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Blue jets produced by quasi-electrostatic pre-discharge thundercloud fields

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Abstract. Pre-discharge quasi-electrostatic (QE) fields immediately above the thundercloud lead to the formation and upward propagation of streamer type ionization channels with features in good agreement with recent video observations of Blue Jets.

Introduction

Blue Jets are upward moving (~100 km/s) highly collimated beams of luminosity, emanating from the tops of thunderclouds, extending up to ~50 km altitude and exhibiting primarily blue color [*Sentman and Wescott*, 1994; *Wescott et al.*,1995*a*, hereafter referred to as 1]. We propose that jets are the result of streamer type ionization channels. We use a modified QE model [*Pasko et al.*, 1995*a*] to evaluate the dynamics of ionization channels and optical emissions above the thundercloud prior to a lightning discharge and compare our results with recent video observations.

Physical Mechanism

Blue Jets as Streamers. Streamers are transient filamentary plasmas, the dynamics of which are controlled by highly localized nonlinear space charge waves [see *Vitello et al.*, 1994; *Grange et al.*, 1995; *Lagarkov and Rutkevich*, 1994, and references therein]. The streamer velocity v_s usually lies in the range ~10^2-10^3 km/s depending on the streamer polarity, the applied electric field (E), the initial radius, the density of the seed ionization which initiates the streamer process, the background electron density [e.g., *Dhali and Williams*, 1987], and the geometry of the boundaries (e.g., point to plane corona discharge) [*Grange et al.*, 1995]. The polarity of a streamer is defined by the sign of the space charge in its 'head'. A negative streamer propagates due to ejection of electrons from its head. Positive streamers require a population of ambient electrons (e.g., produced by cosmic rays) for their development, and have low velocities of ~100 km/s, comparable to electron drift velocities (v_d) in the body of the streamer, which occur for low applied E fields [*Dhali and Williams*, 1987] and in point-to-plane corona discharges [e.g., *Grange et al.*, 1995].

Assuming that the radius of the entire streamer column r_s is approximately equal to that of its head, v_s, r_s and the dielectric relaxation time τ_s within the streamer ($\tau_s = \varepsilon_o/\sigma_s$, where σ_s is the streamer conductivity) are related simply by [*Vitello et al.*, 1994]:

$$\frac{\delta}{r_s} = \frac{v_s\tau_s}{r_s} \simeq \frac{E_b}{E_h} \qquad (1)$$

where E_h, E_b are the E fields at the streamer head and in the streamer body, respectively, and $\delta = v_s\tau_s$ is an effective 'skin depth' for the E field inside the streamer. In most cases $0.1 < E_b/E_h < 1$ so that δ is comparable to r_s [*Lagarkov and Rutkevich*, 1994, p.16] and is typically the only parameter which characterizes the spatial scale of the streamer [e.g., *Dhali and Williams*, 1987]. Streamer type solutions are possible for a variety of transverse dimensions, including the km spatial scales typical for Blue Jets, provided that appropriate initial conditions can occur near the top of the thundercloud. Jets are thus similar to positive streamers which initiate point-to-plane corona discharges [*Grange et al.*, 1995], except for the geometry and maintenance of the field by the thundercloud charge, and the altitude variation of atmospheric neutral density (N) and conductivity (σ).

Formation of Blue Jets. The positive (top) and the negative (bottom) thundercloud charges (Figure 1) slowly (seconds) accumulate due to the current $\vec{J}_s'$ associated with the separation of charges inside the cloud, and directed opposite to the resulting E field. The current may be related to the small and light positively charged ice splinters driven by updrafts, and heavy negatively charged hail particles driven downward by gravity [e.g., *Uman*, 1987, p. 65]. Unusually intense hail activity was indeed observed in association with jets [*Wescott et al.*, 1995*b*], and is a strong indication of intense electrical activity inside the cloud.

Under certain relatively rare conditions, a charge of Q=300-400C can accumulate at ~20 km altitude. This charge may have an extended dish-like distribution and can lead to breakdown ionization in regions with lateral extent ~10^2-10^3 m. The ionization may also be connected with the accumulation of long living (~1-2 sec at ~20 km [*Lowke*, 1992]) metastable O_2 molecules due to upward directed discharges preceding the development of jets [1], corona discharges initiated by hydrometeors [*Griffiths and Phelps*, 1976] or highly charged hailstones triggering instability of charged droplets [*Grigor'ev and Shiryaeva*, 1989] (see next Section). Once formed, the ionized region can act as the seed for the development of an upward propagating positive streamer. We propose that jets are the mesospheric analog of the positive

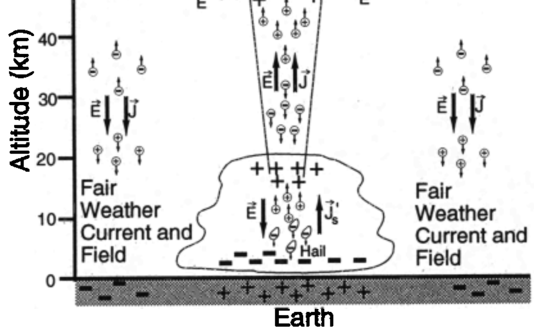

Figure 1. Currents, charges and electric fields associated with the Blue Jet. The Figure is partly adapted from [*Uman*, 1987, p. 30].

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type streamer produced in laboratory point-to-plane corona discharge experiments.

The electric field is nonzero inside the streamer and an upward directed current (I_s) always flows in the streamer body (Figure 1). The streamer propagates freely when I_s is maintained by a source in or near the cloud. Otherwise, the negative charge flowing in the streamer body towards the positive thundercloud charge would reduce the source charge and E and would eventually suppress the propagation. Thus, the streamer can propagate as long as $\vec{J}_s'$ can deliver sufficient positive charge to the top of the thundercloud. An equal amount of negative charge is accumulated at the thundercloud base so that the overall charge in the cloud-streamer system is conserved. The thundercloud plays the role of a 'battery' and the net effect of the streamer attached to this 'battery' is to deliver positive charge to the conducting electrosphere, contributing to the maintainence of the fair weather potential. The streamer propagation can also cease when it reaches the critical altitude at which τ_s within the streamer body is comparable to the relaxation time τ of the ambient conducting atmosphere ($\tau = \varepsilon_o/\sigma$). At this altitude, all current through the channel created by the streamer can be supplied by the flow of atmospheric ions, and the E field at the tip of the streamer is not enhanced since σ is comparable to σ_s.

Model

General Description. A cylindrical coordinate system (r, ϕ, z) is used with the z axis representing altitude. The electric field $\vec{E}$, charge density ρ, and conduction current $\vec{J} = \sigma\vec{E}$ are calculated using the following system of equations:

$$\frac{\partial(\rho + \rho_s)}{\partial t} + \nabla \cdot (\vec{J} + \vec{J}_s) = 0 \qquad (2)$$

$$\nabla \cdot \vec{E} = (\rho + \rho_s)/\varepsilon_o \qquad (3)$$

where ρ_s and $\vec{J}_s$ are the thundercloud source charge and current which satisfy the equation $\frac{\partial \rho_s}{\partial t} = -\nabla \cdot \vec{J}_s'$, where $\nabla \cdot \vec{J}_s' = \nabla \cdot \vec{J}_s + \rho_s\sigma/\varepsilon_o$, and the effective source current $\vec{J}_s'$ (Figure 1) is introduced so as to compensate any change in the thundercloud charge ρ_s due to relaxation processes (e.g., current flow and associated charge accumulation due to the streamer). As can be seen from (2), (3) the introduction of $\vec{J}_s'$ allows us to specify the charge dynamics inside of the cloud as a given function of time.

We assume that positive charge is placed at 20 km altitude, has a spherically symmetric Gaussian distribution with a spatial scale of 3 km, builds up with a time scale τ_f and is completely dissipated with a time constant τ_d. We neglect the lower thundercloud charge due to its proximity to the ground (Figure 1). This charge also may be removed by a series of negative lightning discharges during several seconds before the appearance of jets [*Wescott et al.*, 1995*b*].

The ionization changes and optical intensities are calculated as described in [*Pasko et al.*, 1995*a*] for the same ambient conditions (electron density N_e and ion σ) therein.

Equations (2) and (3) can be derived from the two-fluid streamer equations [e.g., *Vitello et al.*, 1994]. In comparison, equation (2) does not contain an exponentially growing term. The increase in N_e is self-consistently included in our model as σ changes. However, since $v_d \sim v_s$, our model may not accurately predict the small scale details of N_e near the steep boundary at the streamer head. Results of extensive modeling [e.g., *Vitello et al.*, 1994] indicate that for a well developed streamer, τ_s behind the streamer front remains approximately constant. We use this result as an additional condition in our model, placing a bound on the growth of N_e in the streamer front.

Ionization and Attachment. We use the ionization model of [*Papadopoulos et al.*, 1994] and dissociative attachment model derived from swarm experiments [*Davies*, 1983]. A specific breakdown electric field $E_k^o = 3.7 \times 10^6 N/N_o$ V/m ($N_o = 2.688 \times 10^{25}$ m^{-3}) is defined as the field at which the effective ionization coefficient ν_i is equal to the attachment coefficient ν_a, within ~15 % agreement of the $E_k = 3.2 \times 10^6 N/N_o$ V/m [*Papadopoulos et al.*, 1994]. For $E > E_k^o$, N_e grows exponentially in time with rate (ν_i-ν_a)>0 determined as a function of E [*Papadopoulos et al.*, 1994; *Davies*, 1983]. When $E < E_k^o$ (i.e., (ν_i-ν_a)<0 behind the streamer front) electrons may be quickly removed by dissociative attachment to O_2. However, this is not always the case due to the extremely effective detachment process of electrons in the presence of metastable O_2 [*Lowke*, 1992], leading to a reduction of E_k by factor of about 6, in some cases. In previous work [*Davies*, 1983] it was recognized that the role of dissociative attachment of electrons to O_2 is difficult to assess since the measured rates for associative detachment and for collisional detachment are known only within one to three orders of magnitude, respectively. In view of the complexity of the role of detachment, we conservatively assume in our model that (ν_i-ν_a)=0 for $E < E_k^o$.

Optical Emissions. Optical emissions intensities of the 1st ($N_2 1P$) and 2nd ($N_2 2P$) positive bands of N_2, Meinel and 1st negative bands of N_2^+, and the 1st negative band of O_2^+ are calculated using a kinetic model of optical excitation of N_2 and O_2 by electron impact [*Taranenko et al.*, 1993]. For comparison of our model results with video observations of jets, the optical emission intensities are rescaled as described in [*Pasko et al.*, 1995*b*] using red, green and blue video filters and by assuming the distribution of optical emissions as functions of wavelength within particular optical bands to be similar to those in auroral emissions.

Results

Model calculations indicate that the streamer morphology above a thundercloud can be complex, exhibiting large variability in r_s, stopping altitudes and v_s, depending mostly on initial conditions and the source function (e.g., current $\vec{J}_s'$). Such variability is in general agreement with the degrees of freedom allowed for streamer solutions in equation (1) and with recent observations of Blue Starters [*Wescott et al.*, 1995*b*], which exhibit shorter lifetimes, faster velocities (~300 km/s) and smaller transverse and vertical extents in comparison with jets [1].

We assume τ_f=1 sec and τ_d=0.5 sec, and consider τ_s as an input parameter. The initial ionization region and the initial r_s are then defined mostly by the effective volume of space over which $E > E_k^o$, depending on the magnitude and distribution of Q. The initial ionization that forms naturally above the thundercloud plays the same role as the seed ionization in streamer simulations [e.g., *Vitello et al.*, 1994].

The dependence of the streamer characteristics on τ_s and Q are in agreement with (1). A case showing agreement with the observed characteristics of jets [1] is described below.

Electron Number Density, Electric Field and Current. Figure 2a shows E and N_e corresponding to a jet produced by Q =375 C and τ_s =0.05 sec. Altitude scans of E (at r=0) are shown in the left hand panel at selected instants of time, and compared with E_k. The enhancement of E at the tip of the streamer is apparent in the middle panel of the Figure 2a. The characteristic spatial scale δ is comparable with r_s. E barely exceeds E_k, since ν_i becomes very large ($\nu_i \gg \frac{1}{\tau_s}$) for slight increases in E above E_k. Accordingly, it can be assumed that $E_b \simeq E_h$ in (1). N_e shown in the right hand panel illustrates the formation of a beam-like distribution expanding upward with a radius ~2 km at the cloud top and ~7 km at ~45 km altitude.

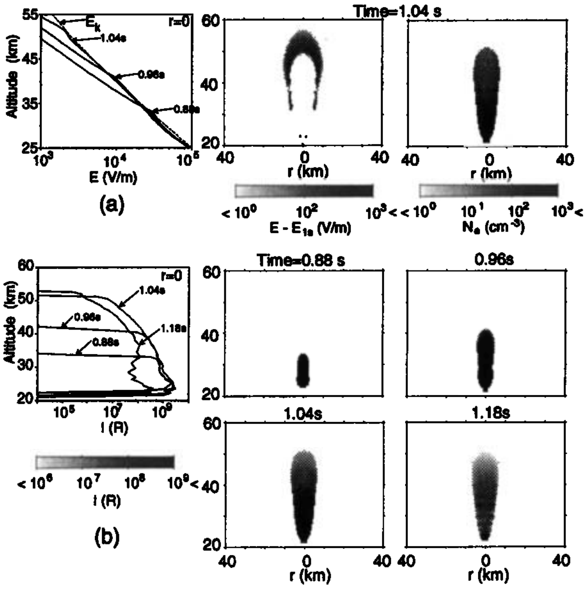

Figure 2. A crossectional view of the distribution of the absolute values of E and N_e (a), and I of $N_2 2P$ (b), at selected instants of time. Right hand panels show altitude scans at $r = 0$.

The simulation results can be qualitatively interpretated based on simple analytical estimates. Behind the front of the jet $E \sim E_k$ (Figure 2a), so that the current $I_s \simeq eN_e v_d \pi r_s^2$ flows in the streamer body where e is the charge, and $v_d = \mu_e E_k$. I_s is estimated to be ~200 A, and can deliver ~100C during the lifetime of the jet to the thundercloud. The electron mobility μ_e for $E \simeq E_k$ is $\mu_e \simeq 4 \times 10^{-2} N_o/N$ [*Davies*, 1983], so that $v_d \simeq$100 km/s and is independent of altitude. I_s is conserved along the jet and since v_d is constant, this implies that the quantity $N_e r_s^2$ should be conserved. In our model, we assumed $\tau_s = \frac{\varepsilon_o}{\sigma_s}$ to be constant, where $\sigma_s = eN_e\mu_e$, which is equivalent to requiring $N_e \sim N$. The conservation of I_s along the streamer implies that $r_s \sim N^{-\frac{1}{2}}$, consistent with the general tendency of the jet to expand toward higher altitudes, in good agreement with our numerical results especially below 40 km. Above 40 km, the expansion slows down because of the increasing role of ionospheric ions in carrying the current in the streamer, as well as the reduction in Q (so that I_s is reduced in later stages of streamer propagation). A comparison of the conditions τ_s=const and $r_s \sim N^{-\frac{1}{2}}$ with (1) shows that $v_s \sim N^{-\frac{1}{2}}$, in good agreement with our numerical results. At the initial stage of jet formation at 24 km altitude v_s ~40 km/s; it reaches a value ~100 km/s at ~35 km altitude and subsequently remains in the range 100-130 km/s until the jet stops. The numerical values of electron density at 24 km and 35 km are 10^3 and 180 cm^{-3}, and streamer radii are 2 and 5 km, respectively. These values satisfy both the conservation of I_s and (1) with reasonable accuracy.

Optical Emissions. The intensity (I) of $N_2 2P$ is shown in Figure 2b. The jet propagates upward with average velocity 88 km/s and stops at ~50 km altitude mainly due to our chosen model of Q with τ_d=0.5 sec. If Q is instead kept constant after 1 sec, the jet propagates to a slightly higher altitude (~53 km) and stops when $\tau_s \simeq \tau$ (τ_s=τ at 49 km altitude for the ion conductivity profile used). The optical emission has the shape of an upward expanding beam with transverse dimensions being essentially the same as for the ionization column shown in Figure 2a. The corresponding cone angle is ~20°. Figure 2b shows that at t =1.18 sec I fades away simultaneously at all points along the jet.

Figure 3a shows the altitude distribution of I at the axis of symmetry for selected bands at t =1.04 sec. The $N_2 1P$ and $N_2 2P$ dominate and have similar intensities. Figure 3b shows the red and blue video responses at t=1.04 sec.

Figure 3c shows the spatially integrated value of I as a function of time. The intensity peaks ~200 ms after the start of the jet and disappears over ~150-200 ms, defined primarily by the chosen τ_d. Additional calculations show that the jet can last as long as the thundercloud charge can support the flow of current from the cloud to the ionosphere. In this case, the jet is stationary and has the shape of a significantly expanded upward luminous column which electrically connects the thundercloud and the electrosphere.

Discussion

Geometrical Shape and Velocity of Blue Jets. The dynamics of Q may play the dominant role in defining r_s and v_s of jets. Equation (1) and the continuity of I_s indicate that v_s can stay constant with altitude if $r_s \sim N^{-1}$ and $N_e \sim N^2$. The initial radii of jets in such a case should be very small (100-500 m) to produce the observed collimated (with apparent cone angle < 30°) beam-like shape of the lower parts of jets with altitude extent of several atmospheric scales. This solution may be consistent with the fan-like upper parts of Blue Jets [1], however, I ($I \sim N_e$) might then dramatically decrease with altitude with a scale height of ~ 3 km.

Brightness of Blue Jets. Figure 3b indicates that I changes by a factor of ~10^2 between the lower and upper ends of the jet, in good agreement with observations [1]. However, the predicted absolute intensities ~5×10^4 kR (Figure 3b) are ~1-2 orders of magnitude above those observed (~500 kR) [1]. In this regard, we note that the excitation rates of the optical emissions depend sensitively on E (e.g., E_k^o) and may change several orders of magnitude in response to small variation in E. In addition, the uncertain role of detachment processes (as discussed in previous Sections) may have contributed to our overestimation of I. The Δv=3,4 sequences of $N_2 1P$ producing red visible emissions may be significantly degraded in comparison with shown on Figure 3b due to reduction in populations of high vibrational levels with increasing pressure [e.g., *Morrill et al.*, 1988].

Blue Jets and Sprites. The streamer type solutions suggested in this paper for jets ($r_s \sim N^{-1}$, $N_e \sim N^2$; or $r_s \sim N^{-\frac{1}{2}}$, $N_e \sim N$) are also directly applicable to Sprites [e.g., *Sentman et al.*, 1995] which we believe in some cases may be a manifestation of streamer processes initiated by intense positive lightning discharges [*Pasko et al.*, 1995*b*]. The splitting of sprites into several filaments and fast downward focusing of these filaments to very sharp edges can naturally be explained as basic properties of streamer type processes in a medium in which the scale height of N is comparable with the spatial scale of the streamer.

Blue Jets and Runaway Electrons (REL). REL have been suggested by several workers as a possible mechanism for

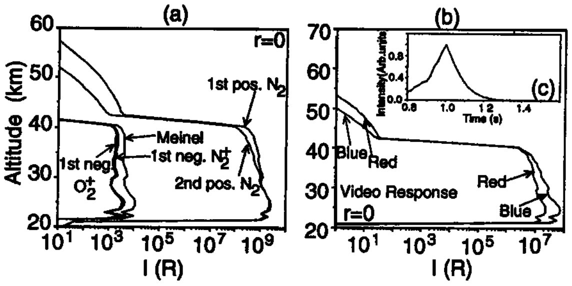

Figure 3. (a) Altitude scans at (r=0) of I corresponding to different bands. (b) Expected red and blue video response corresponding to optical emissions shown in (a). (c) Spatially integrated I as a function of time.

sprites and jets [*Bell et al.*, 1995; *Winckler et al.*, 1995; *Taranenko and Roussel-Dupre*, 1995]. REL may possibly be involved in producing the ionization in the streamer head. This mechanism appears attractive since it has a threshold field E_t which is $\sim$ 10 times lower than E_k. In the lower atmosphere the REL process starts from very low ambient production rates (S_o), requiring many e-folding distances before observable effects can be produced [*Bell et al.*, 1995]. The E field should significantly (5-7 times) exceed E_t to reach a regime of measurable ionization and optical output.

Consider δ_o=7 ($\delta_o = E/E_t$) and two altitudes 30 and 40 km. REL e-folding distances for these altitudes are l_f $\sim$50 m and $\sim$200 m, respectively [*Bell et al.*, 1995]. To support the streamer with τ_s=0.05 s and r_s =2 km, REL should produce sufficient secondary electrons $N_s \simeq 10^3$ cm^{-3} (see Figure 2a) on a time scale much shorter than τ_s, say Δt=1 ms. Using $N_s \simeq cN_R N\sigma_o\Delta t$, where c is speed of light, $\sigma_o = 2.3\times10^{-18}$ cm^2 [*Bell et al.*, 1995] the required number of REL can be estimated as $N_R \simeq 3.9\times10^{-5}$ and 1.8×10^{-4} cm^{-3} at altitudes 30 and 40 km, respectively. The number of required e-foldings n_f can be estimated from $N_R \simeq \frac{S_o l_f}{c}e^{n_f}$, and is equal to 20.1 and 21.6 for 30 and 40 km, respectively, where $S_o = 4.4\times10^{-7}$ cm^{-3} s^{-1}, at 30 km and $S_o = 10^{-7}$ cm^{-3} s^{-1} at 40 km [*Bell et al.*, 1995]. Thus REL should move $\sim$1 km around 30 km and $\sim$4 km around 40 km altitude to produce sufficient N_s. These values are lower then observable scales of jets, so that the runaway mechanism may contribute to their production. This means that N_s would play the major role in establishing current and space charge balance, as well as the general shape of the streamer. Since the thermalization time of N_s is expected to be very fast at low $\sim$30 km streamer development in case of ionization by REL may be similar to that caused by the conventional breakdown (including $v_s\sim$ 100 km/s). However the details of the optical spectra may differ since the REL secondary electrons would be much more energetic.

Summary

Blue Jets are proposed to be streamer type processes occuring on atmospheric spatial scales. A two dimensional and self consistent model produces results in general agreement with most features of jets as observed in video [1]. The model shows that the velocity of upward propagation of jets is $\sim$100 km/s, reproduces the general shape of jets as upward expanding beams of luminosity with cone angles $< 30^\circ$, and simply accounts for the stopping altitudes ($\sim$50 km) for jets. The model agrees with results of video observations showing that the brightness drops $\sim$2 orders of magnitude between the lower part and the tip of the jet, and the fact that the luminosity fades away simultaneously everywhere along the cone of jet. The model naturally explains the blue color of jets as observed in video as emission from $N_2 2P$ excited upon electron impact. Jets are not necessarily associated with lightning discharges and may appear only in relatively rare cases of large ($\sim$300-400C) thundercloud charge accumulation at high ($\sim$20 km) altitudes. Jets are produced during the accumulation phase of the thundercloud charge, so that it is not necessary for large amounts of charge to be removed. It is thus conceivable that a horizontally extended thundercloud charge distribution, consisting of many charge centers located at lower altitudes (< 20km), may produce the E field equivalent to that of simple monopole of $\sim$300-400C at $\sim$20 km altitude.

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