ELECTRIC CHARGE FRACTAL TRANSPORT AND ELECTROMAGNETIC HIGH FREQUENCY RADIATION ON THE LIGHTNING DISCHARGE PRELIMINARY STAGE

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ABSTRACT: We consider the thunderstorm (TC) activity on the base of a cellular automaton model on tree-dimensional lattice. Each site of the lattice is related to a time-dependent scalar that characterises potential of the point. In our model the potential differences between the neighbouring sites are growing due to the instability effects. The potential difference growth is limited by some critical value. As soon as this critical value is reached for any two neighbouring sites on the lattice, breakdown between the sites takes place and the lattice bond between the sites becomes a conductor. We assume that such a fine scale spark discharge can initiate breakdows of the neighbouring lattice bonds (“infect” the neighbours), if the potential difference between the cells exceeds some activation level, which is less than critical one. Interaction of neighbouring cells leads to formation of dynamical chains of microdischarges, which reveal percolation-like behaviour in the wide range of TC parameters. We show that fractal dynamics of electrical microdischarges in a thundercloud can serve as the basis for explanation of main features of a lightning flash on its preliminary stage. Following to step-by-step computer simulations we calculate radio-emission from every microdischarge and sum up wave amplitudes in the reception point from all intracloud volume. The standard model for a separate microdischarge current is taken, and electromagnetic radiation in the wave zone is estimated. The results of simulations are in the satisfactory agreement with experimental data.

INTRODUCTION

Processes in a TC are very diverse and complicated. A classical cloud to ground (CG) lightning discharge includes three stages: preliminary breakdown, leader formation and return stroke [Uman, 1987; MacGorwan, and Rust, 1998]. The existing theoretical models of lightning discharges are based on its similarity with a laboratory long spark. It actually relates to the leader formation and return stroke. But there is a very important difference, which concerns a preliminary stage of the discharge. In the case of a laboratory spark electrical charge is accumulated on a conducting wall(s) of a discharge space and flows down easily into the spark channel. It is not clear what mechanism could provide the electric charge gathering over all intracloud volume (or over its considerable part) to the leader channel. Apparently a certain important process which supplies this gathering, takes place during the preliminary breakdown stage. This stage lasts from tens to hundreds of milliseconds, and consists of numerous (up to 10000) relatively short (with duration about microseconds) discharges (pulses) grouped in trains of various durations. Radio images retrieved with the help of these pulses, reveal a strongly forked intracloud network of microdischarges, resembling the structure of fractal clusters. This stage is just discussed in our paper. We suggest a new model, which can supply the electric charge gathering over the entire volume of a cloud and bring this charge to the leader channel. This model is based on a two-scale structure of a TC electric field where there exist electric cells with size $l \sim 10$ m much smaller than the cloud size in addition to the large-scale field. Microdischarges which are observed during a breakdown preliminary stage, can be actually considered as indirect evidence of the existence of such small-scale electric cells. There is the physical background for our model based on the beam-plasma instability in a TC. This instability predicts the generation of a short-scale electric structure of sizes $\sim 1 \div 10^2$ m. It is borne in mind that the electrical breakdown model which is considered in the paper, differs principally from the famous dielectric breakdown model, which is based on the step-by-step solution of the Laplace equation $\Delta U = 0$ ($U$ is electrical potential) with the self-consistent moving boundary between infinitely conducting and neutral parts of air. In our case the Laplace equation is modified by a background air conductivity and by a current of charged cloud particles and predicts the generation of small-scale electric...
cells [Iudin, and Trakhtengerts, 2001). Thus, an intracloud discharge is developing in the electric field, which is initially strongly inhomogeneous. It is natural to suppose in such a situation that discharges appear inside a separate most intense electric cell and can stimulate discharges in the neighboring cells due to activation processes. In the real atmosphere such processes can include local inhomogeneities of conductivity or runaway electrons generated by microdischarge inside a neighboring cell. The suitable mathematical model for analyses of cells interaction is a cellular automaton model, which is used below in our computer experiments.

MODEL

We will consider the TC activity on the base of a cellular automaton model. 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 \( U_{ijk} \) characterizing the electric potential. In our model the potential differences between the neighboring sites are growing due to the instability effects.

To capture more realistic situation, our intracloud field pattern should have very complicated multi-scale structure, when dispersion of potential distribution growth not only in time but also in space. We use 3D-extension of the Voss’s procedure to produce generalised Brownian potential landscape, that is added to the electric potentials \( U_{ijk} \) at the lattice sites at each step of the model time, see Fig. 1. In the 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 hetero-

Figure 1: Intracloud potential distribution – 2D section. Potential relief looks like spatial brownian noise (dispersion of the distribution linearly grows with scale).

Figure 2: Configuration of intracloud microdischarges.
geneity of conductivity and of fast electrons. It is confirmed as well by the experiments on the initiation of gas breakdown by a laser pulse. 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 $\tau$ (dissipation time) is much smaller than the potential relief growth rate:

$$\frac{D\tau}{U^2_a} \ll 1,$$

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.

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. This is the separation of time scales that turns our system into the SOC-like dynamical state. 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.

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 $U \sim L E_0$ 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.

![Spatial Brownian Noise; Self-avoid Dynamics](image)

![Spark Number vs Time](image)

Figure 3: Model time evolution. The top demonstrates specific number of activated couples, bottom contains spark number time evolution in the same time interval.

The model discussed allowed us to determine the characteristics of radio emission from a thunder-cloud during the preliminary stage of a lightning discharge. We assume that the model 3D lattice is vertically oriented and the distance from its lower boundary to the ground equals to $1\text{km}$, while the reception point is located at a small height of about $10\text{m}$ above the ground at a distance from the cloud center that is much larger than the cloud size (see sketch on Fig. 4). In this case, with allowance for the
reflection from the ground, the total radiation field \( E_z(r, t) \approx 2E_\theta \). Using the spatio-temporal characteristics of the metallisation process, we can easily find the radiation field \( E_z(r, t) \) at any step of model time. Shown on the bottom subplot in Fig. 4 the VHF emission wavelet representation delivers visual proof of selfsimilarity of the signal that is cited on the left top window. We use six oder Symlets wavelets here.

CONCLUSION

Summarizing the above results, we can conclude that exploration of short-scale electrical structure of a thundercloud is very promising for understanding the preliminary stage of a lightning discharge. The small-scale electrical stratification is caused by a thundercloud free energy, which is stored in the multilow 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.

Following to step-by-step computer simulations we calculate radio-emission from every microdischarge and sum up wave amplitudes in the reception point from all intracloud volume. Signal statistical analysis and calculated frequency spectra shows the universal power-low behavior. The results of simulations are in the satisfactory agreement with experimental data. The wave forms demonstrate close similarity to the observed ones.

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REFERENCES

