Journal of Atmospheric and Solar-Terrestrial Physics 136 (2015) 39–45

Contents lists available at ScienceDirect

Journal of Atmospheric and Solar-Terrestrial Physics

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

On the mimimum length of leader channel and the minimum volume of space charge concentration necessary to initiate lightning flashes in thunderclouds

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ARTICLE INFO

Article history:
Received 2 April 2015
Received in revised form
4 August 2015
Accepted 11 September 2015
Available online 24 September 2015

Keywords:
Lightning
Lightning initiation
Lightning leaders
Relativistic avalanche

ABSTRACT

Minimum length to which a leader channel has to grow before it can propagate continuously as a stable leader as a function of the background electric field inside a thundercloud is estimated. For electric field magnitudes comparable to the values measured inside thunderclouds, the minimum length of the leader channel that is required for it to propagate continuously is about 3–5 m. In other words, a leader discharge that originated inside a thundercloud has to grow to a length of 3–5 m before it can culminate in a stable and continuously propagating leader discharge that can give rise to a lightning flash. The minimum size of charge concentrations that can make this event possible have radii in the range of 2–4 m and should carry about 300–900 μC of electric charge, respectively. This in turn shows that the high field regions inside the cloud where electrical discharges that can culminate in stable leader discharges, and hence in lightning discharges, may be confined to volumes which are no larger than a few meters in radius.

1. Introduction

Measurements conducted inside thunderclouds show that the bulk background electric field inside the cloud during lightning initiation lies somewhere around 85 kV/m to 150 kV/m with a tendency for the lower limit to be associated with the higher altitude (Marshall et al., 1995). These measurements were conducted at altitudes between 5 km and 8 km and there is a tendency for the lower fields to appear at high altitudes. In order to cause electrical breakdown in air the electric field has to exceed the dielectric strength of air. The dielectric strength of air at atmospheric density at sea level is about 3×10^6 V/m and it decreases with decreasing air density (Raizer, 1997). For electric fields that lies below the dielectric strength of air the electron attachment coefficient overwhelms the Townsend's first ionization coefficient (referred to hereinafter as ionization coefficient) and no cumulative ionization is possible. As the electric field exceeds the dielectric strength the ionization coefficient becomes larger than the attachment coefficient and this makes the cumulative ionization possible (Raizer, 1997). The result is the generation of electron avalanches. However, electrical breakdown in air will not result until the electric field exceeds the dielectric strength of air over a critical distance. This critical distance depends on how large the background electric field is in comparison to the dielectric strength of air. If the background electric field is just above the dielectric strength of air at atmospheric density this critical distance is about 18 cm (Nasser, 1971). Since the ionization coefficient increases very rapidly with increasing electric field, this critical length decreases with increasing electric field (Nasser, 1971).

As mentioned above the dielectric strength of air decreases with decreasing air density (Raizer, 1997). At heights where lightning flashes originate in thunderclouds the air density is about half of that at ground level (Ahrens, 1985). Thus, the dielectric strength of air at that height is about 1.5×10^6 V/m. Consider a precipitation particle located inside the cloud and exposed to the background electric field of the cloud. Due to polarization of the precipitation particle the electric field at the extremity of the particle would be larger than the background electric field. In the case of a spherical particle the maximum electric field at the surface is three times larger than the background electric field (Moon and Spencer, 1961). The field would be much higher if the particle has an elongated shape (Cooray et al., 1998). Thus depending on the size and shape of the precipitation particles the electric field at their extremities may exceed the dielectric strength of air leading to electrical breakdown. This in turn suggests that in the presence of precipitation particles the electrical breakdown may take place inside the cloud when the background electric field is about 0.5×10^6 V/m. However, such

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http://dx.doi.org/10.1016/j.jastp.2015.09.008
1364-6826/

high electric fields are rarely observed in lightning producing thunderclouds (Marshall et al., 1995). Of course, in order to create electrical breakdown the electric field need not reach the above value over bulk of the cloud volume. Electrical breakdown can take place even if in a small volume inside the cloud the electric field exceeds this value. This is the case because once the electrical breakdown initiation conditions are satisfied in a small volume the maintenance and the continuation of the electrical breakdown over a large volume in the form of leader discharges requires much lower electric fields than the one requires for discharge initiation (Gallimberti et al., 2002).

One of the unsolved problems in lightning research is the mechanism or mechanisms that will give rise to these regions of locally enhanced electric fields where the electric field is strong enough to initiate electrical breakdown in thunderclouds. Loeb (1966) suggested the initiation of positive streamers from polarized raindrops and the resulting concentration of charge could lead to the initiation of a lightning discharge. In his model individual streamer tracks were assumed to conduct charge from a disperse region into a localized region. This hypothesis failed due to lack of conductivity along streamer channels. Actually, streamer channels remains conductive only for a few tens of nanoseconds due to rapid attachment of electrons into oxygen neutrals. The hypothesis of (Griffiths and Phelps, 1976a, 1976b) solved this problem by assuming that a given burst of streamers would cause a small retrograde progression of negative charge along the streamer paths, consistent with the limited streamer conductivity, and that a series of overlapping streamer systems could effectively funnel charge enhancing the electric field locally by an 'order of magnitude'. Nguyen and Michnowski (1996) suggested that series of interacting water drops could lead to the formation of streamers. A similar suggestion is also made by Cooray et al. (1998). Recently, Gurevich et al. (1999) suggested that a runaway breakdown avalanche seeded by a large number of initial electrons from a cosmic shower could produce large amount of thermal electrons generating a region of cold plasma and the polarization of this plasma in the background electric field could provide the high electric field necessary for lightning initiation. However, Dwyer (2005) suggested that this mechanism may not produce large field enhancements due to the dilution of charge density due to the lateral spreading of the relativistic avalanches. But he suggested that continuous generation of relativistic avalanches in the same region due to feed back mechanisms could lead to significant field enhancements. In a more recent study Petersen et al. (2008) suggested that compact regions of high electric field may exist by ordinary means and such compact high field regions could support the mechanism suggested by Griffiths and Phelps (1976a, 1976b) and Petersen et al. (2008). The latter also went into describe microphysical terms how the initial lightning leader forms by analogy to 'space leader' that is being observed in negative stepped leaders (Les Renardiéres Group, 1981). This qualitative description of the formation of the leader is somewhat similar to the ideas used in the present paper.

Initiation of an electrical discharge in air takes place in several stages (Cooray, 2014). When the electric field exceeds the dielectric strength of air, ionization becomes cumulative making it possible for the generation of electron avalanches by the acceleration of free electrons available in air thanks to cosmic radiation (Loeb, 1955). The number of electrons at the head of these avalanches increases as they grow in the electric field and the larger the background electric field the larger will be the number of electrons at the head of these avalanches. At normal atmospheric density when the number of electrons at the head of the avalanche reaches about 10^8 the electric field created by the space charge of positive ions left behind by the forward moving avalanche becomes comparable to the dielectric strength of air and the avalanche will be converted to a self-propagating streamer discharge (Loeb and Meek, 1940). This condition is called avalanche to streamer transition condition. Once this condition is satisfied a burst of streamers could be initiated from the origin of the discharge and all streamers of the burst usually branch out from a common stem located at the origin. The current generated during the creation of the streamer burst is flowing through this stem. Due to Joule heating caused by this current the stem slowly expands increasing the electric field to air density ratio leading to further ionization and heating of the stem (Gallimberti et al., 2002). When the temperature of the stem reaches about 1500 K or above the rapid release of electrons by the electron detachment of negative ions increases the conductivity of the stem. This rapid increase in conductivity of the stem is called the streamer to leader transition and the resulting conducting channel is called the leader. Experimental and theoretical evaluations show that in order to cause streamer to leader transition the charge associated with the streamer discharge should be larger than about 1 μC (Gallimberti, 1979). In order for this series of processes to take place the electric field at some place inside the thundercloud has to exceed the dielectric strength of air inside the cloud. Let us call such places locally enhanced high field regions. Furthermore, the electric field necessary for the propagation of a leader depends on its length. The temperature of a newly created leader channel may lie in the region of 1500–5000 K and the current associated with the leader is no more than a few amperes (Gallimberti et al., 2002). Such a leader is not thermalized and the temperature of the electrons in the leader channel is about 2×10^4 K (Gallimberti et al., 2002). In other words the electrons are not in thermal equilibrium with the neutral gas. A newly created leader may need an electric field several times larger than 100 kV/m for its propagation but with increasing length it will require lower and lower background electric fields to propagate. As the leader grows in length the current fed into the leader from the streamer bursts increases and the electron density and the temperature of the leader channel continue to increase. When the electron density in the channel increases to about 10^{17} per cm^3 a rapid heating of the channel caused by the transfer of electron energy to neutrals via the coulomb interactions between the electrons and positive ions takes place (Gallimberti, 1979). This process is called thermalization and the result is a leader channel with a temperature in the range $10–20 \times 10^3$ K. Such thermalized leaders could propagate in background electric fields as low as several kV/m (Gallimberti et al., 2002). Since the background electric field inside a thundercloud is about 100 kV/m, a leader has to grow to a minimum length before it can propagate continuously inside the thundercloud. This means that the locally enhanced high field region where the leader is initiated should also be able to support the subsequent growth of the leader to the minimum length necessary for it to start continuous propagation inside thunderclouds. To the best of our knowledge, none of the papers addressing the mechanism of lightning initiation has applied these conditions in a quantitative manner to investigate whether the mechanisms suggested in these papers could actually lead to a leader discharge. On the other hand, whatever the mechanism that leads to a lightning discharge in the low-field environment of the cloud it has to generate a high concentration of charge in a small volume, where leader discharges could be initiated and subsequently grow to the minimum size necessary for the continuous propagation in the bulk background electric field of the thundercloud. The goal of this paper is to obtain, utilizing the theory pertinent to the initiation of electrical discharges in the atmosphere, the minimum length of the leader channel that is required before it can start propagating continuously inside the background electric field of the thundercloud. We will also estimate the minimum radius and the corresponding electric charge of space charge concentrations