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New evidence for the brightness and ionization of blue starters and blue jets

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Abstract. Blue jets and blue starters are partially ionized luminous cones of primarily blue light that propagate upward out of the top of thunderstorms at speeds of order 100 km s^{-1}. Blue jets propagate up ~40 km, but blue starters, which resemble blue jets, terminate abruptly after only a few kilometers of upward travel. Theories on the origin of blue jets have proposed that they are due to either positive or negative streamers or runaway electrons. Quantitative analysis of new multi-instrument observations of a blue starter from an aircraft during the Energetics of Upper Atmospheric Excitation by Lightning, 1998 (EXL98) campaign of July 1998, shows that the ionization accounts for ~3 % of the observed intensity. Quantitative analysis of a remarkable color photograph of a blue jet taken from Réunion Island in the Indian Ocean shows that the minimum optical energy deposition was ~0.5 MJ. The same photograph shows details of streamers never before seen.

1. Introduction

Fifty-one blue jets and 30 blue starters were first documented and named from 1994 aircraft TV observations of a severe storm near Texarkana, Arkansas [*Wescott et al.*, 1995]. Blue jets propagate upward out of the top of thunderstorms at a mean vertical speed of 112 ± 24 km s^{-1} to a mean terminal altitude of 37 ± 5 km, based on the triangulation of 34 examples [*Wescott et al.*, 1998]. Blue starters, which resemble blue jets, terminate abruptly after only a few kilometers of upward travel, mean value 20.8 ± 4.7 km [*Wescott et al.*, 1996]. Prior to 1998, single blue jets had been recorded from aircraft over Kansas (July 4, 1994) and Central America (August 29, 1995). What appears to be a blue jet was captured on film by an Australian photographer, Peter Jarver, and published [*Lyons*, 1997], but all the rest have been seen on low light level TVs with only moderate resolution. *Pasko et al.* [1996] have proposed a theory which accounts for the essential features of blue jets and starters based upon positive streamers, which seems to agree with the fact that jets and streamers seem to occur in regions of thunderstorms producing negative cloud-to-ground (CG) flashes. The streamers would have a concentration of positive charges at the front.

Sukhorukov et al. [1996] proposed negative streamers as the cause of jets but required a positive CG (+CG) flash to initiate the streamer. *Roussel-Dupré et al.* [1998] and *Symbalisty et al.* [1998] have suggested upper atmospheric discharges due to air breakdown by runaway electrons as a possible cause of blue jets. *Sukhorukov and Stubbe* [1998] and *Rowland* [1998] discuss the theories of blue jet formation.

Wescott et al. [1998] have previously presented evidence from color TV images of blue jets and starters that suggested that the blue light must have an ionized N_2^+ component. The 1998 aircraft observations included a camera with a narrow band filtered at ionized N_2^+ (first negative group (1 NG)), 427.8-nm. The 427.8 nm data clearly demonstrates that the blue starters are partially ionized and by association that blue jets are also ionized beams. The knowledge of the ionization allows a better estimate of the energy involved and the effects on the upper atmosphere by these phenomena.

In this paper we present three new observations of blue jets/starters. (1) A color photograph obtained in March 1997 by one of the authors, P. Huet, from Réunion Island. This beautiful photograph, which shows the highest-resolution details ever captured, has been quantitatively analyzed for its brightness. (2) Blue starter images obtained during the Energetics of Upper Atmospheric Excitation by Lightning, 1998 (EXL98) aircraft campaign during July 1998 and analyzed in detail to determine their ionization properties. (3) A blue jet, captured over Iowa also during the EXL98 aircraft campaign, exhibiting a time-varying rate of ascent.

2. Analysis of Color Photograph

A color photograph of a blue jet Plate 1, was taken by one of the authors, P. Huet, from St.-Denis, Réunion Island, in the Indian Ocean (20° 51.84' S latitude, 55° 27.6' E longitude) while photographing lightning from a large evening thunderstorm over the ocean to the north. The photograph is a 2-min time exposure using 400 ISO Fujicolor SG 400 film in a Zenith reflex camera with a 58-mm lens at, *f*/4 or 5.6. The date is uncertain, but the lightning photography was definitely between March 3 and 7, 1997. Unfortunately, the weather service on Réunion Island does not keep records of storms over the ocean, so we have not been able to obtain further information about the thunderstorm associated with the event. Analysis of the star background reveals that if the date was March 3, the time was 1745 UT, by matching the horizon with the rotation of the stars. The time would be 4 min later each day after March 3, and the azimuth and elevation would not change appreciably. Assuming March 3, we determined that the azimuth was ~13° east of north. The azimuth and elevation of the base, where it appears above the apparent cloud top, and the tip were determined from the star field. If we

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assume reasonable values for the altitude of base and the jet tip, 18, and 40 km, respectively [*Wescott et al.,* 1998], the jet was located at about 19.6° S latitude and 55.7° E longitude, 145 km distant from the camera.

The image was digitized on a 24-bit color scanner and separated into its constituent red, green, and blue components. The blue jet is very evident in all three color separations, but red and green only appear in the very brightest lower one third of the jet. This is most likely due to saturation of the film and not to real red or green emissions from the jet. In theory, there are red

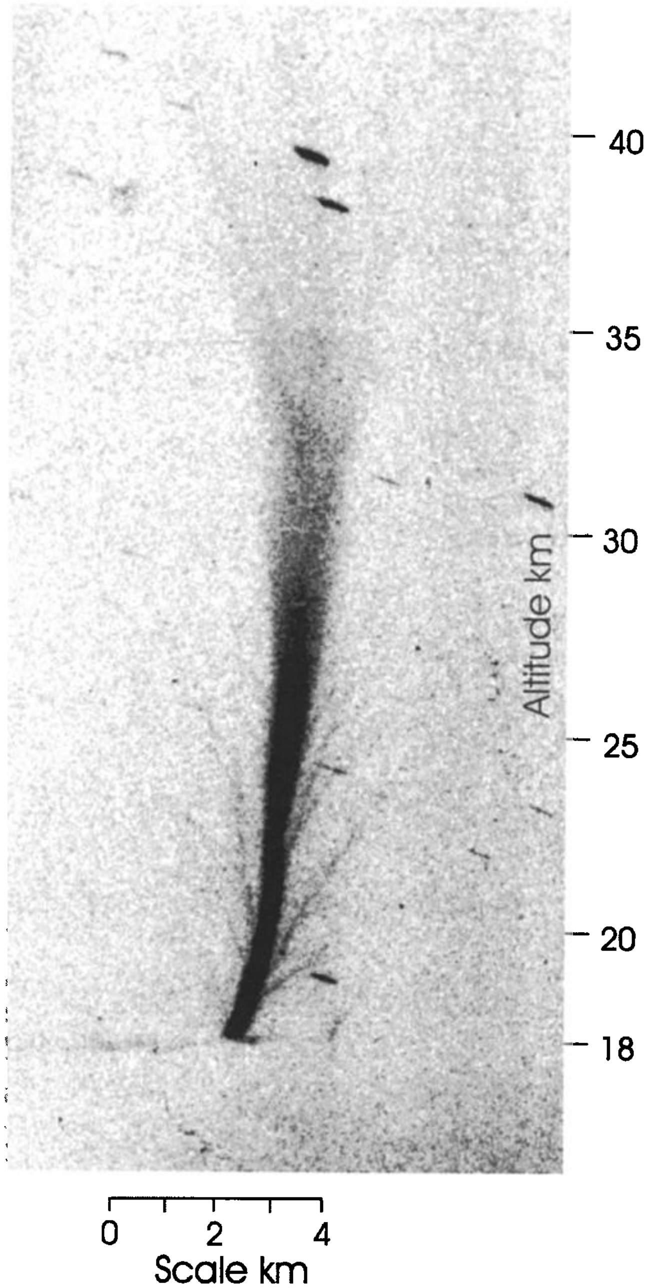

Figure 1. Inverted black and white image (5.9° horizontal by 10.2° vertical) of the blue component of the Réunion Island blue jet film photograph. Note the eight narrow streamers branching out from the main jet and the small streamer coming up above the cloud top to the right. The background, contrast, and brightness have been adjusted in the image to show these faint features. The streaks are star tracks from the 2-min exposure.

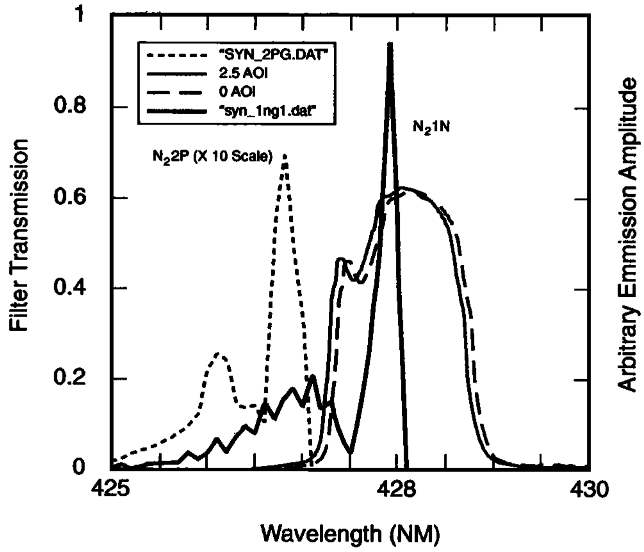

Figure 2. The band-pass transmission curves for the 427.8-nm filter at normal incidence and at 2.5° off axis, and the synthetic spectra of the N_2^+(1 NG) ionized emissions and the N_2 (2 PG) neutral emissions (plotted at a x10 scale for comparison).

N_2 (first positive group (1 PG) emissions, but they are strongly quenched at these altitudes, and there are no likely green emissions. We determined the brightness of the blue jet in the blue separation by comparison with the stars, which were not saturated. Nineteen stars ranging from 3.89 to 7.4 magnitude were color corrected and used to provide a brightness calibration for a single pixel, using the method of *Johnson and Mitchell* [1975]. Of the blue jet pixels, 6.6 % in the lower one-third portion of the jet were saturated, with a background-corrected count of 190. One pixel subtends 3.38 x 10^{-7} sr in the vicinity of the jet. We calculate that a saturated pixel has a minimum brightness of 6.76 MR, and non saturated pixels are proportionate to their background corrected count divided by 190. A rayleigh is defined as 10^6 photons cm^{-2} column s^{-1}, and can be converted to optical energy in joules. We calculated the minimum value of the optical energy in the blue portion of the film response by summing all the background-corrected pixel values and converting to 0.5 MJ of optical energy. The saturated pixels account for 25% of the total optical energy. The true value of the total optical energy associated with the jet is higher because of the saturated pixels and the band emissions (e.g., 391.4 nm) below the film cutoff at 400 nm. *Wescott et al.* [1996] estimated that a single blue starter deposited 1 MJ, based on the energy of an average lightning flash.

Figure 1 shows the blue image in reverse black and white which has been contrast adjusted to show the faint features. The most interesting feature consists of eight faint filamentary features (streamers) branching off the main jet and one small streamer coming up above the cloud top to the right. The apparent widths of the small streamers range from 50 to 100 m. At the base of the blue jet the apparent diameter is ~400 m. The diameter does not vary appreciably up to ~22-km altitude. At 30 km it broadens to ~2 km and is ~3 km at 35 km. It is more diffuse at the top but is estimated to be ~4.5 km in diameter at 40-km altitude. Some structure can also be seen in the main jet above the saturated portion about half way up. The typical horn shape is evident in the top one third, with a suggestion of limb brightening as if the cone were hollow.

Plate 1. Color photograph of a blue jet over a large thunderstorm north of Réunion Island in the Indian Ocean taken by one of the authors, P. Huet, in March 1997. The field of view is 9.0° horizontal by 12.4° vertical in the constellation Ursa Major. The base of the blue jet where it can be seen above the top of the clouds is ~18-km altitude, and the tip is at ~35 km. The pink streak across the bottom is due to an aircraft passing during the 2-min exposure.

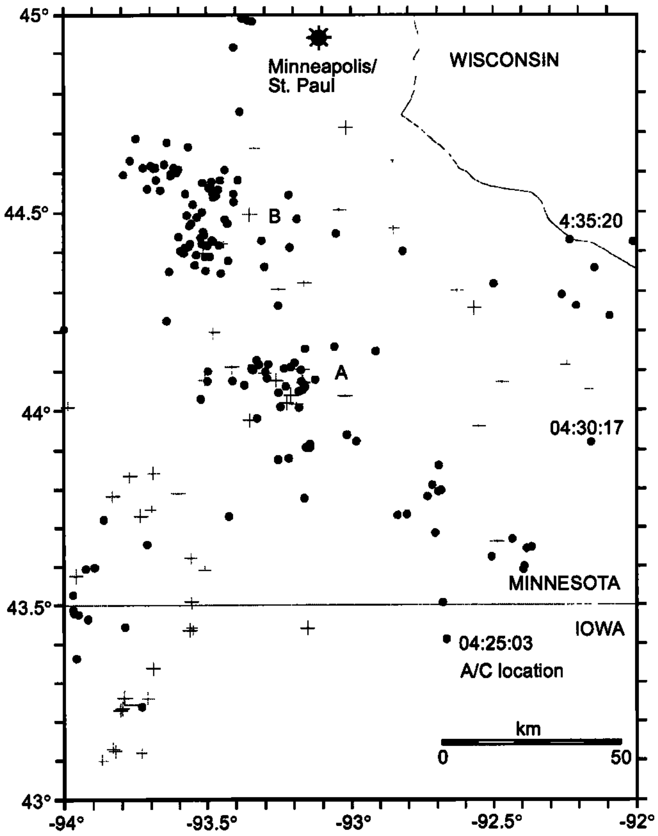

Figure 3. Map of National Lightning Detection Network (NLDN) flashes in the time interval 0425:03 -0440:19 UT, July 19, 1998, in the vicinity of blue starters. Negative flashes are filled circles, and positive flashes are plus signs. Storm cell A had five probable starters, and cell B had seven. Only one in cell B is absolutely identified as a starter. See Figure 4. One more in cell B is probably a starter, but the remaining five are more uncertain.

3. Multispectral Video Observations of a Partially Ionized Blue Starter

The EXL98 sprite aircraft campaign involved a Gulfstream 2 jet aircraft flying from the Jefferson County Airport located midway between Denver and Boulder, Colorado. It was equipped with six low light level imagers: a color TV system, a wide-angle unfiltered low light level TV (LLLTV), a narrow field of view LLLTV with a narrowband (1.25 nm) 427.8-nm filter, a near ultraviolet camera (NUV) filtered at 340 nm, and a near-infrared (NIR) camera. All imagers viewed out left-side windows, which were specifically selected to pass UV or NIR emissions. The 427.8-nm filter was carefully chosen to include the N_2^+(1 NG) band at 427.8-nm, yet exclude the nearby nonionized N_2(2 PG) neutral band. Figure 2 shows the filter curves and the synthetic spectra of both the ionized N_2^+(1 NG) and the N_2 (2 PG) neutral emissions.

On the evening of July 19, 1998, fifteen possible blue starters were recorded over two thunderstorm cells in Minnesota (see map, Figure 3). Storm cell A had five probable starters, and cell B had seven. Only one at 0434:26.33 UT in cell B is absolutely identified as a starter. See Figure 4. One more in cell B is probably a starter, but the remaining five are more uncertain. Figure 4 (left frame) shows the 3.1° vertical by 3.5° horizontal field of view portion of the starter in the unfiltered visible light camera frame, which saturated the LLLTV. The saturation of the video signal causes the apparent size of the starter to appear larger than it is in reality. The ionized N_2 light at 427.8 nm is shown in Figure 4 (right frame) with the same field of view. The blue starter is only 0.8° off axis, so one can see from the filter curves in Figure 2 that there is no contribution from the N_2 (2 PG) band.

This is conclusive evidence that the blue starter was partially ionized. No stars were detected through the narrow 427.8-nm filter in this frame, but at another time, αVirgo (Spica), a magnitude 0.98, B1 V spectral type star, was visible through the filter. We used this as a calibration and calculated that the combination of the 427.8, 470.9, and 391.4-nm ionized bands in the brightest part of the starter would be 31 kR. The known ratios of ionized N_2 bands at 391.4- and 470.9-nm to 427.8-nm emissions are 3.28 and 0.2, respectively [*Vallance-Jones*, 1974]. These transitions are all from the same level (v'=0) and are independent of the excitation mechanism. Although the starter in visible white light, Figure 3, was very saturated, we were able to use the color TV image, which showed five stars ranging in magnitude from 2.23 to 4.24 with known spectra, for calibration. We calculate that the maximum blue band starter brightness was

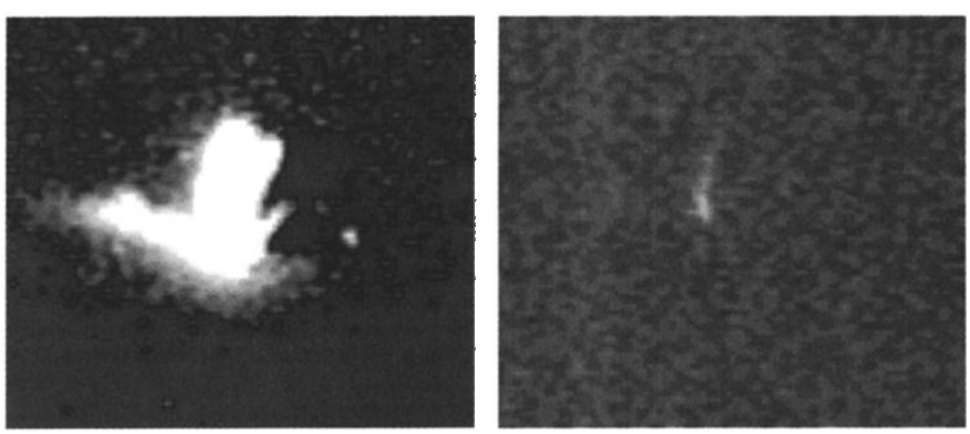

Figure 4. The blue starter event at 0434:26.33 UT. The left frame shows a 3.1° vertical by 3.5° horizontal field of view portion of the unfiltered visible light camera frame, which is saturated. The ionized N_2(1 NG) emission at 427.8 nm is shown in the right frame with the same field of view. This is clear proof that the blue starter was partially ionized. The unfiltered image is very overexposed, which makes it look much larger than it is in reality. Quantitative analysis using star calibrations and the color TV frame shows that the ionized N_2 emissions amount to 3% of the blue light.

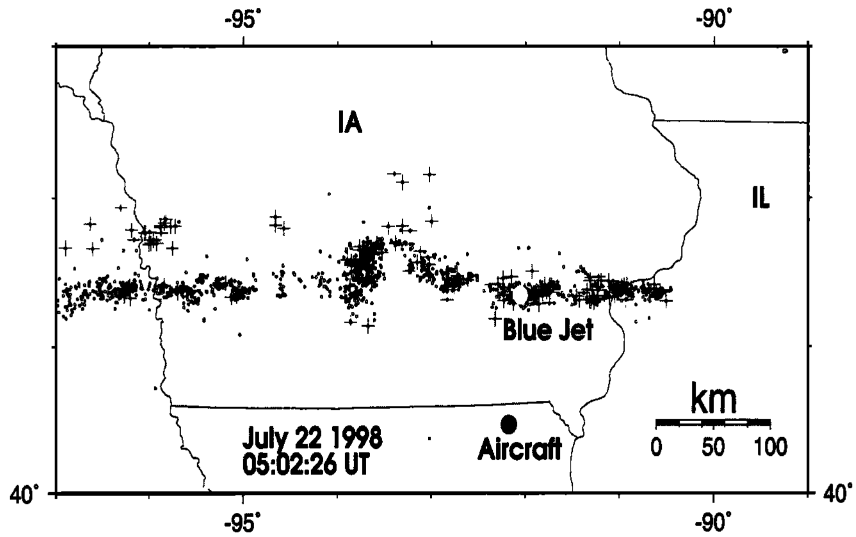

Figure 5. A map showing the NLDN cloud-to-ground (CG) lightning locations for a period of 15 min preceding the blue jet, the aircraft position, and the probable location of the blue jet (a large dot), assuming it is centered in the storm on the azimuth determined from the stars. The –CG lightning is shown as black dots, and the + CG lightning is shown as +pluses.

1 MR. Thus the 31 kR of ionized light amounts to ~3% of the blue total.

In the color TV frame there is primarily blue camera response (1 MR), presumably from the neutral N_2 (2 PG) band, but there is also ~70 kR or 7% of the blue total in both the red and green channels. We have no explanation for the green emissions, as there are no likely molecular sources, and the red N_2 (1 PG) bands are strongly quenched at these altitudes. Starters are not upward tropospheric lightning, which would have atomic broadband emissions and therefore have similar brightness in all three channels of the camera. Consistent with the observations of *Wescott et al.* [1996, 1998], no +CG or -CG flash can be associated with this event although negative flashes were predominant in the region of the starter.

4. Blue Jet: "Rocket Lightning"

Mackensie and Toynbe [1886] and Corliss [1977, 1983], published anecdotal reports of what was called "rocket lightning" propagating upward from the tops of thunderclouds. It is not clear from those reports exactly what was seen, sprites or blue jets, but perhaps the sort of blue jet that we recorded in 1998 from the aircraft fits the anecdotal observations. This blue jet was recorded at 0502:26 UT on July 22, 1998, as the aircraft was flying parallel to a narrow (~50 km) frontal thunderstorm extending over 500 km east-west across Iowa. Figure 5 shows a map of the National Lightning Detection Network (NLDN) lightning, the aircraft position, and the probable location of the blue jet, assuming it is centered in the storm on the azimuth determined from the stars. The location in Iowa is not near any major population center, and the records of the National Weather Service for the two nearest counties (Mahaska and Keokuk) do not contain any reports of large hail such as has been reported for blue jets and starters by Wescott et al.,[1996, 1998]. The Storm Data and Unusual Weather Phenomena [July1998; available at http://www5.ncdc.noaa.gov/pubs/publications.html] reported only urban and small stream flooding, with some property and crop damage in central Iowa.

Figure 6 presents a 350-ms sequence of unfiltered narrow field TV images. The unusual feature of this blue jet is that at 0.200 s the jet has separated into two parts. The jet starts at t=0 and propagates upward at 23 km s^{-1}, until it brightens considerably at

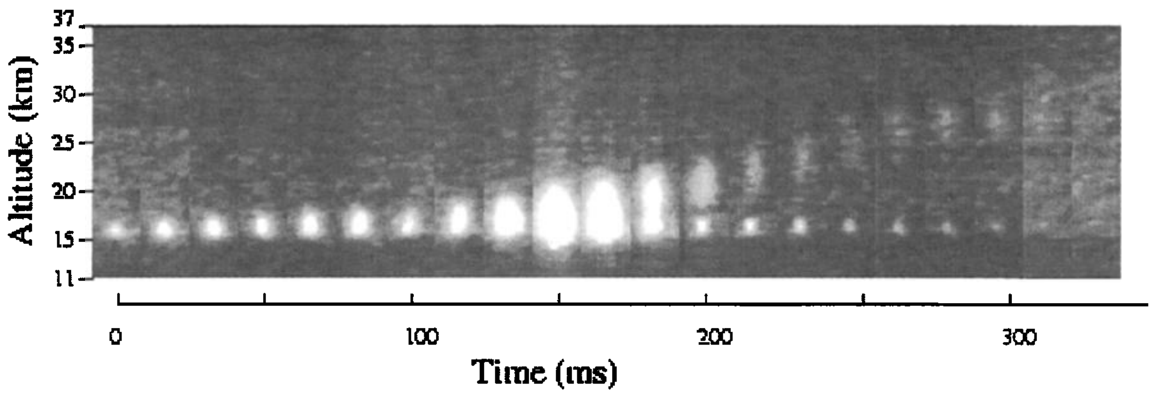

Figure 6. A 350-ms sequence of unfiltered narrow field TV images, 16.67 ms apart, of the blue jet event at 0502:26 UT on July 22, 1998. At *t*=0, the jet appears at 15.5-km altitude and propagates upward at 23 km s^{-1}, until it brightens considerably at *t*=0.133 s. The lower portion of the jet disappears completely after ~0.266 s. After that the upper portion of the jet continues upward at 91 km s^{-1} and disappears from sight after 0.333 s at an altitude of ~35 km.

t=0.133 s. Next the upper tip of the jet continues upward at 91 km s^{-1} and disappears below observing threshold after 0.300 s at an altitude of ~35 km. The lower part decays away while the upper portion continues upward. The 91 km s^{-1} motion has smeared out the apparent length of the upper portion during the 33-ms integration of the TV field by 3 km, so the actual length of the separated ionized streak is ~3 km. This blue jet followed three -CG flashes and one +CG flash located ~70 km to the west and 4 s after a -CG flash at 14-km distance. This confirms the previous conclusions that blue jets are not associated with any particular CG flash.

5. Summary

The new observations of blue jets and starters reported in this paper confirm some previous conclusions and reveal several new results:

1. The total optical brightness in the visible blue end of the spectrum of a large blue jet over the ocean north of Réunion Island, recorded on a color photograph by one of the authors, is at least 6.76 MR.

2. Jets are due to streamers, and from the arguments of *Wescott et al.* [1998] they are probably positive. The Réunion photograph shows eight smaller streamers (50- to 100-m diameter) starting near the base of the main jet.

3. Blue starters, and by association also blue jets, emit only a small fraction of the total light from the ionized N_2 (1 NG) band at 427.8 nm, proving that they are at least partially ionized. From star calibrations a 1 MR starter recorded in multiple wavelengths was found to have 3% ionization.

4. In one remarkable blue jet event the streamer front separated from the source at the base and continued upward for ~ 100 ms, reaching an altitude of ~35 km.

5. Blue jets are not associated with any particular CG lightning flash, but they do occur in regions of thunderstorms of mostly -CG activity. They are not restricted to areas of large hailfall over land. They also occur over tropical ocean thunderstorms.

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