Plasma Phys. Control. Fusion **50** (2008) 124050 (22pp) doi:10.1088/0741-3335/50/12/124050

# Blue jets and gigantic jets: transient luminous events between thunderstorm tops and the lower ionosphere

**V P Pasko**

CSSL, Penn State University, University Park, PA 16802, USA

Received 30 May 2008, in final form 31 July 2008
Published 6 November 2008
Online at stacks.iop.org/PPCF/50/124050

**Abstract**

An overview of general phenomenology and proposed physical mechanisms of large scale electrical discharges termed 'blue jets' and 'gigantic jets' observed at high altitude in the Earth's atmosphere above thunderstorms is presented. The primary emphasis is placed on summarizing available experimental data on the observed morphological features of upward jet discharges and on the discussion of recently advanced theories describing electrodynamic conditions, which facilitate escape of conventional lightning leaders from thundercloud tops and their upward propagation toward the ionosphere. It is argued that the filamentary plasma structures observed in blue jet and gigantic jet discharges are directly linked to the processes in streamer zones of lightning leaders, scaled by a significant reduction of air pressure at high altitudes.

(Some figures in this article are in colour only in the electronic version)

## 1. Introduction

Transient luminous events (TLEs) are large scale optical events occurring at high altitudes, which are related to the electrical activity in underlying thunderstorms [1–4]. Although eyewitness reports of TLEs above thunderstorms have been recorded for more than a century, the first image of one was captured only in 1989, serendipitously during a test of a low-light television camera [5]. Since then, several different types of TLEs above thunderstorms have been documented and classified and some are illustrated in figure 1. These include relatively slow-moving fountains of blue light, known as 'blue jets' (BJ), which emanate from the top of thunderclouds up to an altitude of 40 km [6, 7]; 'sprites' that develop at the base of the ionosphere and move rapidly downward at speeds up to 10 000 km $s^{-1}$ [1, 8–10]; 'elves', which are lightning induced flashes that can spread over 300 km laterally [11–15]; and upward moving 'gigantic jets' (GJ), which establish a direct path of electrical contact between thundercloud tops and the lower ionosphere [3, 16–21].

BJs develop upward from cloud tops to terminal altitudes of about 40 km at speeds ∼100 km $s^{-1}$ and are characterized by a blue conical shape [6, 7, 22, 23]. Blue starters (BS) are believed to be closely related to BJs, and they are distinguished from BJs by a much

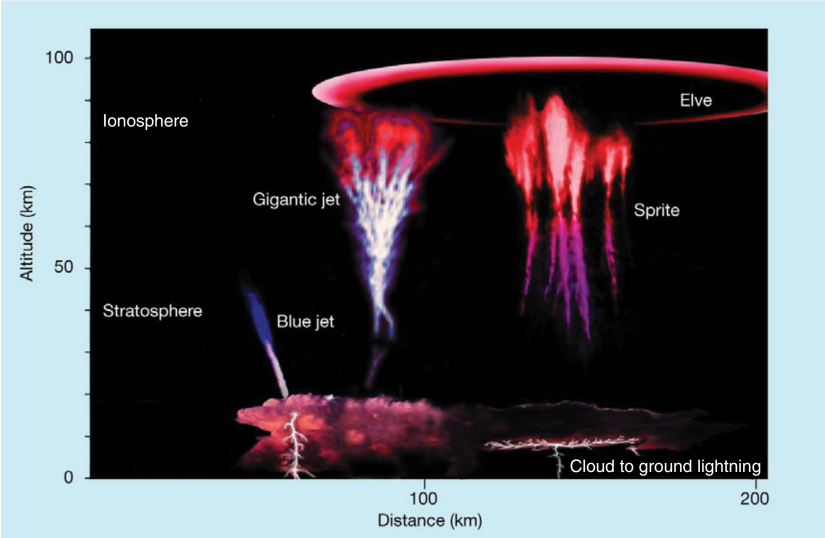


**Figure 1.** Lightning related TLEs. Reprinted from [3] by permission from *Nature*.

lower terminal altitude. They protrude upward from the cloud top (17–18 km) to a maximum 25.5 km in altitude [23, 24]. BJs were originally documented and classified as such during airplane based observations [6]. An earlier (October 21, 1989) observation of a phenomenon closely resembling BJs using the payload bay TV cameras of the space shuttle was reported by Boeck *et al* [25]. Ground observations of BJs are believed to be difficult due to severe Rayleigh scattering of blue light in the atmosphere [22, 26, p 74]. Several ground based video recordings of jet-like events, which also electrically connected a thundercloud with the lower ionosphere, have recently been reported [3, 16, 17]. This type of events is now termed GJs [17]. Recent photographic [23] and video [16] observations of jet phenomena above cloud tops at a close range have shown the small scale streamer-like structure in these events, predicted in [27], and similar to that reported in sprites [28–31].

A discussion of sprite discharges in the context of their molecular physics and similarity with laboratory discharges has recently been provided in [32]. The goal of this paper is to provide an overview of some of the recent experimental and theoretical developments in studies of BJs and GJs.

## 2. Streamers and leaders

At atmospheric pressure electrical gas discharges take different forms depending on the discharge gap size, electrode geometry and material, applied electric field magnitude and polarity and other factors. These discharges are utilized in many applications including advanced combustion systems, treatment of flue gases, aerodynamic flow control and energy-efficient lighting devices [33, and references therein]. The discharges exhibit features ranging from millimeter scales in atmospheric pressure dielectric barrier discharges, which are of current interest for deposition of thin film coatings [34], to kilometer scales in tropospheric lightning discharges [35]. Many known forms of electrical discharges at atmospheric pressure can be scaled to lower air pressures at higher altitudes in the Earth atmosphere using their similarity properties. A review of similarity relations and classification of different discharge mechanisms in air with focus on the interpretation of the observed features in TLEs is provided in [36]. In this section we provide an overview of the concepts of streamers and leaders, which are needed for discussion of BJs, BSs and GJs in sections 3 and 4.

An important reference field for air discharges is the conventional breakdown threshold $E_k$ defined by equality of ionization and dissociative attachment coefficients [37, p 135]. We assume $E_k \simeq 32\,\mathrm{kV\,cm^{-1}}$ at atmospheric pressure [38].

Streamers are narrow filamentary plasmas, which are driven by highly nonlinear space charge waves [37, p 327]. At ground level, the streamer has a radius of $10^{-1}$–$10^{-2}$ cm and propagates with a velocity of $10^5$–$10^7\,\mathrm{m\,s^{-1}}$. The dynamics of a streamer is mostly controlled by a highly enhanced field region, known as a streamer head. A large amount of net space charge exists in the streamer head, which strongly enhances the electric field in the region just ahead of the streamer, while screening the ambient field out of the streamer channel. The peak space charge field can reach a value many times the $E_k$ threshold. The large space charge field leads to a very intense electron impact ionization occurring in the streamer head. This ionization rapidly raises the electron density from an ambient value to the level in the streamer channel, resulting in the spatial extension of the streamer. The streamer polarity is defined by a sign of the charge in its head. The positive streamer propagates against the direction of the electron drift and requires ambient seed electrons avalanching toward the streamer head for the spatial advancement [39]. The negative streamer is generally able to propagate without the seed electrons since electron avalanches originating from the streamer head propagate in the same direction as the streamer [40, 41]. 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 $E_{cr}^{+} = 4.4\,\mathrm{kV\,cm^{-1}}$ [42], in agreement with results of numerical simulations of positive streamers [43, 44]. The absolute value of the similar field $E_{cr}^{-}$ for negative streamers is a factor of 2–3 higher [37, 43, p 136]. One of the estimates of this field is $E_{cr}^{-} = 12.5\,\mathrm{kV\,cm^{-1}}$, in accordance with figure 7 in [43]. The value $E_{cr}^{-} \simeq 12.5\,\mathrm{kV\,cm^{-1}}$ is not well established, and different sources list various values ranging from $7.5\,\mathrm{kV\,cm^{-1}}$ [45] to $10\,\mathrm{kV\,cm^{-1}}$ [46, p 198]. 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 [27]. Streamers can be launched by individual electron avalanches in large fields exceeding the $E_k$ threshold or by initial sharp points creating localized field enhancements, which is a typical case for point-to-plane discharge geometries [47, 48]. The possibility of simultaneous launching (in opposite directions) of positive and negative streamers from a single midgap electron avalanche is documented experimentally [37, 49, p 335] and reproduced in numerical experiments [38, 50, 51]. The pressure scaled streamer-type discharges exist in sprites [10, 31]. The scaling properties of streamers as a function of gas pressure, and their geometrical discharge patterns (i.e. branching) are affected by photoionization properties of the gas through which they propagate. Significant efforts have been devoted to the development of efficient models of photoionization [51–55].

The breakdown in air gaps of many meters at atmospheric pressure and in lightning discharges occurs via growth of a leader from one electrode to the other: a thin channel that is conducting, with conductivity orders of magnitude higher than the streamer channel [37, p 327]. The conducting channel transfers the electric potential of the supporting electrode. A strong enhancement of the electric field is present in the leader head. The ionization process in the leader head transforms the medium into a conductor. The electron density of the leader and streamer channel just behind of their respective heads is of the same order; however, the conductivity of a streamer channel often decreases due to attachment or recombination processes while the leader channel is able to keep its conductivity relatively constant. The key processes contributing to sustainment of the conducting leader channel are accelerated direct, stepwise and associative ionization and detachment reactions by the elevated gas temperature in the leader channel [46, p 59]. 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 which is filled with highly branched streamers [56, p 203, 253]. Many streamers connect to the tip of the leader and draw a large total current from it, and this large current can heat the gas in the leader channel to the required temperature 5000–6000 K for streamer-to-leader transition. Due to its high conductivity, the leader channel can be considered as equipotential [37, p 364]. In large experimental gaps (>100 m) and in thunderclouds, the electric fields required for propagation of positive and negative polarity leaders are known to be nearly identical; however, the internal structure of their streamer zones, which is closely associated with the direction of electron avalanches, is very different (see [37, p 375] and [56, p 253]). The minimum electric field capable of supporting the propagation of leaders in a several tens of meters gap is $E_l \sim 1\,\mathrm{kV\,cm^{-1}}$, and this field can be as low as a few hundreds $\mathrm{V\,m^{-1}}$ for lightning leaders [45].

Under thunderstorm conditions, due to its equipotential properties, the leader head can carry a large portion of the cloud potential $U = 10$–$100\,\mathrm{MV}$ toward the ground. A half of this potential drops in the leader streamer zone [46, p 253]. The electric fields in streamer zones of positive and negative leaders remain at constant values $E^+_{\mathrm{cr}} \simeq 4.4\,\mathrm{kV\,cm^{-1}}$ and $E^-_{\mathrm{cr}} \simeq 12.5\,\mathrm{kV\,cm^{-1}}$, respectively. This is supported by measurements inside the streamer zones of positive [57] and negative [58] leaders, which indicate that $E^+_{\mathrm{cr}}$ and $E^-_{\mathrm{cr}}$ are close to the integral fields established by positive and negative streamer coronas in regions of space through which they propagate. The size of the streamer zone can therefore be simply evaluated as $R_{\mathrm{s}} \simeq U/2E^{\pm}_{\mathrm{cr}}$. Assuming that $U = 20\,\mathrm{MV}$, the streamer zone size of a negative leader can be evaluated as $R_{\mathrm{s}} \simeq 10\,\mathrm{m}$.

The streamers in both positive and negative leaders originate from the surface of the leader head. It is believed that at the surface of a leader head the electric field can reach values comparable to $E_k$ (i.e. $\sim 1.5E_k$ [46, p 68]). The frequency with which a leader head emits streamers is estimated to be $\sim 10^9\,\mathrm{s^{-1}}$, and about $10^5$ streamers are present in a leader streamer zone at any given time [46, p 70].

Although details are still not fully understood, the published laboratory experiments and observations of natural lightning indicate a quasi-continuous development of positive leaders and a more impulsive, stepwise development of negative leaders. References [45] and [46, p 197] represent two sources, covering the stepping process in detail and allowing one to appreciate the many complex features of the phenomenon.

One of the components of the stepping process in negative leaders is the formation of a 'space leader', which originates near the external boundary of the negative streamer zone. The space leader propagates as a bi-directional discharge, whose positive end propagates toward the negative leader head. The junction of the space leader with the negative leader head resembles a return stroke accompanied by a strong illumination of the entire leader channel. The tip of the main leader 'jumps' over to a new location, which was previously occupied by the space leader, and delivers to it the high potential of the previous leader head. The sudden rise in the space leader potential causes the inception of a negative corona flash [46, p 199]. The length of the new streamer zone is determined by the same relationship $R_{\mathrm{s}} \simeq U/2E^-_{\mathrm{cr}}$. A new space leader originates near the external boundary of the newly formed negative streamer zone and the process is repeated. The negative corona flash stage of the development of negative leaders at thundercloud altitudes and GJs above cloud tops is believed to be responsible for production of thermal runaway electrons, which can reach relativistic energies (>10 MeV) and may be responsible for x-ray and $\gamma$-ray bursts observed during lightning discharges on the ground [59, 60] and on satellites [61, 62], as proposed in [63].

The above-mentioned values of $E_k$, $E^+_{\rm cr}$, $E^-_{\rm cr}$ and $E_l$ correspond to ground pressure. We assume that most of these fields can be directly scaled proportionally to atmospheric neutral density $N$ to find corresponding values at altitudes of BJs, BSs and GJs. This approach is generally justified by similarity laws [36]. We note, however, that the actual scaling of $E^+_{\rm cr}$ and $E^-_{\rm cr}$ for the altitude range covered by BJs, BSs and GJs has not yet been verified experimentally, and the simple scaling of $E^+_{\rm cr}$ and $E^-_{\rm cr}$ proportionally to $N$ should be considered as an approximation. The exact details of the $E_l$ field scaling with $N$ are not known at present. The $E_l$ field is related to Joule heating and may exhibit deviations from the $N$ scaling [64].

It is helpful to put BJs and GJs in relationship with different polarity leader processes. Assuming that both types of jets originate from streamer zones of conventional lightning leaders propagating upward from thundercloud tops, the continuous positive leader-like propagation of optically observed BJs should be contrasted with the impulsive rebrightening of GJs, resembling negative leader processes [65]. The polarity itself is not sufficient to explain all the morphological differences in jet events observed to date (as discussed in the following sections the location of jet initiation and charge configuration in a thundercloud are also defining parameters for jet development). Nevertheless, most of the GJs and BJs observed to date are believed to be associated with normal polarity thunderstorms and we will associate BJs with positive leaders and GJs with negative leaders. The GJs are visually more energetic than BJs, they extend to higher altitude than BJs and have more impulsive and structured appearance. Although to date absolute optical intensities of BJs and GJs have not yet been compared, their appearance in available video records (i.e. figure 2) allows us to speculate that GJ events are also optically brighter. An extensive discussion on possible classification schemes of different jet events is given in [65, and Supplementary Information therein].

## 3. Phenomenology of BJs, BSs and GJs

Reports of unusual large scale luminous discharges above thunderclouds have appeared in the scientific literature for over a century [66–79]. For reviews of these observations, readers are referred to [7, 80, 81]. Boeck *et al* [82] summarize early observations of TLEs, and discuss an important role of the space shuttle videotape observations during the years before 1993 in the search, discovery and confirmation of various types of TLEs known to us today. Many early reports contain details of discharges describing typical features of BJs [6, 22] or GJs [16, 17]. Heavner [26] provides a summary of old and more recent anecdotal reports of TLEs, some of which closely correlate with known features of BJs and GJs.

During the Sprites 1994 aircraft campaign two jet aircraft equipped with both black and white and color cameras were used to capture the first images of BJs and BSs [1, 6]. During one mission on the night of July 1, 1994 Wescott *et al* [6] reported capturing fifty-six examples of BJs—further analysis of the images later showed that five of these images were actually BSs [24]. Thirty-four of the remaining fifty-one BJs were viewed by both aircraft, giving sufficient data for BJ triangulations [22].

From the triangulations of thirty-four BJs, Wescott *et al* [22] calculated the mean starting altitude for BJs to be 17.7 km, and their upper extent 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$^{-1}$ [6]. The cone angle of 18 BJs was measured by Wescott *et al* [6] to be 14.7° ± 7.5°, and the observed lifetime of BJs was 200–300 ms, with the jet brightness decaying simultaneously along the entire jet.

BSs resemble BJs, but BSs terminate at much lower altitudes. Wescott *et al* [24] calculated the starting altitude of 30 BSs to be 17.7 ± 0.9 km, with terminating altitudes ranging from 18.1 to 25.7 km. The velocities of six BSs were measured by Wescott *et al* [24], ranging from

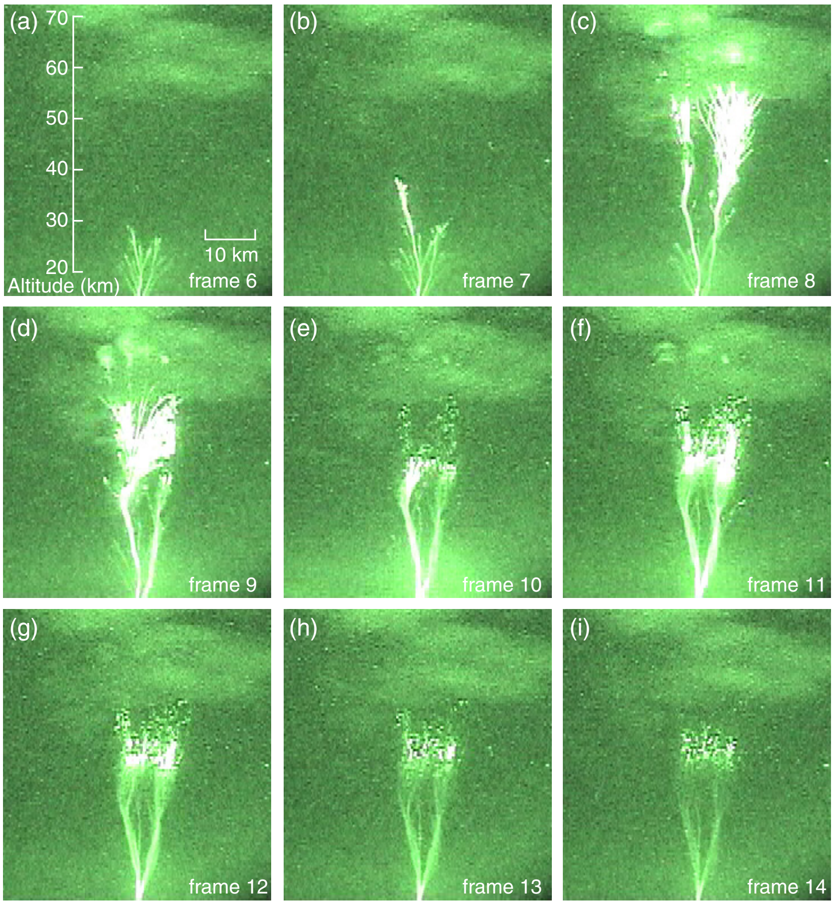


**Figure 2.** The dynamics of the GJ event [16]. Panels (*a*)–(*i*) correspond to frames 6–14 as discussed in the text. Reprinted from [16] by permission from *Nature*.

27 to 153 km s$^{-1}$, although these velocities varied over the lifetimes of the starters. Wescott *et al* [23] recorded fifteen possible BSs, with one event positively identified as a BS and showing evidence that it was partially ionized. While BSs do not appear to coincide with either positive or negative cloud-to-ground (CG) 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 [24].

Additional characteristics of BJs include association with both high negative cloud-to-ground discharge rates—although not with a particular flash—and large hail [22], as well as more frequent occurrences earlier in thunderstorm life [6, 26, p 20]. BJs are neither absolutely vertical nor aligned with the geomagnetic field.

Lyons *et al* [7] reported 17 upward propagating discharges arising out of the convective dome of a high plains supercell storm. The discharges were estimated to be less than 200 m wide and they did not grow more than 1 km above the cloud top. They appeared to be brighter, much more compact in shape and more optically uniform than the BSs described in [24]. Lyons *et al* [7] speculated that these events could be BSs which appeared brighter when imaged at a close range using a next generation intensified imager. Alternatively, they may also represent events of different (i.e. negative) polarity with respect to BSs reported in [24], as recently suggested in [65].

The first ground video recording of a GJ event, which also electrically connected a thundercloud with the lower ledge of the Earth's ionosphere at about 70 km altitude, has been obtained from a very close range, ∼200 km [16]. The event lasted a total of 24 video frames (∼33 ms each) and concluded with an intense lightning flash in the underlying thundercloud. Figure 2 shows a sequence of nine images extracted from frames 6 through 14. The full video sequence is available at http://pasko.ee.psu.edu/Nature. The apparent speed of upward propagation of the observed phenomenon remained remarkably stable during the first five frames and is estimated to be $0.5\times10^5$ m s$^{-1}$ ($\pm0.07\times10^5$ m s$^{-1}$), consistent with known speeds of the leader process in conventional lightning [83]. The speed increased to $1.6 \times 10^5$ m s$^{-1}$ between frames 5 and 6 and to $2.7 \times 10^5$ m s$^{-1}$ between frames 6 and 7. The analysis of two video fields corresponding to frame 8 indicates that the large altitude change between frames 7 and 8 happened in two steps. During the first field the left branch, clearly visible in frame 7, extended up to the altitude ∼70 km, while during the second field the right branch formed with a wider tree-like structure. The altitude change ∼32 km for the left branch and ∼37 km for the right branch happened faster than the duration of one video field (16.7 ms). The estimated speed in the range (1.9–2.2) $\times$ $10^6$ m s$^{-1}$ therefore represents a lower possible value of the actual speed, which likely was higher [16].

The term 'gigantic jet' was introduced in [17]. Su *et al* [17] reported observations of five GJs that established a direct link between a thundercloud (∼16 km) and the ionosphere at about 90 km elevation. Extremely-low-frequency radio waves from four events were detected, while no CG lightning was observed to trigger these events [17]. The results in [17] indicated that GJs had negative polarity and therefore resembled negative cloud-to-ionosphere discharges. The morphology of the observed events was classified in two categories: 'tree' jets and 'carrot' jets. Su *et al* [17] also described three distinct stages of evolution of GJs: leading jet, fully developed jet and trailing jet. The form and evolution of the leading jets reported in [17] were similar to the event reported in [16], but had a much shorter duration and propagated to a higher altitude, possibly reflecting variations in strength of thundercloud sources producing these events. In terms of stages of evolution proposed in [17] panels (*a*) and (*b*) in figure 2 could be classified as the leading jet stage, panels (*c*) and (*d*) as the fully developed jet and panels (*e*) through (*i*) as the trailing jet stage. Several tens of coulombs of negative charge can be transferred in one GJ event from the thundercloud to the lower ionosphere [17].

The photographic [23] and video [16] observations of upward jet discharges have clearly shown the filamentary streamer-like structure of these events (see figure 2) predicted in [27]. We note that Petrov and Petrova [27] originally proposed a streamer zone of positive leader as a mechanism for BJs and suggested a conceptual relationship of sprites and negative stepped leaders.

A jet event over northern Mexico closely resembling morphological features of previously documented GJs has been recently reported in [21]. The previous records of GJs were obtained from Puerto Rico [16] and Taiwan [17] over oceanic thunderstorms in tropical regions. The GJ [21] was imaged with 4 s time resolution and represented a first observation of this type of phenomenon over continental North America. The estimates presented in [21] indicate that the bright lower channel ended in a fork at around 50–59 km height with very dim upper branches extending to 69–80 km altitude. In terms of terminology introduced in [17] the bright lower channel most likely corresponds to the persisting in time leading and trailing jets and the dim upper branches to a relatively transient fully developed jet. The electromagnetic records available during the time interval of the GJ indicated no significant charge moment changes of the magnitude characteristic of sprite discharges. Following the GJ event 30 sprites were observed on the same night by the same imaging instrument allowing an indirect comparison of the GJ brightness and sprite brightness. van der Velde *et al* [21] stated that while the bottom of GJ channel had appeared of similar brightness as the brightest of tendrils of the subsequent sprites, the wispy top part appeared much less luminous. Having assumed that the durations of the upper branches and sprites are the same, the brightness of the upper branches must have been less than most sprites [21].

Krehbiel *et al* [65] recently reported observations of an upward jet, which was obtained with a three-dimensional very high frequency (VHF) lightning mapping array [84] during the STEPS 2000 campaign [85]. This observation is especially important for the understanding of mechanisms of jet discharges discussed in the next section as it provided information about evolution of lightning and charge structures inside the cloud prior to the jet discharge. The jet lasted 120 ms and propagated 4 km upward in the first 60 ms to 13.5 km altitude, 2 km above the radar-detected cloud top. No imaging data are available for this event, but its development was characteristic of an upward negative leader [84, 86] that would have been visible above the cloud top. This discharge may have been similar to the upward propagating discharges observed later during STEPS [7]. Krehbiel *et al* [65] also reported VHF and photographic observations of so-called 'bolts-from-the-blue' (BFB) lightning discharges, which provided key information needed for the understanding of formation of negative GJs above cloud tops (see next section). 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 [87, 88] (see figure 4(*a*)). VHF mapping observations show that BFB discharges begin as regular, upward-developing intracloud flashes in normally electrified storms [84, 86, 89] (e.g. figure 4(*a*)). Instead of terminating in the upper positive charge, however, the breakdown continues horizontally out of the upper side of the storm and turns downward to the ground (e.g. figure 4(*e*)). Although the lightning channel outside the cloud appears to originate in the upper positive charge, the leader continues to be of negative polarity and the resulting cloud-to-ground stroke lowers the negative charge to the ground from the storm mid-level [65].

BJs and BSs have been captured by black and white and color video cameras, allowing for some important conclusions concerning optical bands responsible for the observed blue color [6]. Evidence from color TV suggesting that the blue light must have an ionized 1st negative $N_2^+$ component has been presented in [22]. The first conclusive evidence of 427.8 nm (one of the bands in the 1st negative $N_2^+$ band system) emission in BSs has been reported in [23]. The authors of [23] also analyzed color TV frames associated with BSs and concluded that the combined red and green channel intensity constituted 7% of the total blue channel intensity.

In 1957, Rumi published the first VHF radar data indicating that thunderstorms produce additional ionization of the middle atmosphere [90], possibly related to BJs and GJs known today. High frequency echoes from middle atmospheric ionization potentially associated with high-altitude discharges were reported by Roussel–Dupre and Blanc [91]. A first attempt to detect lower ionospheric effects of lightning using Arecibo Observatory incoherent scatter radar (ISR) was made in [92]. No lightning location and timing information was available during this study and no D-region density changes were detected [92]. The attempts to reproduce Rumi's experiments using VHF radars brought contradictory results [93–95]. To date the levels of ionization in BJs and GJs have not yet been conclusively probed with HF/VHF/UHF radars.

We note that there are several features in sprite type of TLEs, which exhibit some close similarities with BJs, BSs and GJs. For instance, a secondary breakdown process having a form of thin multiple fingers which started near the horizon and propagated upward toward the remnants of a sprite was reported during the EXL98 campaign [96]. These observations have been previously discussed in the context of possible attachment of sprites to cloud tops, creating favorable conditions for establishing a highly conducting link between the Earth's surface and the lower ionosphere [97]. So-called 'trolls' are jet-like features propagating upward from near cloud tops to 40–50 km at 150 km $s^{-1}$ along the preceding sprite tendrils [98]. There are some similarities in the appearance of the GJs and the so-called 'palm tree' events, which are vertically extended emissions consisting of a single stem coming up the cloud top and spreading out into a wider crown near 60–70 km altitude and which follow the occurrence of large groups of sprites and exhibit the same red color as sprites [26, 99]. However, some other features of the GJs, such as their long duration, the altitude extent and no apparent association with a positive CG lightning discharge, do not match those typical for sprites. Additional information on secondary sprite processes near cloud tops become available with introduction of high speed (∼1 ms resolution) video observations of sprites [100]. Moudry [99] provides a summary of three distinct types of these secondary processes, which are broadly referred to as 'crawlers'. So-called 'smooth crawlers' appear as beads of slowly varying luminosity moving upward with speeds on the order of $10^4$ m $s^{-1}$, without any apparent connection to clouds [99]. An 'embler' typically develops and brightens over ∼1 ms as a small (<2 km diameter) bead within decayed sprite tendrils at an altitude <60 km [99]. The bead then decays in brightness while remaining stationary, but initiates a secondary, down-propagating patch of luminosity toward the cloud top that moves at a speed on the order of $10^6$ m $s^{-1}$ [99]. After 1–30 ms, another bead may brighten (on average at the position higher than its predecessor) and initiate the downward-moving brightness [99]. This irregular upward stepping process is only resolved with 1 ms resolution imaging and with standard TV-rate (16–33 ms) cameras the downward motion of the individual emblers is blurred and only the average upward motion is visible [99]. The third type of crawlers corresponds to above-mentioned 'palm trees'. Marshall and Inan [101] estimated velocities of upward propagating palm trees to be at least $1.5 \times 10^6$ m $s^{-1}$. In contrast to previous conclusions reported in [26] the analysis of photometric data reported in [101] indicates that palm trees are likely to be predominantly blue. The average altitudes of palm trees were estimated to be between $32 \pm 4$ and $57 \pm 6$ km, and the authors noted that observations at altitudes lower than 32 km were difficult due to cloud obstruction and atmospheric attenuation [101]. Moudry [99] noted that the jet event observed in [16] may be an example of a crawler, which was not preceded by a sprite. This is a valid hypothesis as both processes may share common discharge physics of negative stepped leaders modified by a significantly reduced air density above cloud tops. No high time resolution video records (i.e. milliseconds and sub-milliseconds) of BJs, BSs and GJs are available yet.

## 4. Physical mechanisms and modeling BJs, BSs and GJs

Theories of BJs and GJs may be classified into two general categories: (1) the mechanism of conventional air breakdown based on streamers and leaders [27, 65, 81, 102–108] and (2) the mechanism of relativistic runaway air breakdown [109–114]. Several reviews of jet theories have been published [22, 115–117]. No theory has yet accounted for all BJ and GJ characteristics.

The relativistic runaway air breakdown is admittedly the most attractive mechanism by which the $\gamma$-ray flashes of terrestrial origin (TGFs) [61, 62] can be produced in the Earth's atmosphere ([118, 119] and references therein). However, recent observations of x-rays from relatively compact regions of space associated with steps of negative lightning leaders [59, 60] and theoretical analysis presented in [63] indicate the existence of direct acceleration of thermal (i.e. originally several electronvolts) electrons to >10 MeV energies in streamer zones of conventional lightning leaders. These thermal runaway electrons can provide an alternative source of relativistic electrons which were previously thought to require galactic cosmic rays and a relativistic avalanche multiplication process with spatial scales exceeding dimensions of streamer zones of lightning leaders by orders of magnitude ([120–122] and references therein). The results of a numerical modeling of the relativistic runaway air breakdown demonstrate that this process may account for the observed blue color of BJs [111, 114]. The current theories based on conventional air breakdown generally favor a phenomenological link between BJs and GJs and streamer zones of lightning leaders and it has been suggested that the thermal runaway electron process operating in leaders may contribute to the production of TGFs from the jet discharges [63]. However, the link between TGFs and BJs and GJs has not yet been established experimentally. The existing theories of BJs and GJs based on the relativistic electron multiplication mechanism originally proposed in [120] do not specifically address most of the currently known geometrical and dynamical characteristics of BJs and GJs summarized in section 3.

Early theories of BJs based on conventional air breakdown suggested the concepts of positive [102] and negative [103] streamers as the underlying physical mechanism for this phenomenon. The Pasko *et al* [102] model proposes that BJs 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* [103] proposes that a strong intracloud discharge creates the BJ driving field. These models were able to describe some of the observed characteristics of BJ dynamics. The main difficulty of both models is that both effectively postulated the transverse size of modeled streamers, which therefore have not been modeled fully self-consistently [102, 103] (see also related discussion in [116]). 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 with the color video observations [6, 22]. The subsequent analysis of similarity laws for streamer discharges at different altitudes above thunderstorms established that at typical altitudes at which BJs are observed (∼30 km), the atmospheric pressure-controlled transverse dimension of stably propagating streamers should be on the order of several centimeters [32, 123], substantially lower than streamer sizes postulated in [102, 103].

Petrov and Petrova [27] proposed that BJs correspond qualitatively to the development of the streamer zone of a positive leader and therefore should be filled with streamers. Pasko *et al* [104] applied a 2D and Pasko and George [81] 3D fractal models of streamer coronas to describe observed shapes of BJs and GJs. The predictions in [27] and the modeling results in [81, 104] appeared to be in remarkable agreement with the recent experimental discoveries indicating the streamer-like structure of jet discharges [16, 23]. Although Petrov and Petrova [27] discussed positive leaders and one or both events in [16, 23] may correspond to negative polarity events, this does not diminish the importance of predictions by Petrov and Petrova [27], who for the first time linked the observed jet events to streamer components in leader processes.

Pasko and George [81] proposed that conditions leading to the formation of BJs and BSs include 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 and postulated the presence of a conventional positive leader above this charge center. Pasko and George [81] (see also [124]) note that the experimentally documented electric fields $E_{cr}^{+}$ and $E_{cr}^{-}$ required for propagation of streamers, which constitute essential components of the leader streamer zone, are substantially higher than the ambient fields typically observed in thunderclouds, 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 complexity its macroscopic characteristics remain stable under a variety of conditions, and the measurements inside the streamer zone of positive [57] and negative [58] leaders indicate

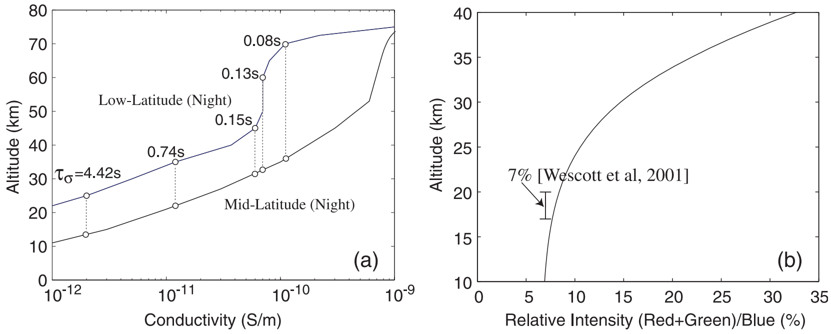


**Figure 3.** (*a*) Examples of the nighttime atmospheric conductivity distributions [81, 125, 126] including information on the dielectric relaxation time $\tau_\sigma = \varepsilon_o/\sigma$ at selected altitudes, which is important for the definition of terminal altitudes of jets [16, 81]. (*b*) Ratio of the combined red and green emissions to the total blue emission as a function of altitude [81]. Reprinted from [81] by permission from American Geophysical Union.

that the $E^+_{\rm cr}$ and $E^-_{\rm cr}$ fields are also close to the integral fields established by positive and negative streamer coronas, respectively, in regions of space through which they propagate. Pasko and George [81] suggest that if, due to the fast growth of the thundercloud charge, the large scale electric field does exceed the $E^+_{\rm cr}$ threshold, then positive streamer coronas, which are normally confined close to the leader head, can quickly (with speeds $>10^5$ m s$^{-1}$, exceeding typical leader speeds $\sim 2\times 10^4$ m s$^{-1}$ [56, p 227]) fill a large volume of space in the vicinity of a thundercloud. The streamer coronas themselves self-consistently modify the electric field distribution. Results of 3D fractal modeling of streamer coronas under these circumstances [81] demonstrate that under a variety of initial conditions the streamer coronas form upward propagating conical shapes similar to the experimentally observed geometry of BJs. The results in [81] resemble BJ and BS characteristics in terms of their altitude extents, transverse dimensions and conical structure and indicate that BSs are related to the initial phases of BJs.

The importance of the ambient conductivity at the stratospheric altitudes for the formation of jets has been discussed in [112]. The conductivity $\sigma$ defines an effective dielectric relaxation time scale ($\varepsilon_o/\sigma$) over which the conducting medium responds to changes in the applied electric field. Shaw [112] speculated that in order to bring and sustain large electric fields needed for the development of BJs at stratospheric altitudes some special mechanism is needed to either preferentially place charge center at higher altitudes or to reduce electrical conductivity of the air above cloud heights. It was proposed in [112] that the reduction of $\sigma$ above clouds due to large ions associated with pollution aerosols transported to the lower stratosphere/upper troposphere by upward convective currents can result in the development of higher electric field strengths above cloud tops.

Figure 3(*a*) shows examples of the nighttime atmospheric conductivity distributions [81, 125, 126]. The low-latitude profile in figure 3(*a*) is consistent with $\sigma = 6\times 10^{-12}$ S m$^{-1}$ recently measured in Brazil at 34 km altitude above a thunderstorm [127] and is consistent with $\sigma = 1.1\times 10^{-12}$ S m$^{-1}$ at 20 km altitude in a model recently proposed in [128]. The conductivity measurements conducted over thunderstorms from high-altitude NASA U-2 airplane in the US in the summer of 1986 indicated values of $\sigma = 4.5\times 10^{-12}$ S m$^{-1}$ at 20 km altitude [129], consistent with $\sigma = 7\times 10^{-12}$ S m$^{-1}$ at 20 km for the mid-latitude profile in figure 3(*a*). The same U-2 measurements indicated fields $\sim$7 kV m$^{-1}$ at 20 km over intense storm centers [129], which were a factor of 4 lower than $E^+_{\rm cr} = 30$ kV m$^{-1}$ at 20 km altitude.

There were no clear indications from the conductivity data alone to indicate that the plane was over a storm [129]. Instead the conductivity remained rather steady as the U-2 aircraft, which flew at a nearly constant altitude, repeatedly approached, passed above and then receded from storm cells [129]. These findings are not consistent with conductivity reductions above thunderstorms suggested in [112].

The role of atmospheric conductivity in the definition of upper terminal altitudes of BSs, BJs and GJs and in the formation of the jet type of phenomena in general is discussed in [81] in the context of a 'moving capacitor plate' model originally proposed by Greifinger and Greifinger [130–134] to characterize the electrodynamic response of the weakly-conducting middle atmosphere to fast charge rearrangements at lower (i.e. thundercloud) altitudes. The lower values of $\sigma$ and longer dielectric relaxation times $\tau_\sigma = \varepsilon_o/\sigma$ above cloud tops observed at low latitudes (see figure 3(*a*)) should create more favorable conditions for creation of jets in tropics in comparison with mid-latitudes [16].

The fractal model developed in [81] allows an accurate determination of the macroscopic electric fields in regions of space occupied by streamers. The results for positive polarity events indicate that for a variety of input parameters these fields are close to $E^+_{\rm cr}$, consistent with earlier findings [97, 104, 135, 136] and measurements of Petrov *et al* [57]. We note, however, that the low fields on the order of $E^+_{\rm cr}$ are generally not sufficient to excite any observable optical emissions [81]. The fractal model does not allow direct modeling of physics of streamers, does not resolve 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 the electric field enhancements around streamer tips reach values $\sim 5E_k$ [38–40, 43, 51, 123, 137]. This property of streamers is also valid for positive streamers propagating in low ambient electric fields comparable to $E^+_{\rm cr}$ [44, 54, 138, 139], similar to the ambient conditions for propagation of streamer coronas considered in [81]. Therefore, the observed optical luminosity in BJs and BSs arises from large electric fields existing in narrow regions of space around tips of small scale corona streamers constituting them.

Figure 3(*b*) presents a comparison of recent spectral observations reported in [23] discussed in section 3 and the calculated ratio of the combined red and green emissions to the total blue emission assuming the driving field to be $5E_k$. The comparison is performed using an optical model documented in [38, 81] and accounts for the atmospheric transmission and aircraft window corrections [23]. The resultant ratio is in agreement with the recent analysis of color TV frames associated with BSs reported in [23], which concluded that the combined red and green channel intensity constituted 7% of the total blue channel intensity.

Tong *et al* [105] investigated conditions for initiation of GJs above thunderclouds in terms of geometry, magnitude and altitude of thundercloud charges. Having considered the evidence that GJs are analogous to negative cloud-to-ionosphere discharges [17], Tong *et al* [105] associated the GJ process with an upward propagating negative streamer assuming that the pressure scaled thundercloud electric field should exceed the $E_k$ threshold in order to initiate the GJ. It was found that a negative charge −203.57 C with a spherically symmetric Gaussian distribution with scale 2 km placed at altitude of 16 km would satisfy this criteria at altitude 18.63 km. Tong *et al* [105] have not considered the leader process as a mechanism of GJs.

Tong *et al* [106] developed a 3D model of GJs in which upward propagation of a negative stepped leader is considered as a field controlled random growth process. The thundercloud is considered as one electrode igniting GJs and the ionosphere is assumed as the other. The discharge propagation concept of the model presented in [106] is similar to the fractal models developed previously in [81, 140]. In contrast to [105], in [106] the GJ in its entire altitude extent is considered as a negative leader phenomenon. The physics of stepping of negative leaders and their streamer zones has not been modeled in [106]. The model assumed the ground pressure value of the field inside the leader channel to be equal to $E_l = 1\,\mathrm{kV\,cm^{-1}}$. This field was reduced exponentially with scale height of 10 km at higher altitudes. The same criteria for initiation of GJs as in [105] based on the $E_k$ threshold were employed in [106]. After the leader initiation, it was allowed to propagate as soon as the field remained above the $E_{\mathrm{cr}}^-$ threshold. The ground pressure value of $E_{\mathrm{cr}}^-$ was assumed to be $12.5\,\mathrm{kV\,cm^{-1}}$ and scaled down exponentially with altitude with scale 8 km. The model produced propagation of the model channels up to 72 km altitude and agreed well with the overall picture of the observed GJs. The initiation criteria for GJs presented in [105, 106] based on the $E_k$ threshold have the same limitations as an earlier work by Pasko *et al* [102] as it requires unusually high magnitudes and concentrations of thundercloud charges. In [106] the altitude scaled values of the leader channel field $E_l$ and the leader propagation field $E_{\mathrm{cr}}^-$ become equal at 101 km altitude; however, implications of this relationship for terminal altitudes of GJs have not been discussed.

Raizer *et al* [107, 108] associated both BJs and GJs with streamer zone of a positive leader, which is postulated to be initiated above the positive charge center positioned at altitude 12 km. Raizer *et al* [107, 108] demonstrated that upward transfer of the high thundercloud potential by a leader channel to lower air density regions with a proportionally lower $E_{\mathrm{cr}}^+$ threshold for propagation of streamers allowed the sustainment of BJ streamers by moderate cloud charge of 50 C with radius 3 km. Raizer *et al* [107, 108] summarized the properties of streamer zones of leaders, which are of importance for the interpretation of observations of BJs and GJs. At ground level the three-body electron attachment time scale at fields around $E_{\mathrm{cr}}^+$ is $\sim 0.1\,\mu\mathrm{s}$ (see figure 1a in [38]) and at 18 km is $\sim 10\,\mu\mathrm{s}$ (increased inversely proportionally to the air density squared). Raizer *et al* [107, 108] explain that these short times of electron losses do not allow existences of long streamers, and a streamer zone of the leader is filled with a large number of streamers having different initiation times and lengths. The frequency with which a leader head emits streamers is estimated to be $\sim 10^9\,\mathrm{s^{-1}}$ [46, p 70], and only the 'younger' shorter streamers are connected directly to the leader tip, while 'old' advance through the streamer zone with substantially decayed electron density in their tails, and both types of streamers act collectively to establish a positive macroscopic charge density in the streamer zone of the positive leader maintaining the electric field at the $E_{\mathrm{cr}}^+$ level [107, 108]. The fractal model employed in [81] is not capable of resolving the physics of individual streamers (i.e. high fields in streamer tips) and links connecting grid points should not be directly interpreted as streamer channels. The fractal model is physically adequate for representation of an integral action of many streamers in the leader streamer zone in agreement with experiments [58, 57] and for modeling of volumetric properties of sprites and jets as explained in [81, 97, 136]. The existing video records of BJs and GJs are obtained with time resolution $\sim 16$ ms, which in accordance with recent high speed video observations of streamers in sprites [29, 30, 31] is about two orders of magnitude greater than $\sim 50\,\mu\mathrm{s}$ needed to resolve dynamics of individual streamer heads at altitudes $\sim 70$ km. It is highly likely therefore that the individual channels in figure 2 are produced by superposition and time averaging of many bright streamer heads as they moved through the camera's field of view. These sub-millisecond features of BJs and GJs remain unresolved in existing records.

In addition to disagreement with the inferred negative polarity of GJs, the limitation of models proposed in [81, 104, 107, 108] in support of the original idea expressed in [27] that jets correspond to the upward development of the pressure scaled streamer zone of a conventional leader is that they all postulate the presence of a leader near the cloud top without providing a link to experimentally documented charge distributions and lightning phenomenology in thunderstorms leading to the initiation and upward escape of the leader process from the thundercloud top. There is an experimental evidence that GJs are initiated as normal polarity intracloud lightning discharges between upper positive and lower negative charge centers [65, 141] and the models advanced in [81, 104, 107, 108] do not reflect related scenarios.

Recently, Krehbiel *et al* [65] discussed the charge imbalances in thunderstorms as a fundamental condition allowing propagation of leaders downward as CG lightning or upward as jet discharges, therefore demonstrating that upward discharges are analogous to cloud-to-ground lightning and providing a unified view on how lightning escapes from a thundercloud. Krehbiel *et al* [65] note that in accordance with the existing experimental evidence the lightning initiation happens between adjacent charge regions of different polarities where the electric field is maximum. If the negative and positive charge centers are approximately equal in magnitude the bi-directional discharge propagates in the form of positive leaders inside the negative charge region and in the form of negative leaders inside the positive charge region [35]. In this situation the leader system, which is assumed to be overall equipotential and neutral, remains at nearly zero potential [35]. Krehbiel *et al* [65] demonstrate that when the two charges are not balanced the leader potential can be significantly shifted in the direction defined by the charge with dominant magnitude and the propagation of the leader becomes essentially independent of the weaker charge center, allowing it to penetrate through the weaker charge center and to escape from the thundercloud. Krehbiel *et al* [65] present a combination of observational and modeling results that indicate two principal ways in which upward discharges can be produced. The related experimental results have already been reviewed in section 3. The modeling presented in [65] indicates that BJs 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. GJs are indicated to begin as a normal intracloud discharge between dominant mid-level charge and a screening-depleted upper-level charge, which continues to propagate out of the top of the storm [65]. Figure 4 summarizes the results of simulating different types of discharges in normally electrified storms from [65] using a lightning model [35], which satisfies a hypothesis of equipotentiality and overall neutrality of the discharge [142, 143]. The type of discharge 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 (figure 4(*a*)) [65]. The negative -CGs (figures 4(*b*) and (*e*)) occur as descending precipitation generates a lower positive charge [88] or as the storm accumulates a net negative charge and can go either directly to ground or indirectly as a bolt-from-the-blue discharge [65]. The negative -GJs (figure 4(*f*)) provide an alternate way of relieving the mid-level negative charge, by discharging it to the upper atmosphere rather than to the ground [65]. The positive +BJs do the opposite, namely, transport positive charge upward (figure 4(*d*)) [65].

Results presented in [65] provide experimentally substantiated mechanisms of escape of lightning leaders from cloud tops complementing the previous theoretical works [27, 81, 104, 106–108]. The application of ideas advanced in [107, 108] concerning the possibility of mapping high potentials at the cloud top to higher altitudes using conducting leaders depends on the possibility of sustaining the leader process at low air pressures at high altitude. The understanding of the streamer-to-leader transition and the development of numerical parametrizations of streamer zones of lightning leaders, especially under low air pressure conditions, represent currently unsolved problems [36, 64]. The general scaling of the Joule heating time scale in the streamer channels as a function of the air density can be deduced

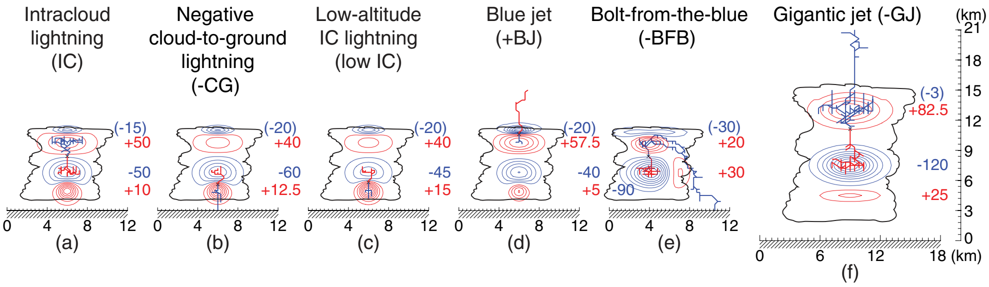


**Figure 4.** Simulated discharges illustrating the different known and postulated lightning types in a normally electrified storm [65]. (*a*)–(*f*) The contours and numbers with signs indicate negative and positive charge regions and charge amounts (in C), each assumed to have a Gaussian spatial distribution. A partially analogous set of discharges occurs or would be predicted to occur in storms having inverted electrical structures (see figure S5 in [65, Supplementary Information]). Reprinted from [65] by permission from *Nature Geoscience*.

from similarity analysis to be inversely proportional to the square of air density [36, 144, 145]. Therefore, it is expected that the heating processes and resulting streamer-to-leader transition should be delayed with the reduction in air pressure and it should be possible to define a set of conditions (i.e. altitude range, reduced electric field $E/N$, etc) for which the transition becomes impossible. The appearance of some BJs and GJs (see figure 2, figure 1 in [23] and figure 10 in [81]) is suggestive of a transition from hot lightning channels to a cold streamer dominated region at higher altitudes. In terms of negative leader phenomenology discussed in section 2, figure 2(*c*) showing moment of attachment of GJ to the lower ionospheric boundary can be interpreted as the 'final jump stage', when the leader streamer zone makes contact with the opposite electrode [56, p 212]. This stage may also have some resemblance to the negative corona flash stage of negative leader development discussed in section 2. The range of observed speeds during the final jump, $5\times10^4$ m s$^{-1}$ to $10^6$ m s$^{-1}$ [56, p 212], is similar to the range of speeds, from $5\times10^4$ m s$^{-1}$ to more than $2\times10^6$ m s$^{-1}$, reported in [16]. The bright persistent channel below ∼40 km altitude in panels (*e*) through (*i*) in figure 2, designated as a trailing jet in [17], can be interpreted as an attempt of the negative leader to form a next step, which has not succeeded (possibly due to a fast dielectric relaxation response of a conducting atmosphere or a lengthening of the heating time scales at low air pressures). As discussed above, at least 100 times better time resolution is required to resolve many missing details of the jet dynamics in figure 2.

Whether BJs have long-lived by-products leading to long-term consequences of their occurrence was questioned soon after their discovery [146, 147]. Chemical transformations in the ozone layer due to BJs have been numerically simulated [148], where perturbations of nitric oxide and ozone content due to a single BJ 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 [148].

Lehtinen and Inan [149] utilized a model of stratospheric/lower ionospheric chemistry to demonstrate that substantial ionization associated with GJs may persist more than 10 min. The results indicate an initial rapid (few seconds) recovery due to electron attachment, followed by a long enduring recovery (>10 min) determined by the time scale of mutual neutralization of negative and positive ions [149]. Such recovery signatures may be observable in perturbations of subionospherically propagating VLF (3–30 kHz) long-range communication signals [149].

Recent observations and theoretical analysis showing that BJs and GJs have small scale streamer structure allow us to make some additional comments as to their expected chemical effects. The non-thermal streamer plasma at atmospheric pressure with several electron-volt electrons embedded in ambient temperature air is of practical interest as it provides a good source of highly reactive species used for chemical treatment of hazardous and toxic pollutants [150]. Due to the ability of streamer filaments to produce high electric fields around their tips, the non-thermal streamer plasmas easily generate electrons with energies sufficient to dissociate oxygen molecules. The dissociation initiates a chain of reactions leading to the formation of ozone in air, the process which has been used for industrial ozone production for over a century [150]. Due to the dramatic reduction in the air pressure at high altitudes above thunderstorms, the same streamers, which develop on time scales of several nanoseconds and possessing diameters of a fraction of millimeter at ground level, appear as many kilometer long channels with diameters of the order of hundred meters and formation time of several milliseconds, easily observable above thunderclouds by low-light imaging systems deployed hundreds of kilometers away [10, 16, 17]. These streamers preserve their ability to produce highly active chemical species [151–154] and can effectively treat thousands of cubic kilometers of atmosphere in a single event. The branching observed in atmospheric TLE discharges is also known, but not the fully understood property of streamers at ground pressure, which is currently recognized as an important parameter control which is desirable for effective chemical treatment of large gas volumes [155].

Although perturbations of atmospheric chemistry are possible in localized volumes affected by BJs and GJs, their effects on regional and global scales have not yet been quantified. Rodger *et al* [156] recently reported a study making use of night time observations of $NO_2$ by the GOMOS instrument to test whether TLEs are producing significant $NO_x$ enhancements in the middle atmosphere on a regional scale. Comparing regional variations of $NO_2$ with 2–3 order of magnitude variations in lightning activity these authors show that within the detection levels of the instrument there is no significant impact of TLEs, including BJs and GJs, upon $NO_x$ levels in the stratosphere and mesosphere (20–70 km) [156]. This particular study therefore shows that variation in $NO_x$ due to TLEs does not appear to be significant on regional scales or beyond.

Additional consequences of BJs and GJs may include effects on the global electric circuit, in which the Earth-ionosphere potential difference of $\sim$300 kV is predominantly driven by upward currents from thunderstorms [16, 157–161]. Video recordings showing jet events extending from the cloud tops to the ionosphere [16, 17] may indicate that these events play a larger role in the global electric circuit than previously expected. Krehbiel *et al* [65] note that positive BJs contribute to the charging of the global electric circuit, while negative GJs discharge the circuit. Knowing how frequently these events occur will help to understand their contribution to the global electric circuit.

## 5. Conclusions

We have presented a review of the phenomenology and physical mechanisms of BSs, BJs and GJs. An attempt was made to summarize the available experimental data on morphological features of jet events and interpretation of these features in the context of known phenomenology of leader and streamer discharges documented in atmospheric pressure experiments. We have also reviewed some of the modeling efforts related to BSs, BJs and GJs. Finally, we identified a need for high speed imaging of the jet phenomena and outlined some presently unsolved problems in the theory of BSs, BJs and GJs, including the definite need for better understanding of the streamer-to-leader transition and the development of numerical parametrizations of streamer zones of lightning leaders of different polarities under low air pressure conditions.

## Acknowledgments

This research was supported by NSF grants ATM-0734083 and ATM-0741589 to Penn State University. The author thanks C Hidalgo, P Lalousis, S Moustaizis, F Massines and members of the Program Committee of the 35th EPS Plasma Physics Conference for the invitation to write this paper and to present a plenary lecture at the conference.

## References

[1] Sentman D D, Wescott E M, Osborne D L, Hampton D L and Heavner M J 1995 Preliminary results from the Sprites94 campaign: red sprites *Geophys. Res. Lett.* **22** 1205–8
[2] Neubert T 2003 On sprites and their exotic kin *Science* **300** 747–9
[3] Pasko V P 2003 Electric jets *Nature* **423** 927–9
[4] Fullekrug M, Mareev E A and Rycroft M J 2006 *Sprites, Elves and Intense Lightning Discharges* (*NATO Science Series II: Mathematics, Physics and Chemistry* vol 225) (Heidleberg: Springer)
[5] Franz R C, Nemzek R J and Winckler J R 1990 Television image of a large upward electric discharge above a thunderstorm system *Science* **249** 48
[6] Wescott E M, Sentman D, Osborne D, Hampton D and Heavner M 1995 Preliminary results from the Sprites94 aircraft campaign: II. Blue jets *Geophys. Res. Lett.* **22** 1209–12
[7] Lyons W A, Nelson T E, Armstrong R A, Pasko V P and Stanley M A 2003 Upward electrical discharges from thunderstorm tops *Bull. Am. Meteorol. Soc.* **84** 445–54
[8] Lyons W A 1996 Sprite observations above the U.S. high plains in relation to their parent thunderstorm systems *J. Geophys. Res.* **101** 29641–52
[9] Stanley M, Krehbiel P, Brook M, Moore C, Rison W and Abrahams B 1999 High speed video of initial sprite development *Geophys. Res. Lett.* **26** 3201–4
[10] Gerken E A, Inan U S and Barrington-Leigh C P 2000 Telescopic imaging of sprites *Geophys. Res. Lett.* **27** 2637–40
[11] Boeck W L, Vaughan O H, Blakeslee R J, Vonnegut B and Brook M 1992 Lightning induced brightening in the airglow layer *Geophys. Res. Lett.* **19** 99
[12] Fukunishi H, Takahashi Y, Kubota M, Sakanoi K, Inan U S and Lyons W A 1996 Elves: lightning-induced transient luminous events in the lower ionosphere *Geophys. Res. Lett.* **23** 2157–60
[13] Inan U S, Barrington-Leigh C, Hansen S, Glukhov V S, Bell T F and Rairden R 1997 Rapid lateral expansion of optical luminosity in lightning-induced ionospheric flashes referred to as 'elves' *Geophys. Res. Lett.* **24** 583–6
[14] Mende S B, Frey H U, Hsu R R, Su H T, Chen A B, Lee L C, Sentman D D, Takahashi Y and Fukunishi H D 2005 region ionization by lightning-induced EMP *J. Geophys. Res.* **110** A11312
[15] Frey H U, Mende S B, Cummer S A, Chen A B, Hsu R R, Su H T, Chang Y S, Adachi T, Fukunishi H and Takahashi Y 2005 Beta-type stepped leader of elve-producing lightning *Geophys. Res. Lett.* **32** L13824
[16] Pasko V P, Stanley M A, Matthews J D, Inan U S and Wood T G 2002 Electrical discharge from a thundercloud top to the lower ionosphere *Nature* **416** 152–4
[17] Su H T, Hsu R R, Chen A B, Wang Y C, Hsiao W S, Lai W C, Lee L C, Sato M and Fukunishi H 2003 Gigantic jets between a thundercloud and the ionosphere *Nature* **423** 974–6
[18] Hsu R R *et al* 2005 Gigantic jet observation by the ISUAL payload of FORMOSAT-2 satellite *Eos Trans. Am. Geophys. Union* **86** (Fall Meet. Suppl., Abstract AE23A-0992)
[19] Fukunishi H, Hiraki Y, Adachi T, Tong L and Nanbu K 2005 Occurrence conditions for gigantic jets connecting the thundercloud and the ionosphere *Eos Trans. Am. Geophys. Union* **86** (Fall Meet. Suppl., Abstract AE11A-02)
[20] Kuo C L, Chen A B, Hsu R R, Su H T, Lee L C, Mende S B, Frey H U, Fukunishi H and Takahashi Y 2007 Analysis of ISUAL recorded gigantic jets *Workshop on Streamers, Sprites, Leaders, Lightning: from Micro- to Macroscales (Lorentz Center, Leiden University, 8–12 October 2007)*
[21] van der Velde O A, Lyons W A, Nelson T E, Cummer S A, Li J and Bunnell J 2007 Analysis of the first gigantic jet recorded over continental North America *J. Geophys. Res.* **112** D20104
[22] Wescott E M, Sentman D D, Heavner M J, Hampton D L and Vaughan O H Jr 1998 Blue jets: their relationship to lightning and very large hailfall, and their physical mechanisms for their production *J. Atmos. Sol.-Terr. Phys.* **60** 713–24

[23] Wescott E M, Sentman D D, Stenbaek-Nielsen H C, Huet P, Heavner M J, and Moudry D R 2001 New evidence for the brightness and ionization of blue jets and blue starters *J. Geophys. Res.* **106** 21549–54

[24] Wescott E M, Sentman D D, Heavner M J, Hampton D L, Osborne D L and Vaughan O H Jr 1996 Blue starters: brief upward discharges from an intense Arkansas thunderstorm *Geophys. Res. Lett.* **23** 2153–6

[25] Boeck W L, Vaughan O H, Blakeslee R J, Vonnegut B, Brook M and McKune J 1995 Observations of lightning in the stratosphere *J. Geophys. Res.* **100** 1465–75

[26] Heavner M J 2000 Optical spectroscopic observations of sprites, blue jets and elves: inferred microphysical processes and their macrophysical implications *PhD Thesis* University of Alaska Fairbanks, Fairbanks, AK

[27] Petrov N I and Petrova G N 1999 Physical mechanisms for the development of lightning discharges between a thundercloud and the ionosphere *Tech. Phys.* **44** 472–5

[28] Gerken E A and Inan U S 2005 Streamers and diffuse glow observed in upper atmospheric electrical discharges *IEEE Trans. Plasma Sci.* **33** 282–3

[29] Cummer S A, Jaugey N C, Li J B, Lyons W A, Nelson T E and Gerken E A 2006 Submillisecond imaging of sprite development and structure *Geophys. Res. Lett.* **33** L04104

[30] McHarg M G, Stenbaek-Nielsen H C and Kanmae T 2007 Streamer development in sprites *Geophys. Res. Lett.* **34** L06804

[31] Stenbaek-Nielsen H C, McHarg M G, Kanmae T and Sentman D D 2007 Observed emission rates in sprite streamer heads *Geophys. Res. Lett.* **34** L11105

[32] Pasko V P 2007 Red sprite discharges in the atmosphere at high altitude: the molecular physics and the similarity with laboratory discharges *Plasma Sources Sci. Technol.* **16** S13–S29

[33] Ebert U, Montijn C, Briels T M P, Hundsdorfer W, Meulenbroek B, Rocco A and van Veldhuizen E M 2006 The multiscale nature of streamers *Plasma Sources Sci. Technol.* **15** S118–S129

[34] Massines F, Gherardi N, Naude N and Segur P 2005 Glow and Townsend dielectric barrier discharge in various atmosphere *Plasma Phys. Control. Fusion* **47** B577–88

[35] Riousset J A, Pasko V P, Krehbiel P R, Thomas R J and Rison W 2007 Three-dimensional fractal modeling of intracloud lightning discharge in a New Mexico thunderstorm and comparison with lightning mapping observations *J. Geophys. Res.* **112** D15203

[36] Pasko V P 2006 Theoretical modeling of sprites and jets *Sprites, Elves and Intense Lightning Discharges* (*NATO Science Series II: Mathematics, Physics and Chemistry* vol 225) ed Füllekrug M *et al* (Springer: Heidleberg) pp 253–311

[37] Raizer Y P 1991 *Gas Discharge Physics* (New York: Springer)

[38] Liu N Y and Pasko V P 2004 Effects of photoionization on propagation and branching of positive and negative streamers in sprites *J. Geophys. Res.* **109** A04301

[39] Dhali S K and Williams P F 1987 Two-dimensional studies of streamers in gases *J. Appl. Phys.* **62** 4696–707

[40] Vitello P A, Penetrante B M and Bardsley J N 1994 Simulation of negative-streamer dynamics in nitrogen *Phys. Rev.* E **49** 5574–98

[41] Rocco A, Ebert U and Hundsdorfer W 2002 Branching of negative streamers in free flight *Phys. Rev.* E **66** 035102(R)

[42] Allen N L and Ghaffar A 1995 The conditions required for the propagation of a cathode-directed positive streamer in air *J. Phys. D: Appl. Phys.* **28** 331–7

[43] Babaeva N Y and Naidis G V 1997 Dynamics of positive and negative streamers in air in weak uniform electric fields *IEEE Trans. Plasma Sci.* **25** 375–9

[44] Morrow R and Lowke J J 1997 Streamer propagation in air *J. Phys. D: Appl. Phys.* **30** 614–27

[45] Gallimberti I, Bacchiega G, Bondiou-Clergerie A and Lalande P 2002 Fundamental processes in long air gap discharges *C. R. Physique* **3** 1335–59

[46] Bazelyan E M and Raizer Y P 2000 *Lightning Physics and Lightning Protection* (Bristol/Philadelphia: Institute of Physics Publishing)

[47] Raizer Y P, Milikh G M, Shneider M N and Novakovski S V 1998 Long streamers in the upper atmosphere above thundercloud *J. Phys. D: Appl. Phys.* **31** 3255–64

[48] Briels T M P, Kos J, van Veldhuizen E M and Ebert U 2006 Circuit dependence of the diameter of pulsed positive streamers in air *J. Phys. D: Appl. Phys.* **39** 5201–10

[49] Loeb L B and Meek J M 1940 The mechanism of spark discharge in air at atmospheric pressure *J. Appl. Phys.* **11** 438–47

[50] Vitello P A, Penetrante B M and Bardsley J N 1993 Multidimensional modeling of the dynamic morphology of streamer coronas *Non-Thermal Plasma Techniques for Pollution Control* (*NATO ASI Series* vol G34, part A) ed B M Penetrante and Schultheis S E (New York: Springer) pp 249–71

[51] Bourdon A, Pasko V P, Liu N Y, Celestin S, Segur P and Marode E 2007 Efficient models for photoionization produced by non-thermal gas discharges in air based on radiative transfer and the Helmholtz equations *Plasma Sources Sci. Technol.* **16** 656–78
[52] Segur P, Bourdon A, Marode E, Bessieres D and Paillol J H 2006 The use of an improved Eddington approximation to facilitate the calculation of photoionization in streamer discharges *Plasma Sources Sci. Technol.* **15** 648–60
[53] Luque A, Ebert U, Montijn C and Hundsdorfer W 2007 Photoionization in negative streamers: fast computations and two propagation modes *Appl. Phys. Lett.* **90** 081501
[54] Liu N Y, Celestin S, Bourdon A, Pasko V P, Segur P and Marode E 2007 Application of photoionization models based on radiative transfer and the Helmholtz equations to studies of streamers in weak electric fields *Appl. Phys. Lett.* **91** 211501
[55] Liu N Y, Celestin S, Bourdon A, Pasko V P, Segur P and Marode E 2008 Photoionization and optical emission effects of positive streamers in air at ground pressure *IEEE Trans. Plasma Sci.* **36** doi:10.1109/TPS.2008.927088
[56] Bazelyan E M and Raizer Y P 1998 *Spark Discharge* (New York, NY: Chemical Rubber Company Press)
[57] Petrov N I, Avanskii V R and Bombenkova N V 1994 Measurement of the electric field in the streamer zone and in the sheath of the channel of a leader discharge *Tech. Phys.* **39** 546–51
[58] Petrov N I and Petrova G N 1993 Physical mechanisms for intracloud lightning discharges *Tech. Phys.* **38** 287–90
[59] Moore C B, Eack K B, Aulich G D and Rison W 2001 Energetic radiation associated with lightning stepped-leaders *Geophys. Res. Lett.* **28** 2141–4
[60] Dwyer J R *et al* 2005 X-ray bursts associated with leader steps in cloud-to-ground lightning *Geophys. Res. Lett.* **32** L01803
[61] Fishman G J *et al* 1994 Discovery of intense gamma-ray flashes of atmospheric origin *Science* **264** 1313
[62] Smith D M, Lopez L I, Lin R P and Barrington-Leigh C P 2005 Terrestrial gamma-ray flashes observed up to 20 MeV *Science* **307** 1085–8
[63] Moss G D, Pasko V P, Liu N Y and Veronis G 2006 Monte Carlo model for analysis of thermal runaway electrons in streamer tips in transient luminous events and streamer zones of lightning leaders *J. Geophys. Res.* **111** A02307
[64] Pasko V P and Bourdon A 2007 Air heating associated with transient luminous events *Proc. 28th Int. Conf. on Phenomena in Ionized Gases (ICPIG)* number 5P07-12 (*Prague, Czech Republic, 15–20 July 2007*) (Institute of Plasma Physics) pp 1908–11
[65] Krehbiel P R, Riousset J A, Pasko V P, Thomas R J, Rison W, Stanley M A and Edens H E 2008 Upward electrical discharges from thunderstorms *Nature Geoscience* **1** 233–7
[66] Toynbee H and Mackenzie T 1886 Meteorological phenomena *Nature* **33** 245
[67] Everett W H 1903 Rocket lightning *Nature* **68** 599
[68] Boys C V 1926 Progressive lightning *Nature* **118** 749–50
[69] Wright J B 1950 A thunderstorm in the tropics *Weather* **5** 230
[70] Wood C A 1951 Unusual lightning *Weather* **6** 64
[71] Ashmore S E 1950 Unusual lightning *Weather* **5** 331
[72] Wilson C T R 1956 A theory of thundercloud electricity *Proc. R. Soc. Lond. Ser.* A **236** 297–317
[73] Vonnegut B 1980 Cloud-to-stratosphere lightning *Weather* **35** 59–60
[74] Vaughan O H Jr and Vonnegut B 1982 Lightning to the ionosphere? *Weatherwise* **35** 70–1
[75] Vaughan O H Jr and Vonnegut B 1989 Recent observations of lightning discharges from the top of a thundercloud into the clear air above *J. Geophys. Res.* **94** 13179–82
[76] Gales D 1982 Another account *Weatherwise* **35** 72
[77] Corliss C R 1983 *Handbook of Unusual Natural Phenomena* (Garden City, NY: Doubleday)
[78] Vonnegut B, Vaughan O H Jr and Brook M 1989 Nocturnal photographs taken from a U-2 airplane looking down on tops of clouds illuminated by lightning *Bull. Am. Meteorol. Soc.* **70** 1263–71
[79] Hammerstrom J H 1993 Mystery lightning *Aviation Week and Space Technol.* August 30 1993 6
[80] Rodger C J 1999 Red sprites, upward lightning and VLF perturbations *Rev. Geophys.* **37** 317–36
[81] Pasko V P and George J J 2002 Three-dimensional modeling of blue jets and blue starters *J. Geophys. Res.* **107** 1458
[82] Boeck W L, Vaughan O H, Blakeslee R J, Vonnegut B and Brook M 1998 The role of the space shuttle videotapes in the discovery of sprites, jets and elves *J. Atmos. Sol.-Terr. Phys.* **60** 669–77
[83] Uman M A 2001 *The Lightning Discharge* (Mineola, NY: Dover)
[84] Rison W, Thomas R J, Krehbiel P R, Hamlin T and Harlin J 1999 A GPS-based three-dimensional lightning mapping system: initial observations in central New Mexico *Geophys. Res. Lett.* **26** 3573–6

[85] Lang T J *et al* 2004 The severe thunderstorm electrification and precipitation study *Bull. Am. Meteorol. Soc.* **85** 1107–25
[86] Behnke S A, Thomas R J, Krehbiel P R and Rison W 2005 Initial leader velocities during intracloud lightning: possible evidence for a runaway breakdown effect *J. Geophys. Res.* **110** D10207
[87] Krehbiel P R 1986 The electrical structure of thunderstorms *The Earth's Electrical Environment* (Washington, DC: National Academy Press) pp 90–113
[88] Williams E R 1989 The tripolar structure of thunderstorms *J. Geophys. Res.* **94** 13151–67
[89] Thomas R J, Krehbiel P R, Rison W, Hamlin T, Harlin J and Shown D 2001 Observations of VHF source powers radiated by lightning *Geophys. Res. Lett.* **28** 143–6
[90] Rumi G C 1957 VHF radar echoes associated with atmospheric phenomena *J. Geophys. Res.* **62** 547
[91] Roussel-Dupré R A and Blanc E 1997 HF echoes from ionization potentially produced by high-altitude discharges *J. Geophys. Res.* **102** 4613–22
[92] Showen R L and Slingeland A 1998 Measuring lightning-induced ionospheric effects with incoherent scatter radar or with cross-modulation *J. Atmos. Sol.-Terr. Phys.* **60** 951
[93] Tsunoda R T, Livingston R C, Buonocore J J, Lyons W A, Nelson T E and Kelley M C 1998 Evidence of a high-altitude discharge process responsible for radar echoes at 24.4 MHz *J. Atmos. Sol.-Terr. Phys.* **60** 957–64
[94] Groves K M, Quinn J M, Shinn E R, Ning P and Cox M R 1998 An upper limit on ionization in sprites *Eos Trans. Am. Geophys. Union* **79** F165
[95] Groves K M, Quinn J M, Shinn E R and Ning P 1998 An upper bound on ionization associated with sprites *National Radio Science Meeting, Program and Abstracts (Boulder, CO, USA, 5–8 January)* p 152
[96] Siefring C L, Morrill J S, Sentman D D, Moudry D R, Wescott E M, Heavner M J, Osborne D L and Bucsela E J 1999 Do sprites sometimes connect to the cloud tops? *Eos Trans. Am. Geophys. Union* **80** F225
[97] Pasko V P, Inan U S and Bell T F 2001 Mesosphere-troposphere coupling due to sprites *Geophys. Res. Lett.* **28** 3821–4
[98] Lyons W A, Stanley M, Nelson T E and Taylor M 2000 Sprites, elves, halos, trolls and blue starters above the STEPS domain *Eos Trans. Am. Geophys. Union* **81** F131
[99] Moudry D R 2003 The dynamics and morphology of sprites *PhD Thesis* University of Alaska Fairbanks, Fairbanks, AK
[100] Stenbaek-Nielsen H C, Moudry D R, Wescott E M, Sentman D D and Sao Sabbas F T 2000 Sprites and possible mesospheric effects *Geophys. Res. Lett.* **27** 3829–32
[101] Marshall R A and Inan U S 2007 Possible direct cloud-to-ionosphere current evidenced by sprite-initiated secondary TLEs *Geophys. Res. Lett.* **34** L05806
[102] Pasko V P, Inan U S and Bell T F 1996 Blue jets produced by quasi-electrostatic pre-discharge thundercloud fields *Geophys. Res. Lett.* **23** 301–4
[103] Sukhorukov A I, Mishin E V, Stubbe P and Rycroft M J 1996 On blue jet dynamics *Geophys. Res. Lett.* **23** 1625–8
[104] Pasko V P, Inan U S and Bell T F 1999 Large scale modeling of sprites and blue jets *Eos Trans. Am. Geophys. Union* **80** F218 (Fall Meet. Suppl., Abstract A42E-11)
[105] Tong L Z, Nanbu K and Fukunishi H 2004 Numerical analysis of initiation of gigantic jets connecting thunderclouds to the ionosphere *Earth Planets Space* **56** 1059–65
[106] Tong L Z, Nanbu K and Fukunishi H 2005 Simulation of gigantic jets propagating from the top of thunderclouds to the ionosphere *Earth Planets Space* **57** 613–17
[107] Raizer Y P, Milikh G M and Shneider M N 2006 On the mechanism of blue jet formation and propagation *Geophys. Res. Lett.* **33** L23801
[108] Raizer Y P, Milikh G M and Shneider M N 2007 Leader–streamers nature of blue jets *J. Atmos. Sol.-Terr. Phys.* **69** 925–38
[109] Roussel-Dupré R A and Gurevich A V 1996 On runaway breakdown and upward propagating discharges *J. Geophys. Res.* **101** 2297–312
[110] Taranenko Y and Roussel-Dupré R 1996 High altitude discharges and gamma-ray flashes: a manifestation of runaway air breakdown *Geophys. Res. Lett.* **23** 571–4
[111] Yukhimuk V, Roussel-Dupré R A and Symbalisty E M D 1998 Optical characteristics of blue jets produced by runaway air breakdown, simulation results *Geophys. Res. Lett.* **25** 3289–92
[112] Shaw G E 1998 Above cloud electrical discharges: the effect of aerosol transport *Geophys. Res. Lett.* **25** 4317–20
[113] Kutsyk I M and Babich L P 1999 Spatial structure of optical emissions in the model of gigantic upward atmospheric discharges with participation of runaway electrons *Phys. Lett.* A **253** 75–82
[114] Babich L P, Kudryavtsev A Y, Kudryavtseva M L and Kutsyk I M 2008 Atmospheric gamma-ray and neutron flashes *J. Exp. Theor. Phys.* **106** 65–76

[115] Rowland H L 1998 Theories and simulations of elves, sprites and blue jets *J. Atmos. Sol.-Terr. Phys.* **60** 831–44

[116] Sukhorukov A I and Stubbe P 1998 Problems of blue jet theories *J. Atmos. Sol.-Terr. Phys.* **23** 725–32

[117] Mishin E V and Milikh G M 2008 Blue jets: upward lightning *Space Sci. Rev.* **137** doi:10.1007/s11214-008-9346-z

[118] Lehtinen N G, Bell T F and Inan U S 1999 Monte Carlo simulation of runaway MeV electron breakdown with application to red sprites and terrestrial gamma ray flashes *J. Geophys. Res.* **104** 24699–712

[119] Lehtinen N G, Bell T F and Inan U S 2001 Effects of thunderstorm-driven runaway electrons in the conjugate hemisphere: purple sprites, ionization enhancements and gamma rays *J. Geophys. Res.* **106** 28841–56

[120] Gurevich A V, Milikh G M and Roussel-Dupré R A 1992 Runaway electron mechanism of air breakdown and preconditioning during a thunderstorm *Phys. Lett.* A **165** 463–8

[121] Gurevich A V and Zybin K P 2001 Runaway breakdown and electric discharges in thunderstorms *Phys. Usp.* **44** 1119–40

[122] Gurevich A V and Zybin K P 2005 Runaway breakdown and the mysteries of lightning *Phys. Today* **58** 37–43

[123] Pasko V P, Inan U S and Bell T F 1998 Spatial structure of sprites *Geophys. Res. Lett.* **25** 2123–6

[124] Pasko V P 2004 Correction to Three-dimensional modeling of blue jets and blue starters *J. Geophys. Res.* **109** A09311

[125] Hale L C, Croskey C L and Mitchell J D 1981 Measurements of middle-atmosphere electric fields and associated electrical conductivities *Geophys. Res. Lett.* **8** 927–30

[126] Hale L C 1994 Coupling of ELF/ULF energy from lightning and MeV particles to the middle atmosphere, ionosphere and global circuit *J. Geophys. Res.* **99** 21089–96

[127] Holzworth R H, McCarthy M P, Thomas J N, Chin J, Chinowsky T M, Taylor M J and Pinto O Jr 2005 Strong electric fields from positive lightning strokes in the stratosphere *Geophys. Res. Lett.* **32** L04809

[128] Thomas J N, Holzworth R H, McCarthy M P and Pinto O Jr 2005 Predicting lightning-driven quasi-electrostatic fields at sprite altitudes using in situ measurements and a numerical model *Geophys. Res. Lett.* **32** L10809

[129] Blakeslee R J, Christian H J and Vonnegut B 1989 Electrical measurements over thunderstorms *J. Geophys. Res.* **94** 13135–40

[130] Greifinger C and Greifinger P 1976 Transient ULF electric and magnetic fields following a lightning discharge *J. Geophys. Res.* **81** 2237–47

[131] Hale L C and Baginski M E 1987 Current to the ionosphere following a lightning stroke *Nature* **329** 814–16

[132] Pasko V P, Inan U S, Bell T F and Taranenko Y N 1997 Sprites produced by quasi-electrostatic heating and ionization in the lower ionosphere *J. Geophys. Res.* **102** 4529–61

[133] Pasko V P, Inan U S, Bell T F and Reising S C 1998 Mechanism of ELF radiation from sprites *Geophys. Res. Lett.* **25** 3493–6

[134] Pasko V P, Inan U S and Bell T F 1999 Mesospheric electric field transients due to tropospheric lightning discharges *Geophys. Res. Lett.* **26** 1247–50

[135] Niemeyer L, Ullrich L and Wiegart N 1989 The mechanism of leader breakdown in electronegative gases *IEEE Trans. Electr. Insul.* **24** 309–24

[136] Pasko V P, Inan U S and Bell T F 2000 Fractal structure of sprites *Geophys. Res. Lett.* **27** 497–500

[137] Kulikovsky A A 1997 The mechanism of positive streamer acceleration and expansion in air in a strong external field *J. Phys. D: Appl. Phys.* **30** 1515–22

[138] Grange F, Soulem N, Loiseau J F and Spyrou N 1995 Numerical and experimental-determination of ionizing front velocity in a dc point-to-plane corona discharge *J. Phys. D: Appl. Phys.* **28** 1619–29

[139] Liu N Y and Pasko V P 2006 Effects of photoionization on similarity properties of streamers at various pressures in air *J. Phys. D: Appl. Phys.* **39** 327–34

[140] Niemeyer L, Pietrono L and Wiesmann H J 1984 Fractal dimension of dielectric breakdown *Phys. Rev. Lett.* **52** 1033–6

[141] Mathews J D, Stanley M A, Pasko V P, Wood T G, Inan U S, Heavner M J and Cummer S A 2002 Electromagnetic signatures of the Puerto Rico blue jet and its parent thunderstorm *Eos Trans. Am. Geophys. Union* **83** (Fall Meet. Suppl., Abstract A62D-02) F91

[142] Kasemir H W 1960 A contribution to the electrostatic theory of a lightning discharge *J. Geophys. Res.* **65** 1873–8

[143] Mazur V and Ruhnke L H 1998 Model of electric charges in thunderstorms and associated lightning *J. Geophys. Res.* **103** 23299–308

[144] Achat S, Teisseyre Y and Marode E 1992 The scaling of the streamer-to-arc transition in a positive point-to-plane gap with pressure *J. Phys. D: Appl. Phys.* **25** 661–8

[145] Tardiveau P, Marode E, Agneray A and Cheaib M 2001 Pressure effects on the development of an electric discharge in non-uniform fields *J. Phys. D: Appl. Phys.* **34** 1690–6

[146] Sentman D D and Wescott E M 1995 Red sprites and blue jets: Thunderstorm-excited optical emissions in the stratosphere, mesosphere and ionosphere *Phys. Plasmas* **2** 2514–22

[147] Sentman D D and Wescott E M 1996 Red sprites and blue jets: High-altitude optical emissions linked to lightning *Eos Trans. Am. Geophys. Union* **77** 1–5

[148] Mishin E V 1997 Ozone layer perturbation by a single blue jet *Geophys. Res. Lett.* **24** 1919–22

[149] Lehtinen N G and Inan U S 2007 Possible persistent ionization caused by giant blue jets *Geophys. Res. Lett.* **34** L08804

[150] van Veldhuizen E M (ed) 2000 *Electrical Discharges for Environmental Purposes: Fundamentals and Applications* (New York: Nova Science)

[151] Enell C F *et al* 2008 Parameterisation of the chemical effect of sprites in the middle atmosphere *Ann. Geophys.* **26** 13–27

[152] Arnone E, Kero A, Dinelli B M, Enell C F, Arnold N F, Papandera E, Rodger C J, Carlotti M, Ridolfi M and Turunen E 2008 Seeking sprite-induced signatures in remotely sensed middle atmosphere $NO_2$ *Geophys. Res. Lett.* **35** L05807

[153] Sentman D D, Stenbaek-Nielsen H C, McHarg M G and Morrill J S 2008 Plasma chemistry of sprite streamers *J. Geophys. Res.* **113** D11112

[154] Gordillo-Vazquez F J 2008 Air plasma kinetics under the influence of sprites *J. Phys. D: Appl. Phys.* **41** at press

[155] van Veldhuizen E M and Rutgers W R 2002 Pulsed positive corona streamer propagation and branching *J. Phys. D: Appl. Phys.* **35** 2169–79

[156] Rodger C J, Seppala A and Clilverd M A 2008 Significance of transient luminous events to neutral chemistry: experimental measurements *Geophys. Res. Lett.* **35** L07803

[157] Bering E A, Few A A and Benbrook J R 1998 The global electric circuit *Phys. Today* **51** 24–30

[158] Rycroft M J, Israelsson S and Price C 2000 The global atmospheric electric circuit, solar activity and climate change *J. Atmos. Sol.-Terr. Phys.* **62** 1563–76

[159] Rycroft M J 2006 Electrical processes coupling the atmosphere and ionosphere: an overview *J. Atmos. Sol.-Terr. Phys.* **68** 445–56

[160] Tinsley B A 2008 The global atmospheric electric circuit and its effects on cloud microphysics *Rep. Prog. Phys.* **71** 066801

[161] Rycroft M J, Harrison R G, Nicoll K A and Mareev E A 2008 An overview of Earth's global electric circuit and atmospheric electricity *Space Sci. Rev.* **137** doi:10.1007/s11214-008-9368-6