Three-dimensional modeling of blue jets and blue starters

Victor P. Pasko and Jeremy J. George
CSSL Laboratory, Pennsylvania State University, University Park, Pennsylvania, USA

Received 8 May 2002; revised 1 August 2002; accepted 26 August 2002; published 20 December 2002.

[1] Blue jets and blue starters are considered as positive streamer coronas expanding from the streamer zones of conventional lightning leaders under conditions when large-scale electric fields near the thundercloud tops exceed the minimum field required for the propagation of positive streamers in air. Results from a three-dimensional fractal model based on a phenomenological probabilistic approach to the modeling of streamer coronas indicate, in particular, that blue jets and blue starters can be formed by a fast (~1 s) accumulation of ~110–150 C of positive thundercloud charge distributed in a volume with effective radius ~3 km near the cloud top at ~15 km. The model simulates the propagation of branching streamer channels constituting blue jets and blue starters as a three-dimensional growth of fractal trees in the electric field created by thundercloud charges and self-consistently accounts for the electric field effects due to the propagating streamers. Model results closely resemble blue jet and blue starter characteristics in terms of their altitude extents, transverse dimensions, and conical structure and indicate that blue starters are related to the initial phases of blue jets. The proposed model is supported by the recent spectroscopic observations of blue jets and blue starters, in particular, by the documentation of the 427.8 nm (first negative N_2^+) emission in blue starters as well as by the low-pressure laboratory experiments on emission spectroscopy of corona streamers in air. The model results also appear to be in excellent agreement with the recent discovery of the streamer structure of blue jets. *INDEX TERMS:* 2427 Ionosphere: Ionosphere/atmosphere interactions (0335); 3304 Meteorology and Atmospheric Dynamics: Atmospheric electricity; 3324 Meteorology and Atmospheric Dynamics: Lightning; 0310 Atmospheric Composition and Structure: Airglow and aurora; 2435 Ionosphere: Ionospheric disturbances; *KEYWORDS:* Blue jets, blue starters, sprites, leaders, corona streamers, fractals

Citation: Pasko, V. P., and J. J. George, Three-dimensional modeling of blue jets and blue starters, *J. Geophys. Res.*, *107*(A12), 1458, doi:10.1029/2002JA009473, 2002.

1. Introduction

[2] In this paper we report new theoretical findings related to the recently documented large-scale optical phenomena above thundercloud tops, termed blue jets [*Wescott et al.*, 1995] and blue starters [*Wescott et al.*, 1996]. Blue jets develop upwards from cloud tops to terminal altitudes of about 40 km at speeds of the order 100 km/s and are characterized by a blue conical shape [*Wescott et al.*, 1995, 1998, 2001]. Blue starters are distinguished from blue jets by a much lower terminal altitude. They protrude upward from the cloud top (17–18 km) to a maximum 25.5 km in altitude [*Wescott et al.*, 1996, 2001].

[3] Below we briefly survey the currently available information related to experimentally measured properties and theoretical modeling of blue jets and blue starters.

1.1. Observations of Blue Jets and Blue Starters

[4] Reports of unusual large-scale luminous discharges above thunderclouds have appeared in the scientific literature for over a century [e.g., *Toynbee and Mackenzie*, 1886; *Everett*, 1903; *Boys*, 1926; *Wright*, 1950; *Wood*, 1951; *Ashmore*, 1950; *Wilson*, 1956; *Vonnegut*, 1980; *Vaughan and Vonnegut*, 1982, 1989; *Gales*, 1982; *Corliss*, 1983; *Vonnegut et al.*, 1989]. For an excellent review of these observations, readers are referred to [*Rodger*, 1999, and references therein].

[5] It was not until an "image of an unusual luminous electrical discharge over a thunderstorm" was serendipitously captured during a low-light-level TV camera test on 5 July 1989 from the O'Brien Observatory of the University of Minnesota [*Franz et al.*, 1990] that research leading to the eventual discovery of blue jets and blue starters began. We now briefly survey accounts of some early sightings of luminous discharges above thunderstorms that may have been blue jets and blue starters. We then provide a detailed summary of their known properties in accordance with the most recent observations.

[6] Many early reports contain details of discharges describing typical features of blue jets [*Wescott et al.*, 1995, 1998]. For example, *Wright* [1950] was flying near Fiji in a region of heavy showers when he observed "out from the top of the cloud shot a burst of light like a firework display…not just a burst of light but rather a series of streamers extending from a single point at the center of the

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anvil and spreading out like a water fountain.'' This letter sparked several replies, including one by *Ashmore* [1950], who explained that this type of phenomenon was known at the time as *flachenblitz*, which usually ''consists of flames appearing to shoot up from the top of the cloud or, if the cloud is out of sight, the flames seem to rise from the horizon.'' From the ground, *Everett* [1903] observed several instances of ''rocket lightning'' that ''grew up steadily from below, and then disappeared at once,'' and *Wilson* [1956] ''observed what appeared to be discharges ... from a thundercloud below the horizon. There were diffuse fan-shaped flashes of greenish color extending up into a clear sky.'' At least one description, made by *Hammerstrom* [1993] of vertical shafts of blue light seen by several American Airline pilots while flying south of Panama, has been clearly recognized [see *Wescott et al.*, 1995] as a blue jet.

[7] Other reported observations, however, differ from typical blue jet characteristics. For example, high-altitude flashes were reported to last anywhere from a very short time [*Gales*, 1982] to several seconds [*Wright*, 1950] and even up to 5 s [*Vonnegut*, 1980], while the blue jets reported by *Wescott et al.* [1995, 1998] last only 200–300 ms. Also, while typical blue jets flare out at the top so the overall shape is conical [*Wescott et al.*, 1995], several early observers describe what appears to be more like lightning shooting upwards and having a definite end, with no branching or spreading [e.g., *Everett*, 1903; *Boys*, 1926; *Vonnegut*, 1980; *Vaughan and Vonnegut*, 1982].

[8] During the Sprites 1994 aircraft campaign, scientists from the University of Alaska used two jet aircraft equipped with both black and white and color cameras to capture the first images of blue jets and blue starters [*Wescott et al.*, 1995; *Sentman et al.*, 1995]. During one mission on the night of 1 July 1994, while observing a very intense storm, *Wescott et al.* [1995] reported capturing 56 examples of blue jets; further analysis of the images later showed that five of these images were really blue starters [*Wescott et al.*, 1996]. Thirty-four of the remaining 51 blue jets were viewed by both aircraft, giving sufficient data for blue jet triangulations [*Wescott et al.*, 1998].

[9] From the triangulations of 34 blue jets, *Wescott et al.* [1998] calculated the mean starting altitude for blue jets to be 17.7 km, and their upper extent (including 17 blue jets observed by only one camera) was 37.2 ± 5.3 km. Analyses of sequences of images captured over the lifetime of blue jets show vertical velocities of 112 ± 24 km/s [*Wescott et al.*, 1995]. The cone angle of 18 blue jets was measured by *Wescott et al.* [1995] to be $14.7 \pm 7.5°$, and the observed lifetime of blue jets was 200–300 ms, with the jet brightness decaying simultaneously along the entire jet.

[10] Blue starters resemble blue jets, but starters terminate at much lower altitudes. *Wescott et al.* [1996] calculated the starting altitude of 30 blue starters to be 17.7 ± 0.9 km, with terminating altitudes ranging from 18.1 to 25.7 km. The velocities of 6 blue starters were measured by *Wescott et al.* [1996], ranging from 27 to 153 km/s, although these velocities varied over the lifetimes of the starters. *Wescott et al.* [2001] recorded 15 possible blue starters, with one event positively identified as a blue starter and showing evidence that it was partially ionized. While blue starters do not appear to coincide with either positive or negative cloud-to-ground flashes, the rate of negative CG flashes is constant prior to a starter, followed by an abrupt decrease for ~3 s after the event, followed by the resumption of lightning activity [*Wescott et al.*, 1996].

[11] Additional characteristics of blue jets include association with both high negative cloud-to-ground discharge rates, although not with a particular flash, and large hail [*Wescott et al.*, 1998], as well as more frequent occurrences earlier in thunderstorm life [*Wescott et al.*, 1995; *Heavner*, 2000, p. 20]. Blue jets are neither absolutely vertical nor aligned with the geomagnetic field. Relatively few recordings of blue jets have been made, but this might not indicate a lack of blue jet activity above thunderstorms. Ground observations of blue jets are difficult due to transmission of blue light through the atmosphere resulting in severe Rayleigh scattering [*Wescott et al.*, 1998; *Heavner et al.*, 2000, p. 74]. However, the first ground video recording of a blue jet, which also electrically connected a thundercloud with the lower ledge of the Earth's ionosphere, has recently been obtained from very close range, ~200 km [*Pasko et al.*, 2002]. *Sukhorukov and Stubbe* [1998] explain that lightning activity is highest during the day, when it is unlikely for blue jets to be seen due to the brightness of the Sun, although there is no known reason for blue jet activity to be reduced during daylight hours.

[12] Whether blue jets have long-lived by-products leading to long-term consequences of their occurrence was questioned soon after their discovery [*Sentman and Wescott*, 1995, 1996]. Chemical transformations in the ozone layer due to blue jets have been numerically simulated [*Mishin*, 1997], where perturbations of nitric oxide and ozone content due to a single blue jet formed by an attachment-controlled ionizing wave were considered. Results show local perturbations of nitric oxide content of 10% and ozone content 0.5% at 30 km altitude [*Mishin*, 1997]. Additional consequences of blue jets may include affects on the global electric circuit, in which the Earth–ionosphere potential difference of several hundred thousand volts is most likely driven by upward currents from thunderstorms [*Rycroft et al.*, 2000]. A video recording showing a blue jet extending from the cloud tops to the ionosphere [*Pasko et al.*, 2002] may indicate that blue jets play a larger role in the global electric circuit than previously expected.

[13] Recent photographic [*Wescott et al.*, 2001] and video [*Pasko et al.*, 2002] observations of blue jets have clearly shown the streamer structure of blue jets. A remarkable color photograph taken from Réunion Island in the Indian Ocean shows a blue jet with eight narrow streamers branching from the main jet [*Wescott et al.*, 2001]. The recent blue jet video recording reported by *Pasko et al.* [2002] agrees with these findings and provides the most detailed evidence presented to date of internal streamer structure of blue jets predicted by *Petrov and Petrova* [1999].

[14] Blue jets and blue starters have been captured by black and white and color video cameras, allowing for some important suggestions concerning optical bands responsible for the observed blue color [*Wescott et al.*, 1995]. Evidence from color TV suggesting that the blue light must have an ionized first negative N_2^+ component has been presented by *Wescott et al.* [1998]. The first conclusive evidence of 427.8 nm (first negative N_2^+) emission in blue starters has been recently reported by *Wescott et al.* [2001]. *Wescott et al.*

[2001] also analyzed color TV frames associated with blue starters and concluded that the combined red and green channel intensity constituted 7% of the total blue channel intensity.

1.2. Theoretical Mechanisms of Blue Jets and Blue Starters

[15] Theories of blue jet production mechanisms may be classified in two general categories: (1) the mechanism of conventional air breakdown [*Pasko et al.*, 1996, 1999; *Sukhorukov et al.*, 1996; *Petrov and Petrova*, 1999] and (2) the mechanism of relativistic runaway air breakdown [*Roussel-Dupré and Gurevich*, 1996; *Taranenko and Roussel-Dupré*, 1996; *Yukhimuk et al.*, 1998; *Shaw*, 1998; *Kutsyk and Babich*, 1999]. Several reviews of blue jet theories have recently been published [*Wescott et al.*, 1998; *Rowland*, 1998]. The readers are also referred to the recent review of problems in blue jet theories by *Sukhorukov and Stubbe* [1998]. Each of these reviews has concluded that no theory has yet accounted for all blue jet characteristics.

[16] The relativistic runaway air breakdown is admittedly the most viable mechanism by which the recently discovered gamma ray flashes of terrestrial origin [*Fishman et al.*, 1994] can be produced in the Earth's atmosphere [*Lehtinen et al.*, 1999, 2001, and references therein]. The results of a numerical modeling of the spectra of optical emissions produced by the runaway air breakdown demonstrate that this process may account for the observed blue color of blue jets [e.g., *Yukhimuk et al.*, 1998]. However, the link between gamma ray flashes of terrestrial origin and blue jets has not yet been established, and the existing theories of blue jets based on the runaway mechanism do not specifically address most of the currently known geometrical and dynamical characteristics of blue jets summarized in section 1.1 of this paper.

[17] Early theories of blue jets based on conventional air breakdown suggested the concepts of positive [*Pasko et al.*, 1996] and negative [*Sukhorukov et al.*, 1996] streamers as the underlying physical mechanism for this phenomena. These theories provided some ideas and physical insight into how the charge and current systems in thunderclouds may support the upward propagation of blue jets. The *Pasko et al.* [1996] model proposes that blue jets are driven by an electric field created by a fast-growing positive charge at the thundercloud top, with no associated lightning activity. The model of *Sukhorukov et al.* [1996] proposes that a strong intracloud discharge creates the blue jet driving field. These models were able to describe in a reasonable detail some of the observed characteristics of blue jet dynamics. The main difficulty of both models, however, is that both effectively postulated the transverse size of modeled streamers, which therefore have not been modeled fully self-consistently [*Pasko et al.*, 1996; *Sukhorukov et al.*, 1996; see also related discussion by *Sukhorukov and Stubbe*, 1998]. As a result, both models used substantially underestimated values of the electric field around the streamer fronts and therefore produced unrealistically high red emission intensities, when compared to the color video observations of *Wescott et al.* [1995, 1998]. This aspect will be further discussed in section 4.2 of this paper.

[18] The subsequent analysis of similarity laws for streamer breakdown at different altitudes above thunderstorms established that at typical altitudes at which blue jets are observed (~30 km), the atmospheric pressure-controlled transverse dimension of stably propagating streamers should be on the order of several centimeters [*Pasko et al.*, 1998a], substantially lower than streamer sizes postulated by *Pasko et al.* [1996] and *Sukhorukov et al.* [1996].

[19] *Petrov and Petrova* [1999] proposed that blue jets correspond qualitatively to the development of the streamer zone of a positive leader and therefore should be filled with a branching structure of streamer channels. *Pasko et al.* [1999] applied a two-dimensional fractal model of streamer coronas to describe general observed shapes of blue jets. The predictions of *Petrov and Petrova* [1999] and the modeling results of *Pasko et al.* [1999] appear to be in remarkable agreement with recent experimental discoveries indicating the streamer structure of blue jets [*Wescott et al.*, 2001; *Pasko et al.*, 2002].

1.3. Purpose of This Paper

[20] In this paper, the theoretical concepts established by *Petrov and Petrova* [1999] and *Pasko et al.* [1999] are accepted and further developed as the basic physical mechanism of blue jets and blue starters (sections 2.1–2.6). This discussion is followed by the review of the three-dimensional fractal model (section 3.1) and the optical emission model (section 3.2) used in our studies. Section 4.1 reports results from a new large-scale three-dimensional modeling of blue jets and blue starters. Section 4.2 provides a comparison of model optical spectra of blue jets and blue starters with the most recent spectral measurements of these phenomena, and section 4.3 compares the fractal model results with the most recent observations of the streamer structure in blue jets.

2. Physical Mechanism of Blue Jets and Blue Starters

[21] We follow the suggestion of *Petrov and Petrova* [1999] that blue jets correspond qualitatively to the development of the streamer zone of a positive leader. Below we outline a possible scenario of events leading to the upward launch of blue jets and blue starters, which occupy volumes of atmosphere above thunderstorms measured in thousands of cubic kilometers; many orders of magnitude greater than volumes typically associated with the conventional lightning processes at lower altitudes.

2.1. Experimental Data on Thundercloud Electric Fields

[22] It is now well established that electric fields measured from balloons at different altitudes in thunderstorms very rarely exceed 50–100 kV/cm [e.g., *Winn et al.*, 1974; *Marshall et al.*, 1996, 2001, and references therein]. Results of one study specifically devoted to the investigation of electric field magnitudes and lightning initiation conditions in thunderstorms indicate that in most observed cases the thundercloud electric field as a function of altitude is bounded by the relativistic runaway threshold field E_t, which has value close to 2 kV/cm at ground level and is reduced with altitude proportionally to the atmospheric neutral density [e.g., *Marshall et al.*, 1995]. The E_t field is referred to as the breakeven field in some publications

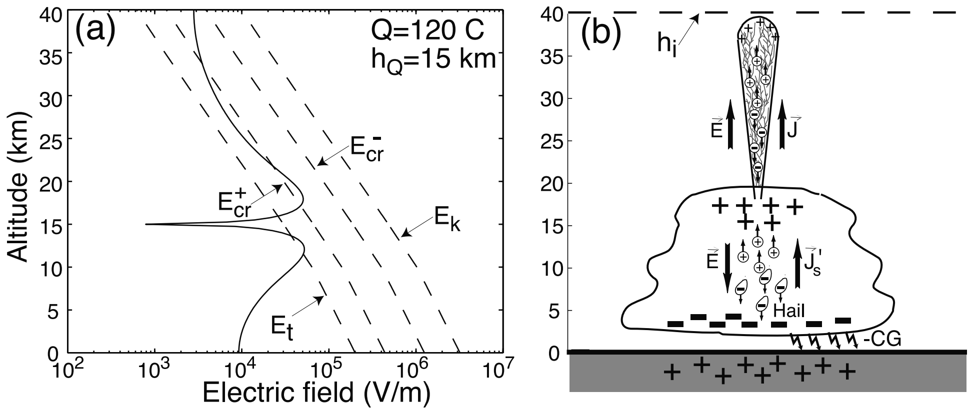

Figure 1. (a) Altitude scan of the electrostatic field produced by a 120 C thundercloud charge placed in the center of the simulation box at altitude 15 km (solid line). Dashed lines show the characteristic fields E_t, E_{cr}^+, E_{cr}^-, and E_k. (b) Currents, charges, and electric fields associated with blue jets.

[e.g., *Marshall et al.*, 1995], and it is the minimum field needed to balance the dynamic friction force acting in air on a relativistic electron with ~1 MeV energy [e.g., *McCarthy and Parks*, 1992; *Gurevich et al.*, 1992; *Roussel-Dupré et al.*, 1994; *Lehtinen et al.*, 1999; *Gurevich and Zybin*, 2001]. In fields above the E_t threshold the 1 MeV electrons, which are readily available in the Earth's atmosphere as cosmic ray secondaries, gain more energy from electric field than they lose in collisions with ambient neutral gas (i.e., become runaways). The possibility of acceleration of energetic cosmic ray secondary electrons in thunderclouds was first suggested by *Wilson* [1925], and the role of this process in charge redistribution in thunderclouds, in lightning initiation, and in production of observed X-ray fluxes in thunderstorms still remains a subject of active research (see related discussions by *McCarthy and Parks* [1992], *Marshall et al.* [1995], and *Eack et al.* [1996a, 1996b]). An interesting aspect of the relativistic runaway process is that an avalanche multiplication of electrons is possible when a fraction of secondary electrons produced in ionizing collisions appear with energies high enough to become runaways themselves [*Gurevich et al.*, 1992; *Gurevich and Zybin*, 2001]. For the purposes of our discussion in this paper we use E_t only as a reference upper bound on fields which are typically observed inside thunderclouds, making no direct association of the relativistic runaway phenomena with blue jets and blue starters. The E_t field as a function of altitude is illustrated in Figure 1a.

2.2. Streamer Coronas as Part of the Leader Process

[23] We note that the threshold field E_t appears to be very close to the documented minimum fields (~1 kV/cm) required for propagation of positive and negative leaders in long gaps with sizes exceeding several tens of meters [*Raizer*, 1991, p. 362]. The leader process is also a well-documented means by which conventional lightning develops in thunderstorms [*Uman*, 2001, p. 82]. We note that the electric fields in thunderstorms can occasionally exceed the E_t threshold, and in those rarely observed cases lightning usually followed, immediately destroying the electric field meters at the place where the electric field went substantially above the E_t value [*Marshall et al.*, 1995]. In two out of three such cases reported by *Marshall et al.* [1995], the E_t threshold was exceeded at altitudes close to 10 km, and in both cases the electric field was upward directed, so that positive streamers would have propagated upward [*Marshall et al.*, 1995]. The maximum field enhancement observed by *Marshall et al.* [1995] before the instrument was struck and destroyed by lightning is 1.6 E_t. The only other report of electric field observations substantially greater than E_t known to us at this time is that by *Winn et al.* [1974], who observed fields on the order of 4 E_t. The fact that fields greater than E_t are observed only rarely in balloon sounding data does not necessarily mean that they are uncommon in thunderclouds, if one considers a reasonable argument that regions exhibiting these fields may be localized and also that their persistence in time may be limited by the fast development of a lightning discharge which would try to reduce them. *Marshall et al.* [1995] point out that the balloon soundings give the electric field only at the balloon location and that electric fields substantially larger than E_t might be present elsewhere in the cloud.

[24] It is assumed that as soon as the electric field inside the thundercloud approaches the E_t threshold the leader process is developed. The normal role of the leader process is to initiate a discharge of the system, leading to a reduction of charge accumulation in the thundercloud responsible for the field enhancement. The leader process itself is known to be quite complex, and its initiation mechanism and internal physics are not yet fully understood [e.g., *Uman*, 2001, p. 79; *Raizer*, 1991, p. 370; *Bazelyan and Raizer*, 1998, p. 203 and 253]. For the purposes of discussion here, we do not consider specifics of the leader initiation and postulate presence of this process in high field (~E_t) regions of the thundercloud.

[25] The head of the highly ionized and conducting leader channel is normally preceded by a streamer zone looking as a diverging column of diffuse glow and filled with highly branched streamer coronas [e.g., *Bazelyan and Raizer*, 1998, p. 203 and 253]. Due to its high conductivity, the leader channel can be considered as equipotential and therefore plays the primary role in focusing/enhancement of the electric field in the streamer zone, where the relatively weakly conducting streamer coronas propagate [e.g., *Raizer*, 1991, p. 364]. Leaders of positive polarity attract electron avalanches, while in those of negative polarity the avalanch-

ing electrons move in the same direction as the leader head. In large experimental gaps (>100 m) and in thunderclouds, the electric fields required for propagation of leaders of the positive and negative polarity are known to be nearly identical, but the internal structure of their streamer zones, which is closely associated with the direction of electron avalanches, is very different [*Raizer*, 1991, p. 375; *Bazelyan and Raizer*, 1998, p. 253].

2.3. Critical Fields for Streamer Breakdown

[26] We note that the experimentally documented electric fields required for propagation of streamer coronas, which constitute essential components of the leader streamer zone, are substantially higher than the ambient E_t, and as a result the leader streamer zone is normally confined to a limited region of space around the leader head. A remarkable feature of the streamer corona is that in spite of its internal structural complexity, involving multiple highly branched streamer channels, its macroscopic characteristics remain relatively stable under a variety of external conditions. The minimum field required for the propagation of positive streamers in air at ground pressure has been extensively documented experimentally and usually stays close to the value E_{cr}^{+} = 4.4 kV/cm [*Allen and Ghaffar*, 1995], in agreement with recent results of numerical simulations of positive streamers [*Babaeva and Naidis*, 1997; *Morrow and Lowke*, 1997]. The absolute value of the similar field E_{cr}^{-} for negative streamers is a factor of 2–3 higher [e.g., *Raizer*, 1991, p. 361; *Babaeva and Naidis*, 1997]. We assume E_{cr}^{-} = −12.5 kV/cm, in accordance with the study of *Babaeva and Naidis* [1997, Figure 7]. The field measurements inside the streamer zone of positive [*Petrov al.*, 1994] and negative [*Petrov and Petrova*, 1993] leaders indicate that E_{cr}^{+} and E_{cr}^{-} are also close to the integral fields established by positive and negative corona in regions of space through which they propagate.

[27] It should be emphasized that the fields E_{cr}^{+} and E_{cr}^{-} are the minimum fields needed for the propagation of individual positive and negative streamers, but not for their initiation [e.g., *Petrov and Petrova*, 1999]. Streamers can be launched by individual electron avalanches in large fields exceeding the conventional breakdown threshold E_k, defined by equality of the ionization and dissociative attachment coefficients in air [e.g., *Raizer*, 1991, p. 135; *Pasko et al.*, 1998a], or by initial sharp points creating localized field enhancements, which is a typical case for point-to-plane discharge geometries [e.g., *Raizer et al.*, 1998]. The possibility of simultaneous launching (in opposite directions) of positive and negative streamers from a single midgap electron avalanche is well documented experimentally [e.g., *Loeb and Meek*, 1940; *Raizer*, 1991, p. 335] and reproduced in numerical experiments [e.g., *Vitello et al.*, 1993]. We assume E_k = 32 kV/cm [*Raizer*, 1991, p. 135]. Figure 1a shows an altitude scan of the electric field created by a static charge of 120 C, having a Gaussian spatial distribution with spatial scale 3 km placed at 15 km altitude between two perfectly conducting planes placed at the ground (0 km) and at 40 km altitude (the choice of this upper boundary will be discussed separately below), as well as the critical fields E_t, E_{cr}^{+}, E_{cr}^{-}, and E_k, which scale with altitude proportionally to the neutral atmospheric density.

[28] We note that although from the streamer similarity laws one generally would expect the critical fields E_{cr}^{+} and E_{cr}^{-} to scale with altitude proportionally to the air neutral density N, similarly to the runaway E_t and the conventional breakdown E_k fields (Figure 1a), the actual scaling of E_{cr}^{+} and E_{cr}^{-} for the altitude range of interest has not yet been verified experimentally, and a limited amount of data currently available in the literature [*Griffiths and Phelps*, 1976; *Bazelyan and Raizer*, 1998, p. 216] indicate possible deviations from the N scaling. In experiments reported in [*Griffiths and Phelps*, 1976; *Bazelyan and Raizer*, 1998, p. 216] the measurements were performed for a set of relatively high pressures corresponding to altitudes <12 km, and the E_{cr}^{+} was found to drop with altitude faster than N. These deviations may be a manifestation of the effects, which are able to destroy the streamer similarity at high pressures (i.e., possibly related to the neutral gas heating and the three-body electron attachment) and which are not yet well understood at this time. The simple scaling E_{cr}^{+} and E_{cr}^{-} adopted in our model and shown Figure 1a therefore should be considered as one of the approximations of the model, which can be improved as more data on this subject become available.

[29] We note that the fields (E_{cr}^{+}, E_{cr}^{-}, and E_k) can be comfortably exceeded at high altitudes (>70 km) following intense positive cloud-to-ground lightning discharges leading to sprite phenomena [e.g., *Pasko et al.*, 2000, 2001, and references therein]. However, these fields (especially E_k) are much greater than the large-scale fields typically observed inside thunderclouds, as discussed above and illustrated by the E_t altitude distribution shown in Figure 1a. The large-scale electric field enhancement inside thunderclouds above even E_{cr}^{+} (which is closest to the E_t) should be considered as an unusual and rare circumstance.

2.4. Blue Jets and Blue Starters as Streamer Coronas

[30] In view of the above discussion it is clear that if, due to the fast growth of the thundercloud charge, the large-scale electric field does exceed the E_{cr}^{+} threshold, then positive streamer coronas, which are normally confined close to the leader head, can quickly (with propagation speeds >10^5 m/s, substantially exceeding typical leader speeds ~2×10^4 m/s) [e.g., *Bazelyan and Raizer*, 1998, p. 227] fill a large volume of space in the vicinity of a thundercloud. This circumstance is illustrated in Figure 1a. Although the initial volume of space occupied by streamer coronas is defined by the geometry of thundercloud charges (the volume of space in which electric field exceeds the E_{cr}^{+} threshold), the streamer coronas themselves self-consistently modify the electric field distribution. Section 4.1 reports results of three-dimensional modeling of streamer coronas under these circumstances, with results clearly demonstrating that under a variety of initial conditions the streamer coronas form upward propagating conical shapes closely resembling the experimentally observed geometry of blue jets.

[31] We emphasize that in our model the minimum field E_{cr}^{+} required for the upward propagation of positive coronas, which we associate with blue jets, is a factor of 2 greater than the relativistic runaway threshold field E_t in a wide range of altitudes (≥20 km) above the thundercloud top (Figure 1a). Since the driving electric field is directed

upward the relativistic runaway process is expected to develop downward, from the higher atmospheric regions toward the thundercloud top. The characteristic e-folding length of the relativistic electron avalanche is $l_a \simeq 50$ m $\times$ (E_t/E) (N_0/N) [*Gurevich and Zybin*, 2001], which gives estimates for l_a of 363, 1754, and 8086 m at altitudes 20, 30, and 40 km, respectively, assuming $E/E_t \simeq 2$. A substantial progress has been achieved in recent years in the modeling the relativistic runaway process using finite volume [*Symbalisty et al.*, 1998] and Monte Carlo [*Lehtinen et al.*, 1999] techniques, and calculations of different authors generally agree with the above estimates within a factor of 2 [*Lehtinen et al.*, 1999]. Given the extremely low production rates of the cosmic ray produced runaway seed electrons in the Earth's atmosphere (above $\simeq$10 km the production rate is reduced exponentially with altitude, proportionally to the atmospheric neutral density N as $S_0 \simeq 10^{-5} N/N_0$ cm^{-3} s^{-1}) [e.g., *McCarthy and Parks*, 1992] the avalanching runaway electrons should cover several tens of e-folding distances l_a before any noticeable effects of these electrons and their secondaries in terms of the ionization and the optical emission production can be observed [e.g., *Lehtinen et al.*, 1999]. From the above estimates one can see that under the field conditions, which we specified for our modeling (e.g., Figure 1a), the runaway process may play important role at thundercloud altitudes $<\sim$20 km, possibly contributing to changes in conductivity conditions and the leader/lightning initiation in the vicinity of the thundercloud [e.g., *Gurevich and Zybin*, 2001], however, would not produce any contribution to the electrodynamics of corona streamers over the blue jet altitudes $\geq$30 km. Also, as it has been discussed in the previous section, there are experimental indications (although at present limited) that the actual E_{cr}^+ drops with altitude faster than the currently adopted in our model (Figure 1a). This effect would lead to the reduction in magnitudes of the thundercloud fields required for launching blue jets and therefore also would lead to an additional reduction in contribution to the system dynamics from the relativistic runaway process at higher altitudes.

[32] Although the streamer-to-leader transition [e.g., *Raizer*, 1991, p. 363; *Bazelyan and Raizer*, 1998, p. 238] may be a part of the blue jet/starter phenomena, we assume that their initial formation is due solely to the streamer coronas expanding from the leader streamer zone at lower altitudes. Modeling of the streamer-to-leader transition is beyond the scope of this paper. However, estimates based on the elementary theory [e.g., *Pasko et al.*, 1998a] indicate that on typical timescales of the development of blue jets ($\sim$300 ms), the neutral atmosphere heating and thermal ionization in the streamer channels becomes pronounced at altitudes below $\sim$40 km. The available imaging data reported recently by *Wescott et al.* [2001] and *Pasko et al.* [2002] indicates that the streamer-to-leader transition may be happening in the lower parts of blue jets and at the later stages of their development.

2.5. Thundercloud Current and Charge Systems Supporting Blue Jets and Blue Starters

[33] In our model, formulation of large-scale charge and current systems in thunderclouds, which support upward propagation of blue jets and blue starters, closely follows the model proposed by *Pasko et al.* [1996], which is based on a fast-growing positive charge at the thundercloud top. It is assumed that this charge is a primary source of the electric field that drives blue jets and starters, with no association with lightning activity. The positive (top) and the negative (bottom) thundercloud charges (Figure 1b) accumulate due to the current $\vec{j}_s'$ associated with the separation of charges inside the cloud and directed opposite to the resulting electric field. We assume that the charge accumulation timescale can in some cases be very fast (fraction of a second). This timescale, in combination with the middle atmospheric conductivity profile, plays a primary role in defining the upper termination altitude of blue jets, as will be discussed in the next subsection. The current $\vec{j}_s'$ may be related to the small and light positively charged ice splinters driven by updrafts and heavy negatively charged hail particles driven downward by gravity [e.g., *Uman*, 2001, p. 65]. Unusually intense hail activity was indeed observed in association with blue jets and blue starters [*Wescott et al.*, 1995, 1996] and is a strong indication of intense electrical activity inside the cloud. The recently observed blue jet event in Puerto Rico [*Pasko et al.*, 2002] was produced during a fast growth stage of thunderstorm development. The electromagnetic data that were available for both the *Wescott et al.* [1995, 1996] and the *Pasko et al.* [2002] observations indicate no direct triggering of blue jets and blue starters by a lightning event. We note that in case of *Pasko et al.* [2002] observations the blue jet exhibited a dramatic rebrightening approximately 0.6 s after the event onset in association with a large sferic event, although there were no sferics coincident with the first appearance of the jet in the video (M. Stanley, private communication, 2002) with remarkably stable speed of upward propagation of the jet $\simeq$50 km/s during the first five frames (0.16 s). It is assumed that a charge of $\sim$110–150 C with Gaussian spatial distribution of scale $\sim$3 km can accumulate at altitude $\sim$15 km, creating electric field magnitudes capable of crossing the E_{cr}^+ threshold as depicted in Figure 1a and discussed above in this paper. As a general note, we emphasize that although our model results presented in the following section depend on the spatial scale of the charge, the charge value and the charge altitude, and these parameters are expected to vary for conditions existing in real thunderclouds, the results appear to be extremely robust in terms of production of upward conical shapes of blue jets as long as the large-scale fields exceed the E_{cr}^+ threshold at the thundercloud top. In part this has to do with the general geometry of electric field lines created by a localized charge placed between two conducting plane boundaries and the exponential reduction of E_{cr}^+ as a function of altitude. Following the study of *Pasko et al.* [1996], we neglect the lower (negative) thundercloud charge due to its proximity to the ground (Figure 1b). This charge also may be removed by a series of negative lightning discharges during several seconds before the appearance of jets [*Wescott et al.*, 1995, 1996]. The electric field is nonzero inside the positive streamer coronas constituting blue jets and blue starters, and an integral upward-directed current always flows in the jet body (Figure 1b). The blue jet propagates when this current is supported by a source in or near the cloud. Otherwise, the negative charge flowing toward the positive thundercloud charge would reduce the source charge and the electric field above the cloud and

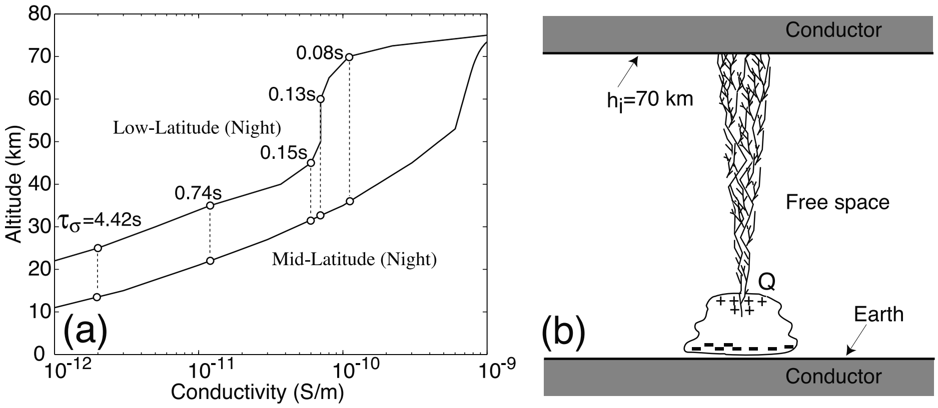

Figure 2. (a) Examples of the nighttime middle atmospheric conductivity distributions. Dielectric relaxation timescales τ_σ are indicated for selected altitudes. (b) Physical mechanism of a blue jet propagating to ~70 km altitude.

would eventually suppress the propagation. Thus, the blue jet or blue starter can propagate as long as $\vec{j}_s'$ can deliver sufficient positive charge to the thundercloud top. An equal amount of negative charge is accumulated at the thundercloud base so that the overall charge in the cloud-jet/starter system is conserved. In the fractal model employed for studies reported in this paper, we simply assume that the source thundercloud charge remains unchanged during the development of the phenomena, which physically corresponds to a situation when thundercloud current $\vec{j}_s'$ compensates any reduction in the source charge due to the jet current.

2.6. Terminal Altitudes of Blue Jets and Blue Starters

[34] In our fractal model the upper terminal altitude of blue jets is defined by the location of the upper boundary of the simulation box, as discussed in the next section (i.e., 40 km for most runs reported in this paper). In this section we discuss important physical factors which play a role in establishing the upper terminal altitudes of blue jets and blue starters in the realistic atmosphere. This discussion is important in view of the recent report by *Pasko et al.* [2002] indicating that blue jets are able to establish a direct path of electrical contact between the thundercloud top and the lower ledge of the Earth's ionosphere.

[35] We use a "moving capacitor plate" model proposed by *Greifinger and Greifinger* [1976] to characterize the electrodynamic response of the weakly conducting middle atmosphere to fast charge rearrangements at lower (i.e., thundercloud) altitudes. The fast charge rearrangement may, for example, involve a redistribution of charges produced by a cloud-to-ground lightning discharge leading to the sprite phenomena [e.g., *Pasko et al.*, 1998b] or a fast growth of the thundercloud charge due to the meteorological processes discussed in section 2.5. We note that the response of the middle atmosphere to the electric field enhancements generated as a result of these processes is very similar and only defined by the ambient conductivity profile $\sigma(h)$ as a function of altitude h and the timescale τ_f of the forced deposition or generation of charge at the lower altitudes. For a highly impulsive charge deposition case (i.e., like in the case of lightning, when τ_f is much less then the dielectric relaxation timescale $\tau_\sigma(h) = \varepsilon_o/\sigma(h)$ at all altitudes of interest) the *Greifinger and Greifinger* [1976] model defines a downward moving boundary h_i, which separates regions of the atmosphere dominated by the conduction (above) and displacement (below) currents. For an atmospheric conductivity $\sigma(h)$, which increases monotonically with altitude h, h_i as a function of time t elapsed after the lightning discharge is uniquely defined by the equation $t = \varepsilon_o/\sigma(h_i)$ [e.g., *Hale and Baginski*, 1987]. The electric field solution below the h_i boundary has the same form as the static solution in free space between two conducting planes (at the ground and at altitude h_i) [e.g., *Greifinger and Greifinger*, 1976; *Pasko et al.*, 1997, 1998b]. On the same physical grounds it is clear that the h_i boundary can also be defined in cases when the thundercloud charge is generated with a relatively slow timescale τ_f on the order of several seconds. In these cases the h_i boundary is not simply moving down as a function of time t after the impulsive charge deposition at $t = 0$ in accordance with $t = \varepsilon_o/\sigma(h_i)$, but rather should be defined by the equation $\tau_f \simeq \tau_\sigma(h_i) = \varepsilon_o/\sigma(h_i)$. This equation simply indicates the altitude h_i at which the rate of increase of the electric field is equal to the rate of the electric field relaxation in the conducting atmosphere. Figure 2a shows two examples of the nighttime middle atmospheric conductivity distributions [*Hale et al.*, 1981; *Hale*, 1994] and also provides information about the dielectric relaxation timescales $\tau_\sigma = \varepsilon_o/\sigma$ at selected altitudes. For relatively low ambient conductivities and fast thundercloud charge growth timescales $\tau_f \sim 0.1$ s, the h_i boundary can appear at altitudes as high as 70 km, explaining the observed propagation of a blue jet to this altitude [*Pasko et al.*, 2002] (this circumstance is schematically depicted in Figure 2b and is further illustrated by our modeling results presented in section 4.3). It is clear from Figure 2a that, depending on the ambient conductivities and the charge accumulation rates, the h_i boundary may appear in a wide range of altitudes between the thundercloud tops and the lower ionosphere. Since information about the charge accumulation rates and the middle atmospheric conductivity profiles corresponding to the observed cases of blue jets is unavailable, in our modeling we simply define the upper terminal altitudes of blue jets in accordance with video observations (i.e., by

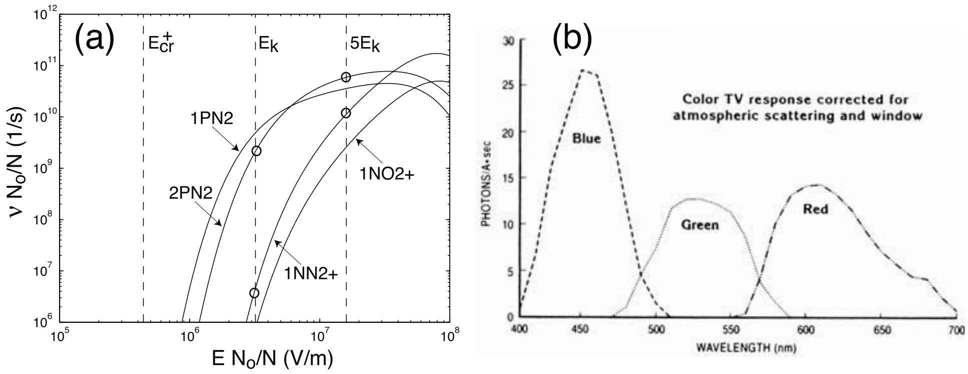

Figure 3. (a) Optical excitation coefficients as a function of the reduced electric field in air. (b) Color TV response corrected for atmospheric scattering and transmission through the aircraft window. Figure 3b reprinted from *Wescott et al.* [1998], with permission from Elsevier Science.

selecting 40 km as the upper boundary of our simulation box for most runs presented in this paper).

3. Model Formulation

3.1. Fractal Model

[36] We model blue jets using a three-dimensional fractal model documented by *Pasko et al.* [2001]. The model simulates the propagation of a streamer corona as a three-dimensional growth of fractal trees composed of a large number of line channels. The fractal model is based on a phenomenological probabilistic approach proposed by *Niemeyer et al.* [1989] for modeling of a streamer corona and uses experimentally and theoretically documented properties of positive and negative streamers in air for a realistic determination of the propagation of multiple breakdown branches in a self-consistent electric field. The fractal model follows the dynamics of highly branched electrical breakdown in large volumes of space without actually resolving the internal physics of individual streamer channels, but rather relying on demonstrated collective characteristics of streamers in air [see *Pasko et al.*, 2000, 2001, and references therein].

[37] For most of the blue jet and blue starter simulations reported in this paper, we chose the simulation box to have Cartesian (i.e., x, y, and z) dimensions of 80 × 80 × 40 km. To compare the model results with recent blue jet observations [*Pasko et al.*, 2002], the upper boundary of the simulation box was set to 70 km altitude, with the transverse dimensions of the simulation box increased proportionally to 140 km. The relationship of the choice of the upper boundary in our simulations to the physical parameters of the system (i.e., the charge accumulation timescale and the middle atmospheric conductivity profile) was discussed in section 2.6. The source charge Q is centered (with respect to the x and y coordinates) inside the simulation box at altitude $z = h_Q$ = 15 km and is assumed to have a Gaussian spatial distribution with a characteristic spatial scale 3 km. The model electric field distribution as a function of altitude (i.e., z) for a charge value Q = 120 C in the center of the simulation box is shown in Figure 1a.

[38] In order to compare our simulation results with observations of blue jets we estimate the effective cone angle of our model blue jets. This is accomplished by viewing blue jets horizontally from the x and y faces and considering the most outer "radial" points at all altitudes for which branches end on both sides of the vertical center of the charge source. We determine the approximate cone angle θ as the addition of angles between a least squares fit line through the points of maximum radial distances on both sides of the center and average over the x and y faces.

3.2. Optical Emissions

[39] For comparisons of our model results with recently obtained spectroscopy data of blue jets and blue starters (see section 1.1), we employ an optical emission model similar to that documented by *Pasko et al.* [1997]. We consider optical emissions from the first and second positive bands of N_2, the first negative bands of N_2^+ and the first negative bands of O_2^+, which have short lifetimes and are expected to produce the most intense optical output during short time durations of blue jets and starters. We exclude Minel N_2^+ bands from our analysis due to the expected strong quenching of this emission at typical altitudes of blue jets and blue starters [e.g., *Vallance-Jones*, 1974, p. 119]. We use updated optical excitation coefficients as a function of the reduced electric field in air shown in Figure 3a [*Pasko et al.*, 1999; *Barrington-Leigh et al.*, 2000, 2002] and the color TV responses corrected for atmospheric scattering and transmission through the aircraft window (Figure 3b) corresponding to observational conditions of blue jets and blue starters [*Wescott et al.*, 1998]. In this paper the optical emission model is used only for calculating ratios of different optical emissions, with no discussion of absolute emission intensities in blue jets and blue starters. The model employs the same radiation transition and quenching rates as specified by *Pasko et al.* [1997].

4. Results and Discussion

4.1. Large-Scale Modeling of Blue Jets and Blue Starters

[40] Figures 4a–4e show representative examples of the model results for different thundercloud charge values Q in the range 110–150 C. The model was run 10 times for each charge value, and the resultant distribution of the mean and standard deviation of the blue jet cone angle θ as a function of Q is shown in Figure 4f. The horizontal dashed lines in

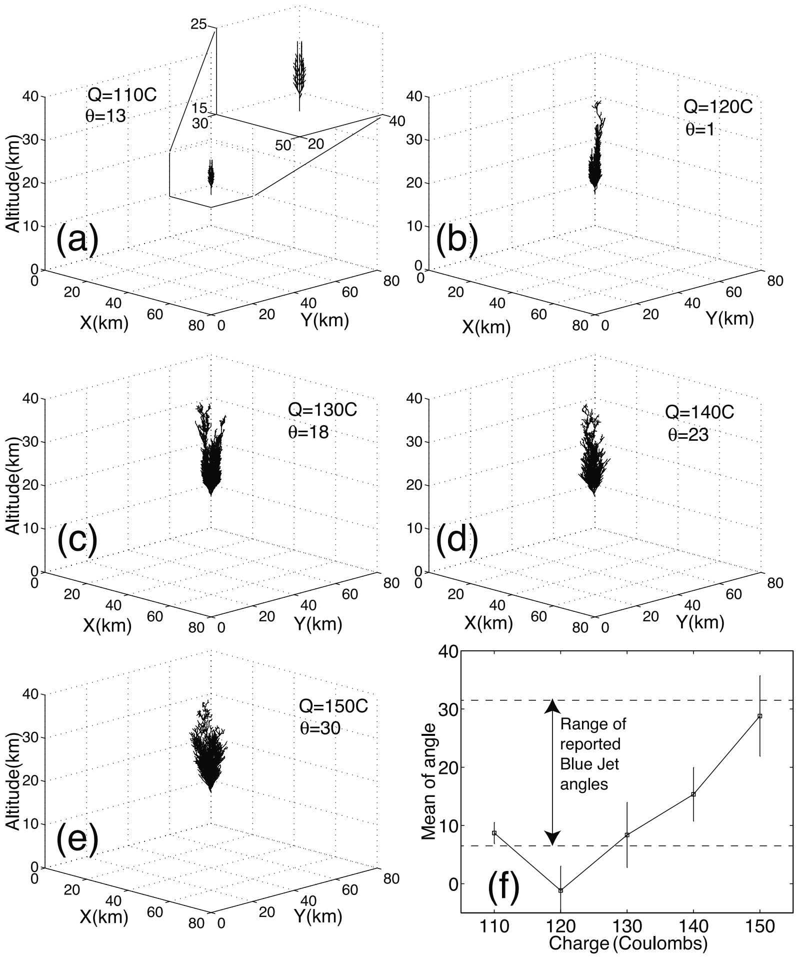

Figure 4. Large-scale modeling of blue jets. (a)–(e) Representative examples of blue jets for thundercloud charge values Q from 110 to 150 C. (f) Mean and standard deviation distribution of blue jet cone angle θ as a function of Q. Horizontal dashed lines indicate minimum and maximum blue jet angles reported by *Wescott et al.* [1995].

Figure 4f bound the range of observed blue jet cone angles reported by *Wescott et al.* [1995].

[41] The results shown in Figures 4a and 4b demonstrate a transition between blue starters, which are confined to the altitude range ∼17–25 km, and fully developed blue jets extending upward to the altitude of 40 km. All simulations for Q = 110 C produced blue starters with terminal altitudes around 25 km, which is within the range of blue starter altitudes reported by *Wescott et al.* [1996] (18.1–25.7 km). Due to the probabilistic nature of the model, both blue jets and blue starters resulted from simulations using charge Q = 120 C. In this case blue starters had a wider extent and a slightly higher terminal altitude (∼28–30 km) than those produced with Q = 110 C, and some exhibited negative cone angles (i.e., focusing toward the higher altitudes).

[42] In our model, the blue starter formation for small thundercloud charge values corresponding to Figures 4a and 4b is dictated by relatively small electric fields (produced by the source thundercloud charges combined with the self-consistent enhancements around streamer corona tips), which are not able to sustain the upward propagation. In the real atmosphere two additional factors, not directly modeled in our fractal model, may contribute to the formation of short blue jets or blue starters. The first is associated with the slow rate of charge buildup at the thundercloud top when the *Greifinger and Greifinger* [1976] boundary h_i, discussed in section 2.6, appears at low altitudes close to the thundercloud top. The second factor is connected to the case when the thundercloud source current $\vec{j}_s'$ (section 2.5 and Figure 1b) is not able to compensate the source charge reduction due to the upward starter/jet current and is therefore unable to sustain the upward propagation of the blue jet or blue starter.

[43] Figures 4c–4e show progressively larger cone angles for blue jets produced by charges of 130, 140, and 150 C, respectively. Values of the cone angle θ calculated in our simulations span the range of experimentally reported angles shown by the dashed lines in Figure 4f.

[44] We found that the model results, in terms of the blue jet cone angle, show dependence on the spatial resolution of the model (i.e., the grid size) in cases when the grid size becomes comparable to the characteristic scale of variation of the large-scale electric field. The results shown in Figures 4a–4e were obtained using grid size 0.5 km and the number of grid points 160 × 160 × 80 (in the x, y, and z dimensions, respectively), which provided a reasonable

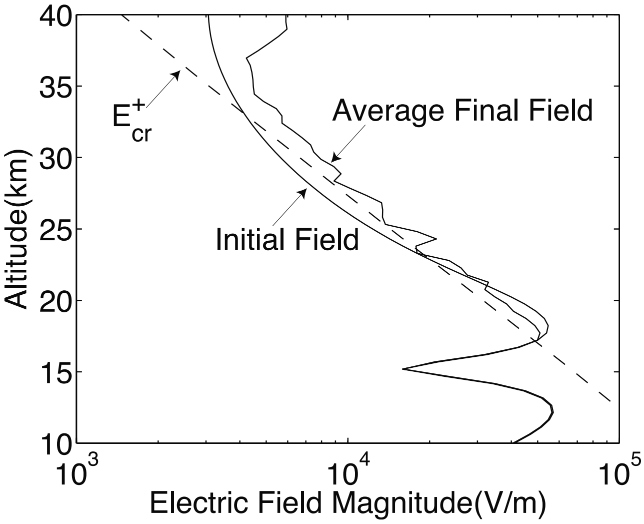

Figure 5. Altitude scan of the macroscopic electric fields associated with a blue jet created by a source charge Q = 130 C. The initial static electric field is shown along with the final field after blue jet formation (averaged over 10 blue jet simulations). The critical field E^+_{cr} is shown, with a dashed line, for comparison.

compromise between the resolution required to correctly resolve the blue jet/blue starter spatial features and the code execution time.

[45] We emphasize that the results reported for different charge values Q in Figure 4 are produced for the specific charge altitude (15 km) and effective size (3 km) specified in section 3.1. These parameters, although realistic, are expected to vary in real thunderclouds. Additional calculations demonstrate that, for a wide range of variation in these parameters, the production of the upward conical shapes of fractal trees appears to be a robust feature of the model as long as the large-scale electric fields near the thundercloud top exceed the E^+_{cr} threshold. In particular, the increase/decrease in the effective size of the thundercloud charge requires a corresponding increase/decrease in the thundercloud charge value Q in order to achieve results similar to those shown in Figure 4.

4.2. Spectral Properties of Blue Jets and Blue Starters

[46] The fractal model allows accurate determination of the macroscopic electric fields in regions of space occupied by streamers. Our results indicate that for a variety of input parameters these fields are very close (within several %) to the minimum electric field required for propagation of positive streamers in air, E^+_{cr}. This behavior is consistent with earlier findings [*Niemeyer et al.*, 1989; *Pasko et al.*, 2000, 2001] and experimental measurements of *Petrov et al.* [1994]. Figure 5 shows an altitude scan (in the center of the simulation box) of the average electric field over 10 model runs corresponding to the source charge value Q = 130 C. We observe that the electric field remains close (within 15.4%) to the E^+_{cr} value, except in a region above 35 km, where fields are enhanced between tips of fractal trees and their images in the upper simulation box boundary. Comparison of the model results shown in Figure 5 and the optical excitation coefficients for different field values in Figure 3a indicate that the macroscopic electric fields on the order of E^+_{cr} established inside blue jets (E^+_{cr} is also shown by a vertical dashed line in Figure 3a) are generally not sufficient to excite any observable optical emissions.

[47] The fractal model employed in our studies does not allow resolution of microscopic properties of individual streamer channels constituting streamer coronas and therefore does not allow resolution of the regions of space around streamer tips. It is known that under a variety of conditions the electric field enhancements around streamer tips reach values ~5 E_k [e.g., *Dhali and Williams*, 1987; *Vitello et al.*, 1994; *Babaeva and Naidis*, 1997; *Kulikovsky*, 1997; *Pasko et al.*, 1998a, 1998b], where E_k is the conventional breakdown threshold field discussed in section 2.3 and shown in Figure 1a. This property of streamers is also valid for positive streamers propagating in low ambient electric fields comparable to E^+_{cr} [e.g., *Grange et al.*, 1995; *Morrow and Lowke*, 1997], similar to the ambient conditions for propagation of streamer coronas considered in this paper. Our conclusion, therefore, is that the observed optical luminosity in blue jets and starters arises from large electric fields existing in narrow regions of space around tips of small-scale corona streamers constituting them.

[48] In order to demonstrate that the electric fields around streamer tips on the order of 5 E_k are indeed the primary producers of optical emissions in blue jets and blue starters, we perform a direct comparison of the optical emission model employed in our studies (section 3.2) and available experimental results on emission spectroscopy of corona discharges in air at 10 torr [*Teich*, 1993], which corresponds to the atmospheric pressure at 30 km altitude. The second positive bands of N_2 and the first negative bands of N_2^+ are well resolved between 320 and 460 nm in measurements of *Teich* [1993], results of which are reproduced in Figure 6a. Inspection of the optical excitation coefficients corresponding to these two emissions, shown in Figure 3a, indicates that their ratio is very sensitive to the driving electric field value. In particular, the ratio of the excitation coefficients for these two emissions is ~1000 for electric fields magnitudes around E_k and ~5 around 5 E_k as shown for reference by the vertical dashed lines and open circles in Figure 3a. The ratio of these two emissions can therefore be used as a sensitive tool for determination of the effective electric field values responsible for production of these emissions. Figure 6b shows the spectrum corresponding to these two emissions at 30 km altitude (i.e., 10 torr pressure) calculated using the model described in section 3.2. The effects of excitation, photon emission, and quenching are taken into account in model calculations; the effects of atmospheric scattering and transmission through the aircraft window are not accounted for because these are not applicable to the experimental setup used by *Teich* [1993]. Figure 6b shows the results of model calculations for the electric field 5 E_k. The comparison of experimental and theoretical results presented in Figure 6 and the known properties of streamers discussed at the beginning of this section provide convincing evidence that the optical luminosity coming from the corona streamers constituting blue jets and blue starters is indeed produced by electric fields on the order 5 E_k existing in narrow regions of space around streamer tips. These conclusions agree with the evidence from color TV observations presented by *Wescott et al.* [1998] suggesting that the blue light of blue jets must

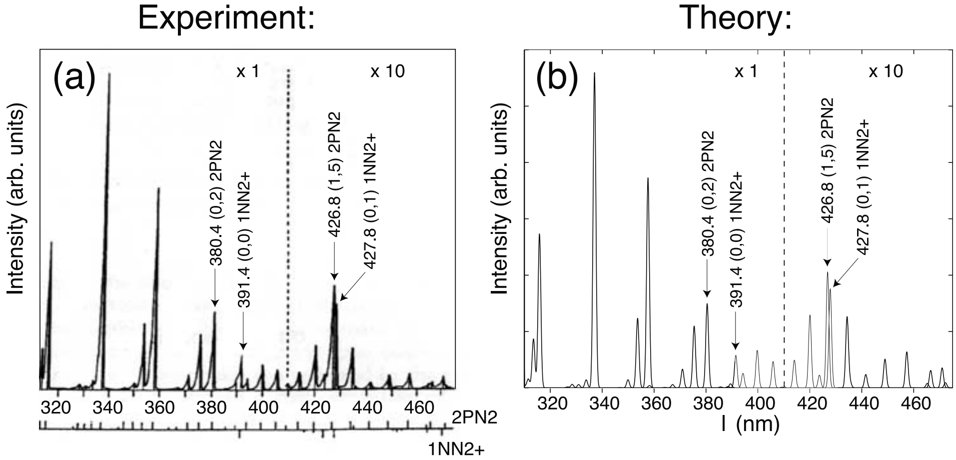

Figure 6. (a) Experimental spectrum of the second positive N_2 and first negative N_2^+ bands [*Teich*, 1993]. (b) Model spectrum corresponding to the same two emissions.

have an ionized first negative N_2^+ component. These conclusions also agree with the first conclusive evidence of 427.8 nm (first negative N_2^+) emission in blue starters, which has been recently reported by *Wescott et al.* [2001]. We emphasize that the model distribution shown in Figure 6b is very sensitive to the driving electric field value (see Figure 3a), so that even small deviation from 5 E_k leads to significant changes in ratios between second positive N_2 and first negative N_2^+ emissions leading to disagreement with experimental data shown in Figure 6a.

[49] To compare our model results with the results of recent spectral observations reported by *Wescott et al.* [2001], we calculate the ratio of the combined red and green emissions to the total blue emission using model formulation presented in section 3.2, accounting for the atmospheric transmission and aircraft window corrections pertinent to experimental conditions of *Wescott et al.* [2001] (Figure 3b) and assuming the driving field to be 5 E_k. The resultant ratio is shown in Figure 7a and appears to be in good agreement with the recent analysis of color TV frames associated with blue starters reported by *Wescott et al.* [2002], who concluded that the combined red and green channel intensity constituted 7% of the total blue channel intensity.

[50] Our model results also indicate that the second positive N_2 and first negative N_2^+ bands are the dominant contributors to the observed blue emissions. Their relative contributions are ~80% and ~20%, respectively, at the base of blue jet and ~60% and ~40% at altitude 40 km, as shown in Figure 7b.The red emissions are dominated by the first positive bands of N_2, the contribution from which to the total red intensity is greater than 85% in the altitude range between 10 and 40 km. The next contributors to the red intensity are the first negative bands of O_2^+ (~5–10%). The green intensity receives contributions from the first negative N_2^+, the first negative O_2^+ and the second positive N_2 bands, and our model calculations indicate, in particular, that these contributions are nearly equal at altitudes around 30 km. These results, however, have not yet been confirmed

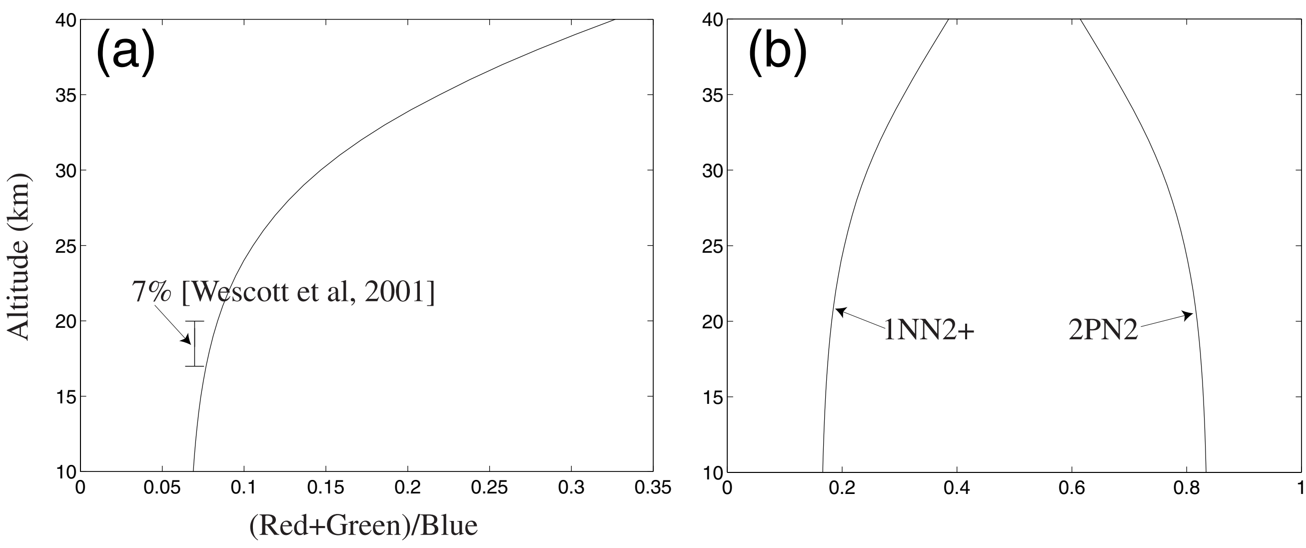

Figure 7. (a) Ratio of the combined red and green emissions to the total blue emission. (b) Relative contributions of the second positive N_2 and the first positive N_2^+ bands to the blue color of blue jets.

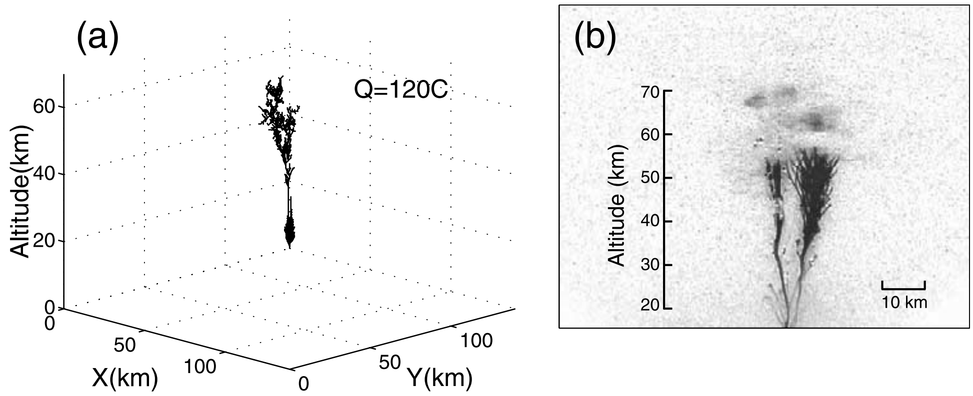

Figure 8. (a) Model results for thundercloud charge $Q = 120$ C and the upper simulation box boundary at 70 km. (b) Image of a blue jet at the moment of attachment to the lower ionospheric boundary. Figure 8b reprinted by permission from *Nature* [*Pasko et al.*, 2002] MacMillan Publishers Ltd.

experimentally and at this time should be considered as predictions of the model.

4.3. Comparison With Recent Observations of Blue Jets

[51] The recent reports by *Wescott et al.* [2001] and *Pasko et al.* [2002] provide an opportunity to perform a direct comparison between observations of blue jets and the model results. Results of our model generally demonstrate the formation of upward cone-shaped blue jets for a wide range of altitudes of the upper simulation box boundary. This was true for the boundary varied between several km above the thundercloud top and up to the lower ledge of the Earth ionosphere at altitudes ~70–80 km (see section 2.6 for the related discussion on physical factors determining the terminal altitudes of blue jets and section 4.1 for discussion on mechanisms of blue starters). Figure 8a shows a result of the model calculation corresponding to the same input parameters as for Figure 4b, but with the upper simulation box boundary set to 70 km altitude, corresponding to the terminal altitude of the blue jet event reported by *Pasko et al.* [2002]. Figure 8b shows one of the images of the blue jet phenomena, taken from the video sequence reported by *Pasko et al.* [2002] and corresponding to the moment of the attachment of the blue jet to the lower ionospheric boundary. This stage of the blue jet development is similar to the "final jump stage" of the leader process observed in laboratory experiments, when the streamer zone makes contact with the opposite electrode [*Bazelyan and Raizer*, 1998, p. 212]. The range of observed speeds during the final jump, 5×10^4 to 10^6 m/s [*Bazelyan and Raizer*, 1998, p. 212], is similar to the range of speeds, from 5×10^4 m/s to more than 2×10^6 m/s, reported by *Pasko et al.* [2002]. Although our model can not provide information on the velocity of streamer coronas, Figure 8 demonstrates good agreement between model results and observations in terms of the general volumetric shape of the blue jet.

[52] The video report of *Pasko et al.* [2002] contains 24 video frames, including the initial growth phase of the blue jet from the thundercloud top. Our model results obtained for a variety of input parameters (i.e., the thundercloud charge values and the upper simulation box boundary) indicate that the initial growth always takes the form of a wide bunch of fractal trees spreading from the initiation point with a large cone angle. This initial cone angle is substantially wider than the effective cone angle of the fully developed blue jet, which forms later. This behavior, in particular, appears to be common for all cases shown in Figures 4b–4e and 8a. Figure 9a shows an example of the initial growth stage corresponding to results of Figure 4d. The initial spreading of fractal trees is a simple reflection of

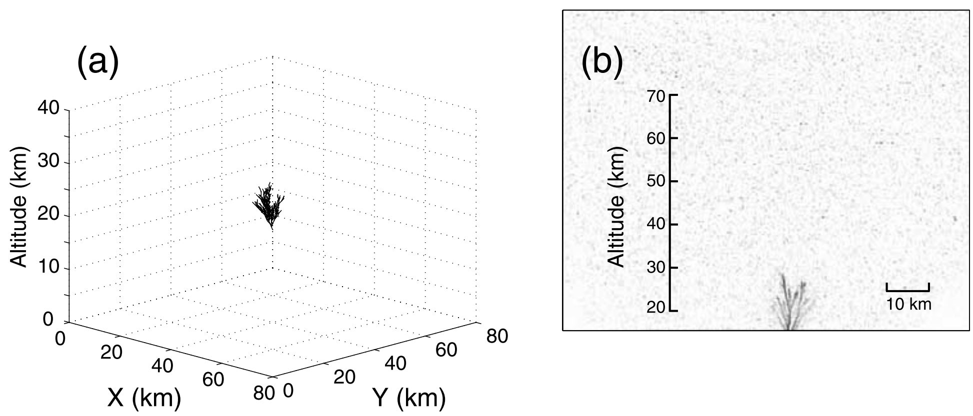

Figure 9. (a) Initial growth stage of the blue jet shown in Figure 4d. (b) An initial video frame of the blue jet event reported by *Pasko et al.* [2002]. Figure 9b reprinted by permission from *Nature* [*Pasko et al.*, 2002] MacMillan Publishers Ltd.

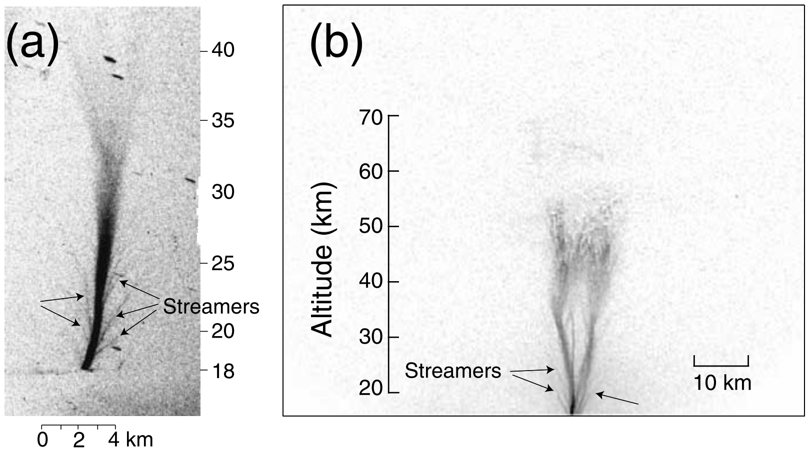

Figure 10. (a) A black and white image of a 2-min time exposure of a blue jet. The image is provided through the courtesy of G. Wescott, University of Alaska [*Wescott et al.*, 2001]. (b) Processed image obtained by averaging the sequence of video fields from the study of *Pasko et al.* [2002].

the geometry of the region in which the thundercloud electric fields exceed the E_{cr}^{+} threshold (see discussion in section 2.4). Figure 9b shows one of the initial video frames of the blue jet event reported by *Pasko et al.* [2002]. The good agreement between the general volumetric shape of modeled (Figure 9a) versus observed (Figure 9b) fractal trees at the initial stages of blue jet development provides additional supporting evidence for the physical mechanism of this phenomena based on positive streamer coronas discussed in section 2.

[53] *Wescott et al.* [2001] have reported a 2-min time exposure color photograph of a blue jet event taken from St. Denis, Réunion Island in the Indian Ocean. The corresponding inverted black and white image from the study of *Wescott et al.* [2001] is reproduced in Figure 10a and shows details of faint streamers diverging from the main body of the blue jet. Figure 10b shows a similarly processed image obtained by averaging 48 video fields extracted from the 24 frame video sequence corresponding to the Puerto Rico blue jet [*Pasko et al.*, 2002]. The image in Figure 10b effectively simulate how the same blue jet would look if captured on a photograph with an exposure time exceeding the total duration of the event ($\sim$0.8 s). Figure 10b shows a very similar structure to Figure 10a in terms of faint streamers diverging at large angles from the main body of the blue jet. The original video sequence of *Pasko et al.* [2002] indicates that these streamers are formed at the initial stage of the blue jet development (see Figures 9a and 9b). Comparison of Figures 10a and 10b and 9a and 9b indicate that the streamer structure reported by *Wescott et al.* [2001] (Figure 10a) was likely formed at the initial stage of the blue jet development, similarly to the event reported by *Pasko et al.* [2002] (Figure 10b). Figure 10b shows a very bright channel at the bottom of the image (between altitudes of approximately 16 and 20 km). We interpret the appearance of this bright feature in both Figures 10a and 10b as the streamer-to-leader transition. This interpretation is supported by the original color photograph from the study of *Wescott et al.* [2001], in which the lower portion of Figure 10a has a bright white color.

[54] The above comparison between model results and observations further supports the mechanism of blue jets as large-scale positive coronas filling large volumes of atmosphere above thundercloud tops in cases of unusually fast growth of the positive thundercloud charge at the cloud top, as discussed in section 2. A puzzling aspect of the blue jet observation reported by *Pasko et al.* [2002] is that although the initial development of the event was not triggered by a lightning discharge (similarly to the originally discovered blue jets and blue starters) [*Wescott et al.*, 1995, 1998], a dramatic rebrightening of the jet was observed in frame 18 (i.e., $\sim$0.6 s after the start of the event) in association with a large sferic with a polarity indicating the upward transport of negative charge (M. Stanley, private communication, 2002). This observation seems to contradict the physical mechanism discussed in section 2, since upward propagating positive streamers effectively transport positive charge upward. We note, however, that due to the observed slow rise time of blue jets [*Wescott et al.*, 1995, 1996, 1998; *Pasko et al.*, 2002] and known very small integral currents which flow in the weakly conducting streamer zones of leaders [*Bazelyan and Raizer*, 1998, p. 236], the high-frequency radiation signature from blue jets may be weak and difficult to detect. In view of the discussion presented in section 2, it is natural to expect that in most cases (when blue jets are not formed), the excess positive thundercloud charge at the cloud top (Figure 1b) is discharged by means of the conventional leader process establishing a link of the positive charge with the ground or with the lower negative charge region in the thundercloud, leading to cloud-to-ground or intracloud discharges, respectively. Both of these conventional discharge mechanisms effectively correspond to the upward transport of the negative charge. In those cases when the blue jet is formed above the thundercloud (this requires some rather extreme circumstances as discussed in section 2), the resultant reduction in the positive charge at the thundercloud top may not be sufficient to prevent the continuation of charge growth due to meteorological factors and the eventual discharge of the system by means of conventional lightning at lower altitudes. The observed upward transport of the negative charge $\sim$0.6 s after the onset of the blue jet reported by *Pasko et al.* [2002] therefore does not contradict the mechanism discussed in section 2.

[55] We further emphasize that the mechanism of blue jets based on negative streamer coronas is unlikely in view of

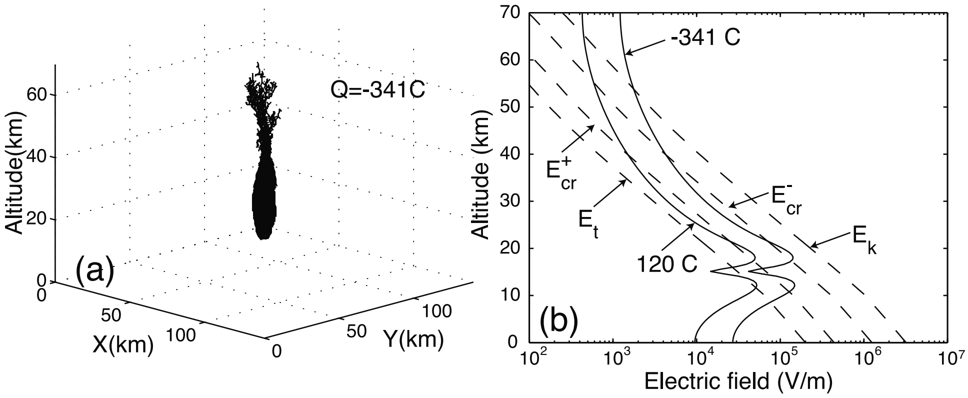

Figure 11. (a) Result of the model calculation of a blue jet created by a negative charge $Q = -341$ C. (b) Altitude scan of the electrostatic fields created by thundercloud charges of 120 and -341 C through the simulation box center (solid lines) along with the characteristic fields E_t, E_{cr}^{+}, E_{cr}^{-}, and E_k (dashed lines).

the discussion presented in section 2.1 (i.e., since negative streamers generally require a factor of 3 greater electric fields to propagate than positive streamers). Figure 11a shows a result of the model calculation of a blue jet created by the negative charge $Q = -341$ C, which corresponds to the same relative enhancement of the electric field above the E_{cr}^{-} threshold as the Q = 120 C creates above the E_{cr}^{+} threshold for the positive polarity (Figure 11b). One can notice substantial geometrical differences between blue jets created by the positive (Figure 8a) and negative (Figure 11a) charge polarity. The negative polarity result shown in Figure 11a is characterized by a very high degree of branching, the formation of numerous downward-directed positive streamers, and an overall shape which does not match well the volumetric shapes of experimentally observed blue jets [*Wescott et al.*, 1995, 1998, 2001; *Pasko et al.*, 2002]. We note also that in addition to being highly unrealistic at the thundercloud altitudes (see discussion in section 2.1), the negative polarity field magnitude also exceeds the conventional breakdown threshold E_k in a wide range of altitudes above ~55 km (Figure 11b). This enhancement would readily lead to the development of the high-altitude electrical breakdown from individual electron avalanches, similar to sprites. No such effects were reported during observations of *Pasko et al.* [2002].

5. Summary

[56] Following the original suggestion of *Petrov and Petrova* [1999] that blue jets correspond qualitatively to the development of the streamer zone of a positive leader, a scenario of events leading to the upward launch of blue jets and blue starters has been identified. The scenario involves the fast growth of positive charge near the thundercloud top, leading to the creation of large-scale electric fields exceeding the critical field required for the propagation of positive streamers in air. Under these conditions, positive streamer coronas originating from the streamer zones of conventional leader channels can quickly expand and fill the large volume of atmosphere over which the critical field is exceeded. The streamer coronas self-consistently modify the electric field distribution, and results from a three-dimensional fractal model indicate that under a variety of conditions these streamer coronas form upward propagating conical shapes closely resembling the observed altitude extents, transverse dimensions, and conical structure of blue jets.

[57] The model results indicate, in particular, that blue jets and blue starters can be formed by a fast (~1 s) accumulation of ~110–150 C of positive thundercloud charge distributed in a volume with effective radius ~3 km near the cloud top at ~15 km. Model calculations corresponding to a blue jet upper terminal altitude of 40 km and a source thundercloud charge varying from 110 to 150 C indicate a transition from blue starters to blue jets, with the blue jet cone angle showing an increasing trend with the increasing thundercloud charge value. A thundercloud charge of 110 C always produced blue starters with terminal altitudes around 25 km, while a charge of 120 C created both blue starters (with higher terminal altitudes) and blue jets. Source charges greater than 120 C always created blue jets, whose cone angles spanned the range of experimentally observed blue jets [*Wescott et al.*, 1995].

[58] The fractal model allows accurate determination of the macroscopic electric fields in regions of space occupied by streamers, and for a variety of input parameters these fields are very close to the minimum electric field required for propagation of positive streamers in air. As these fields are generally insufficient to excite any observable optical emissions, it is concluded that the observed optical luminosity in blue jets and blue starters arises from large electric fields existing in narrow regions of space around tips of small-scale corona streamers constituting them.

[59] An optical emission model similar to that used by *Pasko et al.* [1997] indicates that the optical emissions of blue jets and blue starters have an ionized first negative N_2^+ component. This result agrees with the recent evidence of 427.8 nm emission in blue starters presented by *Wescott et al.* [2001]. The model results also show that the combined red and green emissions constitute ~7% of the total blue emissions, in good agreement with the experimental observations of *Wescott et al.* [2001]. The model results indicate that the second positive N_2 and the first negative N_2^+ bands are the dominant contributors to the observed blue emissions, with their relative contributions ~80% and ~20%, respectively, at the base of the blue jet and ~60% and ~20% at 40 km altitude. The model results predict that red emissions are due to the first positive bands of N_2 and the first negative bands of O_2^+, and green emissions are due to

the first negative N_2^+, the first negative O_2^+, and the second positive N_2 bands.

[60] The fractal model allows for the propagation of blue jets to the lower ledge of the Earth's ionosphere, in good agreement with the recent observations of *Pasko et al.* [2002]. The model results also show good agreement with observations of *Pasko et al.* [2002] in terms of the initial phases of blue jet development and in terms of the general volumetric shape of the blue jet. A comparison of the video sequence from the study of *Pasko et al.* [2002], the 2-min time exposure photograph from the study of *Wescott et al.* [2001], and the fractal model results indicates that the blue jet streamer structure reported by *Wescott et al.* [2001] was likely formed during the initial stages of the blue jet development.

[61] **Acknowledgments.** This research was supported by NSF ATM-0134838 and NASA NAG5-11832 grants to Pennsylvania State University. We thank Mark Stanley for many useful discussions.

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J. J. George and V. P. Pasko, CSSL Laboratory, Pennsylvania State University, 211 B EE East, University Park, PA 16802-2706, USA. (vpasko@psu.edu)

Correction to "Three-dimensional modeling of blue jets and blue starters"

Victor P. Pasko

Received 18 July 2004; published 30 September 2004.

INDEX TERMS: 2427 Ionosphere: Ionosphere/atmosphere interactions (0335); 2435 Ionosphere: Ionospheric disturbances; 3304 Meteorology and Atmospheric Dynamics: Atmospheric electricity 3324 Meteorology and Atmospheric Dynamics: Lightning; 0310 Atmospheric Composition and Structure: Airglow and aurora; 9900 Corrections

Citation: Pasko, V. P. (2004), Correction to ''Three-dimensional modeling of blue jets and blue starters,'' *J. Geophys. Res.*, *109*, A09311, doi:10.1029/2004JA010693.

[1] In the paper "Three-dimensional modeling of blue jets and blue starters" by Victor P. Pasko and Jeremy J. George (*J. Geophys. Res.*, *107*(A12), 1458, doi:10.1029/2002JA009473, 2002) the electric field magnitudes measured from balloons in thunderstorms are incorrect. The correct text appears below.

[2] Paragraph [22]: It is now well-established that electric fields measured from balloons at different altitudes in thunderstorms very rarely exceed 50–100 kV/m (not 50–100 kV/cm as in the original manuscript).

0148-0227/04/2004JA010693$09.00