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Recent advances in theory of transient luminous events

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[1] This paper presents an overview of the recent modeling efforts directed to the interpretation of observed features of transient luminous events termed sprites, blue jets, and gigantic jets. The primary emphasis is placed on interpretation of various emissions documented to date from sprites and comparison of exiting models with recent high-speed video and satellite-based observations of sprites. We also discuss the recently advanced theories of blue jet and gigantic jet discharges describing electrodynamic conditions, which facilitate escape of conventional lightning leaders from thundercloud tops and their upward propagation toward the ionosphere. The paper concludes with a brief survey of the recent literature on chemical and global electric circuit effects of sprite and jet discharges.

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1. Introduction

[2] Transient luminous events (TLEs) are large-scale optical events occurring at stratospheric and mesospheric/lower ionospheric altitudes, which are directly related to the electrical activity in underlying thunderstorms [e.g., *Sentman et al.*, 1995; *Neubert*, 2003; *Pasko*, 2003, and references therein]. Although eyewitness reports of TLEs above thunderstorms have been recorded for more than a century, the first image of one was captured in 1989, serendipitously during a test of a low-light television camera [*Franz et al.*, 1990]. Since then, several different types of TLEs above thunderstorms have been documented and classified with several types illustrated in Figure 1. These include "elves," which are lightning-induced flashes that can spread over 300 km laterally [*Boeck et al.*, 1992; *Fukunishi et al.*, 1996; *Inan et al.*, 1991, 1997; *Mende et al.*, 2005; *Cheng et al.*, 2007; *Frey et al.*, 2005; *Kuo et al.*, 2007]; "sprites" that develop at the base of the ionosphere and move rapidly downward at speeds up to 10,000 km/s [*Sentman et al.*, 1995; *Lyons*, 1996; *Stanley et al.*, 1999; *Gerken et al.*, 2000; *Cummer et al.*, 2006b; *McHarg et al.*, 2007; *Stenbaek-Nielsen et al.*, 2007; *Stenbaek-Nielsen and McHarg*, 2008]; "halos," which are brief descending glows with lateral extent 40–70 km, which sometimes (but not always) are observed to accompany or precede more structured sprites [*Barrington-Leigh et al.*, 2001; *Frey et al.*, 2007]; relatively slow-moving fountains of blue light, known as "blue jets," that emanate from the top of thunderclouds up to an altitude of 40 km [*Wescott et al.*, 1995; *Boeck et al.*, 1995; *Lyons et al.*, 2003]; and upward moving "gigantic jets," which establish a direct path of electrical contact between thundercloud tops and the lower ionosphere [*Pasko et al.*, 2002; *Su et al.*, 2003; *Pasko*, 2003; *Hsu et al.*, 2005; *Fukunishi et al.*, 2005; *van der Velde et al.*, 2007; *Kuo et al.*, 2009; *Cummer et al.*, 2009; C. L. Kuo et al., Analysis of ISUAL recorded gigantic jets, paper presented at Workshop on Streamers, Sprites, Leaders, Lightning: From Micro- to Macroscales, Lorentz Cent., Leiden Univ., Leiden, Netherlands, 2007]. The recent satellite-based surveys by ISUAL instrument on FORMOSAT-2 indicate that elves are the most dominant type of TLEs and estimate the global occurrence rates of sprites, halos, and elves to be ~1, ~1, and ~35 events/min, respectively [*Chen et al.*, 2008]. Analysis of emissions from elves conducted by *Mende et al.* [2005] indicate that elves produce significant ionization with an average electron density 210 cm^{-3} over region with 165 km diameter and 10 km vertical extent. VLF remote sensing of ionization produced by elves conducted by *Cheng et al.* [2007] indicated electron density enhancements of 460 cm^{-3} averaged over 220-km radius and 10-km high region. The analysis of a large database of TLEs collected by the ISUAL instrument indicate that sprites, halos, and elves have spatially averaged brightness 1.5, 0.3, and 0.17 MR, and the energy deposition 22, 14, and 19 MJ per event, respectively [*Kuo et al.*, 2008]. The global energy deposition rates in the upper atmosphere are estimated to be 22, 14, and 665 MJ min^{-1} from sprites, halos, and elves, respectively [*Kuo et al.*, 2008]. Owing to the high preset triggering level of ISUAL spectrophotometers and relatively large distances to events (≥3700 km), only elves produced by intense lightning discharges with high peak currents are detected [*Kuo et al.*, 2007]. Similarly, recent reports indicate exponential growth of optical luminosity of sprite streamers in time on sub-millisecond scales with very high sensitivity to the magnitude of applied electric fields [*Stenbaek-Nielsen et al.*, 2007; *Liu et al.*, 2009a]. It is likely, therefore, that many elves, sprites, and other types of TLE events remain subvisual and undetected by current observing schemes.

[3] The transient luminous events are arguably the most dramatic recent discovery in solar-terrestrial physics [*Fullekrug et al.*, 2006b]. During the 2 decades elapsed since the original

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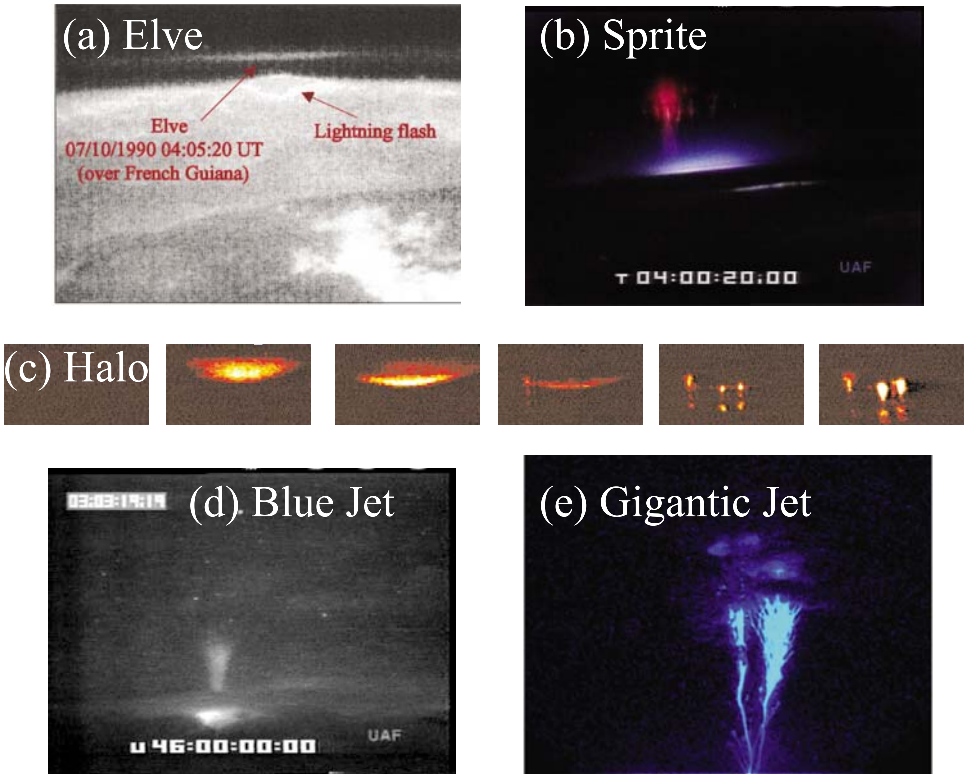

Figure 1. Lightning-related transient luminous events (TLEs): (a) elves [*Boeck et al.*, 1992]; (b) sprites [*Sentman et al.*, 1995]; (c) halos (2 ms sequence showing downward progression of halo before development of vertical sprite structure) [*Barrington-Leigh et al.*, 2001]; (d) blue jets [*Wescott et al.*, 1995]; and (e) gigantic jets [*Pasko et al.*, 2002]. Figures 1a, 1b, 1c, and 1d are reprinted from *Boeck et al.* [1992], *Sentman et al.* [1995], *Barrington-Leigh et al.* [2001], and *Wescott et al.* [1995], respectively. Figure 1e is reprinted from *Pasko et al.* [2002] by permission from Nature.

discovery in 1989 several hundred papers have been published in refereed scientific literature reflecting advances in this new and exciting research area, and related research activities culminated in a first book on TLEs that appeared in print in 2006 [*Fullekrug et al.*, 2006b]. Planetary atmospheric electricity aspects relevant to TLEs have been recently covered in the work of *Leblanc et al.* [2008]. Early theories of TLEs have been reviewed by *Rowland* [1998], *Sukhorukov and Stubbe* [1998], and *Wescott et al.* [1998]. The experimental and theoretical findings related to TLEs have been summarized in several extensive review articles [*Boeck et al.*, 1998; *Rodger*, 1999; *Inan*, 2002; *Lyons et al.*, 2003; *Pasko*, 2007, 2008; *Neubert et al.*, 2008; *Roussel-Dupre et al.*, 2008; *Mishin and Milikh*, 2008; *Ebert and Sentman*, 2008; *Siingh et al.*, 2008]. The goal of the present paper is to provide a limited overview of some of the most recent theoretical and modeling developments in studies related to sprites, blue jets, and gigantic jets.

2. Physical Mechanism and Modeling Sprites

2.1. Electrodynamic Conditions Leading to Formation of Sprites

[4] The possibility of large-scale gas discharge events above thunderclouds, which we currently know as sprite phenomenon, was first predicted in 1925 by the Nobel Prize winner C.T.R. Wilson [*Wilson*, 1925]. He first recognized that the relation between the thundercloud electric field which decreases with altitude r (Figure 2) as $\sim r^{-3}$ and the critical breakdown field E_k which falls more rapidly (being proportional to the exponentially decreasing gas density) leads to the result that "there will be a height above which the electric force due to the cloud exceeds the sparking limit" [*Wilson*, 1925]. Here, and in subsequent parts of this paper, E_k is used to denote the conventional breakdown threshold field defined by the equality of the ionization and dissociative attachment coefficients in air [*Raizer*, 1991, p. 135]. In the discussion which follows, we assume $E_k \simeq 32$ kV/cm at atmospheric pressure, which agrees with typical figures observed in centimeters-wide gaps [*Raizer*, 1991, p. 135] and also with the ionization and two-body attachment models used recently for streamer modeling in the work of *Liu and Pasko* [2004]. It should be noted that due to the finite atmospheric conductivity above thunderclouds the dipole field configuration shown in Figure 2 is realized at mesospheric altitudes only during very transient time periods, ~1–10 ms, following intense lightning discharges. This defines similarly transient nature of the observed sprite and halo phenomena [*Pasko et al.*, 1997; *Barrington-Leigh et al.*, 2001; *Pasko*, 2007, and references therein].

[5] Figure 3 shows model calculations of the vertical component of the electric field at altitudes 50, 60, 70, and 80 km directly above a positive lightning discharge that removes $Q = 200$ C of charge from altitude $h_Q = 10$ km in 1 ms

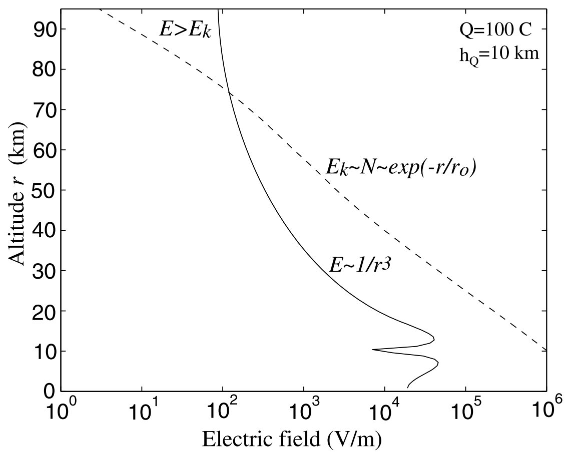

Figure 2. Physical mechanism of sprites [*Wilson*, 1925]: "While the electric force due to the thundercloud falls off rapidly as r increase, the electric force required to causing sparking (which for a given composition of the air is proportional to its density) falls off still more rapidly. Thus, if the electric moment of a cloud is not too small, there will be a height above which the electric force due to the cloud exceeds the sparking limit."

[*Pasko et al.*, 1997]. During a very transient time period of ~1 ms, mostly defined by atmospheric conductivity profile, the electric field can reach values on the order of the critical breakdown threshold field E_k at mesospheric/lower ionospheric altitudes (i.e., $E_k \simeq 217$ V/m and 48 V/m at 70 and 80 km, respectively). The quasi-static approximation employed here is valid for relatively slow source variations with timescales >0.5 ms [*Pasko et al.*, 1999b].

[6] The charge moment change Qh_Q (i.e., charge removed by lightning Q times the altitude from which it was removed h_Q) represents the key parameter which is used in current sprite literature to measure the strength of lightning in terms of sprite production potential [*Cummer et al.*, 1998; *Hu et al.*, 2002, 2007; *Li et al.*, 2008; *Cummer*, 2003; *Cummer and Lyons*, 2004, 2005; *Cummer et al.*, 2006a]. Extremely large charge moment changes were reported on long timescales ~100 μs by *Fullekrug* et al. [2006a]. One of the major unsolved problems in current sprite research, which is also directly evident from the Figure 2 depicting the field created by a charge moment Qh_Q = 1000 C km, is the observed initiation of sprites at altitudes 70–80 km by very weak lightning discharges with charge moment changes as small as 120 C km [*Hu et al.*, 2002]. Several theories have been advanced to explain these observations, which include localized inhomogeneities created by small conducting particles of meteoric origin [*Zabotin and Wright*, 2001] and the formation of upwardly concave ionization regions near the lower ionospheric boundary associated with sprite halos [*Barrington-Leigh et al.*, 2001].

[7] In spite of the apparent simplicity of the basic mechanism of penetration of large quasi-electrostatic fields to the mesospheric altitudes, the sprite morphology, sprite altitude structure, and relationship of sprite morphology and in-cloud lightning processes appear to be quite complex (see, for example, discussion in the work of *van der Velde et al.* [2006]).

[8] *Pasko et al.* [1998a] proposed a theory indicating that sprite structure as a function of altitude should exhibit a transition from essentially nonstructured diffuse glow at altitudes ≥85 km to the highly structured streamer region at altitudes ≤75 km (Figure 4). It is proposed that the vertical structuring in sprites is created due to interplay of three physical timescales: (1) the dissociative attachment timescale τ_a (which is defined by the maximum net attachment frequency as $1/(\nu_a - \nu_i)_{\max}$, where ν_i and ν_a are the ionization and attachment frequencies, respectively); (2) the ambient dielectric relaxation timescale $\tau_\sigma = \varepsilon_o/\sigma$, where σ is conductivity and ε_o is permittivity of free space; (3) the timescale for the development of an individual electron avalanche into a streamer t_s (this is an effective time over which the electron avalanche generates a space charge field comparable in magnitude to the externally applied field [*Pasko et al.*, 1998a]). The interplay between these three parameters creates three unique altitude regions as illustrated in Figure 4: (1) the diffuse region ($\tau_\sigma < \tau_a$, $\tau_\sigma < t_s$) characterized by simple volumetric multiplication of electrons (Townsend electron multiplication mechanism); (2) the transition region ($\tau_\sigma > \tau_a$, $\tau_\sigma < \sim t_s$) characterized by strong attachment of ambient electrons before the onset of the electrical breakdown; (3) the streamer region ($\tau_\sigma > \tau_a$, $\tau_\sigma > t_s$) also characterized by the strong attachment as well as by individual electron avalanches evolving into streamers. The upper and the lower boundaries of the transition region shown in Figure 4 represent an estimate of the altitude range in which the actual transition between the diffuse and streamer regions is expected to occur. The upper boundary may shift downward under conditions of an impulsive lightning discharge which generates substantial electron density (i.e., conductivity) enhancement associated with the sprite halo at the initial stage of sprite formation [*Barrington-Leigh et al.*, 2001]. The lower boundary may shift upward due to streamers originating at lower altitudes but propagating upward toward the lower ionosphere [e.g., *Stanley et al.*, 1999; *McHarg et al.*, 2007].

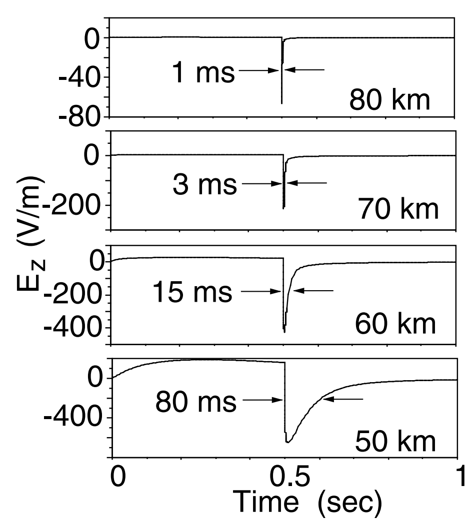

Figure 3. Time dynamics of the vertical component of the electric field at selected altitudes directly above a positive cloud to ground lightning discharge [*Pasko et al.*, 1997].

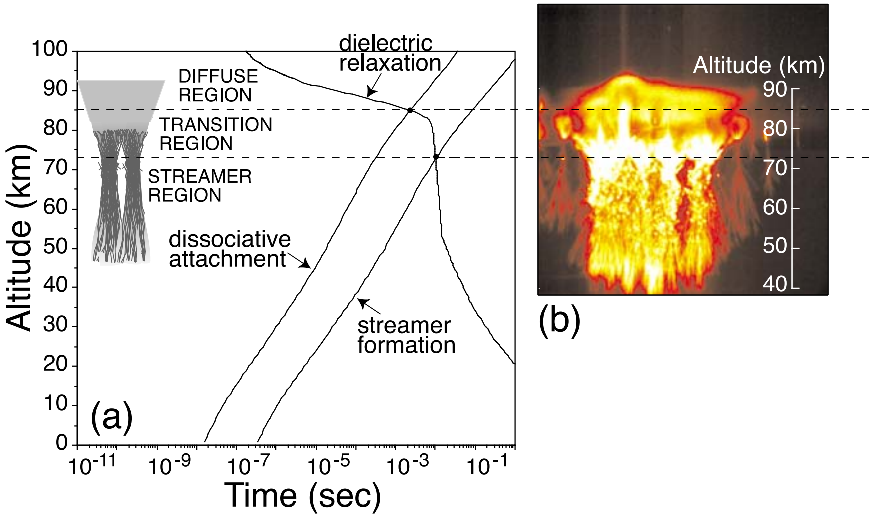

Figure 4. Vertical altitude structuring of optical emissions in sprites. (a) The altitude distribution of different timescales characterizing the vertical structuring of optical emissions in sprites [*Pasko et al.*, 1998a; *Pasko and Stenbaek-Nielsen*, 2002]. (b) Results of video observations [*Stenbaek-Nielsen et al.*, 2000].

[9] *Barrington-Leigh et al.* [2001] conducted one-to-one comparison between high-speed video observations of sprites and a fully electromagnetic model of sprite driving fields and optical emissions. Sprite halos are brief descending glows with lateral extent 40–70 km, which sometimes observed to accompany or precede more structured sprites (see Figure 1c). The analysis conducted by *Barrington-Leigh et al.* [2001] demonstrated a very close agreement of model optical emissions and high-speed video observations (shown in Figure 1c), and for the first time identified sprite halos as being produced entirely by quasi-electrostatic thundercloud fields. Sprites indeed often exhibit sprite halos, which appear as relatively amorphous nonstructured glow at sprite tops and which convert to highly structured regions at lower altitudes [*Stanley et al.*, 1999; *Gerken et al.*, 2000; *Gerken and Inan*, 2002, and references therein]. This vertical structure in sprites is apparent in high-speed video images of *Stenbaek-Nielsen et al.* [2000], and was reported during recent satellite [*Adachi et al.*, 2006] and ground-based [*Cummer et al.*, 2006b] observations of sprites. It should be emphasized that recent reports also indicate that diffuse halos can often occur without visible follow up formation of more structured sprites and in contrast to sprites produced by predominantly by positive cloud-to-ground lightning discharges halos can be driven by negative cloud-to-ground lightning discharges [*Frey et al.*, 2007].

[10] Significant research efforts in recent years have been directed on understanding of the role of lightning current variations on observed sprite structures. *Adachi et al.* [2004] found that the number of sprite columns in each sprite event was proportional to the peak current intensity of positive cloud-to-ground lightning discharges (CGs) while the average vertical length of columns was proportional to the charge moment of the causative positive CGs. Studies of *Gerken and Inan* [2004] indicate that relatively faint and diffuse sprites confined to small altitude range are associated with very high peak currents and short time duration of causative lightning discharges. *Ohkubo et al.* [2005] reported association of sprites with clusters of VLF radio atmospherics, similar to those observed previously in association with subionospheric signal perturbations referred to as "early/fast" VLF events [*Johnson and Inan*, 2000]. Recent study of *van der Velde et al.* [2006] further emphasizes complex relationships between sprite morphology and in-cloud lightning processes. These studies indicate a possible and not yet fully understood role of the time characteristics of the lightning currents in the initiation of sprites.

[11] Computer simulations of *Hiraki and Fukunishi* [2006] and *Asano et al.* [2008] indicate importance of the product of the current (Ih_Q) and charge (Qh_Q) moments for sprite initiation and suggest the threshold value: $(Ih_Q) \times (Qh_Q) = 1.6 \times 10^6$ (A km) (C km). The results of *Hiraki and Fukunishi* [2006] and *Asano et al.* [2008] emphasize importance of the timescale of charge removal by lightning for initiation of sprites. These conclusions are generally in agreement with analysis reported by *Barrington-Leigh et al.* [2001] indicating that a lightning discharge with a fast (<1 ms) charge moment change may be sufficient to cause diffuse emissions at higher altitudes, where the threshold for ionization and optical excitation is lower. If lightning currents do not continue to flow, however, there may not be sufficient electric field to initiate streamers below ~75 km. Conversely, slow continuing currents may cause a (delayed) sprite without a significant initial flash in the diffuse (halo) region [*Barrington-Leigh et al.*, 2001].

[12] In recent years the ELF measurements of the time dynamics of the charge moment changes in sprite-producing lightning have progressed to the point allowing detailed event based testing of sprite theory [*Hu et al.*, 2007; *Li et al.*, 2008]. The modeling analysis reported by *Hu et al.* [2007] provided quantitative information on time variation of lightning current moment, charge moment, and electric field driving sprite phenomena and demonstrated that for bright, short-delayed sprites, the measurement-inferred mesospheric electric field

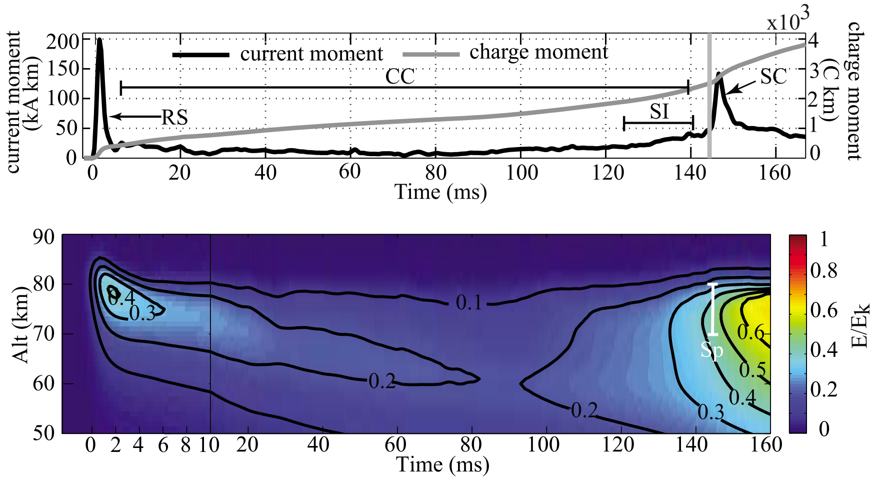

Figure 5. Finite difference time domain (FDTD) simulation results for the typical long-delayed sprite event [*Li et al.*, 2008]. (a) Estimated current moment and total charge moment change. (b) Simulated electric fields above the lightning discharge. Reprinted from *Li et al.* [2008].

agrees within 20% with the threshold electric field for conventional breakdown E_k. However, for long delayed sprite events and dimmer sprites, the measurement-inferred mesospheric electric field for sprite initiation is somehow below E_k values [*Hu et al.*, 2007]. Figure 5 shows measured current and charge moments and the simulated electric fields between 50 and 90 km altitude (normalized by E_k) for the typical long-delayed sprite [*Li et al.*, 2008]. The sprite is initiated at 144.4 ms after the lightning return stroke. The electric field increased before the sprite onset due to slow intensification (SI) of the continuing current. The peak normalized electric field in Figure 5b producing the long-delayed sprite is E/E_k = 0.45 at 72 km altitude, which is similar to those for typical short-delayed sprites that are neither remarkably bright or dim [*Hu et al.*, 2007]. The modeled initiation altitude of 72 km falls in the 70–80 km range estimated from high-speed video images [*Li et al.*, 2008]. Comparison of modeling and observations indicate that the long-delayed sprites initiate 5 km lower than short-delayed sprites [*Li et al.*, 2008].

[13] *Adachi et al.* [2008] combined array photometer data obtained by ISUAL instrument on FORMOSAT-2 satellite with the ELF magnetic field data to deduce temporal evolutions of lightning charge moment changes driving sprites and halos. It was found that the lightning discharge producing a halo without streamers has a short timescale of ~1 ms with a moderate charge moment of Qh_Q~400 C km while that producing streamers as well as a halo have a similar timescale of ~1 ms but a large charge moment of Qh_Q~1300 C km. On the other hand, a lightning discharge producing sprite streamers without a discernible halo has a long timescale of ~10 ms and a large charge moment of ~1300 C km. These conclusions are in agreement with results reported by *Barrington-Leigh et al.* [2001], *Hiraki and Fukunishi* [2006], and *Asano et al.* [2008].

[14] Although the ELF remote sensing discussed above and spectrophotometric (see next sections) measurements of electric fields in sprites indicate field magnitudes on the order of E_k, only very few in situ measurements of electric fields at altitudes of elves, sprites, and halos have been accomplished, and *Thomas et al.* [2008] has recently reported some rare examples of lightning-driven electric field pulses at 75–130 km altitude recorded during rocket experiment from Wallops Island, Virginia, in 1995. The measurements were compared directly to a 2-D numerical model of *Cho and Rycroft* [1998] describing lightning-driven electromagnetic fields at the lower ionospheric altitudes. *Thomas et al.* [2008] indicated that the observed field magnitudes are an order of magnitude lower than predicted by electromagnetic model of *Cho and Rycroft* [1998] and questioned validity of the electromagnetic pulse mechanism of elves. These conclusions are in disagreement with recently performed validation of elves modeling indicating good agreement for direct comparison of fluxes calculated by the model and observed by ISUAL spectrophotometers, direct comparison of modeled and observed morphologies of elves, and direct comparison of the calculated photon fluxes using peak currents for two elve-associated NLDN CGs with those recorded by ISUAL Imager [*Kuo et al.*, 2007]. The measurements reported by *Thomas et al.* [2008] were conducted on 2 September 1995 around evening hours (2122 LT) at which the lower ionosphere likely exhibited enhancement of electron density in comparison with nighttime conditions employed in modeling. Additionally, the NLDN deduced peak currents were employed in modeling with lightning current risetime 60 μs while NLDN is generally sensitive to LF radiation, which for a typical -CG is emitted during the initial 1–5 μs from a vertical part of the return stroke channel a few tens to a few hundreds of meters above the ground [*Krider*, 1976; *Orville*, 2008]. The low-pass filtering with 18 kHz cutoff applied to data reported by *Thomas et al.* [2008] may also contributed to underestimation of magnitudes of observed lightning-induced pulses.

[15] Lightning M components are perturbations or transient enhancements in the continuing current [*Rakov et al.*, 2001]. *Rakov et al.* [2001] speculated that M-component type processes in positive lightning may play a role in the initiation of so-called delayed sprites that occur many tens of milliseconds after the return stroke. Modeling analysis of *Yashunin et al.* [2007] indicates that the occurrence of an M component

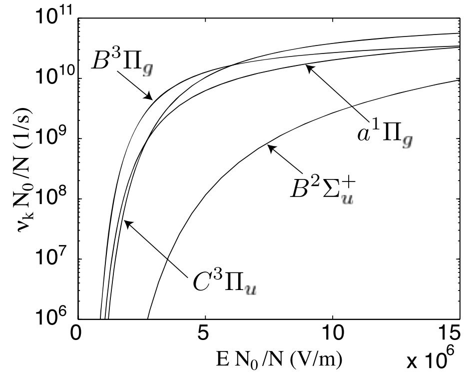

Figure 6. Excitation frequencies ν_k of $B^3\Pi_g$, $C^3\Pi_u$ and $a^1\Pi_g$ states of N_2 and $B^2\Sigma_u^+$ state of N_2^+ as a function of reduced electric field in air [*Liu and Pasko*, 2005; *Moss et al.*, 2006]. See also http://pasko.ee.psu.edu/air.

shifts the electric field maximum from the vertical axis of the lightning channel and increases the likelihood of initiation of sprites spatially displaced with respect to the lightning channel axis. *Asano et al.* [2009b] established through computer simulations that M components in the continuing current with small amplitudes but fast time variations can initiate or enhance the occurrence of sprites. *Asano et al.* [2009a] utilized three-dimensional fully electromagnetic simulations to investigate effects of horizontal components of currents in lightning discharges in addition to the conventional vertical channel. It has been established that the position of sprite can be significantly shifted in response to the length of the horizontal lightning channel [*Asano et al.*, 2009a].

2.2. Modeling Interpretation of Optical Emissions From Sprite Discharges and Comparison With Laboratory Experiments

[16] The principal approaches to remote sensing of electron energy distributions in sprites using absolute intensities and ratios of various emission bands arising from excited electronic states of neutral and ionized molecular nitrogen have been extensively discussed in the existing TLE literature [*Armstrong et al.*, 2000; *Adachi et al.*, 2006, 2008; *Takahashi et al.*, 2000; *Morrill et al.*, 2002; *Pasko and George*, 2002; *Chern et al.*, 2003; *Miyasato et al.*, 2003; *Mende et al.*, 2005; *Liu and Pasko*, 2005; *Kuo et al.*, 2005, 2009; *Liu et al.*, 2006, 2009b]. In particular, Figure 6 illustrates distribution of excitation frequencies for several electronic states of N_2 and N_2^+ of interest in sprite studies (see Table 1) as a function of reduced electric field, which were used in recent modeling studies of sprite streamers [*Liu and Pasko*, 2004, 2005; *Liu et al.*, 2006; *Moss et al.*, 2006; *Liu et al.*, 2009b]. The ratios of various emissions arising from these states are very sensitive functions of the driving electric field and, if measured experimentally, can be directly compared with optical emission models like those used by *Liu and Pasko* [2004, 2005] and *Liu et al.* [2006] (accounting for excitation and photon emission as well as quenching and cascading effects) to extract information about effective driving electric fields and consequently electron energy distributions responsible for these emissions. These approaches are generally similar to those used in spectroscopic studies of laboratory streamers. In particular, *Gallimberti et al.* [1974] discussed general approaches for deriving mean energies of electrons in impulse corona discharges in air at atmospheric pressure using ratios of intensities of various bands belonging of the N_2 second positive and N_2^+ first negative band systems. The results were normalized by intensity of (0, 2) band of the N_2 second positive system and it was noted that the relative intensities of the bands within the the N_2 second positive system could be used to derive information about energy of electrons driving the discharge only for relatively low electron energies, as the ratios become insensitive to the mean electron energy above ~5–6 eV for both Druyvesteyn and Maxwellian electron energy distributions studied by *Gallimberti et al.* [1974]. This result is consistent with findings in the work of *Simek et al.* [1998] and *Simek* [2002], indicating that the vibrational excitation of N_2 $C^3\Pi_u$ state by electron impact increases with electron temperature T_e in the range 1–5 eV but becomes weakly sensitive at $T_e > 5$ eV. The ratios of first negative bands of N_2^+ to the (0, 2) band of the N_2 second positive system discussed by *Gallimberti et al.* [1974] exhibited much steeper variation as a function of mean electron energy and therefore provided a more reliable assessment of the electron energy distribution. The direct inspection of sharp difference between excitation frequencies of $N_2(C^3\Pi_u)$ and $N_2^+(B^2\Sigma_u^+)$ electronic states as a function of reduced electric field shown in Figure 6 further supports essentially the same point by indicating that ratios of emissions arising from these states can be used for accurate measurement of driving electric field. These results illustrate a basic reason why the ratios of intensities of emissions from states with markedly different energy excitation thresholds such as those of $N_2(C^3\Pi_u)$ and $N_2^+(B^2\Sigma_u^+)$ (see Table 1 and Figure 6) are widely used in spectroscopic studies of pulsed corona discharges [*Gallimberti et al.*, 1974; *Teich*, 1993; *Matveev and Silakov*, 1998; *Djakov et al.*, 1998; *Simek*, 2002; *Kim et al.*, 2003, and references therein]. The ratios of emission intensities produced by the 0-0 transitions of the second positive system of N_2 and the first negative system of N_2^+ have also been used recently for spatiotemporal diagnostics of the filamentary and diffuse mode of the barrier discharges in air at atmospheric pressure [*Kozlov et al.*, 2001, 2005]. Essentially the same approaches have been adopted in recent years to studies of sprite dis-

Table 1. Summary of Emissions From Sprites[a]

Emission Band System	Transition	Excitation Energy Threshold (eV)	Lifetime at 70 km Altitude	Quenching Altitude (km)
$1PN_2$	$N_2(B^3\Pi_g)\rightarrow N_2(A^3\ \Sigma_u^+)$	~7.35	5.4 μs	~53
$2PN_2$	$N_2(C^3\Pi_u)\rightarrow N_2(B^3\Pi_g)$	~11	50 ns	~30
LBH N_2	$N_2(a^1\Pi_g)\rightarrow N_2(X^1\Sigma_g^+)$	~8.55	14 μs	~77
$1NN_2^+$	$N_2^+(B^2\Sigma_u^+)\rightarrow N_2^+(X^2\ \Sigma_g^+)$	~18.8	69 ns	~48

[a]From *Liu et al.* [2006].

charges [*Armstrong et al.*, 2000; *Adachi et al.*, 2006, 2008; *Takahashi et al.*, 2000; *Morrill et al.*, 2002; *Pasko and George*, 2002; *Chern et al.*, 2003; *Miyasato et al.*, 2003; *Mende et al.*, 2005; *Liu and Pasko*, 2005; *Kuo et al.*, 2005, 2009; *Liu et al.*, 2006, 2009b]. The $N_2(C^3\Pi_u)$ and $N_2^+(B^2\Sigma_u^+)$ states have certain advantages in case of studies of electron energy distributions at early stages of nonthermal streamer discharges as they are predominantly produced by direct electron impact of ground state N_2 molecule (i.e., are not contaminated by cascading and energy transfer effects) [*Morrill and Benesch*, 1996; *Matveev and Silakov*, 1998; *Djakov et al.*, 1998]. We note that $N_2(B^3\Pi_g)$ state playing important role in sprite emissions is heavily quenched in laboratory experiments conducted at near ground pressures (see Table 1 and *Teich* [1993]).

[17] The electric fields in transient luminous events have been successfully measured by considering the ratios of radiation intensities of band systems with different energy excitation thresholds. For example, *Morrill et al.* [2002] reported analysis of time integrated (33 ms) sprite emissions indicating that electric field in sprites closely followed E_k up to 55 km altitude and dropped below E_k above 55 km, where E_k is the conventional breakdown threshold field. These authors also stated that above 55 km their characteristic energies reflected the upper bound of the cooler phase after ionization, presumably in the tail of the streamer. *Kuo et al.* [2005] used five selected sprite events recorded by ISUAL instrument to estimate the strength of the electric field in sprites to be 2.1–3.7E_k. *Adachi et al.* [2006] analyzed 20 sprite events captured by ISUAL instrument and estimated that electric fields in upper/diffuse region of sprites do not exceed 0.5–0.7E_k and in lower/streamer region are 1–2E_k, which are lower than those estimated by streamer theory presented by *Liu et al.* [2006] (see discussion in the next section). *Adachi et al.* [2008] estimated maximum reduced electric field intensities and average electron energies on the basis of broadband blue and red emission ratios observed with the ISUAL array photometer. For halo events the maximum fields and average energies were found to be (0.59–0.81)E_k and 3.2–4.3 eV, respectively. On the other hand the same quantities were (0.5–1.25)E_k and 2.8–5.3 eV in the upper diffuse region of sprites, and (0.82–3.2)E_k and 4.4–8.9 eV in the lower-structured region, indicating that significant ionization happens in the formation of streamers [*Adachi et al.*, 2008].

[18] It is believed that pulsed positive corona discharges in N_2-O_2 mixtures used for generation of nonequilibrium plasma at atmospheric pressure for environmental applications [*Simek et al.*, 1998, 2002; *Tochikubo and Teich*, 2000; *Ono and Oda*, 2005] represent a closest laboratory analog of sprite streamers formed under impulsive application lightning related quasi-static electric fields. The time resolved spectroscopic studies of pulsed positive corona discharges indicate presence of two distinct phases of the discharge development: the initial phase, associated with propagation of streamers and direct excitation of ground state nitrogen molecules by electron impact; and the postdischarge phase, during which emissions from the discharge are controlled by $N_2(A^3\Sigma_u^+)$ metastable species via energy pooling and resonant energy transfer processes [*Simek et al.*, 1998, 2002; *Tochikubo and Teich*, 2000; *Ono and Oda*, 2005]. During the initial phase most of the $N_2(C^3\Pi_u)$ emission comes from the high field regions around heads of streamers [*Simek et al.*, 1998, 2002], while during the postdischarge period $N_2(C^3\Pi_u)$ formation is dominated by the energy pooling reaction [*Piper*, 1988; *Simek et al.*, 1998]:

$$N_2\left(A^3\Sigma_u^+, w\right) + N_2\left(A^3\Sigma_u^+, v\right) \rightarrow N_2\left(C^3\Pi_u, w'\right) + N_2\left(X^1\Sigma_g^+, v'\right) \tag{1}$$

[19] The analysis of sprite spectra conducted by *Bucsela et al.* [2003] and *Kanmae et al.* [2007] indicated that obtained $N_2(B^3\Pi_g)$ vibrational distributions were consistent with ones observed in laboratory afterglows, indicating an energy transfer process at lower altitudes in sprites (i.e., in sprite tendrils) between vibrationally excited N_2 ground state and the lowest-energy, metastable electronic state [*Piper*, 1989]:

$$N_2\left(A^3\Sigma_u^+, w\right) + N_2\left(X^1\Sigma_g^+, v \geq 5\right) \rightarrow N_2\left(B^3\Pi_g, w'\right) + N_2\left(X^1\Sigma_g^+, v' \sim 0\right) \tag{2}$$

[20] The atomic oxygen formed as a result of dissociation of oxygen molecules by electron impact during the initial phase can interact with $N_2(A^3\Sigma_u^+)$ metastables leading to formation of $NO(X^2\Pi_r)$ species [*Simek et al.*, 1998]. The NO $(X^2\Pi_r)$ species are also effectively formed due to fast interaction of molecular oxygen with excited $N(^2D)$ atoms formed as a result of electron impact dissociation of N_2 [*Kennealy et al.*, 1978; *Bailey et al.*, 2002; *Zhao et al.*, 2005; *Simek et al.*, 2006]. The resonant transfer reaction

$$N_2\left(A^3\Sigma_u^+, w\right) + NO\left(X^2\Pi_r, v\right) \rightarrow NO\left(A^2\Sigma^+, v'\right) + N_2\left(X^1\Sigma_g^+, w'\right) \tag{3}$$

is well established to be the source of NO γ-band emission radiated via $NO(A^2\Sigma^+) \rightarrow NO(X^2\Pi)$ [*Piper et al.*, 1986; *DeBenedictis et al.*, 1997; *Simek et al.*, 1998; *Tochikubo and Teich*, 2000; *Ono and Oda*, 2005]. For these reasons the NO-γ emission is frequently used to monitor evolution of $N_2(A^3\Sigma_u^+)$ species [*Simek et al.*, 1998; *Tochikubo and Teich*, 2000; *Ono and Oda*, 2005]. The NO-γ is expected to be produced in sprite discharges as well, following exactly the same excitation mechanisms. We note that NO-γ emissions generally appear in the same FUV range of wavelengths as LBH N_2 emissions [*Tochikubo and Teich*, 2000] and therefore may have contributed to sprite emissions recently detected in 150–280 nm wavelength range by the ISUAL spectrophotometer on FORMOSAT-2 satellite [*Mende et al.*, 2005, 2006; *Frey et al.*, 2005]. It is noted that the rotational structure of $NO(A^2\Sigma^+)$ is strongly influenced by the reaction process (3) and therefore NO-γ emission does not represent a good measure for gas temperature estimation [*DeBenedictis et al.*, 1997; *Simek et al.*, 1998; *Tochikubo and Teich*, 2000].

2.3. Modeling of Sprite Streamers

[21] Significant efforts in recent years have been devoted to modeling of fine streamer structures in sprites and their interpretation. Streamers are needle-shaped filaments of

ionization embedded in originally cold (near room temperature) air and driven by strong fields due to charge separation in their heads [*Raizer*, 1991, p. 334]. 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 [*Dhali and Williams*, 1987]. 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 [*Vitello et al.*, 1994; *Rocco et al.*, 2002]. A detailed review of various properties of streamers, including fields required for their initiation and propagation, and similarity relationships allowing scaling of streamer parameters as a function of gas pressure for the purposes of interpretation of sprite discharges, is provided by *Pasko* [2006, 2007, 2008]. Below we will emphasize some important properties of streamers and then review related recent work directed to the modeling interpretation of sprite observations.

[22] A significant progress has been achieved in recent years in high spatial [*Gerken and Inan*, 2005] and temporal [*Cummer et al.*, 2006b; *McHarg et al.*, 2007; *Stenbaek-Nielsen et al.*, 2007; *Stenbaek-Nielsen and McHarg*, 2008; *Montanyà et al.*, 2010] resolution imaging of streamers at low air pressures in transient luminous events in the Earth's atmosphere, as well as in relatively small discharge volumes in laboratory experiments at near ground air pressures [*Pancheshnyi et al.*, 2005; *Briels et al.*, 2005, 2006]. Understanding of similarities and dissimilarities of streamers at different pressures observed in these experiments represents an important problem, the resolution of which would synergistically benefit our understanding of streamers in both systems (i.e., due to generally relaxed requirements on time resolution of imaging systems needed for studies of streamers at low air pressures in transient luminous events and easy repeatability of discharges in high pressure laboratory experiments).

[23] Similarity relations [*Roth*, 1995; *Liu and Pasko*, 2006, and references therein] represent a useful tool for analysis of gas discharges since they allow to use known properties of the discharge at one pressure to deduce features of discharges at variety of other pressures of interest, at which experimental studies may not be feasible or even possible. Similarity laws for streamers propagating in nonuniform gaps in air at high (i.e., several atmospheric) pressures have been studied by *Tardiveau et al.* [2001] and *Achat et al.* [1992]. The similarity properties of streamers at different air pressures are also of great interest for interpretation of morphology observed in high-altitude sprite discharges [*Pasko et al.*, 1998a; *Liu and Pasko*, 2004]. The $\leq$100 μs time resolution, which is needed for studies of dynamic properties of streamers in sprites, has recently been achieved by several research groups which successfully performed continuous high-speed video recordings of sprite streamers [*Cummer et al.*, 2006b; *McHarg et al.*, 2005, 2007; *Stenbaek-Nielsen et al.*, 2007; *Stenbaek-Nielsen and McHarg*, 2008; *Montanyà et al.*, 2010]. As was pointed out above, the studies of streamers in sprites at low air pressures, in particular their similarity properties, represent an area of research, which will benefit our understanding of streamers that occur in high-pressure applications (i.e., near ground), that require subnanosecond time resolution for continuous video imaging (see discussion in the work of van *Veldhuizen and Rutgers* [2002]).

[24] It is well established by now that the dynamical properties and geometry of both positive and negative streamers can be affected by the population of the ambient seed electrons, and many of the recent modeling studies have been devoted to understanding of the role of the ambient medium preionization, including effects of photoionization by UV photons originating from a region of high electric field in the streamer head, on the dynamics of negative [*Babaeva and Naidis*, 1997; *Rocco et al.*, 2002] and positive [*Babaeva and Naidis*, 1997; *Kulikovsky*, 2000; *Pancheshnyi et al.*, 2001] streamers in different mixtures of molecular nitrogen (N_2) and oxygen (O_2) gases, and in air at ground pressure.

[25] The importance of the photoionization effects on sprite streamers at low air pressures at high altitudes is underscored by the fact that the effective quenching altitude of the excited N_2 states $b^1\Pi_u$, $b'^1\Sigma_u^+$ and $c'^1_4\Sigma_u^+$ that give the photoionizing radiation is about 24 km (corresponding to the air pressure $p = p_q = 30$ Torr) [*Zheleznyak et al.*, 1982]. The quenching of these states is therefore negligible at typical sprite altitudes 40–90 km, leading to an enhancement of the electron-ion pair production ahead of the streamer tip due to the photoionization, when compared to the previous studies of streamers at ground level. This and other effects have been studied by *Liu and Pasko* [2004] using a streamer model for studies of streamers propagating in strong fields comparable to E_k. Results obtained by *Liu and Pasko* [2004] emphasized acceleration and expansion as important characteristics of streamers, which were later confirmed by observations [*McHarg et al.*, 2007; *Stenbaek-Nielsen et al.*, 2007; *Stenbaek-Nielsen and McHarg*, 2008; *Liu et al.*, 2009a]. The discussion of the validity of the photoionization model of *Zheleznyak et al.* [1982] can be found in the work of *Pancheshnyi* [2005], *Naidis* [2006], and *Aints et al.* [2008]. This model is widely used for streamer simulations and is adopted in the model reported by *Liu and Pasko* [2004] and *Liu et al.* [2009a]. It is noted that fast electron detachment in an electric field could be an effective source of seed electrons for repetitively pulsed discharges in electronegative gases [*Pancheshnyi*, 2005]. The work by *Naidis* [2006] emphasizes importance of accounting for the quenching of radiating states and absorption of photoionizing radiation by water molecules for correct interpretation of recent experimental data on ionizing radiation in discharges in dry and humid air. Recent research indicates that 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 recently to development of efficient computational models of photoionization [e.g., *Segur et al.*, 2006; *Luque et al.*, 2007; *Bourdon et al.*, 2007; *Liu et al.*, 2007, 2008].

[26] While the initial streamer formation in sprites is likely to proceed at high altitudes in regions where the driving electric field reaches values comparable to E_k, as was studied by *Liu and Pasko* [2004], it is well known that a formed streamer can propagate in an electric field substantially lower than E_k ($E_k \simeq 32$ kV/cm at ground pressure and scales proportionally to neutral density at higher altitudes, see

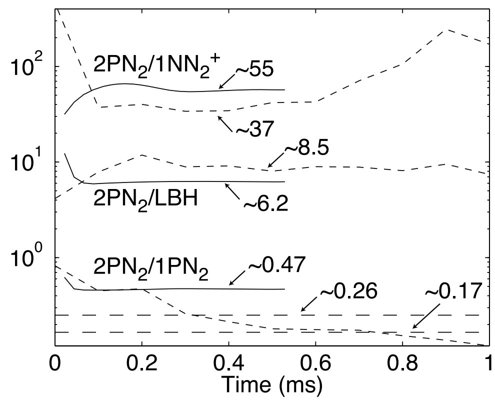

Figure 7. Intensity ratios calculated using modeling results for a streamer (solid line); intensity ratios from ISUAL measurements (dashed line) [*Liu et al.*, 2006].

Figure 2). Experimental and numerical simulation results have demonstrated that the minimum field required for the propagation of positive streamers in air at ground pressure stays close to the value 5 kV/cm [*Babaeva and Naidis*, 1997, and references therein]. The existing sources about the similar field for the negative streamers indicate that this field is a factor of 2–3 higher than the corresponding field for the positive streamers [*Raizer*, 1991, p. 361; *Babaeva and Naidis*, 1997]. For the sprite phenomenon, the lightning-driven quasi-static electric field is smaller than E_k in the region below the sprite initiation altitude (see Figure 2) and the streamers advancing in the weak electric fields ($E < E_k$) likely occupy a substantial part of the overall sprite volume and are responsible for most of the observed sprite emissions. The studies of emissions of sprite streamers in weak fields are therefore important for correct interpretation of experimental data and related results have been reported by *Liu and Pasko* [2005, 2007] and *Liu et al.* [2006, 2009b]. Recently, *Taylor et al.* [2008] reported a limited altitude extend of a sprite produced by negative cloud-to-ground discharge (-CG) when compared to a sprite produced by a positive CG with a similar charge moment change, providing the first experimental evidence of different thresholds required for propagation of streamers of different polarities in sprites, consistent with earlier modeling predictions in the work of *Pasko et al.* [2000].

[27] The major difference between the optical emissions from the model streamers propagating in weak electric fields and those for the strong field cases reported by *Liu and Pasko* [2004] is the dark streamer channel. For a streamer developing in weak electric fields, the channel field is very small and unable to effectively excite the electronic states of N_2, so that the emission intensities in the streamer channel are several orders of magnitude lower than those in the streamer head, so that integral emissions emitted by streamer originate predominantly from the streamer head [*Liu et al.*, 2006]. Figure 7 illustrates the intensity ratios of $2PN_2$ to LBH, $1NN_2^+$, and $1PN_2$ (see Table 1) obtained from the streamer modeling results and ISUAL spectrophotometric measurements [*Liu et al.*, 2006]. The three intensity ratios obtained from streamer modeling results and ISUAL spectrophotometric measurements reach the best agreement (within a factor of 2) at the initial development stage of sprites (within 1 ms after the sprite initiation) [*Liu et al.*, 2006]. These ratios can be directly used for determination of magnitudes of driving electric fields to be $\geq 3E_k$ [*Liu et al.*, 2006].

[28] We note that the electric field magnitudes ($\geq 3E_k$) estimated by *Liu et al.* [2006] are significantly greater than those obtained by *Morrill et al.* [2002] ($\sim E_k$), and the difference may be explained by the low temporal resolution of their observations as discussed by *Liu and Pasko* [2005]. *Kuo et al.* [2005] utilized the $2PN_2/1NN_2^+$ ratio to analyze five sprite events observed by the ISUAL instrument and estimated the upper limit of the electric field driving the sprite emissions to be greater than $3E_k$, in a good agreement with the study reported by *Liu et al.* [2006]. As concluded by *Liu et al.* [2006], the measured high fields are consistent with an assumption that most of the observed sprite emissions during initial sprite development originate from localized high field regions associated with tips of sprite streamers, in full agreement with the similar phenomenology of streamers documented in point-to-plane discharge geometry in laboratory experiments [*Simek et al.*, 1998; *Simek*, 2002; *van Veldhuizen and Rutgers*, 2002; *Yi and Williams*, 2002; *Ebert et al.*, 2006].

[29] *Liu and Pasko* [2007] developed a model to study NO-γ emissions ($NO(A^2\Sigma^+) \rightarrow NO(X^2\Pi) + h\nu$, see discussion in previous section) associated with streamer discharges in air at different pressures. The modeling results indicate that the $NO(A^2\Sigma^+)$ species in sprite streamers at 70 km altitude are mostly produced by interaction of $N_2(A^3\Sigma_u^+)$ metastable species with high-density ambient $NO(X^2\Pi_r)$, molecules via reaction represented by equation (3) in the previous section. Analysis of the production and loss mechanisms for the upper excited states leading to NO-γ and N_2 LBH emissions demonstrates that the total intensity of NO-γ emissions associated with sprites is substantially weaker than that of the N_2 LBH emissions. *Campbell et al.* [2007] recently emphasized importance of $N_2(A^3\Sigma_u^+) + O \rightarrow NO + N(^2D)$ reaction for production of NO in the upper atmosphere. *Gordillo-Vazquez* [2008] indicated possible importance of the direct electron impact excitation of $NO(A^2\Sigma^+)$ in sprite discharges as source of NO-γ emissions. The significance of the direct excitation is determined by the cross section of the related process, which varies by two orders of magnitude in the available literature [see *Gordillo-Vazquez*, 2008, *Liu and Pasko*, 2010, and references therein].

[30] First particle simulations of sprite streamers have been reported by *Chanrion and Neubert* [2008]. The code is in 2-D axisymmetric coordinates with charged particles followed in a Cartesian mesh and the electric field updated with Poisson's equation from the charged particle densities. Collisional processes between electrons and air molecules are simulated with a Monte Carlo technique, according to cross section probabilities. The code also includes photoionization processes of air molecules by photons emitted by excited constituents. *Chanrion and Neubert* [2008] presented detailed comparisons of results from the new particle model with previous fluid model of *Liu and Pasko* [2004] for the case of double headed streamers developing at 70 km altitude in air using identical initial plasma, electric field, and neutral atmosphere parameters. The results demonstrated excellent agreement with the previous fluid modeling. It is shown that

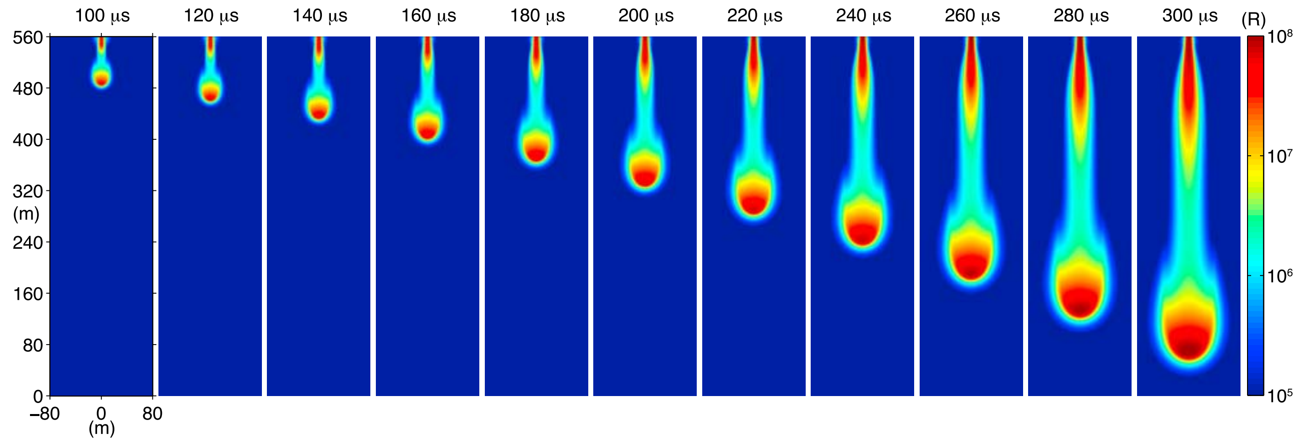

Figure 8. A time sequence of intensity distributions of first positive band system of N_2 for a downward propagating model positive streamer at 75 km altitude [*Liu et al.*, 2009a]. The sequence of images is shown with 20-μs interval, starting at 100 μs and ending at 300 μs. The formatting is consistent with that of *Stenbaek-Nielsen et al.* [2007, Figure 2].

at 1 atm pressure the electric field must exceed similar to 7.5 times the breakdown field to observe runaway electrons in a constant electric field. It is also found that this value is reached in a negative streamer tip at 10 km altitude when the background electric field equals similar to 3 times the breakdown field. It is shown that the energetic runaway electrons produced by streamer tips create enhanced ionization in front of negative streamers. The simulations suggest that the thermal runaway mechanism may operate at lower altitudes and be associated with lightning and thundercloud electrification while the mechanism is unlikely to be important in sprite generation at higher altitudes in the mesosphere [*Chanrion and Neubert*, 2008].

[31] Further analysis of ISUAL spectrophotometric data in the context of sprite streamer modeling has been reported by *Liu et al.* [2009b]. These authors simulated two positive model streamers developing in strong and weak applied electric fields (with respect to E_k) at 70 km latitude. The intensity ratio of the second positive band system of N_2 to the first negative system of N_2^+ was obtained separately from the modeling and the ISUAL measurements. The comparison results indicate that the ratio obtained for the streamer developing in an electric field close to the conventional breakdown threshold field E_k agrees with the ISUAL measurements at the very early stage of the sprite development better than for the streamer developing in a field much lower than E_k. The authors utilized the strong field streamer case in conjunction with the ISUAL data to gain additional information on the poorly known quenching altitude of the $N_2(a^1\Pi_g)$ state, which is responsible for N_2 Lyman-Birge-Hopfield band system. The results supported the conclusions of the previous study by *Liu and Pasko* [2005] that the 77 km is a good estimate for the quenching altitude of $N_2(a^1\Pi_g)$.

[32] Although it has been suggested that sprites may be initiated through simultaneous up and down propagating streamers [*Liu and Pasko*, 2004], the recent observational evidence indicates that the preferential form of sprite initiation is through downward development of positive streamers launched in the region of the lower ledge of the Earth's ionosphere (see discussion by *Stenbaek-Nielsen et al.* [2007]). The exact mechanism of initiation of sprite streamers remains unknown and may be related to formation of upwardly concave ionization regions near the lower ionospheric boundary associated with sprite halos [*Barrington-Leigh et al.*, 2001]. The double headed streamers discussed by *Liu and Pasko* [2004] may be involved in initiation of spites; however, due to the fast exponential increate in streamer brightness in time (see review of *Liu et al.* [2009a] below) the initial appearance of positive streamers is likely realized because of a relatively slow application of the electric field at sprite altitudes (1 ms) [*Marshall and Inan*, 2006; *Hu et al.*, 2007] coupled with lower propagation threshold for positive streamers in comparison with negative ones [*Pasko et al.*, 2000], which creates asymmetric conditions with predominant initial propagation of positive streamers.

[33] *Liu et al.* [2009a] compared sprite streamer modeling results with high-speed video recordings of sprites made with 50 μs temporal resolution [*McHarg et al.*, 2007; *Stenbaek-Nielsen et al.*, 2007]. Both the modeling results and the sprite videos show that sprite streamers propagate with acceleration and expansion during the initial stage of sprite development. The acceleration computed from the modeling for the applied electric fields close to the conventional breakdown threshold field E_k is on the order of $(0.5–1) \times 10^{10}$ m s^{-2} and is in good agreement with the peak values observed experimentally. Mainly due to the increasing radius of the streamer head of an accelerating streamer, the brightness of the streamer head increases as well (see Figure 8). The results reported by *Liu et al.* [2009a] demonstrate that the brightness of a sprite streamer head increases exponentially with time and can span more than 4 orders of magnitude in a very short period of about 1 ms. The rate of increase depends on the magnitude of the applied electric field. *Liu et al.* [2009a] proposed a method for remote sensing of the sprite-driving electric field in the mesospheric and lower ionospheric region by measuring the rate of the change of the brightness. In particular, *Liu et al.* [2009a] report that the sprite event presented by *McHarg et al.* [2007] and *Stenbaek-Nielsen et al.*

[2007] was initiated by fields close to the conventional breakdown threshold E_k.

3. Physical Mechanism and Modeling Blue Jets and Gigantic Jets

3.1. Association of Blue and Gigantic Jets With Leader Processes

[34] A summary of phenomenological features of blue jets and gigantic jets and their relationship to different polarity leader processes has been presented recently by *Pasko* [2008]. 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 blue jets should be contrasted with the impulsive rebrightening of gigantic jets, resembling negative leader processes [*Krehbiel et al.*, 2008]. The polarity itself is not sufficient to explain all the morphological differences in jet events observed to date (as discussed further in this section, the location of jet initiation and charge configuration in a thundercloud are also defining parameters for jet development). Nevertheless, most of the gigantic jets and blue jets observed to date are believed to be associated with normal polarity thunderstorms and we will associate blue jets with positive leaders and gigantic jets with negative leaders. The gigantic jets are visually more energetic than blue jets, they extend to higher altitudes and have a more impulsive and structured appearance. Although to date blue jets and gigantic jets have been observed from different platforms, by different optical instruments, and their absolute optical intensities have not yet been compared, their appearance in available video records allows to speculate that gigantic jet events are also optically brighter. Extensive discussion on possible classification schemes of different jet events is given by *Krehbiel et al.* [2008] (see also supplementary information for *Krehbiel et al.* [2008] available on Nature Geoscience Web site).

3.2. Early Theories of Jet Discharges and Their Relation to Streamers and Electron Runaway Phenomena

[35] Theories of blue jet and gigantic jet production mechanisms may be classified in two general categories: (1) the mechanism of conventional air breakdown based on concepts of streamers and leaders [*Pasko et al.*, 1996; *Sukhorukov et al.*, 1996; *Petrov and Petrova*, 1999; *Pasko et al.*, 1999a; *Pasko and George*, 2002; *Tong et al.*, 2004, 2005; *Raizer et al.*, 2006, 2007; *Krehbiel et al.*, 2008], 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; *Babich et al.*, 2008; *Fullekrug et al.*, 2010].

[36] The relativistic runaway air breakdown is admittedly the most attractive mechanism by which the gamma ray flashes of terrestrial origin [*Fishman et al.*, 1994; *Smith et al.*, 2005] can be produced in the Earth's atmosphere [*Lehtinen et al.*, 1999, 2001, and references therein]. However, recent observations of X rays from relatively compact regions of space associated with steps of negative lightning leaders [*Moore et al.*, 2001; *Dwyer et al.*, 2005] and theoretical analysis presented by *Moss et al.* [2006] indicate existence of direct acceleration of thermal (i.e., originally several eV) electrons to >10 MeV energies in streamer zones of conventional lightning leaders. These thermal runaway electrons can provide 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 [*Gurevich et al.*, 1992; *Gurevich and Zybin*, 2001, 2005, and references therein]. The results of a numerical modeling of the spectra of optical emissions produced by the relativistic runaway air breakdown demonstrate that this process may account for the observed blue color of blue jets [e.g., *Yukhimuk et al.*, 1998; *Babich et al.*, 2008]. *Fullekrug et al.* [2010] recently reported broadband electromagnetic pulses occurring ~4–9 ms after the sprite producing lightning discharge spanning the frequency range from ~50–350 kHz and exhibiting complex waveforms without the typical ionospheric reflection of the first hop sky wave. Computer simulation results presented by *Fullekrug et al.* [2010] indicate that electromagnetic radiation emitted by an electron avalanche beam resulting from relativistic runaway breakdown within the Earth's atmosphere may be responsible for the production of the observed LF pulses.

[37] The current theories based on conventional air breakdown generally favor a phenomenological link between blue jets and gigantic jets and streamer zones of lightning leaders, and it has been suggested that the thermal runaway electron process operating in leaders may contribute to production of terrestrial gamma ray flashes from the jet discharges [*Moss et al.*, 2006]. However, the link between gamma ray flashes of terrestrial origin and blue and gigantic jets has not yet been established experimentally. The existing theories of blue and gigantic jets based on the relativistic electron multiplication mechanism originally proposed by *Gurevich et al.* [1992] do not specifically address most of the currently known geometrical and dynamical characteristics of blue jets and gigantic jets summarized recently in section 3 of *Pasko* [2008].

[38] 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 phenomenon. 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 in the work of *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 below in this section. The subsequent analysis of similarity laws for streamer discharges 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; *Pasko*, 2007], substantially lower than streamer sizes postulated by *Pasko et al.* [1996] and *Sukhorukov et al.* [1996].

[39] *Petrov and Petrova* [1999] were first to propose 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.* [1999a] applied a two-dimensional fractal model and *Pasko and George* [2002] applied a three-dimensional fractal model of streamer coronas to describe general observed shapes of blue jets and gigantic jets. The predictions of *Petrov and Petrova* [1999] and the modeling results of *Pasko et al.* [1999a] and *Pasko and George* [2002] appeared to be in a remarkable agreement with the recent experimental discoveries indicating the streamer-like structure of blue jets and gigantic jets [*Wescott et al.*, 2001; *Pasko et al.*, 2002]. Although *Petrov and Petrova* [1999] discussed positive leaders and one or both events in the work of *Wescott et al.* [2001] and *Pasko et al.* [2002] may in fact correspond to negative polarity events, this does not diminish importance of predictions by *Petrov and Petrova* [1999], who for the first time linked the observed jet events to streamer components in leader processes.

[40] *Pasko and George* [2002] proposed that conditions leading to formation of blue jets 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* [2002] (see also correction in the work of *Pasko* [2004]) note that the experimentally documented electric fields required for propagation of positive E_{cr}^{+} and negative E_{cr}^{-} 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 structural complexity involving multiple highly branched streamer channels, its macroscopic characteristics remain relatively stable under a variety of external conditions. In addition, the field measurements inside the streamer zone of positive [*Petrov et al.*, 1994] and negative [*Petrov and Petrova*, 1993] leaders indicate that the minimum fields required for propagation of positive E_{cr}^{+} and negative E_{cr}^{-} streamers 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* [2002] suggest 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 fill a large volume of space in the vicinity of a thundercloud. It is noted that streamers possess propagation speeds $>10^5$ m/s, substantially exceeding typical leader speeds $\sim 2 \times 10^4$ m/s [e.g., *Bazelyan and Raizer*, 1998, p. 227]. Although the initial volume of space occupied by streamers 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. Results of three-dimensional fractal modeling of streamer coronas under these circumstances [*Pasko and George*, 2002] demonstrate that under a variety of initial conditions the streamer coronas form upward propagating conical shapes similar to the experimentally observed geometry of blue jets. The model results presented by *Pasko and George* [2002] closely resemble blue jet and blue starter characteristics in terms of their altitude extents, transverse dimensions and conical structure, and indicate that blue starters [*Wescott et al.*, 1996] are related to the initial phases of blue jets.

3.3. Effects of Atmospheric Conductivity on Formation of Jet Discharges

[41] The importance of the ambient conductivity profile at the stratospheric altitudes for the formation of blue jet type of phenomena has been discussed in a number of publications. The conductivity σ defines an effective dielectric relaxation timescale (ε_o/σ) over which the conducting medium responds to changes in applied electric field. *Shaw* [1998] speculated that in order to bring and sustain large electric fields needed for development of blue jets at stratospheric altitudes some special mechanism is needed to either preferentially place charge center at higher altitudes, above cloud height, or, more likely, to reduce electrical conductivity of the air above cloud heights. It was proposed by *Shaw* [1998] that the reduction of atmospheric electrical conductivity above cloud 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. In this respect it is important to discuss physical factors which play a role in establishing the upper terminal altitudes of blue jets, blue starters and gigantic jets in the realistic atmosphere. This discussion is important in view of the reports [*Pasko et al.*, 2002; *Su et al.*, 2003; *Cummer et al.*, 2009] indicating that jet type transient luminous events are able to establish a direct path of electrical contact between the thundercloud top and the lower ledge of the Earth's ionosphere.

[42] Figure 9 shows examples of the nighttime middle atmospheric conductivity distributions [*Hale et al.*, 1981; *Hale*, 1994; *Pasko and George*, 2002]. The low-latitude profile in Figure 9 is consistent with $\sigma = 6 \times 10^{-12}$ S/m recently measured in Brazil at 34 km altitude above a thunderstorm [*Holzworth et al.*, 2005] and is also consistent with a value $\sigma = 1.1 \times 10^{-12}$ S/m at 20 km altitude, which can be derived from a conductivity model recently proposed by *Thomas et al.* [2005]. The conductivity measurements conducted over thunderstorms in the Tennessee Valley Region of the United States from high-altitude NASA U-2 airplane in the summer of 1986 indicated values of $\sigma = 4.5 \times 10^{-12}$ S/m at 20 km altitude [*Blakeslee et al.*, 1989]. This value is also in a relatively good agreement with $\sigma = 7 \times 10^{-12}$ S/m at 20 km for midlatitude profile shown in Figure 9. The same U-2 measurements indicated electric fields ~7 kV/m at 20 km over very intense storm centers [*Blakeslee et al.*, 1989], which were a factor of four lower than $E_{\rm cr}^{+} = 30$ kV/m at 20 km

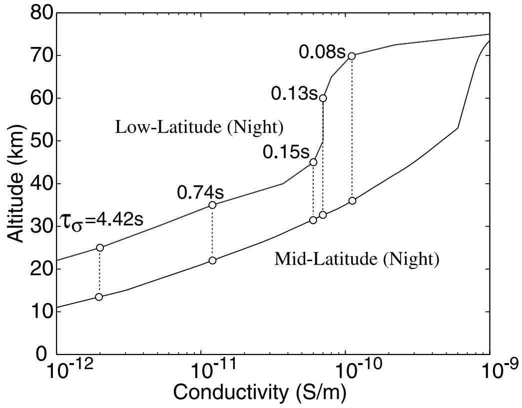

Figure 9. Examples of the nighttime middle atmospheric conductivity distributions [*Hale et al.*, 1981; *Hale*, 1994; *Pasko and George*, 2002]. Reprinted from *Pasko and George* [2002].

altitude. The authors also noted that there were no clear indications from the conductivity data alone to indicate the plane was over a storm. Instead the authors found that the air 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 [*Blakeslee et al.*, 1989]. These findings are not consistent with proposed conductivity reductions above thunderstorms suggested by *Shaw* [1998].

[43] The role of atmospheric conductivity in definition of upper terminal altitudes of blue starters, blue jets, and gigantic jets and in formation of the jet type of phenomena in general is discussed by *Pasko and George* [2002] in the context of a "moving capacitor plate" model originally proposed by Greifinger and Greifinger [*Greifinger and Greifinger*, 1976; *Hale and Baginski*, 1987; *Pasko et al.*, 1997, 1998b, 1999b] 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 σ and longer dielectric relaxation times $\tau_\sigma = \varepsilon_o/\sigma$ above cloud tops observed at low latitudes (see Figure 9a) should create more favorable conditions for creation of jets in tropics in comparison with midlatitudes [*Pasko et al.*, 2002]. Recent research also indicates that taller storms extending to high altitudes (~15 km), as normally the case at low latitudes in tropical regions, lead to more favorable conditions of initiation of jet discharges due to decrease of the electric field required to sustain the phenomena with altitude [*Krehbiel et al.*, 2008].

3.4. Modeling Interpretation of Optical Emissions From Jet Discharges

[44] The fractal model developed by *Pasko and George* [2002] allows accurate determination of the macroscopic electric fields in regions of space occupied by streamers. The results reported by *Pasko and George* [2002] for positive polarity events indicate that for a variety of input parameters these fields are very close (within several percent) 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.*, 1999a, 2000, 2001] and experimental measurements of *Petrov et al.* [1994]. We note, however, that the low fields on the order of E^+_{cr} are generally not sufficient to excite any observable optical emissions [*Pasko and George*, 2002]. The fractal model does 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 ~$5E_k$ [e.g., *Dhali and Williams*, 1987; *Vitello et al.*, 1994; *Babaeva and Naidis*, 1997; *Kulikovsky*, 1997; *Pasko et al.*, 1998b; *Liu et al.*, 2004b; *Bourdon et al.*, 2007], where E_k is the conventional breakdown threshold field. 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; *Liu et al.*, 2006, 2007], similar to the ambient conditions for propagation of streamer coronas considered by *Pasko and George* [2002]. Therefore the observed optical luminosity in jet events arises from large electric fields existing in narrow regions of space around tips of small-scale corona streamers constituting them. This situation is similar to that already discussed with relationship to sprite discharges in section 2.

[45] *Pasko and George* [2002] presented a comparison of spectral observations reported by *Wescott et al.* [2001] and calculated ratio of the combined red and green emissions to the total blue emission assuming the driving field to be $5E_k$. The comparison was performed using an optical model formulation documented by *Pasko and George* [2002] and *Liu and Pasko* [2004], and accounted for the atmospheric transmission and aircraft window corrections pertinent to experimental conditions of *Wescott et al.* [2001]. The resultant ratio appeared to be in a good agreement with the analysis of color TV frames associated with blue starters reported by *Wescott et al.* [2001], who concluded that the combined red and green channel intensity constituted 7% of the total blue channel intensity. This ratio is also consistent with more recent results of *Kuo et al.* [2009] who utilized ISUAL instrument on FORMOSAT-2 satellite for analysis of spectral ratios associated with gigantic jet discharges and obtained fields $E\ N_0/N$ = 10–17 × 10^6 V/m (3.4–5.5E_k), where N is the air density and N_0 is the reference air density at ground level.

3.5. Further Development of Fractal and Streamer Models of Jet Discharges

[46] *Tong et al.* [2004] investigated conditions for initiation of gigantic jets above thunderclouds in terms of geometry, magnitude and altitude of required thundercloud charges. Having considered the evidence presented by *Su et al.* [2003] that gigantic jets are analogous to negative cloud to ionosphere discharges, *Tong et al.* [2004] associated the gigantic jet process with an upward propagating negative streamer assuming that the pressure scaled thundercloud electric field should exceed the conventional breakdown threshold field E_k in order to initiate the gigantic jet propagation. It was found, in particular, that a negative thundercloud charge of −203.57 C with a spherically symmetric gaussian distribution with a scale of 2 km placed at altitude 16 km would satisfy this criteria at an altitude of 18.63 km. *Tong et al.* [2004] did not consider the leader process as a mechanism of gigantic jets.

[47] *Tong et al.* [2005] developed a three-dimensional model of gigantic jets 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 gigantic jets and the ionosphere is assumed as the other. The discharge propagation concept of the model presented by *Tong et al.* [2005] is similar to the fractal models developed previously in the work of *Niemeyer et al.* [1984] and *Pasko and George* [2002, and references therein]. In contrast to *Tong et al.* [2004], in the work of *Tong et al.* [2005] the gigantic jet in its entire altitude extent is considered as a negative leader phenomenon. However, the physics of stepping of negative leaders and their streamer zones has not been modeled in the work of *Tong et al.* [2005]. The model assumed the ground pressure value of the field inside the leader channel to be equal to E_l = 1 kV/cm. This field was reduced exponentially with a scale height of 10 km at higher altitudes. The same criteria for initiation of gigantic jets as in the work of *Tong et al.* [2004] based on the E_k threshold was employed by *Tong et al.* [2005]. After the leader initiation, it was allowed to propagate as soon as the field remained above the E_{cr}^{-} threshold. The ground pressure value of E_{cr}^{-} was assumed to be −12.5 kV/cm and scaled down exponentially with altitude with a scale of 8 km. The model produced propagation of the model channels up to 72 km altitude and agreed well with the overall picture of observed gigantic jets. The initiation criteria for gigantic jets presented by *Tong et al.* [2004, 2005] is based on the conventional breakdown threshold field E_k and has the same limitations as earlier work by *Pasko et al.* [1996] as it requires unusually high magnitudes and concentrations of thundercloud charges. It is interesting to note that in the model published by *Tong et al.* [2005], the altitude scaled values of the leader channel field E_l and the leader propagation field E_{cr}^{-} become equal at 101 km altitude. The implications of this relationship for terminal altitudes of gigantic jets, however, were not discussed by *Tong et al.* [2005].

[48] *Raizer et al.* [2006, 2007] associated both blue jets and gigantic jets with the streamer zone of positive leader, which is postulated to be initiated above the positive charge center positioned at altitude 12 km. *Raizer et al.* [2006, 2007] demonstrated that upward transfer of the high thundercloud potential by leader channel to lower air density regions with proportionally lower electric field threshold for propagation of streamers E_{cr}^{+}, allowed the sustainment of blue jet streamers by relatively moderate cloud charge of 50 C with a radius of 3 km. *Raizer et al.* [2006, 2007] summarized properties of streamer zones of leaders, which are of significant importance for interpretation of observations of blue jets and gigantic jets. At ground level the three-body electron attachment timescale at fields around E_{cr}^{+} is ~0.1 μs [see, e.g., *Liu and Pasko*, 2004, Figure 1a] and at 18 km this timescale is ~10 μs (increased inversely proportionally to air density squared). *Raizer et al.* [2006, 2007] explain that these short electron loss timescales do not allow the existences of long streamers, and a streamer zone of the leader is filled with large number of streamers having different initiation time and length. The frequency with which a leader head emits streamers is estimated to be ~10^9 s^{-1} [*Bazelyan and Raizer*, 2000, p. 70], and only the "younger" shorter streamers are connected directly to the leader tip, while "old" streamers advance through the streamer zone with substantially decayed electron density in their tails. Both types of streamers act collectively to establish positive macroscopic charge density in the streamer zone of positive leader maintaining the electric field at the E_{cr}^{+} level [*Raizer et al.*, 2006, 2007]. In this respect it is important to emphasize that the fractal model employed by *Pasko and George* [2002] is not able to resolve the physics of individual streamers (i.e., high fields in streamer tips as already discussed above) and links connecting grid points should not be directly interpreted as streamer channels. The fractal model is believed to be physically adequate for representation of integral action of many streamers in the leader streamer zone in agreement with experiments [*Petrov and Petrova*, 1993; *Petrov et al.*, 1994], and for modeling of volumetric properties of sprites and jets as explained in detail by *Pasko et al.* [2000, 2001] and *Pasko and George* [2002]. It is also important to emphasize that the existing video records of blue jets and gigantic jets are obtained with time resolution ~16 ms, which in accordance with recent high speed video observations of streamers in sprites [*Cummer et al.*, 2006b; *McHarg et al.*, 2007; *Stenbaek-Nielsen et al.*, 2007; *Stenbaek-Nielsen and McHarg*, 2008] is about two orders of magnitude greater than the minimum ~50 μs time resolution needed to resolve dynamics of individual streamer heads at altitudes ~70 km. Using the analogy with sprites, it is highly likely that the individual channels in existing jet images (i.e., Figure 1e) are produced by a superposition and time averaging of many bright streamer heads as they moved through the camera's field of view. These and probably many other extremely interesting submillisecond dynamical features of blue jets and gigantic jets remain unresolved in existing records, indicating a definite need for further high-speed observations.

[49] *Milikh and Shneider* [2008] utilized the modeling approach proposed by *Raizer et al.* [2007] to study 300–400 nm emissions produced by a jet discharge in order to interpret flashes with 1–64 ms duration observed in equatorial regions by UV instrument on board the microsatellite "Tatiana." The modeling considered second positive band system of N_2 and first negative band system of N_2^+ as primary emissions responsible for the observed flashes and accounted for excitation and well as for pressure dependent quenching effects of the responsible electronic states $C^3\Pi_u$ of N_2 and $B^2\Sigma_u^+$ of N_2^+, respectively (see Table 1). The model calculated UV fluxes are in agreement with those observed in terms of UV pulse duration and magnitude [*Milikh and Shneider*, 2008].

[50] In addition to obvious disagreement with inferred negative polarity of gigantic jets, the limitation of models proposed by *Pasko et al.* [1999a], *Pasko and George* [2002], and *Raizer et al.* [2006, 2007] in support of the original idea expressed by *Petrov and Petrova* [1999] that jets correspond to the upward development of the pressure scaled streamer zone of a conventional leader is that they all postulate presence of a leader near the cloud top. These models do not provide 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, for example, that gigantic jets are initiated as normal polarity intracloud lightning discharges between upper positive and lower negative charge centers [*Mathews et al.*, 2002; *Krehbiel et al.*, 2008] and the models advanced by *Pasko et al.* [1999a], *Pasko and George* [2002], and *Raizer et al.* [2006, 2007] do not reflect related scenarios.

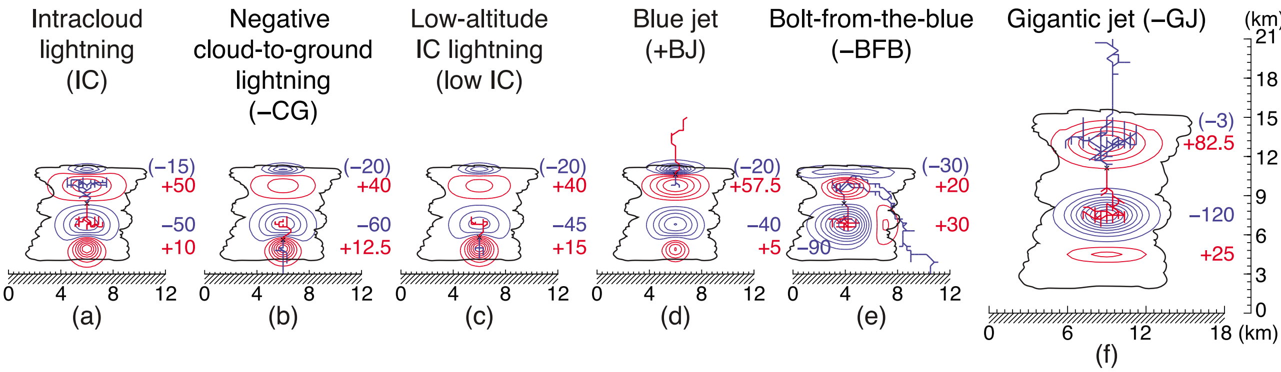

Figure 10. Simulated discharges illustrating the different known and postulated lightning types in a normally electrified storm [*Krehbiel et al.*, 2008]. (a)–(f), Blue and red contours and numbers indicate negative and positive charge regions and charge amounts (in C), respectively, each assumed to have a gaussian spatial distribution. A partially analogous set of discharges occurs or would be predicted to occur in storms having inverted electrical structures (see Figure S5 in the supplementary information of *Krehbiel et al.* [2008]). Reprinted from *Krehbiel et al.* [2008] by permission from Nature Geoscience.

3.6. Charge Imbalance in Thunderstorms as Mechanism of Jet Discharges

[51] Recently, *Krehbiel et al.* [2008] discussed the charge imbalances in thunderstorms as a fundamental condition allowing propagation of leaders downward as cloud-to-ground lightning or upward as jet discharges. This demonstrated that upward discharges are analogous to cloud-to-ground lightning and provided a unified view on how lightning escapes from a thundercloud. *Cummer et al.* [2009] recently reported measurement of total charge of −144 C transferred by a gigantic jet to the lower ionosphere, which is in the range of charge transfers to ground by strong negative cloud-to-ground discharges (-CGs), however, associated with current risetime in gigantic jet (~30 ms), which is four orders of magnitude slower than in conventional -CGs (~5 μs [*Rakov and Uman*, 2003, pp. 7, 146, 154]). *Krehbiel et al.* [2008] note that in accordance with existing experimental evidence the lightning initiation usually happens between adjacent charge regions of different polarity where the electric field is maximum. If the negative and positive charge centers are approximately equal in magnitude, the bidirectional discharge propagates in the form of positive leaders inside of negative charge region and in the form of negative leaders inside of the positive charge region [e.g., *Riousset et al.*, 2007]. In this situation the leader system, which is assumed to be overall equipotential and neutral, remains at nearly zero potential [e.g., *Riousset et al.*, 2007]. *Krehbiel et al.* [2008] 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 from the weaker charge center, allowing it to penetrate through the weaker charge center and to escape from the thundercloud. *Krehbiel et al.* [2008] presented a combination of observational and modeling results that indicate two principal ways in which upward discharges can be produced. The modeling presented by *Krehbiel et al.* [2008] indicates that blue jets occur as a result of electrical breakdown between the upper storm charge and 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. Gigantic jets are indicated to begin as a normal intracloud discharge between dominant midlevel charge and a screening-depleted upper level charge, that continues to propagate out the top of the storm [*Krehbiel et al.*, 2008].

[52] Figure 10 summarizes the results of simulating different types of discharges in normally electrified storms from *Krehbiel et al.* [2008]. The lightning model employed to produce results shown in Figure 10 uses a Lightning-Mapping-Array-Inferred multilayered charge structure positioned above a perfectly conducting flat ground plane [*Riousset et al.*, 2007]. The thundercloud and lightning discharge are modeled in a 3-D Cartesian domain using equidistant grids. The model uses a fractal approach to introduce stochasticity in a self-consistent model of the lightning channel, which fully satisfies Kasemir's hypothesis of equipotentiality and overall neutrality of the discharge [*Kasemir*, 1960; *Mazur and Ruhnke*, 1998; *Riousset et al.*, 2007]. In all cases shown in Figure 10, 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 10a) [*Krehbiel et al.*, 2008]. The negative cloud-to-ground lightning discharges (-CGs, Figures 10b and 10e) occur as descending precipitation generates lower positive charge [*Williams*, 1989] or as the storm accumulates net negative charge and can go either directly to ground or indirectly as a bolt-from-the-blue discharge (see discussion in the work of *Krehbiel et al.* [2008]). The negative gigantic jets (-GJs, Figure 10f) provide an alternate way of relieving the midlevel negative charge, by discharging it to the upper atmosphere rather than to ground [*Krehbiel et al.*, 2008]. The positive blue jets (+BJs) do the opposite, namely transport positive charge upward (Figure 10d) [*Krehbiel et al.*, 2008].

[53] Recently, *Riousset et al.* [2010] introduced a two-dimensional axisymmetric model of charge relaxation in the conducting atmosphere and applied this model in conjunction with three-dimensional lightning model proposed by *Riousset et al.* [2007] to illustrate how blue and gigantic jet discharges are produced above cloud tops. The model reported by *Riousset*

et al. [2010] accounts for the time-dependent conduction currents and screening charges formed under the influence of the thundercloud charge sources and gives particular attention to realistic simulation of the dynamics of the screening charges near the cloud boundaries. The results demonstrate how the prior occurrence of intracloud discharges can prevent the development of a blue jet until a cloud-to-ground discharge enhances the excess of positive charge in the cloud by bringing negative charge to ground. The screening charge gradually developing at the cloud top leads to breakdown initiation near the cloud upper boundary but is insufficient to contain the lightning leader channel within the cloud resulting in occurrence of upward propagating blue jet events. Furthermore, in thunderstorms where convective overturning near the cloud top is sufficiently strong, the screening layer that allowed for blue jet initiation, gets mixed with the storm's upper positive charge region, reducing the net positive charge in this region and causing a substantial charge imbalance between the two main layers of the thundercloud. Quantitative modeling of resulting discharge presented by *Riousset et al.* [2010] reveals that the leader channels cannot be contained in the volume enclosed within the cloud boundary and eventually escape upward to form a gigantic jet, consistent with the ideas first expressed by *Krehbiel et al.* [2008].

[54] Results presented by *Krehbiel et al.* [2008] and *Riousset et al.* [2010] provide experimentally substantiated mechanisms of escape of lightning leaders from cloud tops complementing the previous theoretical work [*Petrov and Petrova*, 1999; *Pasko et al.*, 1999a; *Pasko and George*, 2002; *Tong et al.*, 2005; *Raizer et al.*, 2006, 2007]. The application of ideas advanced in the work of *Raizer et al.* [2006, 2007] concerning possibility to map high potentials at the cloud top to higher altitudes using conducting leaders depends on possibility to sustain the leader process at low air pressures at high altitude. The understanding of the streamer-to-leader transition and the development of accurate numerical parameterizations of streamer zones of lightning leaders of different polarities, especially under low air pressure conditions, represent unsolved problems in current research on transient luminous events [e.g., *Pasko*, 2006; *Pasko and Bourdon*, 2007]. The general scaling of the Joule heating timescale in the streamer channels as a function of air density can be quite easily deduced from basic similarity analysis of gas discharges to be inversely proportional to square of gas density [e.g., *Achat et al.*, 1992; *Tardiveau et al.*, 2001; *Pasko*, 2006]. Therefore it is generally expected that the heating processes and resulting streamer-to-leader transition should be delayed with reduction of air pressure (i.e., at higher altitudes in the Earth atmosphere) and it should be possible to define a set of specific conditions (i.e., altitude range, reduced electric field E/N, etc.) in the Earth atmosphere for which the transition becomes impossible. The visual appearance of some blue jets and gigantic jets [see, e.g., *Pasko et al.*, 2002, Figure 2; *Wescott et al.*, 2001, Figure 1; *Pasko and George*, 2002, Figure 10] is suggestive of a transition from hot lightning like channels to a cold streamer dominated region at higher altitudes. In terms of negative leader phenomenology, the moment of attachment of gigantic jet to the lower ionospheric boundary, can be interpreted as the "final jump stage," when the leader streamer zone makes contact with the opposite electrode [*Bazelyan and Raizer*, 1998, p. 212]. This stage may also have some resemblance to the negative corona flash stage of negative leader development [*Bazelyan and Raizer*, 2000, p. 199]. The high speeds during the final jump, 5×10^4 m/s to 10^6 m/s [*Bazelyan and Raizer*, 1998, p. 212], are consistent with the range of speeds, from 5×10^4 m/s to more than 2×10^6 m/s, reported by *Pasko et al.* [2002]. *Kuo et al.* [2009] recently reported first photometric measurements of the fast ~10^7 m/s upward propagation during the initial stage (also referred to as fully developed stage in the work of *Su et al.* [2003]) of a gigantic jet probably indicating highly overvolted conditions, which streamers experienced as they moved to low air density (high reduced electric field E/N) regions at high altitude. The relatively bright persistent channel below ~40–50 km altitude observed in gigantic jets [*Pasko and George*, 2002; *Su et al.*, 2003] and designated as trailing jet in the work of *Su et al.* [2003], 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 significant lengthening of the heating timescales 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.

4. Chemical Effects of Transient Luminous Events

[55] Whether transient luminous events have long-lived by-products leading to long-term consequences of their occurrence was questioned soon after their discovery [*Sentman et al.*, 1995; *Sentman and Wescott*, 1996].

[56] 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].

[57] Recently, *Lehtinen and Inan* [2007] utilized a model of stratospheric/lower ionospheric chemistry to demonstrate that substantial ionization associated with gigantic jets 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 timescale of mutual neutralization of negative and positive ions [*Lehtinen and Inan*, 2007]. *Lehtinen and Inan* [2007] state that such recovery signatures may be observable in perturbations of subionospherically propagating very low frequency (3–30 kHz) long-range communication signals.

[58] The observations and theoretical analysis showing that blue jets, gigantic jets and sprites have small-scale streamer structure allow to make some additional comments as to their expected chemical effects. The nonthermal streamer plasma at atmospheric pressure, with hot (usually several eV) electrons embedded in cold (ambient temperature) air, is of significant practical interest and importance as it provides a good source of highly reactive species used for chemical treatment of hazardous and toxic pollutants [*van Veldhuizen*, 2000]. Owing to the ability of streamer filaments to produce high electric fields around their tips, the nonthermal streamer plasmas easily generate electrons with energies sufficient to dissociate atmospheric oxygen molecules. The dissociation initiates a chain of reactions leading to formation of ozone in

air, the process, which has been used for industrial ozone production for over a century [*van Veldhuizen*, 2000]. Owing to the dramatic reduction of the air pressure at high altitudes above thunderstorms, the same streamers, which develop on timescales of several nanoseconds and possessing diameters of a fraction of millimeter at ground level, appear as channels of plasma many kilometers long 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 [e.g., *Gerken et al.*, 2000; *Pasko and George*, 2002; *Su et al.*, 2003]. These streamers preserve their ability to produce highly active chemical species [*Hiraki et al.*, 2004, 2008; *Hiraki*, 2009; *Enell et al.*, 2008; *Arnone et al.*, 2008, 2009; *Sentman et al.*, 2008a; *Sentman and Stenbaek-Nielsen*, 2009; *Gordillo-Vazquez*, 2008; *Gordillo-Vazquez and Donko*, 2009] and can effectively "treat" thousands of cubic kilometers of atmosphere in a single event. The branching observed in atmospheric TLE discharges, like those documented by *Pasko and George* [2002] and *Su et al.* [2003] is also known but not fully understood property of streamers at ground pressure. The streamer branching is currently recognized as an important effect control of which is desirable for effective chemical treatment of large gas volumes [*van Veldhuizen and Rutgers*, 2002a].

[59] *Hiraki et al.* [2004] investigated formation of $O(^1D)$ atoms by sprite discharges. The $O(^1D)$ atoms were considered to be generated by electron impact dissociation of O_2 molecules in sprite halo events, where electrons are accelerated in strong electric fields associated with lightning discharges. The peak production rate of $O(^1D)$ in a single sprite halo event was estimated to be as large as 10^4 cm^{-3} for a duration of 1 ms, which is comparable to, or even larger than, the steady rate by solar-UV radiation [*Hiraki et al.*, 2004].

[60] *Sentman et al.* [2008a] (see also *Sentman et al.* [2008b]) conducted the first comprehensive study of the principal chemical effects induced by the passage of a single sprite streamer head through the mesosphere at an altitude of 70 km. The study involved nonlinear coupled kinetic scheme of 80+ species and 800+ reactions. Electrons created by ionization within the streamer head persist within the trailing column for about 1 s, with losses occurring approximately equally by dissociative attachment with ambient O_3, and by dissociative recombination with the positive ion cluster $N_2O_2^+$. On the basis of simulation results, it is concluded that the observed reignition of sprites most likely originates in remnant patches of cold electrons in the decaying streamer channels of a previous sprite. Relatively large populations (fractional densities ~10^{-9}–10^{-8}) of the metastable species $O(^1D)$, $O(^1S)$, $N(^2D)$, $O_2(a^1\Delta_g)$, $O_2(b^1\Sigma_g^+)$, $N_2(A^3\Sigma_u^+)$, and $N_2(a'^1\Sigma_u^-)$ are created in the streamer head. The impulsive creation of these species initiates numerous coupled reaction chains, with most of the consequent effects being of a transient nature persisting for less than 1 s. These include weak (similar to 1 kR), but possibly detectable, OI 557.7 nm and $O_2(b^1\Sigma_g^+ \rightarrow X^3\Sigma_g^-)$ Atmospheric airglow emissions. Neutral active species created in the greatest abundance (fractional densities >10^{-8}) are $N_2(X^1\Sigma_g^+, v)$, $O(^3P)$, $N(^4S)$, and $O_2(a^1\Delta_g)$, which, because of the absence of readily available chemical dissipation channels, persist for longer than 100s of seconds.

[61] Among other effects it is estimated that streamer can produce an integral number of 5×10^{19} NO molecules [*Sentman et al.*, 2008a]. The study reported in the work of *Sentman et al.* [2008a] has recently been extended to include effects of weak electric fields in the trailing columns of sprite streamers [*Sentman and Stenbaek-Nielsen*, 2009]. Results indicate that the electron densities are slightly decreased in comparison with previous study [*Sentman et al.*, 2008a] on account of enhanced dissociative attachment in the undervoltage environment. The effects on the densities of $O(^3P)$ and the metastable species $O(^1D)$ and $N_2(A^3\Sigma_u^+)$ are enhancements by a modest factor of 2 or less compared with a field-free tail. The $O_2(a^1\Delta_g)$ shows slightly greater enhancements, by up to a factor of 3, and O^- shows enhancements by up to a factor of 5 [*Sentman and Stenbaek-Nielsen*, 2009].

[62] *Hiraki et al.* [2008] emphasizes that the streamer discharge has an intense electric field and high electron density at its head, where a large number of chemically active ions and atoms are produced through electron impact on neutral molecules. After the passage of the streamer, densities of minor species can be perturbed through ion-neutral chemical reactions initiated by the relaxation of these radical products. *Hiraki et al.* [2008] evaluated the production rates of ions and atoms using an electron kinetics model and calculated the density variations for NO_x, O_x, and HO_x species using a one-dimensional model of the neutral and ion composition of the middle atmosphere, including the effect of the sprite streamer. Results at the nighttime condition show that the densities of NO, O_3, H, and OH increase suddenly after passage of streamer and that NO and NO_2 can persist for 1 h around 60 km altitude. The authors conclude that that sprites would have the power to impact local chemistry at night [*Hiraki et al.*, 2008].

[63] *Gordillo-Vazquez* [2008] presented a full time-dependent kinetic study for the main microscopic collisional and radiative processes associated with a single sprite streamer passing through an air region of the mesosphere at three different altitudes (63, 68, and 78 km). The chemical model set up for air plasmas included more than 75 species and almost 500 reactions. In addition, a complete set of reactions (more than 110) has been considered to take into account the possible impact of including H_2O (humid chemistry) in the generated air plasmas. The study of *Gordillo-Vazquez* [2008] also considered the vibrational kinetics of N_2 and CO_2 and explicitly evaluated the optical emissions associated with a number of excited states of N_2, O_2, O in the visible, CO_2 in the infrared (IR) and ultraviolet (UV) emissions of sprite streamers due to the N_2 Lyman-Birge-Hopfield (LBH) and the NO-γ band systems. All the calculations are conducted for midnight conditions in midlatitude regions (+38 degrees N) and 0 degrees longitude, using as initial values for the neutral species those provided by the latest version of the Whole Atmosphere Community Climate Model (WACCM). Results demonstrate that at 68 km, the concentrations of NO and NO_2 increase by about one order of magnitude while that of NO_3 exhibits a remarkable growth of up to almost three orders of magnitude [*Gordillo-Vazquez*, 2008].

[64] In the work of *Gordillo-Vazquez and Donko* [2009] a Boltzmann and Monte Carlo analysis of the electron energy distribution function and transport coefficients for air plasmas is presented for the conditions of the Earth troposphere where

some transient luminous events such as blue jets, blue starters, and gigantic jets have been observed. *Gordillo-Vazquez and Donko* [2009] specifically emphasized effects of humidity and gas temperature. The results of the calculations presented in the work of *Gordillo-Vazquez and Donko* [2009] for altitudes 11 and 15 km indicate that the effects of humidity are important if the air temperature is elevated by 100 K with respect to values in ambient atmosphere. The effects are especially pronounced at low electric fields a factor of 5 below the conventional breakdown threshold field E_k that could be controlling the afterglow kinetics of the air plasmas generated by TLEs. However, for much higher fields representative of conditions around streamer tips the impact of increasing the relative humidity and gas temperature is only slightly noticeable in the attachment coefficient that can exhibit an increase of up to one order of magnitude at 11 km and 15 km for temperatures of 313 K and 308 K, respectively [*Gordillo-Vazquez and Donko*, 2009].

[65] It should be emphasized that although very significant perturbations of atmospheric chemistry are possible in localized volumes affected by TLEs their effects on regional and global scales have not yet been fully understood and quantified.

[66] *Rodger et al.* [2008] recently reported a study making use of nighttime observations of NO_2 by the GOMOS instrument to test whether transient luminous events are producing significant NOx 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 transient luminous events, including blue jets and gigantic jets, upon NO_x levels in the stratosphere and mesosphere (20–70 km) [*Rodger et al.*, 2008]. This particular study therefore shows that variation in NO_x due to transient luminous events does not appear to be significant on regional scales or beyond.

[67] *Enell et al.* [2008] investigated through chemical modeling employing an extended version of the Sodankyla coupled Ion-neutral Chemistry model if transient luminous events can be a significant source of odd nitrogen and affect ozone or other important trace species. The inputs for modeling included the rates of ionization, excitation and dissociation based on spectroscopic ratios from ISUAL instrument on FORMOSAT-2. The results of study indicated that the NO_x enhancements were at most one order of magnitude in the sprite streamers. The global production of NO_x by sprites is 150–1500 kg/day with yearly production of up to 10^{31} molecules, which is comparable with the production associated with a stratospheric solar proton event during solar minimum, but much smaller than the global production by cosmic rays or proton events at solar maximum [*Enell et al.*, 2008]. The study reported in the work of *Enell et al.* [2008] therefore indicates that sprites are relatively insignificant as a global source of NO_x. The local effects on ozone are also negligible, but the local enhancement of NO_x may be significant, up to 5 times the minimum background at 70 km in extraordinary cases [*Enell et al.*, 2008]. *Neubert et al.* [2008] estimated global NO_x effects of sprites based on the approximately three sprites per minute global occurrence rate suggested by *Ignaccolo et al.* [2006]. Although the local buildup of NO_x may be significant [*Enell et al.*, 2008], *Neubert et al.* [2008] indicate that the global impact of sprites is diluted by their rarity. The preliminary results presented by *Neubert et al.* [2008] suggest that sprite-related processes are unlikely to play a significant role in the total NO_x budget of the stratosphere and mesosphere. *Neubert et al.* [2008] also indicate that further studies are needed to consolidate our understanding of sprite chemistry.

[68] *Arnone et al.* [2008] investigated the local chemical impact of sprites. The middle atmosphere Michelson Interferometer for Passive Atmospheric Sounding (MIPAS) NO_2 satellite measurements using GMTR (Geofit MultiTarget Retrieval) retrieval package were correlated with ground-based World Wide Lightning Location Network (WWLLN) detections of large tropospheric thunderstorms as a proxy for sprite activity. The authors found no evidence of any significant impact at a global scale but an indication of a possible sprite induced NO_2 enhancement of about 10% at 52 km height in correspondence with active thunderstorms. This local enhancement appears to increase with height from a few percent at 47 km to tens of percent at 60 km. The results of this study were later confirmed by *Arnone et al.* [2009] where further analysis was also presented showing that the NO_2 enhancement was dominated by the contribution from regions north of the Equator (5 degrees N to 20 degrees N) during the first 30 to 40 days of the sample (i.e., the tail of Northern Hemisphere summer) and in coincidence with low background winds.

5. Global Electric Circuit Effects of Transient Luminous Events

[69] Additional consequences of transient luminous events may include effects on the global electric circuit, in which the Earth-ionosphere potential difference of several hundred thousand volts is predominantly driven by upward currents from thunderstorms [*Rycroft*, 2006; *Rycroft et al.*, 2000, 2008; *Tinsley*, 2008]. Video recordings showing jet events extending from the cloud tops to the ionosphere [*Pasko and George*, 2002; *Su et al.*, 2003] may indicate that these events play a larger role in the global electric circuit than previously expected. The recent report of significant charge transfer of −144 C to the lower ionosphere in a gigantic jet event [*Cummer et al.*, 2009] further emphasizes potential importance of these events in the global electric circuit. *Krehbiel et al.* [2008] note that positive blue jets contribute to the charging of the global electric circuit, while negative gigantic jets discharge the circuit.

[70] In a simplified picture of the global electric circuit the Earth surface and the conducting atmosphere and ionosphere above it can be considered as plates of a giant spherical capacitor with the upper plate being maintained at about 300,000 V potential with respect to the potential of the Earth [*Bering et al.*, 1998]. There are many components, which may be contributing to the balancing of the potential difference at the above mentioned levels. The two most critical ones are believed to be thunderstorms, about 2000 of which are present globally at any given time and which act as batteries charging the capacitor, and the fair weather regions, which continuously discharge the capacitor through the weakly conducting atmosphere providing the electrical link between plates with global leakage current of about 1 kA [*Bering et al.*, 1998]. The upper plate of the capacitor is not confined to any single level but rather distributed through the atmosphere,

reflecting exponential increase of the atmospheric conductivity and decrease of the fair weather electric field with a scale height of approximately 7 km. This maintains the quasi-constant current density as a function of altitude continuously flowing vertically through the atmosphere in the fair weather regions [*Bering et al.*, 1998]. Most of the 300,000 V potential drop between the capacitor plates therefore happens within several 7 km e-folding distances from the surface of the Earth.

[71] The voltages and currents in the global electric circuit may be controlled to some degree by blue jets and gigantic jets. The negative polarity gigantic jets, for example, supply large quantities of negative charge to the upper capacitor plate [*Cummer et al.*, 2009] therefore acting to discharge the capacitor. In this context it is important to note that there are several features in sprite type of TLEs, which exhibit some close similarities with blue jets and gigantic jets indicating conducting connection and current flow between thundercloud tops and the lower ionosphere (see discussion in the work of *Pasko* [2008]). 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 EXL98 campaign by *Siefring et al.* [1999]. 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 [*Pasko et al.*, 2001]. So-called "trolls" are jet-like features propagating upward from near cloud tops to 40–50 km at 150 km/s along the preceding sprite tendrils [*Lyons et al.*, 2000]. There are some similarities in appearance of the gigantic jets 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 [*Heavner*, 2000; *Moudry*, 2003]. *Moudry* [2003] provides an excellent summary of three distinct types of secondary sprite processes near cloud tops, which are broadly referred to as "crawlers." *Marshall and Inan* [2007] estimated velocities of upward propagating palm trees to be at least 1.5×10^6 m/s. The average altitudes of palm trees were estimated to be between 32 ± 4 and 57 ± 6 km, and the authors noted that observations at altitudes lower than 32 km were difficult due to cloud obstruction and atmospheric attenuation [*Marshall and Inan*, 2007]. *Moudry* [2003] noted that the jet event observed by *Pasko et al.* [2002] 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., ms and sub-ms) of blue jets and gigantic jets are available yet.

[72] The contribution of sprites to the global atmospheric electric circuit have been discussed by *Fullekrug and Rycroft* [2006]. These authors found that the global atmospheric electric field from individual sprites is less than or similar to 44 mV/m, which can be measured with conventional ULF/ELF radio wave antennas at frequencies less than or similar to 4 Hz.

6. Conclusions

[73] In this paper we have presented an overview of the physical mechanisms and recent modeling efforts related to sprites, blue jets, and gigantic jets. In discussion on sprites a primary emphasis was put on model interpretation of available experimental data on sprite streamers and various emissions documented to date from sprites. There are many important similarities between optical emissions associated with streamers documented in sprite discharges and emissions from pulsed corona discharges in laboratory experiments. The comparison of the laboratory and sprite discharges reveals the importance and the need of further studies of processes related to vibrational excitation of ground state of N_2 molecules, and pooling and resonant energy transfer reactions involving $N_2(A^3\Sigma_u^+)$ metastable species for understanding of emissions originating from $B^3\Pi_g$ and $C^3\Pi_u$ states of N_2, and NO γ-band emissions, during both initial and postdischarge stages of sprite discharge. The work in that direction has already started in the context of development of comprehensive kinetic models for evaluation of chemical effects of sprites and sprite streamers [e.g., *Sentman et al.*, 2008a; *Sentman and Stenbaek-Nielsen*, 2009; *Gordillo-Vazquez*, 2008].

[74] In this paper an attempt also was made to give a model interpretation of morphological features of observed blue jet and gigantic jet events in the context of known phenomenology of leader and streamer discharges documented in high (i.e., atmospheric) pressure experiments. We have also briefly reviewed some of the early and more recent modeling efforts related to blue starters, blue jets and gigantic jets. Finally, we identified a need for high speed imaging of the jet phenomena and outlined some presently unsolved problems in theory of blue starters, blue jets, and gigantic jets, including the definite need for better understanding of the streamer-to-leader transition and the development of accurate numerical parameterizations of streamer zones of lightning leaders of different polarities under low air pressure conditions.

[75] We note that problems discussed in this paper, related to basic physics of sprites, blue jets, and gigantic jets, and their possible chemical and global electric circuit effects reviewed in the last two sections, represent an important component of a broader range of other, currently unsolved, problems in studies of transient luminous events summarized by *Pasko* [2006], which include initiation and propagation of sprite streamers in low applied electric fields, branching of sprite streamers, and effects related to the thermal runaway electron phenomenon in streamer tips in different types of transient luminous events.

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