus on study of the streamer corona, which is the basic of the blue jets (BJs), as well as gigantic blue jets (GBJs). Furthermore BJs and GBJs are of the similar structure, and the both are eventually evolve into the streamer region. Notice that in this paper we limit ourselves to the analysis of the structure of the streamer region of GBJ since it is much better recognizable on the existing images.

The dendritic structure of streamers in corona discharge was treated by means of the fractal theory (Satpathy, 1986), which main parameter is the fractal dimension D. Note that the fractal dimension D of the plasma structure is determined by the power index γ, which depends on the reduced electric field value near the streamer tip (Popov, 2002). (Pasko and George, 2002) numerically simulated the streamer corona of a positive leader as a fractal process. They suggested that the power index γ, that links the probabilities a random choice with electric field value, is $\gamma=1$ and obtained the fractal dimension of the dendritic structure $D=1.37\pm0.13$. The numerical simulations of the streamer corona of blue jets and blue starters as a fractal structures were first presented in (Pasko and George, 2002) although computed for $\gamma=1$.

The objective of this paper is to apply the theory of fractal dimension of streamers in the corona discharge to study formation

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and propagation of blue jets and gigantic blue jets. The proposed model concerns GJs, BJs and streamer corona. However, since the existing images of the streamer corona and of BJs cannot resolve the object's spatial structure, in the present paper we focus entirely on the GBJs. Thus the model is validated by comparison with the existing optical observations of gigantic blue jets.

2. Fractal dimension of a bunch of multiple streamers

Widely used model (Niemeyer et al., 1984; Wiesmann and Pietronero, 1986) describes the spatial structure of branching channels. In this model, the plasma channels propagate toward the highest electric field, provided that the field exceeds the threshold value E_{cr}. The spatial distribution of the electric field is determined from solution of the Laplas equation for the potential having the boundary conditions which consider the conducting channels. All these channels are taking as equal, while the field inside the channels is constant. The probability of the streamer propagation in z-direction P_z is determined by the field distribution near the streamer head.

$$P_z \propto E_z^{\gamma} - E_{cr}^{\gamma} \tag{1}$$

where E_z is the field in the direction z, γ is the power index.

According to (Popov, 2002), the power index γ can be obtained from the equation for the effective ionization frequency:

$$\gamma = \frac{\partial \ln(\nu_{ion} - \nu_{att})}{\partial \ln E} \tag{2}$$

where ν_{ion}–ν_{att} is the difference between the ionization frequency and electron attachment frequency for a given sort of the gas. It depends only on the reduced electric field E/N value.

The major results of the model (Niemeyer et al., 1984; Wiesmann and Pietronero, 1986) is that the plasma structures allow spatial scaling, thus they are self-similar structures or fractals. As shown in (Satpathy, 1986) the fractal dimention D depends entirely on the dimensionality of space d and the power index γ in Eq. (1), $D=D(d, \gamma)$.

Fig. 1 reveals the power index as function of the reduced electric field γ(E/N) for the air, here it is shown by the dashed line. It is computed for the E/N range 200–1200 Td (1 Townsend is equal to 10^{-17} V/cm^2). The respective ionization and electron attachment frequencies ν_{ion}(E/N) and ν_{att}(E/N) were obtained by the Bolsig+code (Hagelaar and Pitchford, 2005).

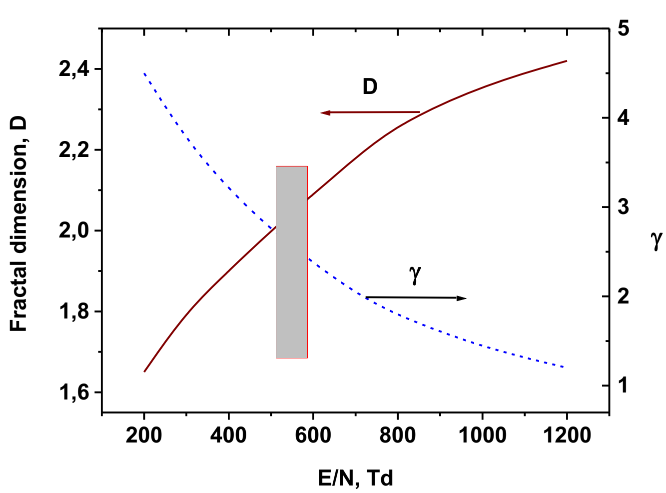

Fig. 1. The fractal dimension D (solid line) and the power index gamma (the dashed line) versus reduced electric field E/N computed for the streamer tips. The rectangular box contains the variations of the coefficient γ and of the fractal dimension in the E/N reduced field range 500–600 Td.

In addition, Fig. 1 reveals the fractal dimension D of the plasma structures formed in BJ, here it is shown by the solid line. The data $D(\gamma)=D(\gamma, d=3)$ obtained in (Satpathy, 1986) for the 3D Laplace field was used. These data were determined by the model (Niemeyer et al., 1984; Wiesmann and Pietronero, 1986) from the solution of 3D Laplas equation for the potential having the boundary conditions which consider the conducting channels. (Satpathy, 1986) computed the number of conducting channels $N(R)$ which cross the sphere of radius R. Then the fractal dimension $D(\gamma)$ was found using Eq. (5). The fractal dimension of the plasma structures vs. E/N (Fig. 1) was found under the assumption that the maximum electric field in the streamer head is constant and equal to E.

The data (Kuo et al., 2009) shows the reduced electric field in the streamer head inside the GBJ in the altitude range $h=40$–90 km. It was obtained using the ratio of the observed intensities of the optical bands N_2(2P) and N_2(1N). Found in the work (Kuo et al., 2009) maximum reduced electric field was $E/N=400$ Td. Notice that due to the shift between the maximum electric field and maximum intensities of the N_2(2P) and N_2(1N) bands in the streamer head (Naidis, 2009; Bonaventura et al., 2011) the real value $(E/N)_{\rm max}$ in the streamers becomes about 1.4 times greater than the optical data gives. According to (Kuo et al., 2009; Bonaventura et al., 2011) we assume that in the streamer head where the branching probability is highest, the value $(E/N)_{max}$ reaches 500–600 Td (it is shown by the dotted area in Fig. 1).

As it follows from Fig. 1 for $E/N=500$–600 Td the fractal dimention of the branching plasma channels yields:

$$D = 2.05 \pm 0.04 \tag{3}$$

Note that it significantly differes from $D=1.37 \pm 0.13$ used by (Pasko et al., 2000).

3. Average number of streamers in blue jets and gigantic jets

According to the fractal theory the full length L of the streamers inside the surface having the radius R can be presented by (Niemeyer et al., 1984; Wiesmann and Pietronero, 1986):

$$L \propto R^D \tag{4}$$

While the number of streamers crossing this surface yields

$$N(R) = \frac{dL}{dR} = \left(\frac{R}{R_0}\right)^{D-1} \tag{5}$$

where R_0 is the characteristic scale within which the streamer branches. The value R_0 cannot be obtained from the fractal theory and thus it should be provided as an input to the model.

Another important result from the fractal theory describes the average inter-streamer distance Λ as the function of R:

$$\Lambda(R) \propto \frac{d^2L}{dR^2} \propto \left(\frac{R}{R_0}\right)^{D-2} \tag{6}$$

Eq. (6) has the proportionality sign which assumes the existence of a dimensional factor, the latter is missing from Eq. (6). The factor will determine dimensionality of the average inter-streamer distance.

Consider $D=2$ (see Eq. (3)) we obtain that $\Lambda(R) \approx const$ i.e. the average inter-streamer distance changes only slightly as the distance R increases. Moreover, using Eq. (5) one can find the total number of the streamers in the Blue Jet, $N(R)$, at the height h_{max}. The latter is the maximum height where the optical steamers are the most distinct, therefore they will be used in our analysis. Here $R=h_{max}-h_0$ and h_0 is the height at which the BJ starts, while R_0 is the characteristic scale of the leader head at the height h_0. The