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Blue starters: Brief upward discharges from an intense Arkansas thunderstorm

E.M. Wescott[1], D.D. Sentman[1], M.J. Heavner[1], D.L. Hampton[2], D.L. Osborne[1] and O. H. Vaughan Jr.[3]

Abstract. This paper documents the first observations of a new stratospheric electrical phenomenon associated with thunderstorms. On the night of 30 June (UT 1 July) 1994, 30 examples of these events, which we have called "blue starters," were observed in a 6 m 44 s interval above the very energetic Arkansas thunderstorm where blue jets were first observed. The blue starters are distinguished from blue jets by a much lower terminal altitude. They are bright and blue in color, and protrude upward from the cloud top (17-18 km) to a maximum 25.5 km (83,655 ft.) in altitude. All blue starters events were recorded from two small areas near Texarkana, Texas/Arkansas where hail 7.0 cm in diameter was falling. Comparison to cloud-to-ground (CG) lightning flashes revealed: 1. Blue starters were not observed to be coincident with either positive or negative CG flashes, but they do occur in the same general area as negative CG flashes; 2. Cumulative distributions of the negative CG flashes in $\pm$ 5 s before and after the starter and within a radius of 50 km shows a significant reduction for about 3 s following the event in the two cells where starters and jets were observed. The energy deficit is approximately 10^9 J. It is possible that blue starters are a short-lived streamer phenomenon.

Introduction

There have been scattered anecdotal reports of phenomena that seem to be ordinary lightning discharges upward from the tops of large thunderstorms (see *Wescott et al.* [1995] for references). Theoretical work by *Wilson* [1956], *Hoffman* [1960] and *Cole* [1966] has predicted such discharges. The observations of *Franz et al.* [1990], *Sentman et al.* [1993], *Lyons* [1994], Boeck et al. [1995], who found upper atmosphere flashes called sprites, were motivated by the search for upward discharges. Sprites are primarily mesospheric/D-region (50-90 km) phenomena.

During June and July, 1994 we, investigated upper atmospheric optical phenomena above evening thunderstorms in the south central U. S. using two corporate jet aircraft equipped with low-light-level television cameras. The use of two aircraft equipped with GPS recorders allowed accurate three-dimensional triangulation of any feature in the field of view of both aircraft. (See *Sentman et al.* [1995] for details of the missions and equipment.) *Wescott et al.* [1995] have reported making observations of 56 examples of "blue jets" during one of these missions flown near a very active storm near the Arkansas-Louisiana border on the night of 30 June-July 1 1994. Blue jets are characterized by the propagation of a narrow cone of blue light upward from the apparent cloud tops at speeds of the order of 100 km/s to a terminal altitude of about 40 km.

In their report, *Wescott et al.* [1995] noted that nearly two dozen other, smaller events also were captured that were not blue jets. These events extended upward from the cloud tops for shorter distances than blue jets, and were interpreted as being actual upward lighting discharges. Here, we present results of a more thorough analysis of these events and their relationship to CG and IC lightning. We conclude that these "blue starters" are not upward lightning discharges, but rather a distinct phenomenon probably related to the initial phases of blue jets.

Observations

Thirty instances of these blue starters were recorded during the 6 m 44 s period 03:02:47 to 03:09:30 UT on 1 July 1994. Twenty eight were simultaneously recorded from both aircraft, and two more from only one of the aircraft. Figure 1 shows a 46° x 21° TV image of an event captured by a monochrome SIT camera aboard one of the aircraft. Here, the blue starter is inclined at 9.6° to the vertical. A few of the events were just barely visible above the apparent cloud tops, reaching altitudes of around 17-19 km (56,000 - 62,000 ft), while several reached altitudes that exceeded 24 km (78,720 ft). All of the blue starters that we observed arose from two small areas near the western end of the Arkansas storm, and close to the aircraft as shown in Figure 2. Most of the blue starters originated from a region about 5 km south-southwest of Foreman, Arkansas, where hail 4.45 cm in diameter was reported at 02:45 UT (Figure 3), and near a prominent turret of the storm. The times of the events are given in Table 1. The second area was close to

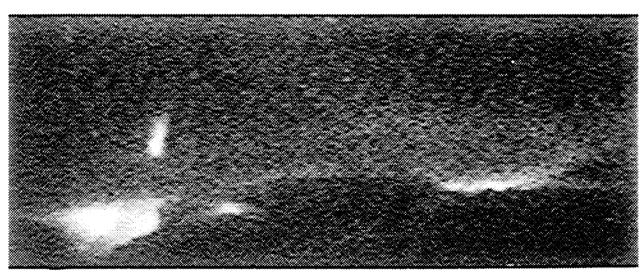

Figure 1. Shown is a 46° H-by-21° V portion of a monochrome SIT TV frame at 03:04:26.166 UT showing a blue starter extending upward to 25.7 km (84,322 ft). The pillar of light is 9.6° off the vertical. Some weak intracloud lightning shows below and to the left of the starter.

[1]Geophysical Institute, University of Alaska, Fairbanks, AK
[2]Now at Ball Aerospace & Technologies, 1600 Commerce St., T-3, Boulder CO
[3]NASA Marshall Space Flight Center, Huntsville, AL

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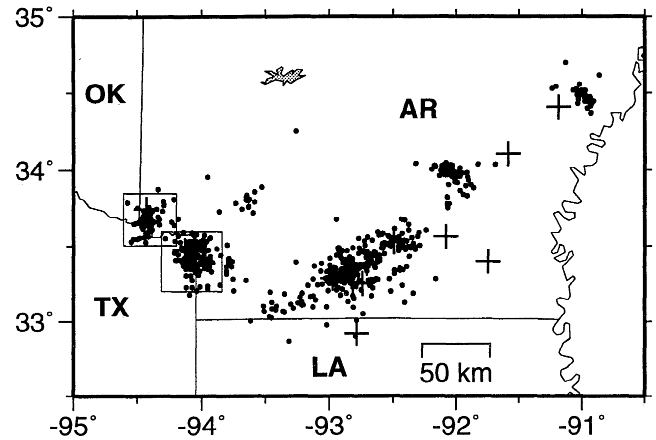

Figure 2. This map shows the location of the CG flashes (dots: negative flashes; and crosses: positive flashes) from the NLDN over the interval 03:00 to 03:10 UT for the whole Arkansas storm. Rectangles show the two detail maps of starters, Figures 3 and 4.

Texarkana, Texas/Arkansas, where hail 7.0 cm in diameter was reported at 03:08 UT (Figure 4). Slightly smaller hail ranging in size from 5.0 to 2.3 cm was reported in an area 70 x 20 km near Texarkana during the storm.

Analysis

The locations of 30 blue starters, 17 blue jets and 5 sprites were triangulated using computer programs STAR and STEREO [*H. Nielsen*, private communication]. See *Wescott et al.* [1995] for the details. In the work presented here, each pixel is 0.174° x 0.174°. Most of the blue starters were found to be at a slant range of about 75 km, so that one pixel represents 230 x 230 m at the source. If there are sufficient stars in the field of view near the object of interest, then one pixel is about the uncertainty of the triangulation. Based on a comparison with the brightness of blue jets at their point of origin [Wescott et al., 1995], we estimate the brightness of the blue starters to be in the order of 1 MR (Mega Rayleigh).

Table 1. Times of Blue Starters, UT, 1 July 1994

Time (UT)	Str.	Time (UT)	Str.	Time (UT)	Str.
03:02:46.800	a	03:07:23.543	k	03:08:33.747	u
03:03:28.541	b	03:07:44.164	l	03:08:34.014	v
03:04:15.722	c	03:07:55.275	m	03:08:34.647	w
03:04:16.456	d	03:07:56.042	n	03:08:42.522	x
03:04:26.166	e	03:08:06.853	o	03:08:50.697	y
03:04:31.338	f	03:08:15.395	p	03:08:53.867	z
03:05:03.536	g	03:08:25.905	q	03:09:11.151	α
03:05:07.207	h	03:08:26.373	r	03:09:12.052	β
03:05:28.495	i	03:08:27.507	s	03:09:27.667	γ
03:06:40.300	j	03:08:28.875	t	03:09:29.936	δ

Triangulated Data

The triangulated altitudes of the tops of the starters ranged from 18.1 to 25.7 km with a mean value of 20.8 km (68,290 ft) and a standard deviation of 1.8 km. Blue jets have a much different distribution of top heights, peaking near 38 km ± 4.7 km. The mean value of the starter bottoms was 17.7 km (58,070 ft) with a standard deviation of 0.9 km. In one example, the starter bottom was clearly seen rising from the anvil with cloud behind; it was triangulated at 17.7 km (58,070 ft).

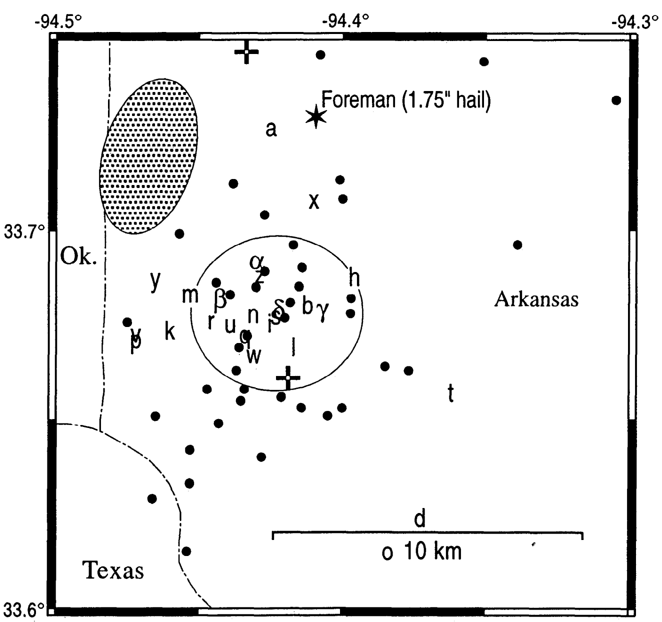

Figure 3. This detail map shows NLDN lightning flashes with the triangulated locations of the blue starters. The 4 x 5 km 1σ distribution ellipse for the locations of the blue starters is shown. A prominent turret with a top near 18.2 km (61,350 ft) was triangulated and is shown as a shaded ellipse northwest of the starters. The times of the blue starters are given in Table 1.

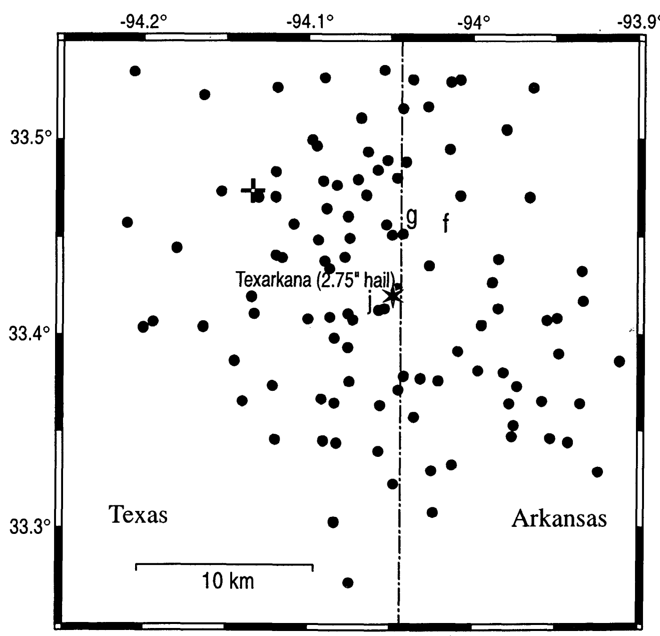

Figure 4. This detail map shows NLDN lightning flashes with the triangulated locations of the blue starters near Texarkana, Texas/Arkansas. Times of the starters are given in Table 1.

Velocity of Blue Starters

The blue starters generally did not persist long enough to be tracked to obtain propagation speeds. We found that by using fields to triangulate (17 ms), we could measure the velocity of six starters. The velocities varied widely, from a low of 27 km/s over 10 fields to a high of 153 km/s. Furthermore, the velocity was not always constant. In most cases starters slowede down with time; but in one case it was observed to increase speed abruptly. With the exception of one blue starter with a velocity 27 km/s, the blue starter velocities are within the range of 15 blue jet velocities (77 km/s up to 218 km/s) now measured.

Blue Starters vs Lightning

Twenty seven of the 30 blue starters recorded originated from one small area near Foreman, Arkansas, with a 1σ event distribution ellipse measuring 4 x 5 km (Figure 3). Figure 3 also shows the triangulated location of the turret, which projected upward about 1 km above the anvil top to an altitude 18.7 km (61,300 ft). No blue starters were observed to originate directly from the turret. Figure 4 shows the locations of three starters and the CG flashes that occurred in a second area near Texarkana during the same time interval.

After inspecting the video tapes, we found that most of the blue starters arise from the anvil during a quiet interval. Sometimes there was intracloud activity in another part of the cell. Blue starters were not observed to coincide with either simultaneous negative or positive CG flashes. However, there was a significant statistical relationship with the cumulative distribution of negative CG flashes with respect to the occurrence of a blue starter.

Figure 5 shows a summary plot of the NLDN lightning flashes within a radius of 50 km and within $\pm$ 5 s of 18 blue starters (keyed to the first starter of multiple groups). In the three seconds leading up to the event, there was an approximately constant lightning rate of 0.50/s. At the time of the events, there was a abrupt decrease in the number of flashes to 0.09/s that persisted for 3 s, followed by resumption of activity at the rate before the event. When we plotted only the flashes in the Texarkana cell keyed to blue starters in the Foreman area the gap was still about the same. To avoid counting the same flash more than once and since there are a number of groups of starters which occur within 3 s of each other, for Figure 5 we only used the first starter of a group . There were also 16 blue jets during the interval of starters, and we have eliminated events where a jet was within the 3 s interval. A completely clean set contains only 6 starters, but the effect is still very clear: There is a relatively constant mean rate of flashes in both storm cells followed by a 3 s gap with much fewer flashes in either cell.

The analysis of 59 blue jets that occurred in the same two cells over a longer time interval reveals a similar, but perhaps significantly different, cumulatively flash plot. It shows an increase of flashes just before the jet, followed by about a 2-second gap and then a resumption of activity. The blue jet analysis will be discussed in a separate paper.

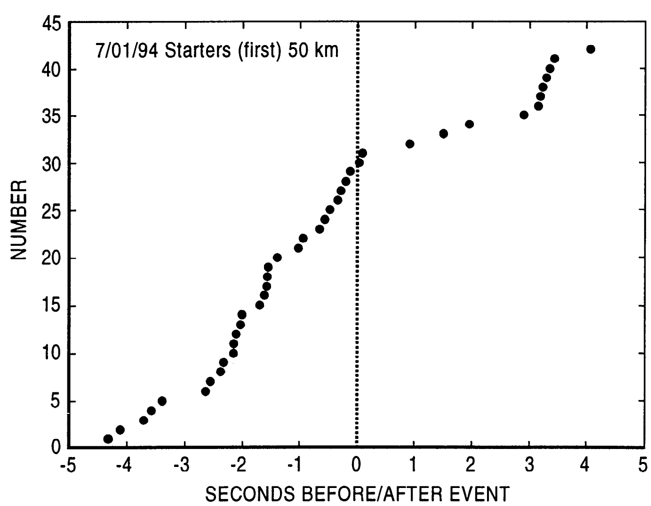

Figure 5. Cumulative distribution of negative CG lightning flashes from the NLDN within a radius of 50 km and $\pm$ 5 s of 18 blue starters is shown. We keyed on the first of any group of multiple starters to avoid counting the same flash more than once. The energy deficit implied by the change of slope at the origin and its duration is estimated to be about 10^9 J.

Discussion

When we compared the distribution of top altitudes of blue jets and blue starters, we found a bi-modal, not a continuous distribution, which argues for separate names.

There was no discernible one-to-one coincidence of blue starters with CG lightning flashes of either polarity. However, blue starters were loosely concentrated near the centroid of the spatial distribution of negative lightning flashes, and also near the location of reported very large hail fall.

The most significant result of our study seen in Figure 5 is that after a blue starter appears, there is a sudden decrease in the average negative CG discharge rate lasting about 3 s apparent in the whole area of the two western cells. The reduction could possibly arise by starters (and jets) extracting electrical energy from the two most westerly storm cells. In our sample base, this reduction corresponded to about the energy of 10^9 - 10^{10} J associated with a typical negative CG flash [*Uman*, 1987]. The average blue starter is estimated to occupy a volume of 2.4 x 10^9 m^3. Assuming a neutral number density of $10^{24}/m^3$ we find the average energy would be 2.7 - 27 x 10^{-6} eV per molecule, which is more than adequate to produce the observed optical brightness. However, the occurrence of the CG flash rate before the blue starter is possibly one factor in creating the electric field configuration leading to the initiation of blue starters and jets. This poses the question: Are the blue starters the cause, or an effect of the change in CG flash rate?

We found that the correlation of decreased flashes after a blue starter relates only to negative CG discharges, but after observing the video tapes, we discovered there does not appear to be any clear relationship to intracloud lightning, because most blue starters arise out of the anvil during a quiet interval.

We also have done cumulant analyses of negative CG flashes keying the $\pm$ Δt's to large (>100 kA) negative flashes and to a large number of positive CG flashes. We found no decrease in the post event rate of flashes for these cases.

The intriguing association of hail with blue starters suggests that they may derive from the same isolated convective energy source. *Chagnon* [1992] reported a close association of negative flashes with hail. The lightning centers associated with the hail generally developed 9 minutes before hail at a point 5 km upstream from the first hail. The lightning activity tended to occur in the regions of the storm center, while the hail usually fell to the right or left flanks of the storm. It is probably the strong upward convection associated with the hail that produces the negative CG strokes and the positive charge at the top of the storm that produces the blue starters. *Byers and Braham* [1949] and *Byers* [1953] indicate that hail only occurs in cells within thunderstorms. They measured updrafts associated with hail that extended up to 20,000 ft at speeds of over 56.4 ft/s. *Vonnegut and Moore* [1958] studied a giant electrical storm that reached heights of 20 km or more, and inferred the associated vertical velocities were on the order of 100 m/s. From the triangulated altitudes of the bottoms of the blue starters, the Arkansas storm anvil top was at about 18 km altitude, with the turret reaching to about 18.7 km (61,260 ft).

All these facts suggest that very strong up drafts were present in the two areas where blue starters were seen, and that such large updrafts may be required to produce the charge separation and spatial configuration necessary for the formation of these events. The simultaneous occurrence of large hail further suggests that the polarity of the charge separation should be such that the positive charge center lies above the negative charge center. Large hail may not be a necessary condition for blue starters, but storms with large hail may present the best opportunities to look for blue starters and blue jets.

Pasko et al. [1996] recently proposed a theory to explain blue jets that may also be applicable to the blue starters described here. In this theory, quasi-electrostatic fields exceeding the threshold of breakdown ionization during the pre-discharge phase of charge accumulation leads to the formation and upward propagation of streamer type ionization channels. Streamers, transient filamentary plasmas whose dynamics are controlled by highly localized nonlinear space-charge waves [Vitello, 1994], are either positive or negative depending upon the sign of the space charge in the head of the streamer. The theory models the essential features of blue jets, including the geometrical shape, velocity, brightness and terminal altitude. The key point in the explanation suggested for blue jets is that the charge accumulation in the cloud must persist long enough to sustain the jet. Starters may be interrupted by the cloud current before a self sustaining jet is developed.

We note that blue starters provide a mechanism for transferring energy from the troposphere into the stratosphere.

No measurements were made of VLF emissions which might be associated with blue starters.

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M.J. Heavner, D.L. Osborne, D.D.Sentman, and E.M. Wescott, Geophysical Institute, University of Alaska, Fairbanks, AK 99775-7320, rocket@giuaf.gi.alaska.edu

D.L. Hampton, now at Ball Aerospace & Technologies, 1600 Commerce St., T-3, Boulder CO, SMTP:dhampton@ball.com

O.H. Vaughan, Jr., NASA Marshall Space Flight Center, Huntsville, AL 35806

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