Journal of Atmospheric and Solar--Terrestrial Physics 154 (2017) 43–46

Contents lists available at ScienceDirect

Journal of Atmospheric and Solar–Terrestrial Physics

journal homepage: www.elsevier.com/locate/jastp

The role of charged ice hydrometeors in lightning initiation

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ARTICLE INFO

Keywords:
Lightning initiation
Positive streamers development
Ice hydrometeors
Discharge modelling

ABSTRACT

In connection with the lightning initiation problem, we consider positive streamer formation around charged, needle-shaped ice hydrometeors in an external electric field. We present results of numerical simulations of the streamer discharges that include the ice dielectric polarization and conductivity, and determine the external field intensity, at which stable streamer development is possible for different hydrometeor sizes and charge magnitudes. We find that the required charge is within the range of measured precipitation charges while the required external field is higher than observed in thunderclouds. We conclude, therefore, that a second mechanism for amplification of thundercloud fields is required for the streamer inception.

1. Introduction

Lightning inception is one of the most important questions that remain unanswered in lightning physics (Dwyer and Uman, 2014). A lightning channel is thought to develop in two stages (Petersen et al., 2008). In the first stage, the thundercloud electric field is amplified in a local region to the self-breakdown magnitude, E_{br}, at which the source of free electrons from electron impact ionization of neutrals, α_{ion}, equals to the loss due to the electron attachment to oxygen molecules, α_{att}. For fields above E_{br} electron avalanches develop and avalanche-to-streamer transition occurs. For dry air, the self-breakdown field strength is of $E_{br}\approx 32$ kV/cm at standard temperature and pressure (STP) conditions (Raizer, 1991) and decreases in inverse proportion to the air density with the altitude. The well-known difficulty here is that measured inside thunderclouds magnitudes of the field intensity, scaled to STP, do not exceed 3–4 kV/cm (Marshall et al., 1995, 2005; MacGorman and Rust, 1998) i.e. is significantly less than the E_{br}.

In the second stage, a hot leader channel is formed because of the streamer corona development. Griffiths and Phelps (1976) formulated a model of the positive streamer corona development in an external electric field. Their main result is that the field is intensified up to 15 kV/cm over a distance scale of a few meters at the altitude 6.5 km. The authors believe that this magnitude is sufficient for the streamer-to-leader transition to occur. However, this does not fully solve the lightning inception problem, as the main question, namely, the origin of the first streamer, giving rise to the corona, still stands.

Lightning initiation has been connected with the field intensification owing to relativistic runaway electron avalanches (RREAs) seeded by MeV-energy electrons of extensive cosmic ray air showers generated by a cosmic particle with the energy of 10^{16} eV (Gurevich et al., 1997). However, RREAs produce a very diffusive ionized domain with a characteristic size of 100 m (Babich et al., 2012); therefore achievable value of the field intensity scaled to STP is only E=8.5 kV/cm and for that an external electric field with E_{ext}=4 kV/cm at STP is required extending more than 2 km (Babich et al., 2012). However, this is above the fundamental limit imposed on the magnitude and spatial extension of the electric field in air (Dwyer, 2003).

The stationary background cosmic radiation can also be a source of electrons initiating RREAs. A development of RREA, seeded by this radiation, leads to a formation of conducting channel sprouting downwards from the upper edge of the negative cloud charge (Dwyer, 2005; Babich et al., 2011, 2012). During the channel development, the field at its front is amplified and reaches the breakdown value over a distance of 10 m. However, for this to happen rather large cloud electrification rates k_{ch}=2–13 C/s are required; with more realistic rates k_{ch}=0.3–0.6 C/s the maximum values of the E_{ext}=6–16 kV/cm at STP (Babich et al., 2011, 2012), reached during the discharge development, are insufficient for the breakdown.

A popular idea, suggested by Loeb (1966), is that positive streamers are initiated in regions of electric field intensification around polarized hydrometeors. Several studies have explored this process (Nguyen and Michnowski, 1996; Blyth et al., 1998; Solomon et al., 2001; Dubinova et al., 2015; Sadighi et al., 2015; Babich et al., 2016). Recently two-dimensional simulations of the discharge development in self-consistent field were executed (Dubinova et al., 2015; Sadighi et al., 2015; Babich et al., 2016). This mechanism we explore further in the present

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http://dx.doi.org/10.1016/j.jastp.2016.12.010
Received 11 July 2016; Received in revised form 21 December 2016; Accepted 22 December 2016

paper.

Dubinova et al. (2015) simulated a positive streamer development near an ellipsoidal ice hydrometeor. The radius of the ellipsoid tip curvature required for the avalanche-to-streamer transition was first computed for different magnitudes of the external field intensity and hydrometeor length. Then the authors simulated the streamer development near a 6 cm long hydrometeor with the tip curvature radius of 0.4 mm in a field of 2.7 kV/cm at 5.5 km altitude. To start the discharge process, the hydrometeor was embedded in a background of free electrons with a number density of 100 cm^{-3} assumed created by an extensive cosmic ray air shower. As a result, a streamer propagating with an average velocity of 10^5 m/s was obtained. The obvious difficulty is that extremely large hydrometeors are required for the streamer inception.

Sadighi et al. (2015) studied the streamer formation from thundercloud hydrometeors in a field with intensity of 0.3 E_{br}. The hydrometeor was modeled by an ionized cylindrical column containing equal numbers of electrons and positive ions that was assumed be a source of the streamer discharge. Thus, the crux of the process, namely, the avalanche-to-streamer transition, was missed. The authors concluded that the generation of streamers requires hydrometeors with lengths from 5 to 8 mm embedded in an electron background with the maximum number density n_{e} of 10^{15} m^{-3}; the background is to be non-uniform to avoid the streamer branching. Previous corona discharges were suggested to be causal to the non-uniformity.

These two studies were focused on uncharged hydrometeors. Recently we performed simulations of the streamers developing near charged water droplets in a uniform external field at the pressure of 0.4 atm corresponding to an altitude of 8 km (Babich et al., 2016) and found that the streamer initiation is possible in fields as low as 4 kV/cm near droplets with characteristic size of 1 mm charged to 200–400 pC. The main question here is whether such droplets can exist because charged raindrops falling in an electric field may become unstable (Babich et al., 2016). Moreover, the temperature at thundercloud tops is well below zero; thus, water inside clouds can exist only in supercooled state. Therefore, we here consider the streamer inception near charged ice hydrometeors by discussing results of two-dimensional simulations of the streamer development in a vicinity of charged ice-needle hydrometeor placed in a uniform electric field.

2. Simulation approach

As in (Liu et al., 2012; Sadighi et al., 2015), the hydrometeor is modeled by a charged cylinder body with two hemispherical caps attached to the cylinder ends. The hydrometeor symmetry axis is aligned with the external field vector $\overrightarrow{E}_{\text{ext}}$. The simulations were carried out using cylinder coordinates (z, r) with $\overrightarrow{z} \uparrow\uparrow \overrightarrow{E}_{\text{ext}}$ and $\overrightarrow{z} \perp \overrightarrow{r}$. We used the same discharge model as in (Babich et al., 2016) with the same boundary and initial conditions. The model allows for the kinetics of electrons, positive and negative ions in self-consistent electric field described by the conventional set of fluid and field equations allowing for the electron impact- and photo- ionization, recombination of charge carriers and electron attachment to the oxygen molecules. On the hydrometeor surface, G_{hm}, we let that the charged particles penetrate into the hydrometeor volume but do not leave it. At the borders of the simulation area, G_{sim}, we used impenetrable boundary for all charged particles, i.e. the particle flux at the boundary was set to be zero. Note that this condition is not quite physical because it does not follow from the real task geometry and therefore it can affect the results (see the end of Section 3). The field potential at the borders of the computation domain, G_{sim}, was computed as a sum of external field potential φ_{ext}, given by the equation $\overrightarrow{\nabla}\varphi_{\text{ext}} = -\overrightarrow{E}_{\text{ext}}$, and space charge field potential φ_{int} calculated using the general solution of the Poisson's equation:

$$\varphi_{\text{int}}(z, r) = \frac{1}{4\pi\varepsilon_0}\int_{D_{\text{sim}}} \frac{(\rho_{\text{hm}}(z', r') + \rho_{\text{dis}}(z', r'))\cdot 2\pi r' dr' dz'}{\sqrt{(z - z') + (r - r')}}, \tag{1}$$

where $\rho_{\text{hm}}(z', r')$ and $\rho_{\text{dis}}(z', r')$ are charge density distributions inside the hydrometeor and in the discharge area, respectively, and D_{sim} is the simulation domain volume.

The model also takes into account the ice dielectric permittivity and conductivity. The permittivity depends on the field frequency; on the nanosecond time scale the ice relative permittivity is $\varepsilon_{\text{ice}}\approx 3$ (Artemov and Volkov, 2014) (the same as in (Dubinova et al., 2015)). For the ice conductivity we use $\sigma_{\text{ice}}=4\cdot 10^{-7}$ S/m (Muchnik, 1974). The Maxwellian field relaxation time $\tau_{\text{m}}=(\varepsilon_0\varepsilon_{\text{ice}})/\sigma_{\text{ice}}\sim 10$ μs is much longer than the discharge formation time, which is of 10 ns, and therefore the hydrometeor dielectric polarization dominates.

To start a discharge in sufficiently strong electric field, at least one electron is required. In the atmosphere, secondary cosmic rays and the radon decay daughters permanently produce seed electrons. If the external field intensity, E_{ext}, exceeds the breakdown value, the seed electron initiates an electron avalanche. The phenomenological criterion for the avalanche-to-streamer transition, given by Loeb and Meek for a gas-discharge gap with interelectrode spacing d and a homogeneous field, is as follows (Raizer, 1991):

$$(\alpha_{\text{ion}}(E_{\text{ext}}) - \alpha_{\text{att}}(E_{\text{ext}}))\cdot d \approx 18 - 20. \tag{2}$$

The field distribution around a hydrometeor is inhomogeneous because of its polarization and accumulated charge. The intensity is the largest at the tips and decreases with distance from the hydrometeor to the background field E_{ext}. Accordingly, the condition (2) should be reformulated as follows:

$$M \equiv \int_{l_{\text{hm}}/2}^{z_{\text{in}}} (\alpha_{\text{ion}}(E(z), P_g(z)) - \alpha_{\text{att}}(E(z), P_g(z)))\cdot dz = 20, \tag{3}$$

where M stands for the Meek number, l_{hm} is the hydrometeor length, z_{in} is the magnitude of z coordinate of the point in which $\alpha_{\text{ion}}=\alpha_{\text{att}}$. The integration is carried out along the hydrometeor symmetry axis.

In the following, we set l_{hm}=5 mm and consider two values of the hydrometeor diameter d_{hm}=0.2 and 0.4 mm. These dimensions are quite realistic. Averaged by results of different measurements minimum magnitude of the field intensity, at which positive streamers development at STP is possible, is of 4.65 kV/cm (Bazelyan and Raizer, 2000). We simulated field intensities E_{ext}=2, 3.2, 4, 6, 8 kV/cm at the concentration of gas molecules $N_{\text{g}}=0.4\cdot N_{\text{L}}$ (≈8 km altitude) corresponding to E_{ext}=5, 8, 10, 15, 20 kV/cm at STP. Here $N_{\text{L}} = 2.7\cdot 10^{19}\text{cm}^{-3}$ is the Loschmidt constant**.**

With the given external field and the hydrometeor size, the hydrometeor charge Q_{hm} is the unique parameter defining the field distribution. By varying the Q_{hm} it is then possible to fit condition (3). In Table 1, the Q_{hm} magnitudes, at which the condition (3) is satisfied, are presented for various combinations of d_{hm}, l_{hm} and E_{ext}. All Q_{hm}

Table 1

Hydrometeor charge Q_{hm} fitting the condition (3) of avalanche-to-streamer transition and streamer velocity υ_f for values of hydrometeor length l_{hm} and diameter d_{hm}. $N_{\text{g}}/N_{\text{L}}$=0.4.

l_{hm} [mm]	d_{hm} [mm]	E_{ext} [kV/cm]	Q_{hm} [pC]	υ_f* [m/s]
5	0.2	2	190	$< 3.5\cdot 10^4$
		3.2	160	$6.8\cdot 10^4$
		4	135	$8.7\cdot 10^4$
		6	78	$1.4\cdot 10^5$
		8	20	$2.1\cdot 10^5$
	0.4	2	275	$< 5.8\cdot 10^4$
		3.2	230	$8.6\cdot 10^4$
		4	200	$1.1\cdot 10^5$
		6	120	$1.6\cdot 10^5$
		8	45	$2.3\cdot 10^5$

* The sign " < " means that the velocity does not reach a stationary value.