FRACTAL DYNAMICS OF THUNDERCLOUD ELECTRIC DISCHARGES*

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ABSTRACT

A cellular automaton model is developed, which describes dynamics of intracloud discharges on lightning discharge preliminary stage. When median electric field is absent these discharges demonstrate percolation-like behavior. Even a weak macroscopic electric field modifies drastically the system dynamical features. The model represents an explosive process of thundercloud dynamical metallization, when short-living conducting elements appear as a consequence of electrical microdischarges. Such a metallization forms drainage conducting system, which gathers a macroscopic electric charge over all volume of the cloud and determines the development of a macroscopic lightning discharge.

INTRODUCTION

The thunderstorm electricity problem is extremely diverse one, and includes a number of key questions. It begins with cloud electrification mechanisms, and ends with flash shaping final stage, when a stepped leader arises and a return stroke is established as the lightning discharge's most powerful manifestation. Considerable progress has been made recently in the understanding and modeling of elementary processes of cloud particle electrification [1]. Advances have been made in model development of the flash channel formation, when a leader accompanies the channel formation and return stroke progression [2].

Understanding the processes that define the preliminary stage of lightning discharge has been a major problem. In its most developed phase, this stage lasts approximately one tenth of a second, and consists of numerous (up to 10,000) relatively weak discharges [3, 4]. Widespread experimental efforts have demonstrated several peculiarities at the preliminary stage, proving it to be a very complex and puzzling phenomenon: Firstly, two subintervals (of approximately equal duration) may be selected in the preliminary breakdown stage. The first subinterval contains very high frequency (VHF) pulses, which appear without any visible DC field changes. A gradual DC field change accompanies VHF during the second subinterval, and is closely connected with leader progression. Secondly, the results obtained with the VHF source location systems reveal pulse duration changes, which are connected with Doppler effect to the radiation of a fast (up to 10^7m/s) moving source. Sometimes VHF emission is observed as a coherent signal consequence [5]. Thirdly, the precursor activity spreads VHF sources throughout much of the cloud. Finally, the universality of the frequency spectrum of electromagnetic signals emitted by the discharges was also established [6].

The question is what physical mechanism could result in the occurrence of such an intricate preliminary dynamic? It is particularly difficult to answer this question, since the median electric field strength in a cloud is of order of magnitude below the typical fields generating sparks in laboratory experiments.

The principal aim of this paper is to raise the idea that the preliminary stage of lightning discharge is closely related to the thundercloud fine electrical structure that has been detected in practically all *in-situ* experiments. Unfortunately, the special resolution of the existing experiments does not permit to obtain quantitative characteristics of a small-scale electric field with the scale less then $100m$. At the same time there is physical mechanism, which support the idea of small-scale electrical stratification inside a thundercloud [10, 11]. This mechanism is based on a beam-plasma discharge in a cloud and predicts appearance of electric cells with a scale $a \sim 10m$. This scale will be taken further as the base for the quantitative formulation of the problem.

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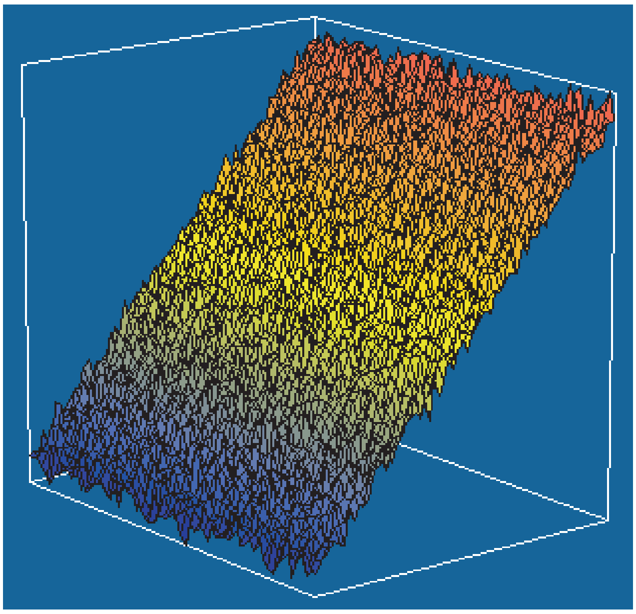

Fig. 1. Potential relief that looks like spatial white noise with linear bias

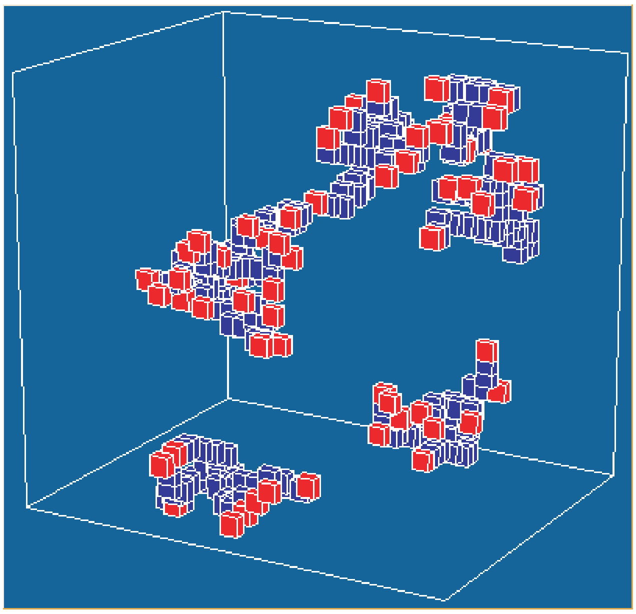

Fig. 2. Configuration of intracloud microdischarges. Red boxes correspond to the microdischarges that appear at the current step of model time.

THUNDERCLOUD METALLISATION

We will consider the TC activity on the base of a cellular automaton model [8]. Taking into account that the size of the active part of the thundercloud is about a few kilometers, the linear size of the model lattice should be about a few hundred of the spatial period. Each site of the lattice is related to a time-dependent scalar U_{ij} characterizing the electric potential. In our model the potential differences between the neighboring sites are growing due to the instability effects.

We consider two random-growth models: the simplest one, when random additions with a normal distribution are added to the electric potentials U_{ij} at the lattice sites at each step of the model time; and the second, when along with random additions we add an external bias field (see Fif. 1) (so, the first case is just particular case of the second with zero bias); In every case, each site, independently of its neighbors, undergoes Brownian motion in the space of electric-potential values.

The potential difference growth is limited by some critical value U_c. As soon as this critical value is reached for any two neighboring sites on the lattice, breakdown between the sites takes place and the lattice bond between the sites becomes a conductor. Its conductivity exponentially disappeared for a few model time steps and correspondent potential difference levels down. We assume that such a fine scale spark discharge can initiate breakdowns of the neighboring lattice bonds (”infect” the neighbors), if the potential difference between the cells exceeds some activation level U_a, which is less than critical one. Below this process will be called as cell’s activation. The broken cells form a short-living conductive cluster. An example of such a metallised cluster is shown in Fig. 2 In our model we use self-avoid metallisation, when broken periphery site may have only one metallised nearest neighbors. The electric field for activation is considerably less than the breakdown value due to the appearance of sharp heterogeneity of conductivity and of fast electrons. It is confirmed as well by the experiments on the initiation of gas breakdown by a laser pulse [9]. The ionization is implied passing activated cluster in one time period step in the model. We choose the voltage drop growth rate so small that even the largest cluster ”burns down” rapidly, before new activated bond grows at its edge. It means that the metallised cluster lifetime τ (dissipation time) is much smaller than the potential relief growth rate:

$$\frac{D\tau}{U_a^2} \ll 1, \tag{1}$$

where D is dispersion of the random additions that are added for nearest neighbors potentials at every step of model time. In other word, the process connected with the external driving of the system is much slower than the internal relaxation processes.

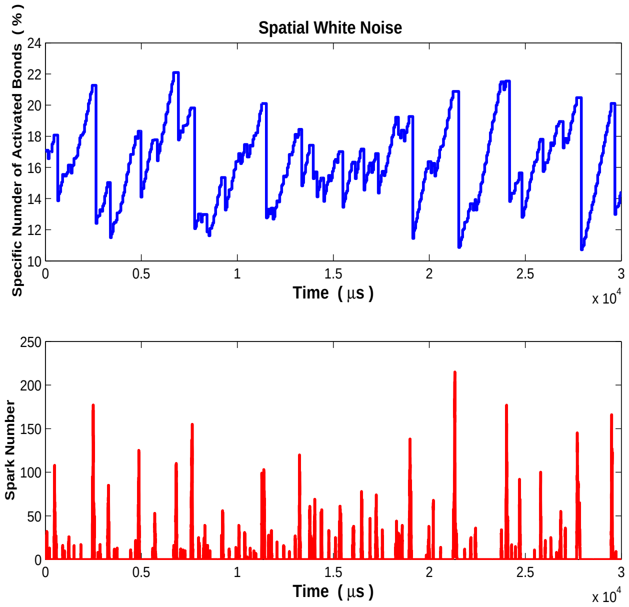

Fig. 3. Model time evolution with zero external field. The top demonstrates specific number of activated couples, bottom contains spark number time evolution in the same time interval.

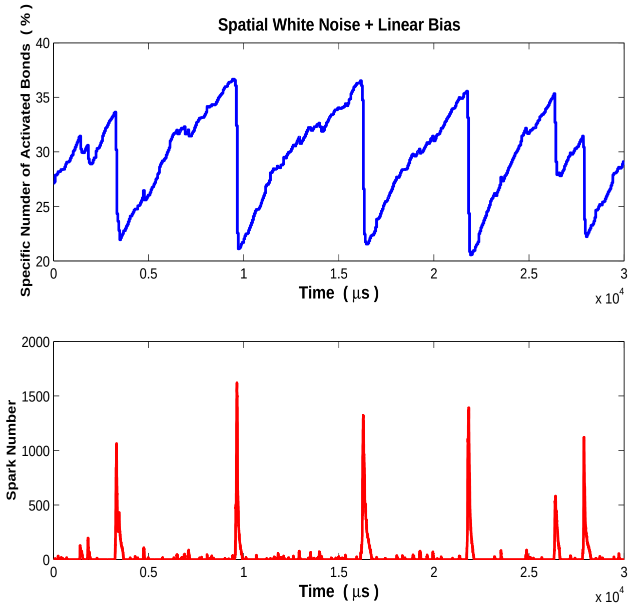

Fig. 4. Specific number of activated couples and spark number time evolution in the case, when linear external field is applied.

RESULTS

Nonlinear interaction of neighboring cells under the growth process discussed leads to formation of dynamical chains of microdischarges, which reveal a fractal behavior in the wide range of TC parameters. Fig. 3 shows time evolution of the model discussed in the simplest situation, when potential relief looks like spatial white noise. Specific number of activated couples of cells for the case on Fig. 3 is always less than site percolation threshold on a simple cubic lattice (25%). This is the separation of time scales that turns our system into the SOC-like dynamical state (see [7]). The separation of time scales is closely connected with the existence of the breakdown threshold. The fine-scale electrical field has to build up enough to pass a certain critical value. This occurs over a much longer period of time than the short breakdown time interval.

Fig. 4 shows how the system is working in the presence of large-scale electric field. The important new effect in this situation is a large-scale electric current, which flows through the conducting clusters and redistributes the large-scale electric charge. To take into account this effect and to model a limited resistance of the cluster, we have added the program of charge smoothing down on every step of cell activation. It is clear with the physical point of view that the large-scale electric field E_0 will determine an electrical discharge in TC, if the potential difference $U \sim LE_0$ on the cluster size L is comparable with the critical value U_c. Near the percolation threshold, when clusters sizes increase, even a small external field changes drastically the electric discharge dynamics (see bottom subplot in Fig. 4).

To capture more realistic situation, our intracloud field pattern should have very complicated multiscale structure, when dispersion of potential distribution growth not only in time but also in space. We use generalised Brownian noise algorithm, see Fig. 5. In the case we obtain an intriguing threshold drop (see Fig. 6) in comparison with linear external field that is shown at the Fig. 1.

The model discussed allowed us to estimate the appearance rate F of microdischarges (activated cells discharges). This rate is determined by the relation

$$F \approx \gamma \frac{V}{a^3} p, \tag{2}$$

here γ is the growth rate, p is specific number of activated couples of cells, and V is the volume of the thundercloud active part, where the instability takes place. On preliminary breakdown stage, when the activated cluster length is large enough for the leader progression, we have $p \sim p_c$ with $p_c = 0.25$ for 3D system. Putting $V \sim 10_{10} m^3$, $a \sim 10m$ and $\gamma \sim 1s^{-1}$, we find: $F \sim 2.5 \cdot 10^5 s^{-1}$; this is in good qualitative agreement with experiment [12]. Summarizing the above results, we can conclude that exploration of short-scale electrical structure of a thundercloud is very promising for understanding the

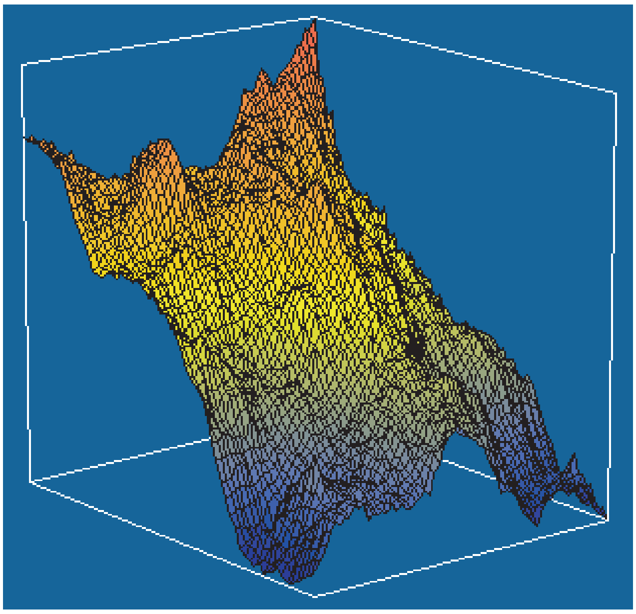

Fig. 5. Intracloud potential distribution – 2D section. Potential relief looks like spatial brownian noise (dispersion of the distribution linearly grows with scale)

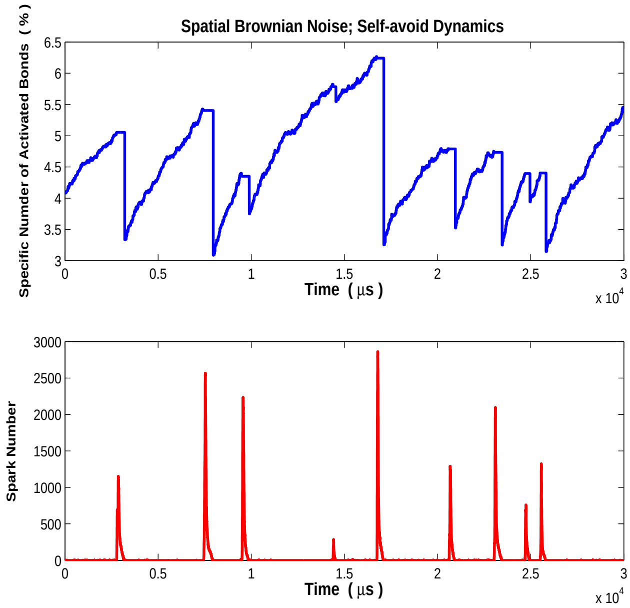

Fig. 6. Configuration of intracloud microdischarges. Red boxes correspond to the microdischarges that appear at the current step of model time

preliminary stage of a lightning discharge. The small-scale electrical stratification is caused by a thundercloud free energy, which is stored in the multiflow motion of the cloud media. Small-scale breakdown spreading, which is accompanied by cluster length growth, can lead to the stepped leader formation at the final stage. The process may be considered as an example of self-organized transport or information system, based on internal small-scale nonlinear dynamics.

We hope that the suggested model may shed some light on the burst-like space-time fluctuations observed in the preliminary breakdown stage, and will stimulate more detailed examination of the thundercloud fine structure.

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