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Blue Jets: their relationship to lightning and very large hailfall, and their physical mechanisms for their production

E. M. Wescott[a,*], D. D. Sentman[a], M. J. Heavner[a], D. L. Hampton[b], O. H. Vaughan Jr[c]

[a] *Geophysical Institute, University of Alaska Fairbanks, Fairbanks, Alaska, U.S.A.*
[b] *Ball Aerospace & Technology, Boulder, Colorado, U.S.A.*
[c] *NASA Marshall Space Flight Center, Huntsville, Alabama, U.S.A.*

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Abstract

Blue jets are narrow cones of blue light that appear to propagate upward from the cloud tops at speeds of about 100 km/s to terminal altitudes of about 40 km (Wescott et al. 1995). In this paper, we present the results of a refined analysis of these optical phenomena and their relationship to cloud-to-ground (CG) and intracloud lightning, and to very large hailfall, their apparent color, and possible mechanisms for their production. In a thunderstorm where more than 50 of these events were observed from aircraft on the night of 1 July 1994, about half of the blue jets occurred in a cluster near Foreman, Arkansas, and the rest in an area near Texarkana, (Texas/Arkansas). Hail 7 cm in diameter fell in those two storm cells at the time of the blue jet occurrences. One other blue jet was observed over an intense multi cell storm in Kansas on the night of 3 July 1994. Comparison to cloud-to-ground (CG) lightning strokes revealed that blue jets were not coincident with either positive or negative CG strokes, but they occurred in the same general area as negative CG strokes and large hail, and that cumulative distributions of the negative CG strokes in ±5 s before and after the jet and within a radius of 15 km showed a significant reduction in the flash rate for 2 s following the event. From an analysis of color TV signal levels and calculations of quenching and atmospheric transmission, we conclude that significant ionization is present in the jets. Theoretical work by others suggests that the mechanism for their production is a streamer, but there remain discrepancies between these theories and the observations.

1. Introduction

During the moon down period of June/July 1994, the University of Alaska flew two corporate jet aircraft equipped with a suite of low-light-level imagers to the vicinity of large thunderstorms to investigate upper atmospheric optical emissions. These dual jet flight missions permitted accurate triangulation of the location and the physical dimensions of upper atmospheric optical events. (See Sentman et al. (1995) for details of the missions and equipment). Wescott et al. (1995) have reported the observations made during one very active storm near the Arkansas/Texas border area. During a 22-minute interval of one of the flights, they documented 56 examples of a phenomenon named blue jets. Blue jets are characterized by the propagation of a narrow cone of blue light upward from the apparent cloud tops at speeds of about 100 km/s, with a terminal altitude of about 40 km: see Fig. 1.

We have now triangulated 34 individual blue jets that occurred in the interval 03:01:25 UT to 03:14:57 UT, on 1 July 1994. From these triangulations, we have derived the velocity of propagation and the maximum altitude of 20 examples. The triangulated positions and times have been compared with those of CG lightning flashes reported by the National Lightning Detection Network (NLDN). Wescott et al. (1995) have given a preliminary analysis of locations, velocities and the essential features of blue jets. In this paper we present the results of a much more complete and detailed analysis.

Wescott et al. (1996a) have also published separately the results of the analysis of 30 examples of a related

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* Corresponding author. e-mail: rocket@giuaf.gi.alaska.edu

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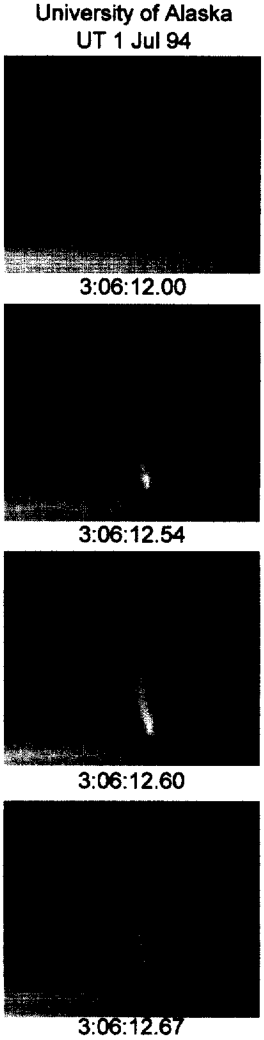

Fig. 1. Time sequence of video frames, 67 ms apart, during a blue jet event on 1 July 1994, from the Jet Commander aircraft. Note that the brightness is starting to fade all along the jet in the last frame.

phenomena called 'blue starters', which were interspersed with the blue jets in a 6 min 40 s interval within the same storm cells. We compare the similarities and differences in these phenomena and the possible mechanisms for their generation.

2. Observations

On the night of 1 July 1994 UT, two aircraft instrumented with wide angle monochromatic silicon intensified target (SIT) TV cameras flew northerly in clear air along the western end of the Arkansas/Texas thunderstorm, making observations of the intense lightning activity within the storm for about 22 minutes. The apparent top of the storm anvil was clearly visible from the aircraft. National Weather Service (NWS) radar measurements indicated the anvil top to be at 63,000 ft (19.2 km). The aircraft flew in a trail formation, separated by about 30 km. Thirty four blue jets, of the 51 total recorded, were in the field of view on the TVs of both aircraft, making three-dimensional triangulation possible. Five of the 56 reported by Wescott et al. (1996a) are now classified as blue starters. The remaining 17 blue jets were seen by only one aircraft, but their locations can be estimated by assuming the altitudes of their bottoms from the triangulated data. One of the aircraft was also equipped with a low light level color TV, which provided valuable data on the color of the phenomenon.

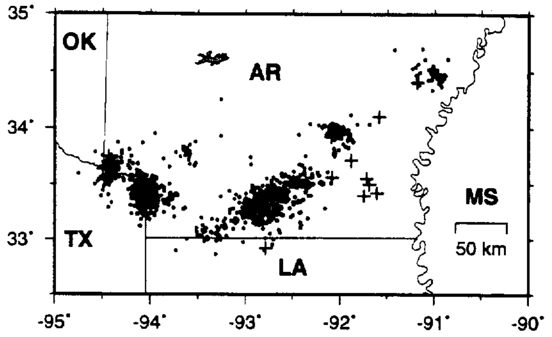

Fig. 2. Map of the National Lightning Detection Network derived locations of the cloud-to-ground (CG) flashes (dots: negative flashes; and crosses: positive flashes) during the Arkansas storm from 03:00–03:20 UT, 1 July 1996.

Figure 2 shows the NLDN derived positions of negative and positive CG flashes over the interval 03:00 to 03:20 UT for the whole Arkansas storm. There were five main storm cells, but the two western-most cells exhibited the greatest activity. It was from these western cells that the blue jets were observed to originate. A newspaper account from the Texarkana area reported winds on the ground of 100 to 120 km/h at the time of the storm, marble-to-baseball sized hail, and about 5 cm accumulated rainfall during the interval of blue jets (Jones-Mosley, 1994). The NWS reported 7 cm diameter hail at Texarkana and New Boston, TX, 5 cm hail at Fouke, AR, 4.45 cm hail at Foreman, AR, and slightly smaller hail at several other locations in Arkansas and Texas.

Two nights later, on 3 July 1994, a single blue jet was recorded from one of the aircraft over an intense storm over Kansas. Figure 3 shows the estimated location of the jet near the centroid of negative CG flashes in one of the cells of the storm (about 70 km in diameter). The NWS radar at Wichita, Kansas, indicated that the anvil top in that cell reached 55,000 ft (16.8 km). At the time of the jet the NLDN negative CG flash rate in the cell was 75 per min. The cell was located in a sparsely popu-

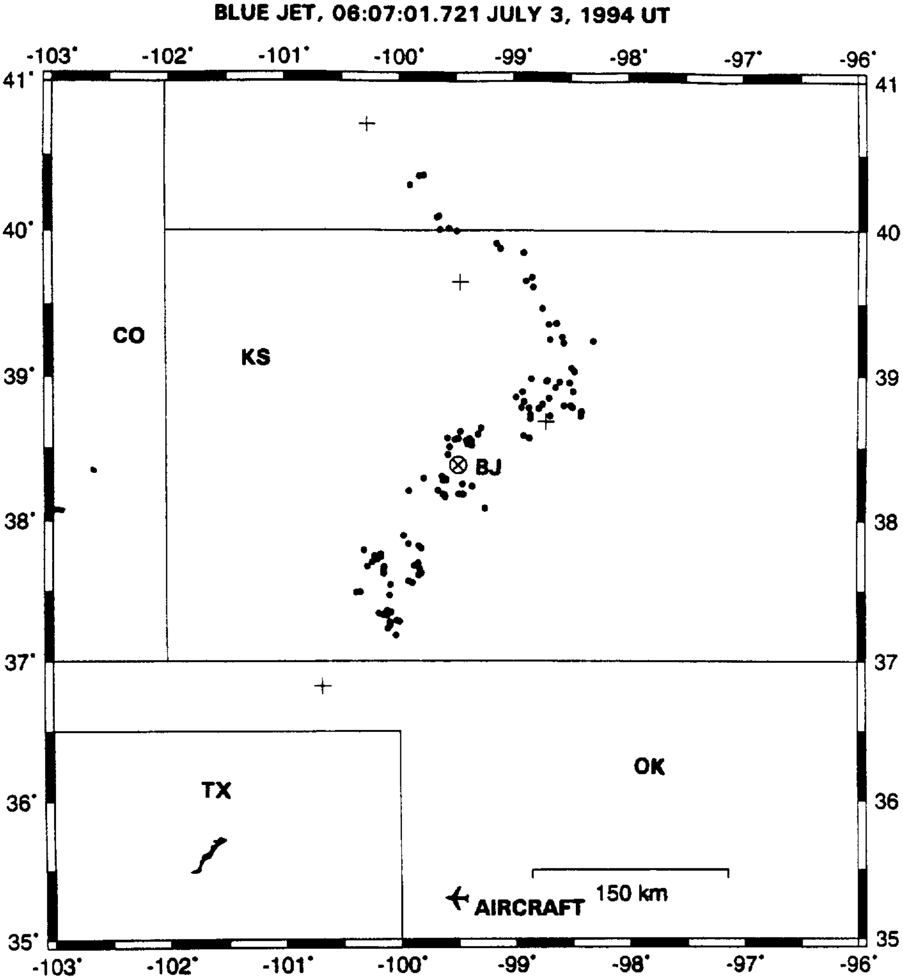

Fig. 3. Map of the National Lightning Detection Network derived locations of the cloud-to-ground (CG) flashes (dots: negative flashes; and crosses: positive flashes) during the Kansas storm from 06:07:01.721 ± 30 s, 3 July 1994. The blue jet, ⊗, location was estimated from accurate measurements of the azimuth and elevation with respect to the star background, and the cloud top altitude.

lated area, and there were no NWS reports of hail. However, there were numerous insurance claims filed for crop damage in the area of the cell, but the size of the hail is unknown.

3. Analysis

The locations of 34 blue jets, 30 blue starters and five groups of sprites that occurred during a 17.5 min interval were triangulated from simultaneous images obtained from the two aircraft using computer programs STAR and STEREO (H. Nielsen, private communication). STAR is used to fit stars from the Smithsonian Observatory catalogue onto observed stars on the video frame. The catalogue star field can be stretched and rotated until a good fit is obtained. This provides the transformation from any pixel location on the video frame to azimuth and elevation. Program STEREO is then used to triangulate on any feature seen from two or more optical sites. In the work presented here the corrected field of view is about 45°. Each pixel is 0.174 × 0.174°. Most of the blue jets were found to be at a slant range of about 100 km, so that one pixel represents 300 × 300 m, the uncertainty of the triangulation. The locations of an additional 17 other blue jets, observed from only one of the two aircraft platforms, were estimated using the same programs and, varying the range so that the bottom altitude of the jet was 17.7 km, the mean value obtained from the triangulations. The times and locations of the blue jets are given in Table 1.

The mean value of the upper extent of the blue jets was 37.2 ± 5.3 km, where the spread relates to the distribution, not to an error in determining the altitude. The mean vertical velocity was 112 ± 24 km/s (excluding one outlier of 217 km/s). Few of the jets were exactly vertical. The mean angle off the vertical was 10.81° ± 7.0°.

Table 1
Blue jets

Time	Lat.	Long	Alt (B)	(T)
FOREMAN JETS				
03:00:00.233	+33.765	−094.374	017.711	
03:00:55.522	+33.712	−094.412	017.701	
03:01:44.404	+33.565	−094.620	017.703	
03:01:48.508	+33.663	−094.449	017.704	
03:03:19.432	**+33.699**	**−094.363**	**017.010**	**040.042**
03:03:28.641	**+33.686**	**−094.390**	**020.120**	
03:03:29.042	**+33.681**	**−094.360**	**017.774**	
03:03:57.103	**+33.672**	**−094.402**	**018.642**	**038.094**
03:03:57.303	**+33.689**	**−094.392**	**017.927**	**035.222**
03:03:57.563	**+33.680**	**−094.680**	**021.598**	**027.467**
03:04:14.187	**+33.694**	**−094.382**	**020.384**	**040.909**
03:05:05.672	**+33.666**	**−094.398**	**019.496**	**041.620**
03:08:07.554	**+33.673**	**−094.454**	**018.228**	**025.847**
03:08:07.687	**+33.675**	**−094.449**	**018.082**	**027.620**
03:08:08.454	**+33.671**	**−094.424**	**018.039**	**039.990**
03:09:36.543	**+33.678**	**−094.413**	**017.521**	
03:10:50.150	+33.561	−094.565	017.704	
03:16:55.048	+33.637	−094.327	017.702	
03:17:05.525	+33.786	−094.447	020.125	
03:18:17.964	+33.731	−094.303	017.703	
03:18:46.960	+33.817	−094.339	017.703	
03:19:43.450	+33.749	−094.284	017.700	
03:19:43.750	+33.749	−094.284	017.700	
TEXARKANA JETS				
02:59:24.731	+33.482	−094.038	017.876	
03:00:06.306	+33.394	−094.007	017.695	
03:00:27.794	+33.426	−094.012	017.703	
03:00:40.907	+33.401	−093.908	017.702	
03:01:25.118	**+33.427**	**−093.999**	**017.558**	
03:01:34.561	**+33.459**	**−093.991**	**019.002**	
03:01:42.969	**+33.384**	**−094.200**	**017.702**	
03:02:01.121	**+33.421**	**−094.047**	**018.637**	**040.496**
03:02:01.138	**+33.434**	**−094.020**	**019.002**	**038.464**
03:02:30.450	**+33.434**	**−094.051**	**020.174**	
03:02:47.267	**+33.420**	**−094.059**	**018.642**	**030.607**
03:02:49.502	**+33.381**	**−094.198**	**017.642**	
03:05:40.774	**+33.431**	**−094.056**	**021.926**	**041.547**
03:05:49.149	**+33.443**	**−094.031**	**020.446**	**040.305**
03:06:12.439	**+33.430**	**−094.011**	**020.500**	**044.214**
03:07:21.274	**+33.442**	**−094.007**	**021.912**	**036.162**
03:09:51.591	**+33.321**	**−093.931**	**019.521**	
03:09:51.658	**+33.380**	**−094.002**	**019.799**	
03:11:12.205	**+33.231**	**−093.643**	**022.023**	
03:11:22.982	**+33.447**	**−094.097**	**019.785**	
03:12:24.811	**+33.409**	**−094.022**	**020.140**	**037.293**
03:12:24.944	**+33.420**	**−094.066**	**019.328**	**037.152**
03:12:25.011	**+33.404**	**−094.044**	**019.920**	**042.308**
03:13:10.223	**+33.452**	**−094.133**	**019.139**	
03:13:46.159	**+33.281**	**−903.953**	**024.312**	**038.758**
03:14:57.397	**+33.299**	**−094.008**	**022.100**	
03:14:57.564	**+33.308**	**−093.973**	**020.441**	
03:17:24.277	+33.422	−094.130	017.703	
Single blue jet on 3 July 1994. Single aircraft position				
06:07:01.721	+38.444	−099.478	18.416	

Times of occurrence, and triangulated/estimated positions/terminal altitudes of blue jets used in this study. All times are in UT, 1 July 1994. Aircraft triangulations are shown in boldface. Bottoms (B) and tops (T) are given in km above mean sea level (MSL).

4. Blue jets vs lightning

All of the blue jets which we observed occurred in two very active thunder cells near the tri-state area of Arkansas, Texas and Oklahoma (see Fig. 2). If blue jets had occurred in the next large cell to the east, we should have been able to observe them as shown in Fig. 4. Figure 5 shows the locations of the jets (dark filled circles, triangulated; light-filled circles, single aircraft estimates). The black dots indicate all of the negative flash locations reported by the NLDN during the interval 03:00–03:20 UT. Positive strokes are shown as a '+'. We triangulated the position of a turret to be located 5.5 km west/southwest of Foreman, AR, extending about 1 km above the anvil to 18.7 km (61,300 ft). No blue jets arose from the turret. Analysis of intracloud and CG flash rates in the cells from the TV fields showed extraordinary rates of 300 flashes/min in the Foreman cell and 200 flashes/min in the Texarkana cell.

Wescott et al. (1996) reported a related phenomenon called blue starters that occurred in the same two storm areas. They compared the occurrence of negative CG lightning flashes to a distance of 50 km from each blue starter, and found that the mean rate of flashes following the events dropped significantly and did not recover to the pre-event flash rate for 2.25 seconds. The mean negative CG flash rate was about 0.5/s, so the 2.25 s drop in the rate is the equivalent of one missing CG flash. The mean energy deficit implied by the change of slope was estimated to be 10^9 J, based on one missing CG lightning stroke (Uman, 1987).

We have performed a similar analysis of lightning flash rates immediately before and after the blue jets. We compared the difference in time Δt between 27 blue jets, which were not preceded or followed by either another blue jet or a blue starter within ±3 s, and negative CG flashes during the interval for ±5 s and within various radii. Figure 6 shows the cumulative flash rate to a distance of 15 km from the event. A lull in activity following a jet can be seen in cumulative flash plots as far as 50 km, but it most clearly shows out to 15 km. Note the changes in slope in the cumulative distribution before and at the time of the event. There is a significant lull in activity for about 2 s after the event. Note that the time of any event can only be determined to one TV field (16.6 ms). There are more flashes prior to the jet (24) than after it (13). In fact, 10 flashes occurred in the 1 s interval just before the blue jets and an average of about 5 in the other 1 s intervals before and after. If we consider the subset of flashes within 10 km of the blue jet, the ratio of flashes

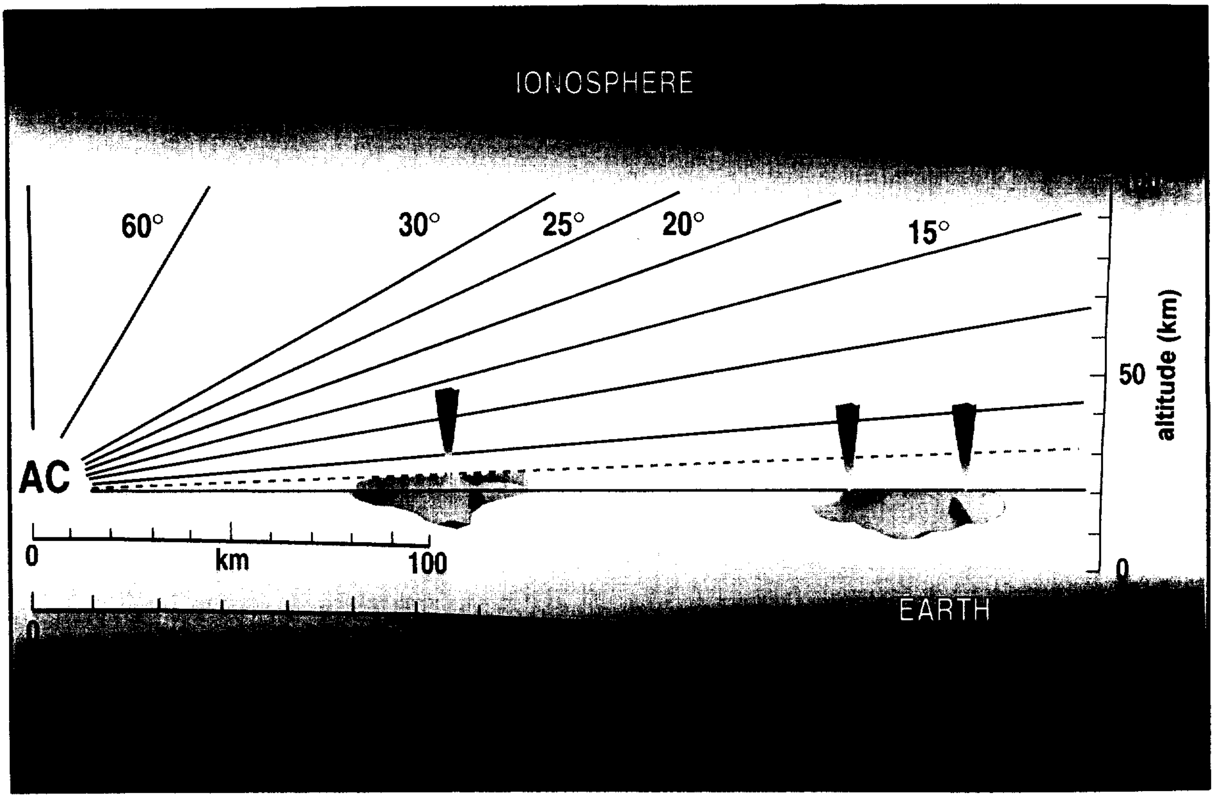

Fig. 4. Scale profile of the view angles from the aircraft to storm cells showing a blue jet in the Texarkana cell and two theoretical blue jets in the next large cell to the East (1 July 1994). If there had been any blue jets in that cell they would have been observed from the aircraft.

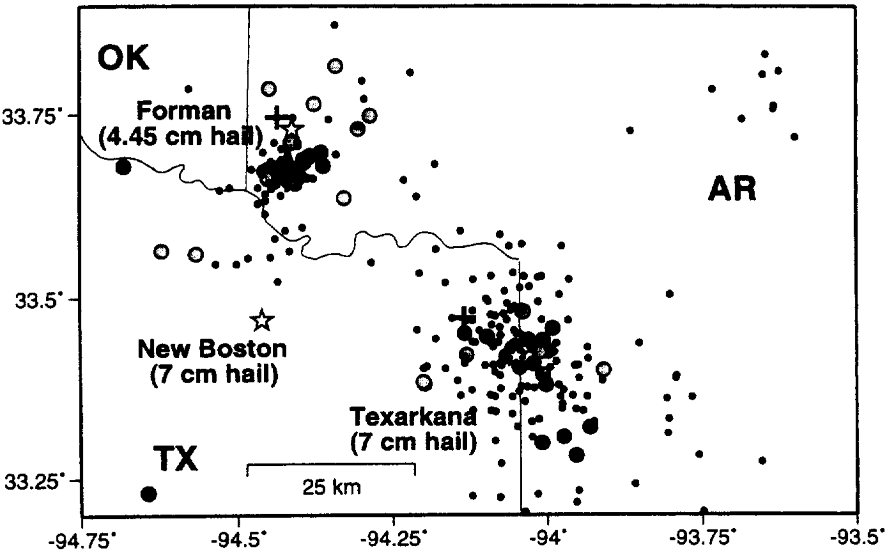

Fig. 5. Detailed map of 1 July 1994 NLDN lightning flashes in the Foreman, Arkansas (AR) and Texarkana, Texas/Arkansas (TX/AR) thunderstorm cell areas with the locations of the blue jets. Towns are indicated by open stars. Negative CG flashes are solid small dots, positive CG flashes are +'s, triangulated blue jets are dark filled circles, and single aircraft estimated locations are light filled circles. a prominent turret was triangulated, located 5.5 km west/south west of Foreman.

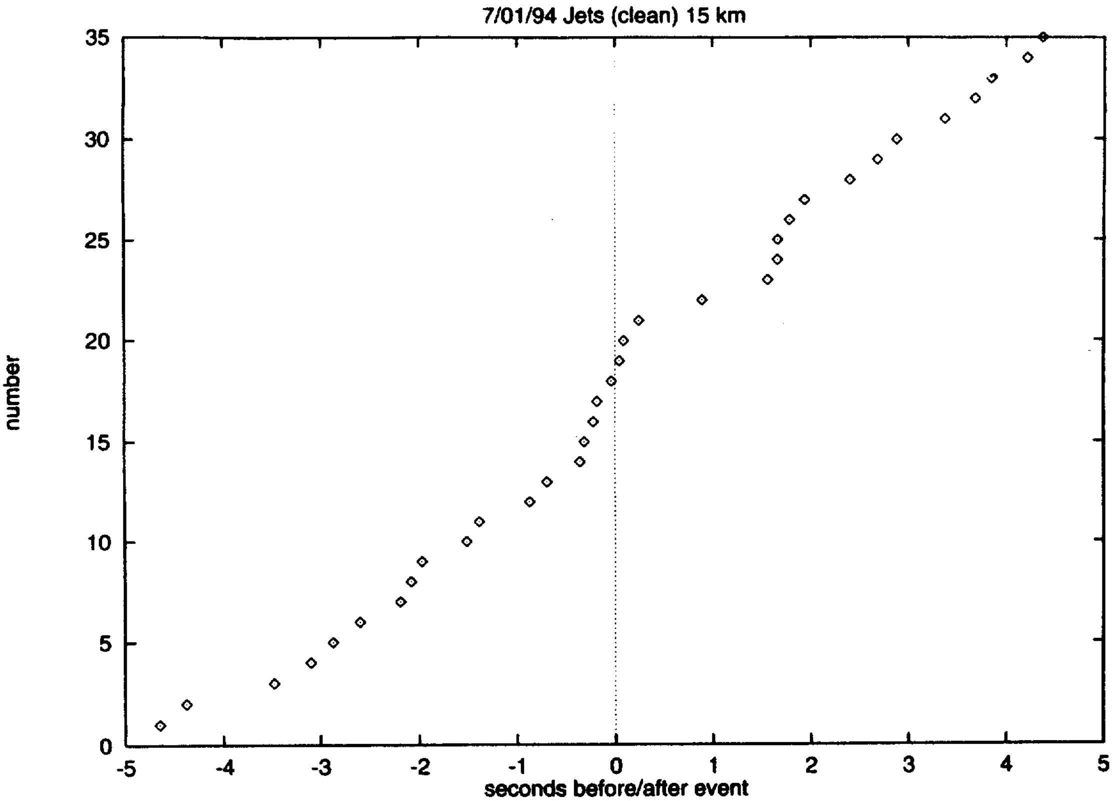

Fig. 6. Cumulative distribution of the 1 July 1994 NLDN negative CG flashes within ±3 s and radius of 15 km of 27 blue jets during the interval 02:59:24 to 03:18:47 UT. Only blue jets with no multiple jets or blue starters within ±3 s were used in this analysis. The main difference between this pattern and that for blue starters (Wescott et al., 1996a) is the obvious increase in the negative CG activity just preceding the jet, but the lull following the jet is similar to the pattern of the blue starters.

prior to the jet to those after the jet is 2:1, the same as for the full set.

The results of this analysis indicates that there is a significant difference between the cumulative CG flash distributions of blue starters and blue jets. For the blue jets it appears that the rate of negative CG flashes within 15 km doubles in the 1 s interval immediately before the jet occurs. Also if we consider the same area (30 km radius) around jet and starters we find that the flash rate is about 25% higher for jets. This suggests that more charge transfer to the ground precedes jets than starters.

Two groups of sprites were observed within 2 min before the interval of the blue jets, and three groups of sprites were observed during the interval and one just after the interval. The sprites were located about 300 km east of the area of the blue starters and blue jets, and were generally associated with a +CG stroke within 50 km, in agreement with the observations of Boccippio et al. (1995).

The observation of a single blue jet over the thunderstorm in Kansas two nights later agrees with the conclusion that blue jets are not associated with positive CG flashes, and that they occur in areas of negative CG flashes, but are not associated with a particular flash.

5. Color of blue jets

Although one of the aircraft was equipped with a low light level TV spectrograph, no spectra were obtained. However, the second aircraft recorded the blue jets with a low light level color TV system, which has three separate SIT systems in red, green and blue, thus serving as a crude spectrograph. Figure 7 shows the responses of the three tubes, corrected for aircraft window and atmospheric transmission. Careful analysis of the individual color signals shows that the emissions from the jets were only detected in the blue tube, whose response peaks at 455 nm. The green tube has no appreciable response below 480 nm. Given the system sensitivity, this implied that the spectrum of the blue jets at the source lies pre-

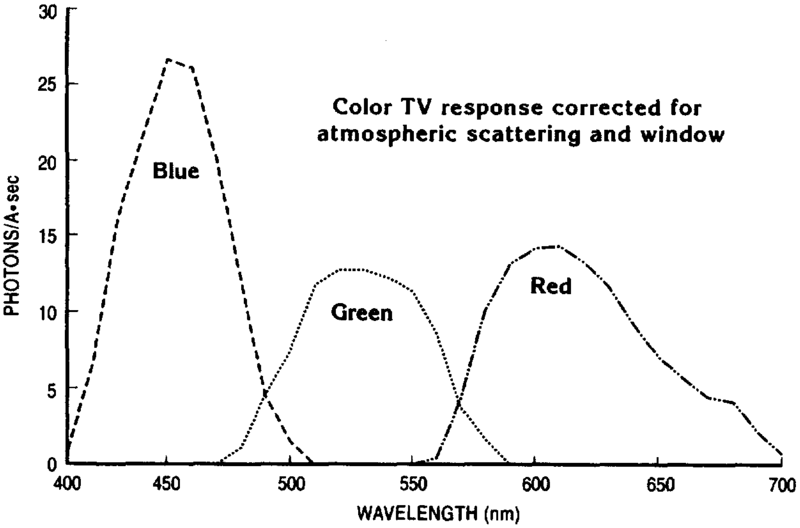

Fig. 7. Response of the color TV system, including the effects of atmospheric transmission along the line of sight to an actual blue jet and the transmission of the aircraft window.

dominately below 480 nm, thus accounting for the blue color.

Wescott et al. (1996b) have measured the spectrum of St. Elmo's fire with a TV spectrograph on another flight through a cloud at an altitude of 13.7 km, and shown that the emissions are almost entirely from the N_2 second positive bands (N_22P) below 480 nm. Although the altitude of the St. Elmo's fire that was observed was lower than that of blue jets, this suggests that the emissions from the blue jets might also be from the N_2 second positive bands. However, we argue below that ionized N_2 may also be an important component.

Due to Rayleigh scattering of light in the atmosphere, violet wavelengths are scattered about 10 times more than the red wavelengths for clear air, and somewhat less when aerosols are present. Guttman (1968) measured the atmospheric extinction coefficient, τ, of light in the visible spectrum in clear atmospheres and with thin cirrus clouds. These values can be used with Beer's law to calculate the transmission vs wavelength:

$$I = I_0 e^{-\tau\omega},$$

where ω is the air mass in the path length from the source to the observer, and τ is the atmospheric extinction coefficient. Figure 8 shows the calculated atmospheric transmission for a typical path length from the base of one of the blue jets to the aircraft, and also to a point on the ground directly under the aircraft. Note that the ratio of the red-to-blue transmission is about 1.7:1. The ratio of the aircraft-blue to ground-blue transmission is about 4.5:1.

Table 2 lists the important nitrogen energy transitions which we consider. We have calculated the quenching factors vs altitude for the N_2 1P, N_2 2P, N_2^+ 1N and N_2^+ Meinel bands using the coefficients of Vallance Jones (1974). These are shown in Fig. 9. The Meinel bands are so severely quenched that they are negligible. Then we convolved the quenching factors with the auroral brightness numbers of Vallance Jones (1974) and the response curves of the blue and red TV tubes, as shown in Fig. 7. Figure 10 (curve a) shows the ratio of blue-to-red intensities in the TV signal using only the N_2 2P as the blue component. If this were actually the emission spectrum of the blue jets, enough red would have been present that they would have appeared purple at the bottom and red near the top, contrary to the purely blue TV response. Figure 10 (curve b) also shows the blue-to-red ratio if we add the contribution of ionized N_2^+ 1N bands. With the assumption of the auroral brightness of the nitrogen bands, the results more closely match the observed blue-to-red ratios, strongly suggesting that the jets must be energetic enough to ionize the air partially.

6. Discussion

The dynamics and electrostatic field distribution within a thunderstorm anvil are very complex. Byrne et al. (1989) reported the results of two balloon flights carrying corona probes to measure electric fields. The balloons passed through the anvil upstream of the precipitation core and measured extensive regions of both net positive and negative charge. They found the thicknesses of screening layers to be approximately an order of magnitude greater than calculated in previous models.

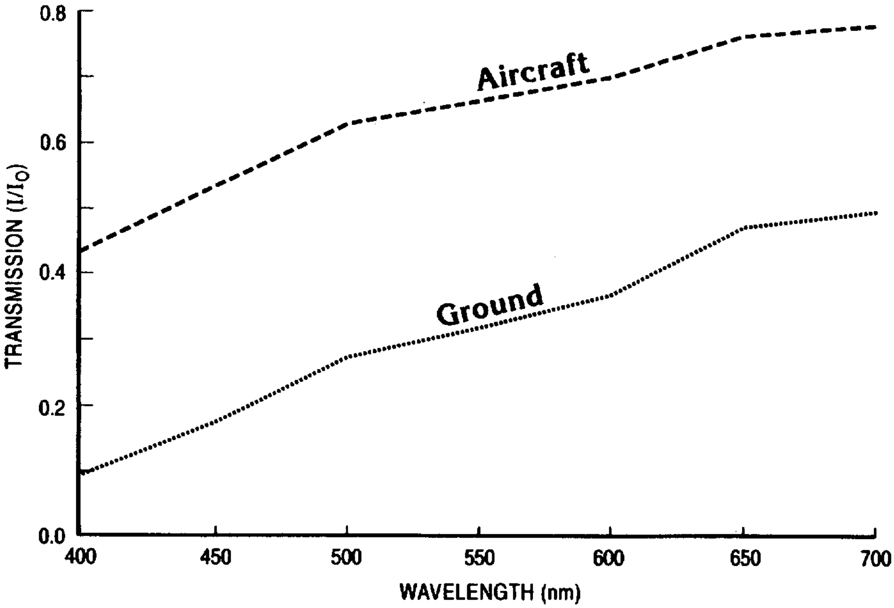

Fig. 8. Atmospheric transmission vs wavelength from the base of an actual blue jet to the aircraft, and to a theoretical observer on the ground under the aircraft.

Table 2
Molecular transitions

Species	Transition	System designation
N_2	$B^3\Pi_g \rightarrow A^3\Sigma_u^+$	First positive (1P)
N_2	$C^3\Pi_u \rightarrow B^3\Pi_g$	Second positive (2P)
N_2^+	$B^2\Sigma_u^{l+} \rightarrow X^2\Sigma_g^+$	First negative (1N)
N_2^+	$A^2\Pi_u \rightarrow X^2\Sigma_g^+$	Meinel

According to the criteria of Marwitz (1972a; 1972b), the 1 July 1994 Arkansas storm would be classed as a multi-cell storm. From Fig. 1, all the blue jets and blue starters which we observed occurred in the two western-most or upstream cells. If any jets had occurred in the large cell located about 100 km further east, we should have been able to observe them when they reached about 25 km altitude (Fig. 4). The additional Rayleigh scattering due to the longer path length would have reduced the apparent brightness, but not to the point of non-detectability. Byers and Braham (1949) and Byers (1953) indicate that hail only occurs in cells within thunderstorms. They measured updrafts over 56.4 ft/s associated with hail up to 20,000 ft. Vonnegut and Moore (1958) studied a giant electrical storm that reached heights of 20 km or more, and indicated that there must have been vertical velocities on the order of 100 m/s. From the triangulated altitudes of the bottoms of the blue starters, the Arkansas storm anvil was at about 18 km altitude with a turret reaching to about 18.7 km (61,260 ft). Ludlam (1985) derived a formula for the fall speed associated with hailstones of radius greater than 1 cm:

$$V \approx 30r^{1/2}\ \mathrm{m/s}\ (r \text{ in cm}).$$

For the 7 cm hail associated with these events $V \approx 80$ m/s, suggesting very strong updrafts in the two cells where blue starters and blue jets were observed.

Carey and Rutledge (1996) have used multi-parameter radar measurements to infer the precipitation structure of a severe hailstorm which they compared with the measured CG lightning flash rate, ground strike locations and polarity of a storm that occurred on 7 June 1995 east of the Colorado Front Range. They found the temporal and spatial behavior of large hail and positive CG lightning to be anti-correlated: 'In fact broad peaks in the positive CG flash rate lag relative maxima in the surface fall of large hail by up to 30 minutes'. This agrees with the hail and the NLDN flash data for the two cells in the Arkansas storm of the present study.

The fact that only two or three other blue jets have been recorded during the order of the more than 100 h of our aircraft observations of active storms, suggests that very strong updrafts may be required to produce the large electric fields necessary to produce blue jets. However, because of severe Rayleigh scattering that occurs in the blue emission region of the blue jets, they may be more frequent than their apparent scarcity in ground observations would signify. Blue jets that we

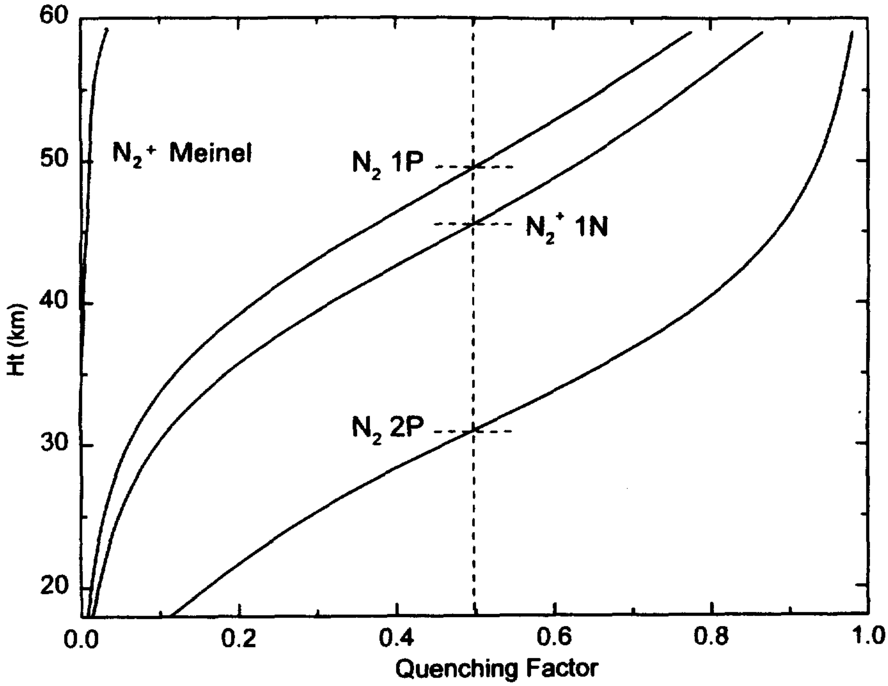

Fig. 9. Quenching factors vs altitude for N_2 1P and N_2^+ Meinel (red), and N_2 2P and N_2^+ 1N (blue).

observed had spectral emissions primarily below 480 nm. The blue emissions are severely scattered by the transmission through the atmosphere to an observer on the ground, as compared to an observer in an aircraft at about 13 km altitude (Guttman, 1968).

Blue jets are not associated with positive CG flashes; nor do they have a 1:1 relationship with negative CG flashes. They do, however, occur near the centroid of the spatial distribution of negative CG flashes, and seem to occur at the end of a more-frequent-than-average series of negative CG flashes. From visual inspection of the video tapes, there is no obvious relationship between the occurrence of a blue jet and intracloud flashes, although this is difficult to quantify.

The blue jets are very bright, at least of the order of a Mega Rayleigh (MR), and the emissions lie almost exclusively in the blue end of the spectrum. The conditions observed in the 1 July 1995 storm are not confined to nighttime, suggesting that blue jets may also occur during the daytime when they cannot be detected optically. We have no data on whether they produce a unique ULF, ELF or VLF signature. However, observations made by Rumi (1957) suggest that he may have recorded many blue jets on a 28 MHz radar looking north from Ithaca, NY. His echoes showed the same range of vertical velocities and terminal altitudes. If these radar echoes were produced by blue jets, this would imply that blue jets have sufficient ionization density to present a significant radar cross section at 28 MHz, and might therefore be detectable by radar during the daytime. This conclusion would agree with our analysis of the color TV signal levels implying the presence of ionized N_2. Mishin et al. (1996) have estimated the electron number density in the wave front of a blue jet to be: $N_e = 10^6$–10^7/cm^3 at 30 km, and the total energy deposited in the front to be 10^{16} eV/cm^{3}s. To our knowledge there are presently two theoretical papers in reviewed journals on blue jets [Pasko et al. (1996) and Sukhorukov et al. (1996)]. Both papers invoke the streamer phenomenon, which can be either positive or negative (Raether, 1939). Streamers are transient filamentary plasmas, the dynamics of which are controlled by highly localized nonlinear space-charge waves (Dhali and Williams, 1987; Vitello, 1994). Grangé et al. (1995) have determined the velocity of positive streamers as 200 km/s using point to plane measurements. Below we summarize the essential features of the Pasko et al. (1996) and Sukhorukov et al. (1996) theories.

6.1. Pasko et al. (1996) positive streamer theory of blue jets

Pasko et al. (1996) have proposed a theory to explain blue jets and blue starters based upon positive streamers, which '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'. This theory accounts for the essential features of blue jets,

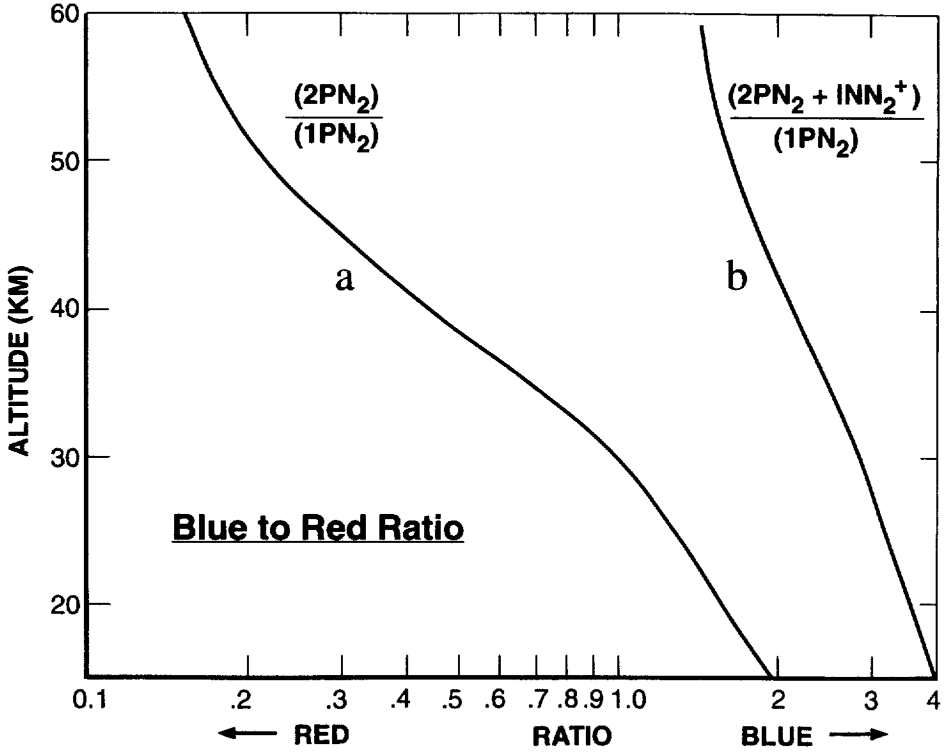

Fig. 10. Curve (a) shows the ratio of TV signal levels in the blue and red tubes corrected for quenching, atmospheric transmission, aircraft window transmission, and TV system response for the N_2 1P (red) and N_2 2P (blue) bands using the auroral brightness numbers of Vallance Jones (1974). The ratio is not blue enough to agree with observations. Curve (b) shows the ratio of blue to red TV signals if the emissions in the N_2^+ 1N bands (blue) have been included.

including the geometric shape, velocity, brightness and terminal altitude. In their model, the thundercloud is charged positive at the top and negative at the bottom. Light, positive-charged ice splinters are driven up, while gravity pulls down heavy negative charged hail. To start a streamer, positive charges are concentrated in an extended dish-like region at the top of the storm cell where $E > E_c$ over 0.1–1 km. (Here E is the electric field and E_c is the critical electrical field for breakdown.) The electric field inside the jet is non-zero, and current always flows. Jets are produced during the cumulative phase of thunderstorm charging, so that it is not necessary for large amounts of charge to be moved. The jet stops at the altitude where the relaxation time, $\tau_s = \varepsilon_o/\sigma_s$, within the streamer body approximately equals the relaxation time τ of the ambient atmosphere, where ε_o is the permittivity of a vacuum, and σ_s is the electrical conductivity within the streamer. At this altitude all current through the channel created by the streamer can be supplied by the flow of atmospheric ions, and E at the tip is not enhanced since the atmospheric conductivity $\sigma = \sigma_s$. The optical brightness peaks at about 200 ms after the start of the streamer. This does not agree with the observations, which show the brightness of the jet to be greatest as soon as it is apparent at the top of the anvil.

Pasko et al. (1996) calculated the expected optical emissions from the N_2 1P (red) bands and N_2 2P (blue) bands of N_2, including quenching. In their Fig. 3(a), the blue-to-red analysis underestimates the red response of the University of Alaska TV system. Given the actual responses of the red, green and blue tubes of the camera, and taking Rayleigh scattering into account, if the ratios of Pasko et al. (1996) are correct we should have detected significant amounts of red and green in our color TV images of blue jets. Their Fig. 3(b) shows the blue-to-red ratio ≈ 3 up from 20 to 30 km, approaching unity near 40 km. This result does not agree with the careful analysis of the three color TV signals, which show no detectable red or green signals. Pasko et al. (1996) also did not take into account the Rayleigh scattering and absorption along the path length shown in Fig. 6, which increases the red-to-blue ratio at the base of a typical blue jet by a factor of ~ 1.6. Therefore, if there were equal amounts of N_2 1P and N_2 2P emissions the red would have certainly been recorded, and we would have called them red, or perhaps purple, jets. If we take the brightness of the various N_2 1P and N_2 2P bands for aurora as given by Vallance Jones (1974), multiply each by the color TV response, and sum the separate red and blue responses, we find that, without quenching, the red-to-blue signal ratio would be 5.7:1. Figure 9 shows our calculations of the quenching factors, and Fig. 10 shows the ratio of blue to red emissions with and without N_2^+ 1N contributions.

6.2. Sukhorukov et al. (1996) negative streamer theory of blue jets

Sukhorukov et al. (1996) have also proposed a blue jet theory based upon streamers. Their model differs from Pasko et al. (1996) in several fundamental ways. Their jet is a negative streamer: 'an attachment-controlled ionizing wave, which moves upward via an electron avalanche in the wavefront due to the mainly vertical, downward directed quasi-electrostatic field caused by the extraordinarily large (>100 C) charge transfer in a high-altitude intracloud discharge or in a positive CG discharge with a long continuing current'. Their theory also accounts for the observed velocity, brightness, spectral emissions and terminal altitudes of the blue jets. The suggested possibility of an extraordinarily large lightning event as the causative agent for a blue jet in this theory may be ruled out by our observations, which clearly show that there are no +CG flashes associated with either of the groups of blue jets. The theory must then rely on IC discharges to produce negative charge accumulations at the top of the cloud, perhaps by 'spider lightning'. Sukhorukov et al. (1996) imply a delay of about 100 ms for the initiation of a jet after the initial illumination of the clouds. We have carefully examined the video tapes of the blue jets, and did not find any evidence of large IC flashes clustered 100 ms before the jets.

In the Sukhorukov et al. (1996) theory, the vertical jet velocity (V_o) is essentially constant and about equal to the electron drift velocity: $V_o \approx eE_o/mv_m$, where e is the electron charge, E_o is the electric field in the wave, m is the electron mass, and v_m is the electron-neutral collision frequency. Using values suggested by other work, they find a vertical velocity of 100–130 km/s, which is constant with altitude since both E_o and v_m depend on pressure. The jet terminates between 40 and 50 km altitude, where the damping time of the quasi-electrostatic field becomes shorter than the ionizing wave propagation time. In the mode of Sukhorukov et al. (1996), the observed blue color is mainly caused by effective quenching of the red N_2 1P bands at heights below about 50 km.

Thus both theories of Pasko et al. (1996) and Sukhorukov et al. (1996) are able to account for some of the features of blue jets, but neither theory is entirely consistent with the fundamental observations. Roussel-Dupré et al. (1996) and Symbalisty et al. (1996) have suggested upper atmospheric discharges due to air breakdown by runaway electrons as a possible cause of blue jets. As of this writing, the details are not published, so here we will not discuss this mechanism further.

7. Summary

The basic results of this paper may be summarized as follows. Blue jets:

(1) Are not associated with positive CG flashes.
(2) Occur in the same storm cells where negative CG activity is intense, with very strong up drafts and large hail.
(3) Occur with an accompanying decrease in the average negative CG flash rate within a radius of 15 km. There is a 2 s pause in CG lightning activity, after which the normal rate resumes.
(4) Have a mean vertical velocity of 112 ± 24 km/s.
(5) Have a mean terminal altitude of 37 ± 5 km.
(6) Have a different altitude distribution from blue starters.
(7) Are probably ionized. Analysis of the color TV red and blue signal indicates that N_2^+ significant ionization is required to match the observations.
(8) Are more energetic than sprites.
(9) Transfer about 10^9 J energy to the stratosphere per jet.
(10) Are similar to streamers. However, it remains unclear whether the streamers are positive or negative.
(11) May not be as rare as the scarcity of optical observations would imply because they are difficult to observe from the ground due to atmospheric scattering of the blue end of the spectrum.

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References

Boccippio, D.J., Williams, E.R., Heckman, S.J., Lyons, W.A., Baker, I.T., Baker, R., 1995. Sprites, ELF transients, and positive ground strokes. Science 269, 1088.

Byrne, C.J., Few, A.A., Stewart, M.F., 1989. Electric field measurements within a severe thunderstorm anvil. J. Geophys. Res. 94, 6297–6307.

Byers, H., Braham Jr., R.R., 1949. The Thunderstorm. U.S. Weather Bureau, Washington, D.C., 24.

Byers, H., 1953. Thunderstorm Electricity, University of Chicago Press.

Carey, L.D., Rutledge, S.A., 1996. Electrical and multiparameter radar observations of a severe hailstorm. Proceedings, 10th International Conference on Atmospheric Electricity, Osaka, Japan, June 1996.

Dhali, Williams, P.F., 1987. Two-dimensional studies of streamers in gases, J. Appl. Phys. 62, 4696–4707.

Grangé, F., Soulem, N., Loiseau, J.F., Spyrou, N.S., 1995. Numerical and experimental determination of ionizing front velocity in a DC point-to-plane corona discharge. J. Phys. D.: Appl. Phys. 28, 1619–1629.

Guttman, A., 1968. Extinction coefficient measurements on clear atmospheres and thin cirrus clouds. Appl. Optics. 7, 2377–2381.

Jones-Mosley, C., 1994. Storm hits area by surprise, Texarkana Gazette, 1 July 1994.

Ludlam, F.H., 1980. Clouds and Storms: The Behavior and Effect of Water in the Atmosphere. Pennsylvania State University Press.

Marwitz, J.D., 1972a. The structure and motion of severe hailstorms, I, Supercell storms. J. Appl. Meteorol. 11, 166–179.

Marwitz, J.D., 1972b. The structure and motion of severe hailstorms, II, Multi-cell storms. J. Appl. Meteorol. 11, 180–188.

Mishin, E.V., Sukhorukov, A.I., Sentman, D.D., 1996. NO perturbation in the ozone layer due to blue jets. Abstract A72C-4, Fall AGU Meeting 1996. Supplement, EOS. 77(46), F67.

Pasko, W.P. Inan, U.S., Bell, T.F., 1996. Blue jets produced by quasi-electrostatic pre-discharge thundercloud fields. Geophys. Res. Lett. 23, 1205–1209.

Raether, H., 1939. Die entwicklung der elektronenlawine in der funkenkanal. Zeits. Phys. 112, 464–489.

Roussel-Dupré, R., Symbalisty, E., Taranenko, Y., Yukhymuk, V., 1996. A parameter study of lightning events that can result in high-altitude runaway discharges, Abstract A72C-10, Fall AGU Meeting 1996. Suppl., EOS. 77(46), F68.

Rumi, G.C., 1957. VHF radar echoes associated with atmospheric phenomena. J. Geophys. Res. 62, 547–564.

Sentman, D.D., Wescott, E.M., Osborne, D.L., Heavner, M., 1995. Preliminary results from the Sprites94 aircraft campaign: Red sprites. Geophys. Res. Lett. 22, 1205–1209.

Sukhorukov, A.I., Mishin, E.V., Stubbe, P.S., Rycroft, M.J., 1996. On the blue jet dynamics. Geophys. Res. Lett. 23, 1625–1628.

Symbalisty, E.M., Roussel-Dupré, R.A., Yukhymuk, V., Taranenko, Y., 1996. Full time evolution of upper atmospheric discharges due to runaway air breakdown, Abstract A11A-19, Fall AGU Meeting 1996. Suppl. EOS. 77(46), F70.

Uman, M.A., 1987. The Lightning Discharge. Academic Press.

Vallance Jones, A., 1974. Aurora. D. Reidel Publishing Co.

Vitello, P.A., Penetrante, B.M., Bardsley, J.N., 1994. Simulation of negative-streamer dynamics in nitrogen. Phys. Rev. E. 49, 5574–5598.

Vonnegut, B., Moore, C.B., 1958. Giant electrical storms. Recent Advances in Atmospheric Aeronomy. Pergamon Press, 339–411.

Wescott, E.M., Sentman, D.D., Osborne, D.L., Hampton, D.L., Heavner, M., 1995. Preliminary results from the Sprites94 aircraft campaign: 2. Blue jets. Geophys. Res. Lett. 22, 1209–1212.

Wescott, E.M., Sentman, D.D., Hampton, D.L., Heavner, M.J., Osborne, D.L., Vaughan Jr., O.H., 1996a. Blue starters: Brief upward discharges from an intense Arkansas thunderstorm. Geophys. Res. Lett. 23, 2153–2156.

Wescott, E.M., Sentman, D.D., Heavner, D.L., Hallinan, T.J., Hampton, D.L., Osborne, D.L., 1996b. The optical spectrum of St. Elmo's fire. Geophys. Res. Lett. 23, 3687–3690.