# Collective Dynamics of Charged Hydrometeors in Thunderclouds and Lightning Initiation

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**ABSTRACT:** The electric fields observed in thunderclouds have the peak values one order of magnitude smaller than the dielectric strength of air. This fact renders the issue of the lightning initiation one of the most intriguing problems of thunderstorm electricity. In this paper, we propose a new lightning initiation scenario, the main role in which belongs to the collective dynamics of charged hydrometeors and which involves two basic stages. In the first stage elevated-conductivity (up to $10^{-9}$ S/m or so) regions with a spatial extent of the order of decimeters and a lifetime of about milliseconds can form inside thunderclouds, leading to the enhancement of the electric field to a level needed for lightning initiation. We show that the elevated-conductivity regions are created in the cloud due to the presence of stochastic small-scale electric field of charged hydrometeors. Fluctuations of this field can briefly exceed the conventional breakdown level, as evidenced by corona discharge accompanying hydrometeor collisions (and nearly collisions). The occurrence rate of field-threshold overshoots is determined by two main factors: hydrometeor concentration and the variance of their charge magnitude distribution. The critical overshoot occurrence rate was estimated to be about $10^2$ $m^{-3}$ $s^{-1}$. The rapid attachment of electrons to neutrals is balanced by their liberation in negative-ion destruction processes, which occur on considerably longer time scale. Further, the drift of ions in the stochastic electric field leads to enlargement of elevated-conductivity regions. The growth of conductivity is limited to spatial-temporal clusters occupying a very small portion of the overall space-time domain, so that the average conductivity of the medium does not change significantly. During the second stage of the proposed scenario the presence of elevated-conductivity regions in a dielectric medium (thundercloud) lowers its effective electric breakdown field, because those regions are essentially equipotential in a quasi-static electric field and serve to enhance the field at their extremities. Such decimeter-scale elevated-conductivity regions by far surpass hydrometeors in their ability to facilitate the formation of lightning seed.

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## INTRODUCTION

It is well known that the maximum electric field measured in thunderclouds, is an order of magnitude lower than the threshold value, which is necessary for the conventional electrical breakdown of air. Specifically, maximum electric fields typically measured in thunderclouds (see Table 3.2 of [Rakov and Uman 2003] and references therein) are $1\text{-}2\cdot 10^5$ V/m (the highest measured value is $4\cdot 10^5$ V/m), which is lower than the expected conventional breakdown field, of the order of $10^6$ V/m. Two mechanisms of lightning initiation have been suggested. One relies on the emission of positive streamers from hydrometeors when the electric field exceeds $2.5\text{-}9.5\cdot 10^5$ V/m, and the other involves cosmic ray particles and the relativistic runaway breakdown that occurs in a critical field, calculated to be of the order of $10^5$ V/m at an altitude of 6 km. Either of these two mechanisms permits, in principle, creation of an ionized region ("lightning seed") in the cloud that is capable of locally enhancing the electric field at its extremities. Such field enhancement is likely to be the main process leading to the formation (via conventional breakdown) of a hot, self-propagating lightning channel.

According to the conventional breakdown mechanism, lightning is initiated via the emission of positive corona from the surface of precipitation particles, highly deformed by strong electric fields in the case of raindrops, coupled with some mechanism whereby the electric field is locally enhanced to support the propagation of corona streamers. Positive streamers are much more likely to initiate lightning than negative ones because they can propagate in substantially lower fields. The most detailed hypothetical scenario of lightning initiation via conventional breakdown, based on laboratory experiments, is presented by Griffiths and Phelps [1976]. Their quantitative estimates involve an extrapolation from the relatively small (up to 1 m) gaps used in laboratory experiments to the relatively large distances (of the order of 100 m) over which streamers might travel in a thundercloud. Loeb [1966] considered a parcel of air containing positively charged raindrops that is swept in the updraft toward the negative charge center to yield positive corona streamers from the raindrops. In this scenario, formation of positive streamers is facilitated by updraft reducing the separation between the oppositely charged regions in the cloud. Nguyen and Michnowski [1996] considered the effects of many closely spaced hydrometeors in lightning initiation. Their hypothetical mechanism involves a bidirectional streamer development assisted by a chain of precipitation particles, as opposed to the scenario that invokes the propagation of positive streamers alone.

Gurevich et al. [1992, 1999] suggested that runaway electrons may play an important role in lightning initiation. In order to "run away", an electron must gain more energy from the electric field between collisions with air particles than it loses in a collision. The so-called breakeven electric field, which must be exceeded for runaway to occur, depends on altitude. At altitudes of 4-6 km, the breakeven electric field is $1.0\cdot 10^5\text{-}1.5\cdot 10^5$ V/m (1-1.5 kV/cm) [Gurevich et al. 2003], which is about an order of magnitude lower than the conventional breakdown field at these altitudes and is consistent with maximum electric fields typically measured in thunderclouds. Different scenarios were proposed, some of which require the presence of very high-energy ($10^{15}\text{-}10^{16}$ eV or greater) cosmic ray particle [e.g., Gurevich and Zybin 2001], while others rely on the steady background cosmic ray flux augmented by relativistic positron feedback [e.g., Dwyer, 2005]. Thus, settling on an order of magnitude lower in-cloud electric field, the relativistic runaway breakdown mechanism requires extra energy to be supplied by an external source (cosmic rays). In the case of background cosmic ray flux, a very large potential difference (450 MV;

[Dwyer, 2005]) across the high-field region where avalanche multiplication takes place (in the in-cloud accelerator) is required. There has been a recent debate on whether a sufficient number of slow electrons can be produced in the Gurevich et al.'s scenario to allow the creation of a plasma patch with conductivity of the order of $10^{-4}$ S/m [Dwyer and Babich 2011, 2012; Gurevich et al. 2012], which is thought to be needed for lightning initiation. For a region with conductivity σ of $10^{-4}$ S/m the charge relaxation time constant ($\tau=\varepsilon_0/\sigma$) is 0.1 μs and 1 μs for $\sigma=10^{-5}$ S/m.

Rison et al. [2016] recently suggested that many or possibly all lightning flashes are initiated by the so-called fast (>$10^{7}$ m/s) positive breakdown in virgin air giving rise to narrow bipolar pulses (NBPs), although most of the flashes do not exhibit the NBP-like signature (either wideband or VHF) at their onset. They rule out the role of runaway breakdown in lightning initiation. Other recent efforts in studying the lightning initiation process appear to focus on various hybrid approaches [e.g., Sadighi et al., 2015; Dubinova et al., 2015; Babich et al., 2016; see also Petersen et al., 2008].

In this paper, we present a hypothetical mechanism by which elevated-conductivity (up to $10^{-9}$ S/m or so) regions (ECRs) that have a spatial scale of the order of decimeters and a lifetime of the order of several tens of milliseconds are created inside the cloud. ECRs appear as rare solitary splashes of ion plasma concentration, which polarization in a weak external field provides stable conditions for the positive streamers development. ECRs represent a fundamental interlink in the transition from the Townsend discharge on hydrometeors to the long spark formation in the electrodeless thundercloud environment. The ECR generation mechanism is based on the effects of small-scale stochastic electric field of charged hydrometeors, the detachment of electrons from negative ions, which becomes efficient on longer time scales and at elevated electric fields, and the mutual influence of tiny sparks and ion spots that remain from them.

It does not require the presence of energetic cosmic ray particles, significant in-cloud accelerator (e.g., 450-MV potential difference in Dwyer [2005]), or unreasonably long streamers originating from a single hydrometeor. We show that the proposed mechanism mostly involve ions dynamics and works over a wide range of thermodynamic parameters. It retains its robustness for various altitudes and temperatures and can adequately explain the origin of the most diverse types of atmospheric discharges.

## THE ESSENCE OF THE APPROACH

The presence of hydrometeors, i.e., airborne particles consisting of liquid or frozen water (droplets, snowflakes, graupel, hail, etc.) moving in the air stream is the main difference between the cloud medium and the ordinary gas atmosphere. Due to cloud electrification processes hydrometeors lose and acquire parcels of electrons, providing the appearance of oppositely charged intra-cloud particles. Strong updrafts and gravity lead to the separation of oppositely charged hydrometeors (they tend to have different sizes) [Rakov and Uman 2003]. As a result, the multiphase and multi-stream nature of the cloud medium ultimately leads to an effective transformation of the mechanical energy of convective motion into electrical energy. The main reservoirs for accumulating electric energy in a thundercloud are i) the large-scale field of the main charged layers that appear due to the large-scale separation of oppositely charged hydrometers, ii) the mesoscale field of charged hydrometeors distributed in the turbulent flow, and finally iii) the small-scale field of polarization charges on the surface of individual solid and liquid water particles. All these three main reservoirs are represented in Figure 1 as boxes with an orange outline.

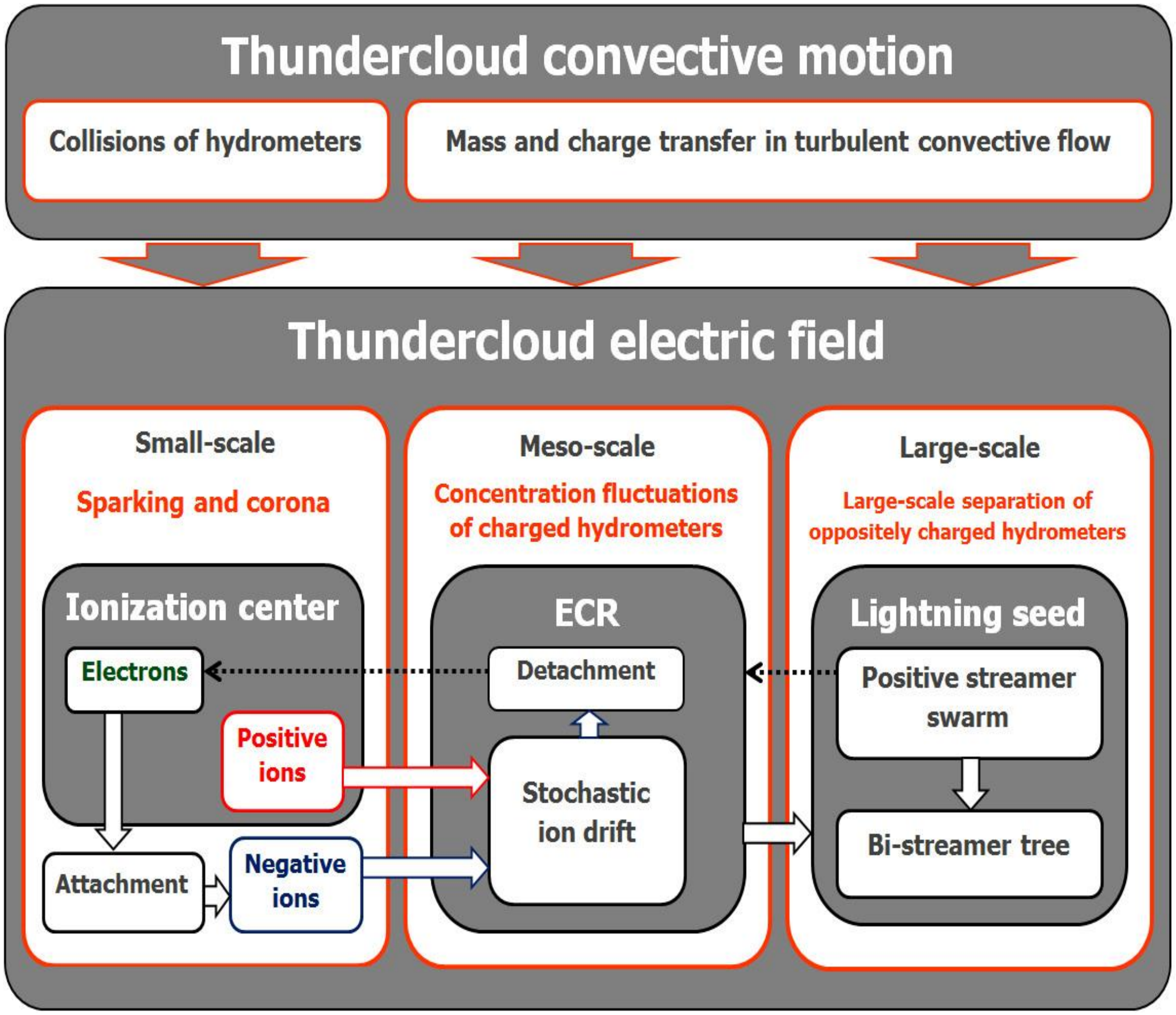


Figure 1. Schematic representation of the chain of processes involved in the formation of elevated-conductivity regions (ECR)

The observed spatio-temporal variations of the large-scale electric field extremely rarely reach values of the order of a tenth of the breakdown field and even more rarely exceed this level [Rakov and Uman 2003]. The described in Section \ref{fine} spatio-temporal variations of the collective electric field of charged hydrometeors appears to be appreciably enhanced by hydrometeors turbulent mixing and stochastic ion drift thereby providing strong mesoscale electric field fluctuations and intermittency to exceed several times the largest value of the large-scale electric field [Iudin 2017]. In their turn the polarization effects enhance the external electric field near the surface of hydrometeors due to their high permittivity [Crabb 1974]. It is worth noting that firstly, the polarization effects are caused by the mutual arrangement of neighboring hydrometeors and secondly, the external electric field with respect to individual hydrometer is represented by superposition of Coulomb field of its nearest neighbors with the large-scale and mesoscale electric fields.

It is common knowledge that within the troposphere free electrons produced due to ionization attach within tens of nanoseconds to oxygen molecules and form negative ions, whose very low mobility makes them unable to cause impact ionization. On the other hand, in comparison with electrons ions have very long lifetime providing a following tiny spark appearance against the backdrop of the negative ion spot remaining from the previous ionization center. This process is depicted in the diagram in Figure 1 as a dashed black arrow.

It should be emphasized that an increase in the amplitude of the local electric field just before the appearance of a new ionization center substantially increases the efficiency of detachment in this local tiny area of cloud space due to the growth of translational temperature of ions that drift in applied electric field. Everyone knows that characteristic time that streamer spends to overcome the interval of several millimeters makes only a few nanoseconds, allowing one to completely neglect the processes of electron detachment from negative ions (even under critical fields) when considering a conventional spark discharge in laboratory. In thunderclouds the increase in the electric field amplitude up to near- and below-critical level arises due to the nearly collisions of hydrometeors and takes time intervals up to several tens of microseconds. This time interval appears to be prolonged enough for the realization of electron detachment from negative ions with an effective detachment frequency of the order of and above $10^5$-$10^6$ $s^{-1}$.

The ion spot through the effective detachment in elevated electric field leads to the corresponding rise in seed electron population just before the field amplitude reaches breakdown value, immediately resulting in higher level of electron and positive ion production when tiny sparking start. Since electrons very quickly turn into negative ions through attachment, we shortly get correspondent portions of negative and positive ions moving in different directions in a local electric field. Thus, the electron detachment and attachment processes close the feedback cycle, which provides a gradual increase in the species number density of the ion spots.

So, the mechanism under discussion comes into operation when the next sparking appears against the spot of negative ions remaining from the previous ionization center and in turn the remnants of this spot will become the background for subsequent tiny spark microdischarges and so on. This step by step process leads to the appearance of increasingly intense positive and negative ion spots with conductivity that gradually increases from cycle to cycle [Iudin 2017]. The time evolution of the species concentrations is shown in Figure 2.

To make available such a relay race condition we need fresh ion spots to overlap with its predecessors in the space-time continuum. Thunderclouds provide following physical conditions that ensure the ion spots overlapping. Firstly, ion's lifetime is as long as tenth of a second at sea level and then gradually increases with altitude up to a second on the cloud top. Secondly, at sparking point, the ion spot has a size just coinciding with the spatial dimension of the ionization center and then over the ion's lifetime considerably expand due to ion drift in mesoscale stochastic field of charged hydrometeors. Iudin [2017] consider the enlargement of ion spots via stochastic drift, using analogy with the advective mixing of scalar impurity in turbulent flow and showed that ion spot expansion can be very significant even for sea level making a couple of decimeters and then is gradually enhanced with altitude up to a meter scale on the cloud top. Notice that positive and negative spots move in opposite directions mainly along the ambient large-scale field direction, thus reducing the level of recombination losses. In the third place, the sparking rate or occurrence rate of the field threshold overshoots (and resultant ionization centers) is provided by turbulent mixing of hydrometeors and could be estimated by the magnitude up to about $10^3$

$m^{-3}s^{-1}$. Under formulated above conditions ion spot overlapping is determined by a simple geometric criterion: the dimensionless parameter that is equal to product of the sparking rate with 4D-volume of ion spot should approach the so-called percolation threshold [Iudin 2017a]. This criterion is quite achievable in thunderclouds, at least at altitudes exceeding several kilometers; thereby ensure the ion spots appearance and growth of their conductivity.

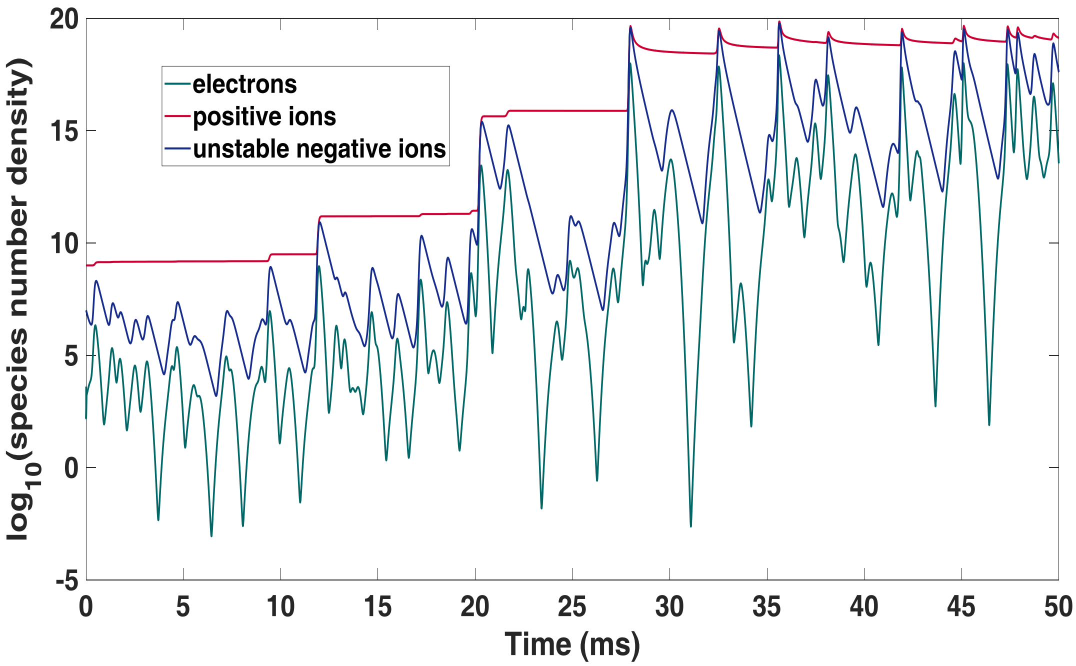


Figure 2. The time evolution of the base-10 logarithm values of space maximum of species concentrations. The concentration is expressed as the number per cubic meter.

As soon as the conductivity of the ion spots rises up to about $10^{-9}$ S/m (that in millions times exceeds the background conductivity), the characteristic time of Maxwellian relaxation becomes equal to the lifetime of a certain ion spot. These are the relatively high conducting ion spots we refer as ECRs. From this point, the process of lightning initiation passes into the final stage. It easy to see that for a hydrometeor located near the positive pole of ECR there is two-level electric field amplification on its surface: three times in the immediate vicinity of the positive pole of the ECR and three times near the pole of the hydrometeor itself. In this way polarization effects due to ambient field (especially with the fluctuations of mesoscale field taking into account) supply positive streamers appearance from hydrometeors falling into immediate vicinity of the positive pole of ECR. Besides, the polarization effects at the poles of the ECRs substantially supply the sparking rate increase. It can be said that in this case the nucleation stage of initiation is replaced by the coalescence stage. Note that due to the ion drift in the ambient field ECRs always have the form of dipoles oriented along the external field [Iudin et al. 2017]. They are represented by a couple of spots: one is dominated by positive ions, the other by negative. If polarization effects and charge asymmetry are taken into account, it becomes obvious that positive streamers will start mainly from hydrometeors located in positive spots.

The emergence of ECRs in a thundercloud active part followed by the generation of numerous positive streamers ensures the appearance of nearly continuous, volume filling short-duration discharges in thunderstorms. The consequences of this discharge activity, which looks like a swarm of positive streamers, depend on the linear size of the area, which is occupied by ECRs: the streamer swarm can produce bi-directional leader in thundercloud area occupied by relatively strong electric field when the linear dimension of the area reaches tens of meters. Detailed description of this spectacular stage goes beyond the scope of this study and will be the subject of a separate paper.

## CONCLUSIONS

In this paper we argue that fluctuations of small-scale electric field of charged hydrometeors can (1) occasionally exceed the critical breakdown level and create ionization centers in the thundercloud and (2) facilitate the stochastic drift of ions from the ionization centers, which leads to enlargement of elevated-conductivity regions. Further, the rapid attachment of electrons to neutrals is compensated by their detachment from negative ions, although this occurs on much longer time scale. Given sufficient time, an increase in concentration of negative ions leads to an increase in the concentration of free electrons, provided that recombination is negligible. As a result, the essentially dielectric cloud becomes seeded by elevated conductivity regions with a spatial extent of the order of decimeters and a lifetime of about tenth of a second. The interacting elevating conductivity regions can lead to the formation of lightning seed (an elongated patch with a spatial extent of the order of 10 m and conductivity of the order $10^{-4}$ S/m), in the absence of energetic particles or extremely long streamers from individual hydrometeors.

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