DYNAMIC AND ELECTROMAGNETIC EFFECTS OF STREAMER INTERACTION WITH LOCALIZED STRONG IONIZATION IRREGULARITIES IN SPRITES AND TROPOSPHERIC DISCHARGES

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ABSTRACT

We consider some consequences of the hypothesis that ubiquitous small conducting dust particles play an active role in initiation and formation of fine structure of sprites and other atmospheric discharges. Physical mechanisms underlying this hypothesis include the ability of such particles to fire in quasi-electrostatic fields caused by a thunderstorm, thus giving strong local irregularities of ionization. In the present paper we suggest a modification of this mechanism taking into account a possible role of dielectric impurities in dust particle composition. We also propose new possibilities for testing our hypothesis experimentally, based on measurements of radio emission spectra of atmospheric discharges.

INTRODUCTION

The inner Solar System is suffused with a vast cloud of "interplanetary dust." This dust cloud is visible with the naked eye as the zodiacal light - a triangular diffuse glow rising above the horizon shortly after sunset or before sunrise. During each passage by the Sun, a typical comet loses roughly 1 m of surface material, composed of ices and dust, forming dust and ion tails millions of kilometers in length. Other important sources of interplanetary dust are asteroids, which produce most of their dust during mutual collisions in the asteroid belt.

The Earth accretes roughly 40,000 tons of interplanetary dust each year. A significant part of the incoming micrometeoroid flux (particles with radii <100 μm) is not destroyed by impact with the atmosphere. In the mesosphere the resulting average number density of the dust particles (radii 20-100 μm) is 10-1000 per km^3. This exceeds the spatial density of particular points (points of origin, branching and decay) in sprite architecture, which can be directly estimated from telescope images to be of the order 0.1-1 km^{-3} [1].

The metal content is at least 1/2 to 2/3 of micrometeoroid composition; the remainder is semi-conducting silicon and a bit of dielectric impurity, so one can approximately consider them as conducting bodies.

In the troposphere metallic dust particles of terrestrial origin are constantly replenished by upflows from the earth's surface and boundary layer during thunderstorms. So some quantity of electrically active dust is available to influence electric discharge behavior at all atmospheric layers [2].

THE EXPLOSION MECHANISM OF A DUST PARTICLE

A conducting body of even ideally spherical shape serves as an amplifier of the ambient electric field. Amplification increases greatly if "microspires" exist on the surface. A simplified model of this physical system is presented in Fig. 1. The amplification coefficient is inversely proportional to the ratio of the spire tip radius and the particle radius, and may achieve very large values (say, $5\cdot10^5$). Microspires surely characterize rough dust microparticle surfaces.

In our earlier publication [2] we modeled a purely conducting dust particle. But further events are only accelerated if dielectric material (a bit of some impurity) is present in the field amplified by a microspire on the microparticle surface (Fig. 2).

Consider a dust particle in the lightning-induced or streamer electric field, of only a few V/cm: In the microspire vicinity it may become ~10^6 V/cm. Electric breakdown occurs in the dielectric, leading to explosion and ionization of some of it. A developing sheath may entail further amplification of the field (see Fig. 3).

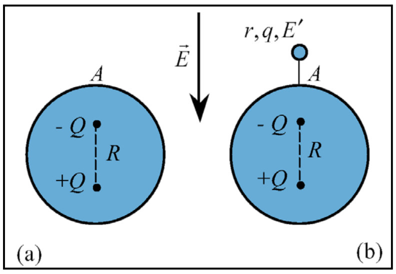

Figure 1.

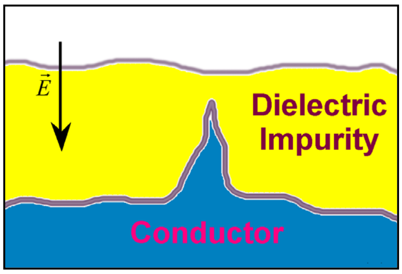

Figure 2.

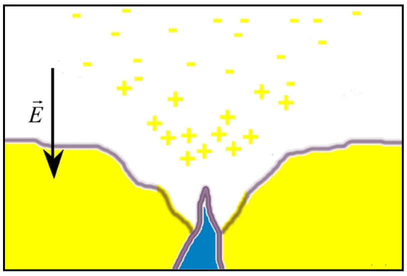

Figure 3.

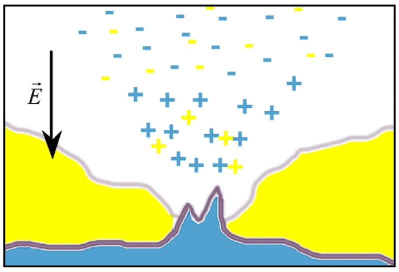

Figure 4.

The field amplifies until autoemission current causes thermal explosion of the spire tip (Fig. 4). The process becomes self-sustained: spires regenerate in the strong field. A metallic dust particle becomes an effective plasma source by this process thus creating strong localized ionization irregularity in the atmosphere.

CONSEQUENCES FOR ATMOSPHERIC DISCHARGE PHYSICS

There are several ways in which dense plasma clouds originating from explosions of metallic dust particles may participate in atmospheric discharge development (see Fig. 5). A streamer can develop directly from such a plasma cloud, obviating the electron avalanche stage. Since preliminary development of the electron avalanche requires a higher ambient electric field than for further streamer propagation, this mechanism of discharge initiation lowers significantly the threshold values of the electric field. The number density of metallic cosmic dust particles of required size at mesosphere altitudes is sufficient to seed observed sprite clusters. The particles of dust that survive exposure to the lightning-induced field can be "fired" if they encounter the quasi-electrostatic field of a propagating streamer's head. Subject to the "collision" geometry three events are possible: the streamer changes its direction upon merging with the nascent plasma cloud, or it terminates motion, or another branching streamer originates from this point. These alternatives may explain sprite dendritic and irregular structure.

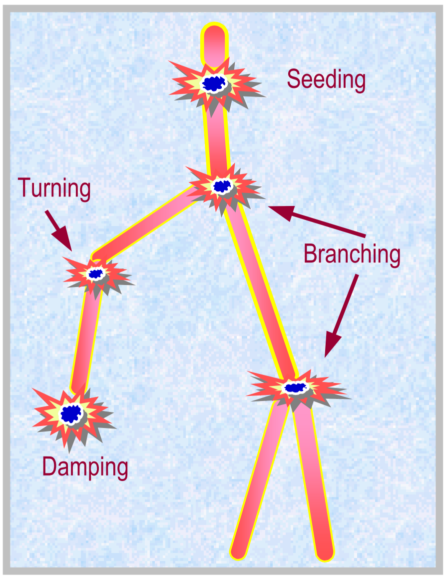

Fig. 5. Features of sprite architecture.

Such mechanisms of streamer initiation and branching may also operate for common lightning strokes in the troposphere. Metallic dust particles of terrestrial origin are constantly replenished by upflows from the earth's surface and boundary layer during thunderstorms. Accretion with water or ice requires time, so that some quantity of electrically active dust is available to influence lightning behavior.

Thus our hypothesis aids to answer the following questions of sprite and thundercloud physics:

- What determines the number density of streamers in the body of sprites?
- Why do streamers branch somewhere (sometimes nowhere) and stop abruptly without apparent cause?
- Why do streamers in the body of sprites arise in some points of space and not in others?

- What are the blobs of luminosity that often appear at the bifurcation points of streamers, persisting longer than the streamers, and sometimes seeming to be detached from them?
- Why do intracloud discharges occur during thunderstorms in lower electric fields than are predicted by theory?

EXPERIMENTAL TESTING OF THE HYPOTHESIS

Several natural tests for this hypothesis have been suggested in [2]. Metals and other elements of dust composition are to be expected in the spectra of special parts of streamer structure: at the seeding points, in the points of branching, and at the termination points. Sprite occurrence may correlate with micrometeoroid flux and with other phenomena influenced by meteoric input, as, for example, ionospheric sporadic E layers.

In the following section we draw attention to the physics of collision of a streamer with the plasma cloud originating from an exploding dust particle. We propose to investigate the interaction of a propagating streamer with a mature plasma cloud, thus setting aside discussion of dust particle explosion mechanisms. Corresponding hydrodynamic and field equations are taken in their simplest appropriate form, and are solved numerically in 2D space. One of our purposes is to determine the conditions when branching of the initial streamer can occur. Then we plan to follow the dynamics of the electric dipole moment of the charge system during this collision. Since this quantity changes non-uniformly, a burst of electromagnetic emission of a specific form must occur. Experimental detection of such bursts (or corresponding radio spectrum features) may provide another independent test of these ideas.

COLLISION OF A STREAMER WITH A LOCALIZED IONIZATION IRREGULARITY

We investigate the minimal anode-directed streamer model, i.e., a fluid approximation with local field-dependent impact ionization reactions in a non-attaching gas like nitrogen (see, for example, [3,4]). Only the ionization reaction is taken into account, i.e., impact of accelerated electrons on neutral molecules. The effective cross-section is taken in the Townsend approximation. Drift of electrons in the local electric field and diffusion are accounted for. The mobility of the ions for the anode-directed streamer can be neglected because it is more than two orders of magnitude smaller than the mobility of the electrons. Modification of the externally applied homogeneous electric field through the space charges of the particles is described by the Poisson equation.

The natural units of the model are given by the ionization length $R_0 = \alpha_0^{-1}$, the characteristic impact ionization field E_0, and the electron mobility μ_e; these determine the velocity $v_0 = \mu_e E_0$ and the time scale $\tau_0 = R_0 / v_0$. Therefore one can introduce the dimensionless coordinates $\mathbf{r} = \mathbf{R} / R_0$ and $t = \tau / \tau_0$; the dimensionless field $\mathbf{E} = \boldsymbol{\varepsilon} / E_0$; the dimensionless electron and ion densities $\rho_e = n_e / n_0$, and $\rho_i = n_i / n_0$, with $n_0 = \varepsilon_0 E_0 / (e R_0)$; and the dimensionless diffusion constant $D = D_e / (R_0 v_0)$. The set of equations is then:

$$
\begin{aligned}
\partial\rho_e / \partial t - \nabla \cdot (\rho_e \mathbf{E} + D \nabla \rho_e) &= \rho_e f(|\mathbf{E}|), \\
\partial\rho_i / \partial t &= \rho_e f(|\mathbf{E}|), \\
\rho_i - \rho_e &= \nabla \cdot \mathbf{E}, \ \mathbf{E} = -\nabla\varphi, \\
f(|\mathbf{E}|) &= |\mathbf{E}| \exp(-1/|\mathbf{E}|).
\end{aligned} \tag{1}
$$

Notice that standard criteria of the avalanche-to-streamer transition [5] are $r \gtrsim 1$ and $\rho_e \sim 1$ in these units. In our first simulations we assume normal conditions and set a uniform background field $|\mathbf{E}_0| =$ 0.15 (30 kV/cm) and $D =$ 0.1. As initial conditions, we set an electrically neutral centrally-symmetric Gaussian ionization seed with the peak density 0.5 and radius 4. We obtain a quasi-steadily propagating streamer as early as $t \sim$ 10 (see Fig. 6). This result illustrates the possibility of a streamer development from the plasma cloud of an exploding dust particle.

The next step includes modeling of the collision between the steadily propagating streamer and a dense plasma cloud suddenly arising on its path. We follow the temporal dynamics of the electric dipole moment of the whole charge system, which is determined by the expression

$$
\mathbf{p} = \int (\rho_i - \rho_e) \mathbf{r} \, d^3 r . \tag{2}
$$

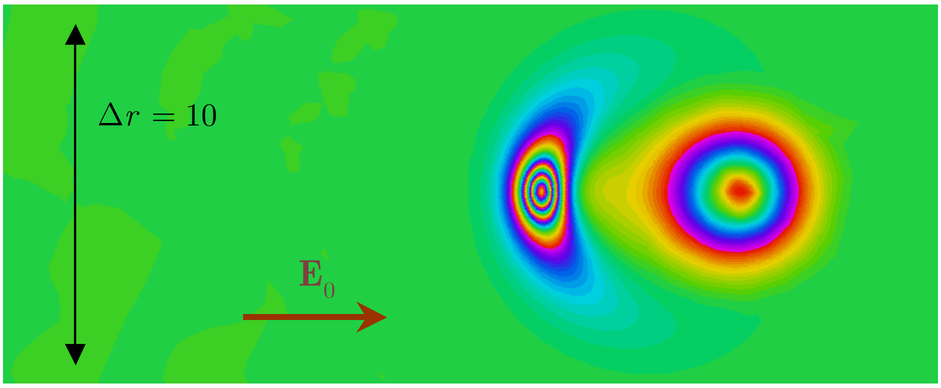

Figure 6. Result of the 2D simulation of a streamer originating from an electrically neutral Gaussian plasma cloud in a strong uniform background electric field $\mathbf{E}_0$. Solution of the equation set (1) is shown for $t = 18.3$. Colors mark levels of constant $\rho_e - \rho_i$.

As is known, the intensity of electromagnetic emission from an unsteady charge system is proportional to $\left|\partial^2 \mathbf{p} / \partial t^2\right|^2$. Calculation of this quantity using numerical solution of the equation set (1) will allow us to estimate the spectral properties of a radio burst resulting from collision of a streamer with an exploding dust particle.

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