Upward electrical discharges from thunderstorms

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Thunderstorms occasionally produce upward discharges, called blue jets and gigantic jets, that propagate out of the storm top towards or up to the ionosphere[1–4]. Whereas the various types of intracloud and cloud-to-ground lightning are reasonably well understood, the cause and nature of upward discharges remains a mystery. Here, we present a combination of observational and modelling results that indicate two principal ways in which upward discharges can be produced. The modelling indicates that blue jets occur as a result of electrical breakdown between the upper storm charge and the screening charge attracted to the cloud top; they are predicted to occur 5–10 s or less after a cloud-to-ground or intracloud discharge produces a sudden charge imbalance in the storm. An observation is presented of an upward discharge that supports this basic mechanism. In contrast, we find that gigantic jets begin as a normal intracloud discharge between dominant mid-level charge and a screening-depleted upper-level charge, that continues to propagate out of the top of the storm. Observational support for this mechanism comes from similarity with 'bolt-from-the-blue' discharges[5] and from data on the polarity of gigantic jets[6]. We conclude that upward discharges are analogous to cloud-to-ground lightning. Our explanation provides a unifying view of how lightning escapes from a thundercloud.

Classical, normally electrified thunderstorms have a dominant dipolar electrical structure consisting of mid-level negative and upper-level positive charges, augmented by lower positive charge and negative screening charge at the upper cloud boundary[7,8] (Fig. 1a). The storm charges and electric fields build up with time as a result of charging currents, believed to be precipitation driven[8], until a breakdown threshold is reached. At this point, bidirectional discharges occur[9,10], producing different lightning types depending on where the triggering occurs first.

Discharges that escape the storm are possible when the breakdown is triggered between adjacent unbalanced charge regions, such as occur in the lower and upper parts of storms[11–13]. Thus, breakdown triggered between the mid-level negative and lower positive charges usually escapes the storm downward to become a negative cloud-to-ground discharge[14] (Fig. 1b). The ability of the discharge to continue through the lower positive charge region is aided by the presence of an overall negative charge imbalance in the storm, which biases the storm potentials negatively and imparts a strongly negative initial potential ('×' in Fig. 1c) to the downward-developing leader.

Normally electrified storms tend to develop an overall negative charge imbalance with time as a result of the negative screening charge flowing to the cloud top[15] (I_{sc} in Fig. 1a). The negative charge is intermittently lowered to ground by negative cloud-to-ground discharges, thereby helping charge the global atmospheric electric circuit[7]. Simple electrodynamic model calculations (see the Supplementary Information) show that the effect of a negative cloud-to-ground discharge is to suddenly change the storm's net charge from negative to positive. As a result, the cloud potential quickly shifts towards positive values (Fig. 1c) and the electric field is enhanced in the upper part of the storm[16] (Fig. 1b). Continued charging can lead to a discharge being triggered in the upper part of the storm within a few seconds (Fig. 1e,f), which would be expected to escape upward above the cloud top. The upward discharge would have the same polarity as the upper storm charge, namely positive for a normally electrified storm producing negative cloud-to-ground discharges. The triggering is suppressed if the screening charge is mixed into the upper storm charge, but if such mixing is weak or absent, upward discharges are predicted to occur commonly. The fact that jets are infrequent implies that mixing of the screening charge is normally strong in storms.

That an upper-level discharge, once triggered, would propagate upward above the cloud top is illustrated in Fig. 1d using results from a stochastic lightning simulation model[17]. The breakdown escapes upward because of the strong positive potential (∼150 MV) in the upper part of the storm, which is imparted to the developing leader channel, coupled with the lack of a potential barrier for upward propagation[13] (Fig. 1f).

Figure 2 shows observations of an upward jet that agree with the basic mechanism described above. The observation was obtained with a three-dimensional very high-frequency (VHF) lightning mapping array[5] during the Severe Thunderstorm Electrification and Precipitation Study[18] (STEPS 2000), and was only recently discovered in the STEPS data. Until then no upward discharges had been seen or confirmed in the VHF mapping data. The jet occurred in a decaying storm system that had an inverted electrical structure[19] and was producing intracloud discharges between an upper layer of negative charge and positive charge below the

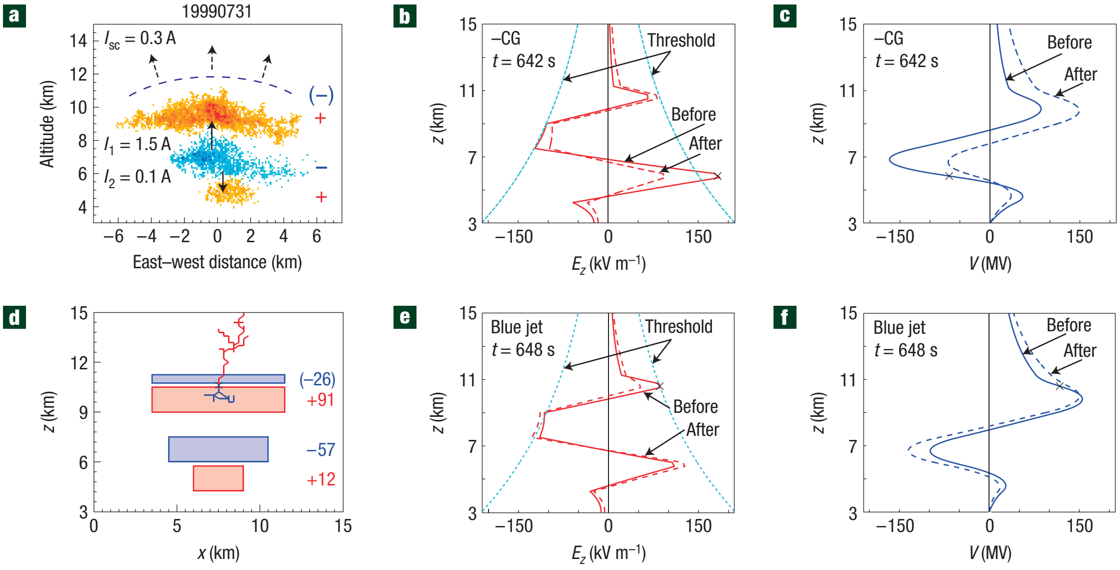

Figure 1 Basic scenario leading to blue jet formation. **a**, Lightning-inferred charge structure[14] and model-estimated charging currents in a normally electrified storm over Langmuir Laboratory on 31 July 1999, including the expected screening charge at the upper cloud boundary (dashed line). **b**,**c**, Vertical electric field (E_z) and potential (V) profiles before and after a negative cloud-to-ground (−CG) discharge, showing how the discharge increases V and E_z in the upper part of the storm, and the assumed breakdown threshold versus altitude. **d**–**f**, Simulated and predicted occurrence of an upward discharge 6 s after the negative cloud-to-ground discharge. × symbols denote E_z and V where each discharge is initiated.

negative. It was initiated midway between the upper negative charge and expected positive screening charge at the upper cloud boundary, 10 s after an intracloud discharge selectively removed positive charge from immediately below the initiation location (Fig. 2b–d). The jet lasted 120 ms and propagated 4 km upward in the first 60 ms ($v = 7 \times 10^4$ m s^{-1}) to 13.5 km altitude, 2 km above the radar-detected echo top (Fig. 2a). Its development was characteristic of an upward negative leader[5,20] that would have been visible above the cloud top. The polarity is confirmed by low-frequency electric field measurements of another, similar jet that occurred later in the same storm. Both discharges may have been similar to the optical 'gnome' observed later during STEPS[21].

The STEPS jet is well simulated using a cylindrical disc charge configuration in which the lower positive charge is reduced relative to the upper negative charge, and capped by a thin positive screening charge (Fig. 2e). Except for the polarities being reversed, the observations are fully consistent with the model of Fig. 1. The intracloud discharge locally unbalanced the storm charge in the vicinity of the initiation region and the upward breakdown occurred 10 s later, directly above the unbalanced region (Fig. 2b).

Other jets should have been detected by VHF mapping systems by now, but have not been. A possible explanation is that most blue-type jets are due to positive upward breakdown[22–24] that radiates weakly at VHF[5,12]. This inference agrees with optical observations of blue jets as occurring in negative cloud-to-ground-producing storms and being preceded by increases in negative cloud-to-ground activity in the storm[1,23,25]. The breakdown probably starts as a leader that transitions within a few kilometres of exiting the cloud top to a streamer-dominated form[22,26] that could continue to higher altitude. The downward negative breakdown that would accompany an upward positive blue jet (Fig. 1d) has not been identified in VHF mapping observations so far.

A second mechanism exists for producing an upward discharge that may explain the occurrence of gigantic jets[3,4]. Gigantic jets extend to higher altitude than blue jets[1,2] and have a different appearance. The continuous positive leader-like propagation of optically observed blue jets[1,23,25] is contrasted with the impulsive rebrightening of gigantic jets[3], resembling negative leader processes. The estimated polarity of the gigantic jet observed by two of us[3] was an issue of considerable uncertainty and debate[22,24,27]. Subsequent further evidence indicated that the gigantic jet was produced by a normally electrified storm and was of negative polarity[6]. The rebrightening events were accompanied by low-frequency sferics corresponding to the upward transfer of negative charge, and the appearance of the gigantic jet in video was preceded 0.8 s earlier by an energetic positive narrow bipolar pulse characteristic of the onset of an upward negative intracloud flash[5,6,28]. The inferred negative polarity agrees with subsequent measurements of gigantic jet sferics[4].

The only way a negative gigantic jet could be produced by a normally electrified storm is that it originate in the mid-level negative storm charge. Evidence for how this can happen is provided by observations of 'bolt-from-the-blue' (BFB) lightning discharges (Fig. 3a). VHF mapping observations show that BFB discharges begin as regular, upward-developing intracloud flashes in normally electrified storms[5,20,28]. Instead of terminating in the upper positive charge, however, the breakdown continues horizontally out the upper side of the storm and turns downward to ground. Although the lightning channel outside the cloud seems to originate in the upper positive charge, the leader continues to be of negative polarity and the resulting cloud-to-ground stroke lowers negative charge to ground from the storm mid-level. The mapping observations show that BFB discharges are surprisingly common in normally electrified storms.

The fact that BFB discharges occur reveals a charge imbalance in which the upper positive charge is depleted in magnitude relative to the mid-level negative charge, most likely by mixing with upper screening charge. In exiting the cloud and turning towards ground, BFB discharges seem to be 'guided' by inferred positive screening

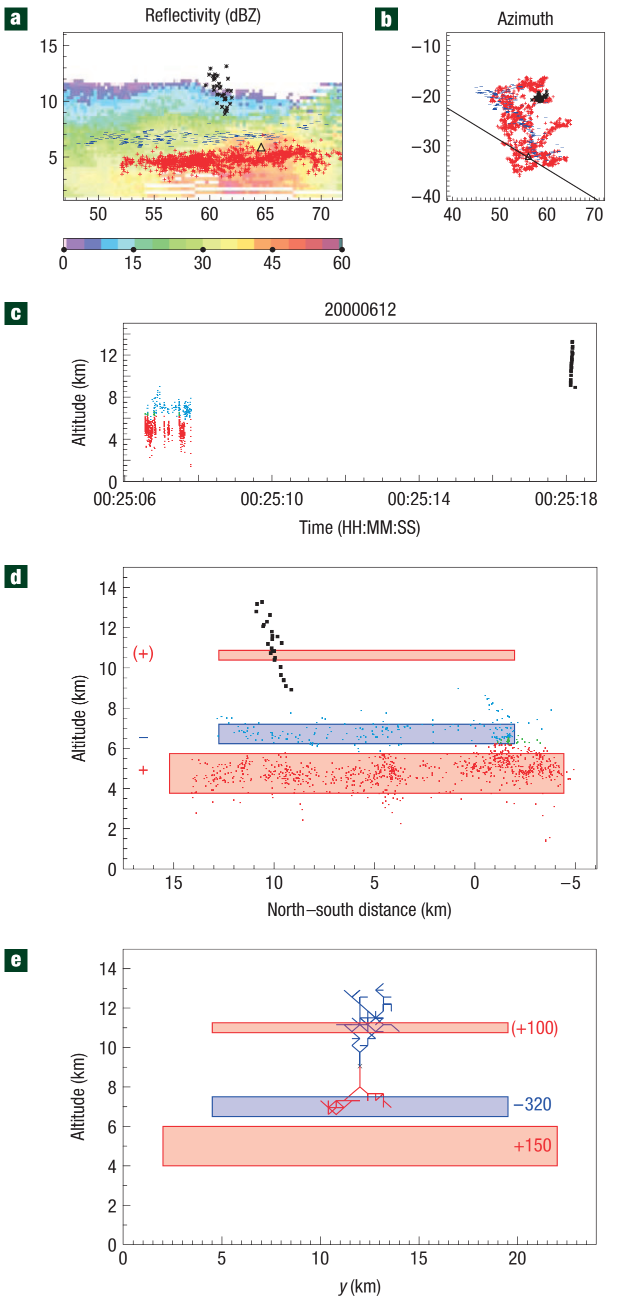

Figure 2 Upward negative jet from an inverted polarity storm on 12 June UTC during STEPS 2000. a–d, VHF mapping observations of the jet (filled black sources) and preceding intracloud discharge, projected onto the closest vertical radar scan through the storm (**a**; line in plan projection, **b**). The jet developed ~2 km above the echo top, beginning immediately above where the intracloud discharge locally removed positive charge from the lower storm level (**b**). Plan radar scans show that the radar top was essentially constant at ~11.5 km altitude above the flash and in the vicinity of the jet. **e**, Numerical simulation of the jet discharge.

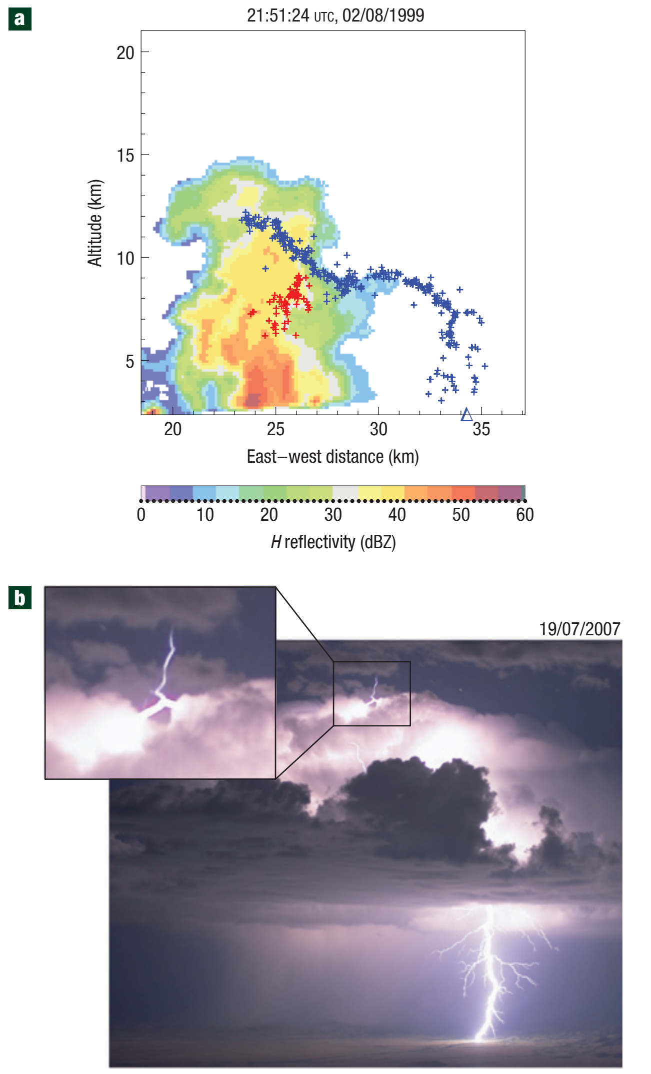

Figure 3 Two bolt-from-the-blue discharges. a, Lightning mapping observations of a negative BFB, superimposed on a vertical radar scan through the storm. The lightning began as an upward intracloud discharge between mid-level negative charge (red sources) and upper positive charge (blue sources), then exited the cloud and went to ground as a negative leader, well away from the storm. The 'triangle' denotes the negative cloud-to-ground strike point. **b**, A cloud-enshrouded BFB that started to develop upward above the storm top before branching horizontally back into the upper part of the storm and turning downward to ground, causing a negative cloud-to-ground discharge on the lower right.

charge attracted to the lateral cloud boundaries by the mid-level negative charge. This is supported by simulation experiments which find that substantial lateral charge is required to make the discharge turn downward to ground (Fig. 4e). In the absence of guiding charge, the preferred discharge mode is upward, as indicated by the negative gigantic jet simulation of Fig. 4f.

Thus, upward discharges can occur as a result of an intracloud flash that encounters depleted upper positive charge and propagates on out of the top of the storm. That such a discharge can exit the storm top and start developing upward is indicated by a BFB photograph (Fig. 3b). Once initiated, the upward discharge can become 'gigantic' because it has as its source the main negative charge of the storm, capable of producing highly energetic discharges. Negative gigantic jets are thus the upward analogue of a downward cloud-to-ground discharge, with the role of the lower positive charge in triggering the discharge replaced by screening-depleted upper positive charge. In both cases, the lightning simulations show that continued propagation of the breakdown channels into the negative charge region maintains the channel

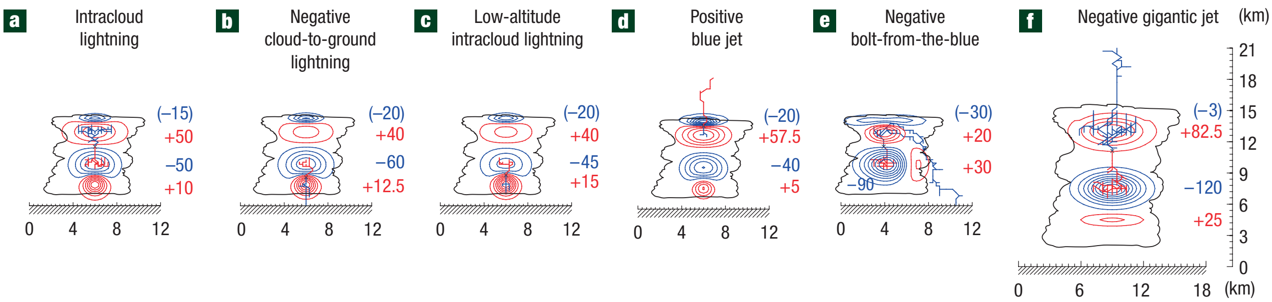

Figure 4 Simulated discharges illustrating the different known and postulated lightning types in a normally electrified storm. a–f, Blue and red contours and numbers indicate negative and positive charge regions and charge amounts (in C), respectively, each assumed to have a gaussian spatial distribution. A partially analogous set of discharges occurs or would be predicted to occur in storms having inverted electrical structures (see Supplementary Information, Fig. S5).

potential at a sufficiently high negative value for the opposite end of the discharge to propagate through the potential well[12] associated with the lower or depleted upper positive charge (for example, Fig. 1c).

At present, gigantic jets have been observed primarily at low latitudes and in storms extending to high altitudes (∼15 km or more)[3,4]. This is possibly due to tropical clouds reaching high altitudes while remaining normally electrified[29]. Optical observations of blue jets also show them emanating at similarly high altitudes from clouds[1,25]. Other things being equal, blue jets would be more readily initiated in taller storms owing to the decrease in breakdown threshold with altitude (Fig. 1b,e).

Figure 4 summarizes the results of simulating the different discharge types in normally electrified storms. In all cases, the type results from a competition as to where breakdown is triggered first. Intracloud discharges usually win this competition because they occur between the two strongest charge regions during a storm's convective stages (Fig. 4a). Negative cloud-to-ground discharges (Fig. 4b,e) occur as descending precipitation generates lower positive charge[8] or as the storm accumulates net negative charge, and can go either directly to ground or indirectly as a BFB. Negative gigantic jets (Fig. 4f) provide an alternative way of relieving the mid-level negative charge, by discharging it to the upper atmosphere rather than to ground. Positive blue jets do the opposite, namely transport positive charge upward (Fig. 4d). Thus, positive blue jets contribute to the charging of the global electric circuit, whereas negative gigantic jets discharge the circuit. Mixing of the screening charge at the cloud top with the upper-level storm charge impedes the triggering of blue jets but encourages BFB and gigantic jet-type discharges. The degree of mixing therefore probably plays a fundamental role in the occurrence and frequency of jet phenomena. Strong mixing seems to be the norm, as demonstrated by the occurrence of BFB discharges. However, storms can get into the mode of producing blue jet-type breakdown[1,21]. The model calculations indicate that this can be the result of increased negative cloud-to-ground production that drives the net storm charge positive, or to decreased mixing in stratiform regions (see the Supplementary Information). In addition, the Fig. 2 observations show that blue jets can be instigated by intracloud discharges. Finally, blue-jet-type discharges are not necessarily confined to be lower-altitude cousins of gigantic jets, as both experience a similar, upwardly unconstrained potential environment once they escape the cloud top.

The results of this study illustrate both the symmetries and asymmetries of the possible discharge types in convective storms[30]. Whereas upward jets are symmetric analogues of downward cloud-to-ground discharges, they are substantially asymmetric in terms of their rate of occurrence. The discharge types are independent of polarity, giving rise for example to inverted intracloud and positive cloud-to-ground discharges in inverted polarity storms[18,19], as well as to the negative jet of Fig. 2. BFB discharges have not been observed in inverted storms, but it is possible that positive gigantic jets could be produced by such storms (see Supplementary Information, Fig. S5). Taken together, the upward breakdown types provide a set of scenarios that can be tested by further observations.

METHODS

LIGHTNING MAPPING AND RADAR OBSERVATIONS

The lightning observations of Figs 1a and 3a were obtained at Langmuir Laboratory using the New Mexico Tech Lightning Mapping Array[5]. The arrival times of impulsive radiation events in the 60–66 MHz VHF band were measured at six or more ground-based stations and were used to determine the development of individual lightning discharges in three-dimensional space and time. Differences in the radiation and propagation characteristics of negative and positive breakdown were used to determine the polarity of the lightning channels[5] (Figs 2a–d, 3a) and to infer the charge structure of an example storm[12,14,19] (Fig. 1a). Vertical radar scans from the National Center for Atmospheric Research S-Pol (10 cm) radar and New Mexico Tech (3 cm) dual-polarization radar provided the structure of the parent storm (Figs 2a and 3a, respectively).

ELECTRODYNAMIC STORM MODEL

The electrodynamic model (see the Supplementary Information) used the lightning polarity data of Fig. 1 as input to estimate the locations and extents of the storm charge regions. It represented the charge structure as a vertical sequence of axially aligned, uniformly charged cylindrical discs (see Supplementary Information, Fig. S1), for which the electric field and potential profiles were calculated along the axis. The storm charging currents were represented by two current sources, I_1 between the mid-level negative and upper positive storm charges, and I_2 between the negative and lower positive charges, the values of which were determined by running the model in time and matching the average flashing rates of intracloud and cloud-to-ground discharges to the observed flashing rates. An above-cloud, ohmic screening current I_{sc} was calculated by the model to simulate the formation of a screening charge at the upper cloud boundary. Lightning was assumed to occur when the on-axis electric field exceeded a specified altitude-dependent electric field threshold. Depending on the initiation location, intracloud, cloud-to-ground or upward jet discharges occurred and the charge content of the appropriate layers was decreased accordingly. The results revealed the role of the screening charge and mixing currents in the occurrence of upward discharges (see the Supplementary Information for further details).

LIGHTNING SIMULATION MODEL

The lightning model[17] uses a Lightning-Mapping-Array-inferred multilayered charge structure positioned above a perfectly conducting flat ground plane (see main text and Fig. 1a). The thundercloud and lightning discharge are modelled in a three-dimensional cartesian domain using equidistant grids. The electric potential on the side and upper boundaries is calculated so that the contributions of all the charges within the simulation domain as well as their ground images are accounted for. These boundary conditions effectively represent 'open boundaries'. The potential at any point in the simulation domain is calculated with a successive overrelaxation method using the cloud charge structure and the boundary conditions described above. The development of bidirectional leaders starts when the cloud charges create an ambient field that exceeds a predefined threshold $E_{\rm init}$ anywhere in the simulation domain. Although controlled by different processes, the propagation thresholds of the positive and negative leaders are known to require nearly identical fields, which in the present study were assumed to be equal to the initiation threshold ($E_{\rm init} = E_{\rm th}^{\pm} = \pm 2.16\,{\rm kV\,cm^{-1}}$ at sea level)[17]. The initiation and propagation thresholds are assumed to scale with altitude z proportionally to the atmospheric neutral density $N(z)$. The simulated leader channel propagates iteratively; at each step, one and only one link is added at either the positive or negative end of the tree. Every point P of the discharge is scanned for its neighbours P'. Among the points P' which form with P a potential difference with corresponding electric field $E(P,P')$ such that $E(P,P') \geq E_{\rm th}^{+}$ or $E(P,P') \leq E_{\rm th}^{-}$, one is chosen to form the next stage of propagation according to the probability $p(P,P') = |E(P,P') - E_{\rm th}^{\pm}| / \sum_{P,P'} |E(P,P') - E_{\rm th}^{\pm}|$ (refs 17,22). After addition of the new segment, the potential is updated to ensure the overall neutrality of the equipotential channel[17]. The model therefore uses a fractal approach to introduce stochasticity in a self-consistent model of the lightning channel, which fully satisfies Kasemir's hypothesis of equipotentiality and overall neutrality of the discharge[9,11].

LIGHTNING PHOTOGRAPH

The BFB photograph of Fig. 3b was taken with a 38 s time exposure from Langmuir laboratory at 3,230 m altitude, 30 km distance from the storm, using an infrared-modified 6 megapixel Canon 300D digital single-lens reflex camera fitted with a Nikon 35 mm/2.0 lens set at f/5.6. The ISO-setting was 100, without noise reduction.

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Author contributions

P.R.K. drafted the manuscript and developed the electrodynamic model. J.A.R. carried out the lightning simulations, prepared the figures and drafted the methods section. J.A.R. and V.P.P. developed the lightning simulation model. W.R., R.J.T. and P.R.K. developed the Lightning Mapping Array, conducted the field programs and carried out the data analyses for the study. M.A.S. carried out low-frequency measurements and analyses. H.E.E. obtained the photograph of Fig. 3b. All authors contributed to discussion of the results and preparation of the manuscript.