

UPWARD ELECTRICAL DISCHARGES FROM THUNDERSTORM TOPS

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Mesospheric lightning-related sprites and elves, not attached to their parent thunderstorm's tops, are being joined by a family of upward electrical discharges, including blue jets, emerging directly from thunderstorm tops.

For over 100 years, persistent eyewitness reports in the scientific literature have recounted a variety of brief atmospheric electrical phenomena above thunderstorms (Lyons et al. 2000). The startled observers, not possessing a technical vocabulary with which to report their observations, used terms as varied as “rocket lightning,” “cloud-to-stratosphere lightning,” “upward lightning,” and even “cloud-to-space lightning” (Fig. 1). Absent hard documentation, the atmospheric electricity community gave little credence to such anecdotal reports, even one originating with a Nobel Prize winner in physics

(Wilson 1956). On the night of 6 July 1989, while testing a low-light television camera (LLTV) for an upcoming rocket launch, the late Prof. John R. Winckler of the University of Minnesota made a most serendipitous observation. Replay of the video tape revealed two frames showing brilliant columns of light extending far into the stratosphere above distant thunderstorms (Franz et al. 1990). This single observation has energized specialists in scientific disciplines as diverse as space physics, radio science, atmospheric electricity, atmospheric acoustics, and chemistry as well as aerospace safety, to explore the linkages between tropospheric lightning and the middle and upper atmosphere. Given concerns for possible impacts on aerospace vehicles, the National Aeronautics and Space Administration (NASA) immediately initiated a review of video tapes from the space shuttle payload bay LLTV employed to image mesoscale lightning events. Over a dozen events appearing to match Winckler's observation were uncovered (Boeck et al. 1998). On 7 July 1993, the first night of observing at the Yucca Ridge Field Station near Fort Collins, Colorado, Lyons (1994) documented over 240 events. Evidently they were not a rare occurrence. The very next night, LLTV cameras onboard the NASA DC-8 detected huge flashes above

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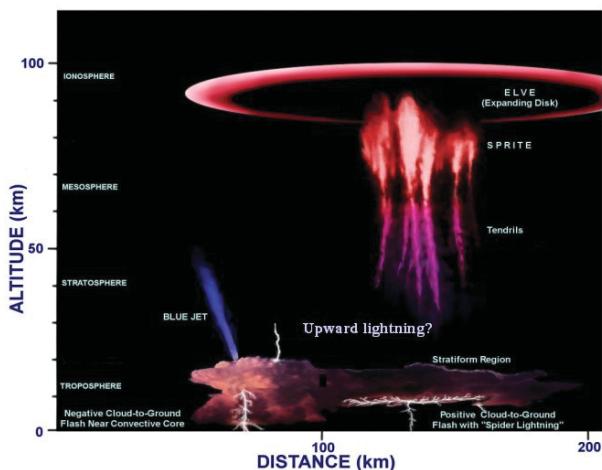


FIG. 1. The morphology of lightning-related, middle atmospheric transient luminous events including red sprites, blue jets, and elves. Also indicated is an additional type of discharge from cumulonimbus tops that may be a true “cloud-to-stratosphere” lightning or simply another manifestation of the blue jet phenomenon. Adapted from Lyons et al. (2000), reprinted with permission of the American Geophysical Union.

a large thunderstorm complex in Iowa (Sentman and Wescott 1993).

With the rush of discoveries, confusion soon arose regarding scientific terminology. Winckler and his colleagues initially termed their discovery a “cloud-to-stratosphere (CS) flash.” Press reports frequently referred to “upward lightning” or “cloud-to-space lightning.” But little was known of the underlying physics of these transient illuminations. Was it “lightning?” In which direction did it really propagate? Did it connect the cloud top with “space”? To avoid assigning a name that might later need revision, Davis Sentman of the University of Alaska proposed calling them “sprites” (mysterious and fleeting characters populating Shakespeare’s *The Tempest*). Sentman’s team also provided the first color images showing sprites to be primarily red with blue highlights on their lower extremities (Sentman et al. 1995), so the term red sprites has become widely used. Sprites, often as bright as an intense aurora, can on some occasions be seen with the naked eye. They extend from near the base of the ionosphere (~90 km), with tendrils sometimes reaching below 40 km, but there is no direct evidence of a conductive current path to the cloud tops below. Sprites appear within several to perhaps 200 ms after a powerful positive polarity cloud-to-ground lightning discharge (+CG). A variety of theories arose to explain the observations (Rowland 1998). Current thinking favors sprites as

complex conventional electric breakdown in the rarefied middle atmosphere triggered by thunderstorm electric fields of electrostatic origin produced by the transfer of large amounts of charge to ground, following the basic suggestion of Wilson (1925). Most sprites start with small initiating zones around 70–75 km followed by complex networks of streamerlike discharges propagating first downward and then upward (Stanley et al. 1999).

Not all thunderstorms produce sprites, including many with substantial numbers of +CGs. Evidence began to accumulate that +CGs occurring with the stratiform regions of large mesoscale convective systems (MCSs) were preferred sprite producers (Lyons 1996). The Severe Thunderstorm Electrification and Precipitation Study (STEPS), conducted on the high plains of Colorado and Kansas during summer 2000, further documented that sprites most commonly occur above the stratiform precipitation region of MCS larger than ~20,000 km². Conditions there appear to favor the formation of unusual +CGs producing extremely large charge moment changes, the product of the charge lowered to ground and the altitude from which it was removed. As inferred from extremely low frequency (ELF) sferics signatures, charge moments of the order of 1000 C km, more than an order of magnitude larger than “normal” lightning flashes, are produced by sprite-parent +CGs (Williams 1998; Huang et al. 1999; Cummer and Stanley 1999; Hu et al. 2002). It is estimated, based on ELF data, that several sprites occur each minute on a worldwide basis (Huang et al. 1999).

Another phenomenon, called elves—toroidal-shaped luminous regions near the base of the ionosphere—were confirmed in 1995 by coordinated observations at Yucca Ridge (Fukunishi et al. 1996). Theoretical modeling by scientists from Stanford University had suggested the electromagnetic pulses from some CGs should cause brief (< 1 ms), outwardly expanding glows between 80 and 100 km (Inan et al. 1996). The impetus for this research was a 1990 LLTV observation from the space shuttle in which there was an apparent transient brightening of the “airglow layer” at 85 km subsequent to a lightning flash in the clouds below (Boeck et al. 1998). Elves, while having a peak optical output of ~1000 kR, are so brief (< 0.5 ms) they are not visible to the human eye and are difficult to detect even with LLTVs.

During 1994, aircraft-mounted LLTVs searching for sprites made a serendipitous discovery reminiscent of reports of “rocket lightning” reported from the ground (MacKenzie and Toynbee 1886) and from the space shuttle LLTV (Boeck et al. 1998). Tenuous fountains of blue light, appearing as grainy and dif-

fuse, trumpet-shaped ejections spurted upward from electrically active thunderstorm tops at speeds $>10^5 \text{ m s}^{-1}$, reaching heights of 40 km or more (Wescott et al. 1995). These rare events appear not to be directly associated with any specific CG lightning flash. Lasting only 100–200 ms, though relatively intense (~500–1000 kR), blue jets are difficult to see with the naked eye at night even under ideal viewing conditions. Jets typically appear to be several kilometers wide at their base, becoming wider with height. Also noted were blue “starters,” blue jets which would attain no more than a few kilometers of vertical extent (Wescott et al. 1996). We note that extensive analyses of the video indicate that the optical emissions of blue jets/starters are confined exclusively to blue wavelengths. Thus, no “white” component of the discharge is anticipated. Though blue jets propagate upward from the storm top into the stratosphere, their video appearance does not resemble “lightning” in any normal usage of the word.

Several competing theories of blue jets include both conventional and runaway breakdown in the stratosphere above cumulonimbus cloud tops (Sukhorukov and Stubbe 1998). Recent theoretical contributions suggest the streamer zone of a conventional positive leader as the underlying physical mechanism of blue jets (Petrov and Petrova 1999; Pasko et al. 1999, 2001). No theory has yet accounted for all blue jet characteristics.

Are there additional phenomena to be uncovered, such as a true “cloud to stratosphere” upward lightning discharge? This paper reviews a growing number of film, video, and eyewitness observations that are clearly neither sprites nor elves, and which also depart from our current understanding of the phenomenology of blue jets. It may be that blue jets express themselves over a wider variety of shapes, morphologies, and optical intensities than the original observations and models would imply.

SOME PUZZLING OBSERVATIONS. Since 1989, more than 10,000 images of sprites, elves, and blue jets have been obtained by various research teams. Even after acknowledging their wide variety of shapes and sizes, especially of sprites, we do know that these phenomena exhibit a generally recognizable morphology. Numerous reports that simply do not fit our current understanding of the phenomenology of these events (Vaughan and Vonnegut 1989; Lyons and Williams 1993) include

- “vertical lightning bolts were extending from the tops of the clouds . . . to an altitude of approxi-

mately 120,000 feet . . . they were generally straight compared to most lightning bolts . . .”

- “at least ten bolts of lightning went up a vertical blue shaft of light that would form an instant before the lightning bolt emerged . . .”
- “a beam, purple in color . . . then a normal lightning flash extended upwards at this point . . . after which the discharge assumed a shape similar to roots in a tree in an inverted position . . .”
- “a brilliant, blue-white spire . . .”
- “an ionized glow around an arrow-straight finger core . . .”
- “a lightning spike”

These above observations simply do not describe sprites, elves, blue jets, or blue starters. Eyewitnesses have, however, reported what appear to be blue jets. Heavner (2000) compiled numerous sightings, including that of a pilot flying at 45,000 ft above a very active thunderstorm at night who commented,

I saw a blue ejection from the top of a storm cloud in the shape of an inverted tear drop (narrow end

UPWARD LIGHTNING—UPCLOSE

In 1973, Ronald Williams, a NASA U-2 pilot, was flying above a typhoon in the Gulf of Tonkin at an altitude of about 20 km. He reported,

I approached a vigorous, convective turret close to my altitude that was illuminated from within by frequent lightning. The cloud had not yet formed an anvil. I was surprised to see . . . a bright lightning discharge, white-yellow in color, that came directly out of the center of the cloud at its apex and extended vertically upwards far above my altitude. The discharge was very nearly straight, like a beam of light, showing no tortuosity or branching. Its duration was greater than an ordinary lightning flash, perhaps as much as five seconds.

(Vonnegut 1980)

This account was one of many collected by the late Bernard Vonnegut of the State University of New York at Albany. Vonnegut, along with his colleague, O. H. (Skeet) Vaughan Jr. of the NASA Marshall Space Flight Center, labored for two decades to assemble the numerous anecdotal reports of lightning-related phenomena above clouds. When the first “hard” evidence of a sprite was captured on video tape by Jack Winckler and his students in 1989, there was already a rich trove of observational material available to facilitate placing this startling new observation in context.

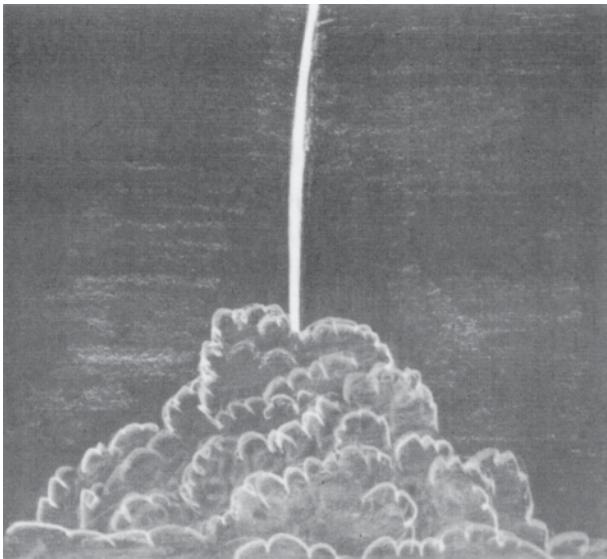


FIG. 2. Sketch of a brilliant, white-colored upward discharge from the convective dome of a high plains thunderstorm as reported by an eyewitness observer during summer 1992 at the Yucca Ridge Field Station, Fort Collins, CO. The event was seen during daylight and appeared to extend upward to a height roughly equal to the cloud depth (~15 km). The event lasted for about 1 s, with no perceptible flickering.

pointed down). . . . The jet looked as if it were made of particles (grainy), it was not a solid image as a lightning bolt would appear . . . it was definitely travelling at a very high rate of speed vertically . . . and lasted no more than a half second. . . .

Another reported,

weird blue flashes above the cloud from time to time . . . they were definitely blue jets because they ‘poofed’ upwards in an inverted cone shape, almost like a fountain . . . noticed 15 to 20 of these.

Heavner (2000) also compiles other observations having distinctly different characteristics:

an American Airlines captain . . . near Costa Rica . . . saw from an anvil of a thunderstorm several discharges vertically to very high altitudes . . . the event was white. . . .

the top of the storm was not flat . . . looked like a dome of a Van de Graaff generator . . . clearly saw several bolts of lightning going upwards . . . dissipating in the clear air above the storm . . . all in all 5 or 6 occurrences of lightning above the storm. . . .



FIG. 3. Upward discharge captured on film by Australian photographer Peter Jarver. The image was obtained during a time exposure of a lightning-illuminated thunderstorm near Darwin during the 1980s. Though difficult to see in reproduction, the original transparency shows an upward-flaring blue flame at the tip of the white channel, which extends at least as far again upward. Photograph kindly made available by Earle Williams.

Staff of the Yucca Ridge Field Station have on four separate occasions made eyewitness observations of unusual lightning-like channels, all emanating from overshooting convective domes of very active storm cells (see sketch in Fig. 2). They all appeared bright white to yellow in color, were relatively straight, did not flicker, extended upward for at least the height of the depth of the cloud (10–15 km), and were notably long lasting (~1 s). Two of the four were observed during *daylight*. These would not appear to represent the phenomenon reported by Wescott et al. (1995).

Several events evoking the above descriptions have actually been captured by chance on film during time exposure storm photography. In the late 1980s, Earle Williams obtained a 35-mm slide from Australian photographer Peter Jarver (Fig. 3). While shooting nighttime images of a lightning-illuminated thunderhead near Darwin he imaged an upward-extending finger of white light (based on the typical dimensions of convective turrets estimated to be about 1 km tall), above which extended a blue “flame,” which broadened slightly as it reached perhaps another kilometer higher. A much more spectacular example was captured by astronomer Patrice Huet on 35-mm slide film (ISO 400, 20-min time exposure) above a thun-

derstorm over the Indian Ocean. The event reached a height of ~35 km. It was classified as a blue jet by Wescott et al. (2001). While the upper two-thirds were capped by a flaring blue flame reminiscent of blue jets, the lower third of the event was a bright, white, lightning-like channel. The lower bright channel would not appear to have counterparts in the many airborne LLTV video images reported by Wescott et al. (1995, 1996). The image also revealed distinct signs of finer-scale streamerlike filaments in the blue flame.

But these images were not the first of their kind. Welsh geographer Tudor Williams, who in 1968 was residing near Mount Ida, Queensland, Australia, visually observed a series of lightning-like channels rising at least several kilometers above the top of a large nocturnal thunderstorm. He photographed several of the approximately 15 events (using 50 ASA 35-mm transparency film, long exposures) that occurred at fairly regular intervals over a 45-min period. In Mr. Williams's words,

the outstanding thing that I remember about the upward strokes which I saw was how slowly they formed. The spark rose slowly from the top of the cloud and took a full two seconds to achieve its full height . . . it faded away rather than shutting off abruptly. This pattern was consistent for every stroke I saw.



FIG. 4. One of several upward discharges (out of about 15) photographed during time exposures above a nocturnal thunderstorm during March 1968, near Mount Ida, Queensland, Australia. The discharges were perceived by the naked eye to be long lasting, propagating upward, and slowly dissipating over a one- or two-second interval. Though taken on very slow (ISO 50) film, the original transparencies reveal a flaring blue flame (difficult to see in this reproduction) coming off the upper tip of the white channel, extending again about as high. Image courtesy of Tudor Williams.

Figure 4 shows the bright upward channel along with a hint of a faint blue flame flaring upward and outward from its upper portion reaching a height equal to or greater than the bright channel. While the lower white channels were easily visible to the naked eye, the blue flame was only apparent upon inspection of the processed film (now faded due to the age of the transparency). These events appear morphologically similar to the Jarver and Huet images. In this case, the visual observations of a credible witness indicate the event duration to be an order of magnitude longer than the blue jets reported by Wescott et al. (1995). It is not possible from time-exposed photographs to determine whether the bright channel precedes, follows, or coincides with the blue flame.

Curiously, during hundreds of hours of ground-based LLTV video monitoring above thunderstorms at Yucca Ridge, we never captured any such events—until the summer of 2000.

MORE THAN SPRITES DURING STEPS. The STEPS campaign was conducted during the summer of 2000. It was a multiorganization field program investigating the coevolving dynamical, microphysical, and electrical characteristics of high plains thunderstorms, especially those producing +CGs. The centerpiece of the experiment was the New Mexico Institute of Technology's 3D Lightning Mapping Array (LMA), which was centered near Goodland, Kansas (Krehbiel et al. 2000). This provided a unique opportunity for the LLTV cameras at Yucca Ridge (275 km to the northwest) to monitor sprites above storms passing through the LMA domain. Well over 100 sprites were successfully recorded above the ~400-km-diameter LMA domain during STEPS.

On 22 July 2000, cameras were imaging sprites above northwestern Kansas when a small supercell-like storm initiated at 0600 UTC, approximately 60 km southeast of Yucca Ridge. It drifted into the field of view of a new GEN III ultrablue sensitive (350–890 nm) LLTV system that was undergoing operational tests. The storm grew rapidly and developed a classic overshooting convective dome structure by 0610 UTC. Ten minutes later it reached its highest base reflectivity (57 dBZ) and radar echo top height (13.7 km). During the first 20 min, the intracloud (IC) flash rate increased rapidly to over 45 fl s^{-1} . The first of only 41 CG strokes (40 of negative polarity) occurred at 0627 UTC. At 0613 UTC, during the time of most rapid vertical development, the LLTV camera began recording a series of unusual luminous events atop the overshooting dome, which continued over a 20-min period. Seventeen of these appeared as



FIG. 5. One of the 17 upward-propagating discharges (“gnomes”) arising out of the convective dome of a high plains supercell storm during a 20-min period at 0612–0633 UTC 22 Jul 2000. The bright spot above the anvil is a star.

brief (33–136-ms duration), upward propagating lightning-like channels (Fig. 5). Estimated to be less than 200 m wide (saturation perhaps overestimating width) they did not grow more than 1 km above the cloud top. Upward propagation speeds cannot be precisely determined, but are estimated to be no more than 10^4 m s^{-1} . They also appeared to be brighter, much more compact in shape, and more optically uniform than the blue starters described by Wescott et al. (1996). Furthermore, we are unable to ascertain their color from the monochrome LDTV video. While it is indeed possible that they represent a different manifestation of Wescott’s blue starters, for discussion purposes we will refer to them as “gnomes” until more definitive data become available.

During this same 20-min period, a series of 83 distinctive, very small but intense dots of light appeared,

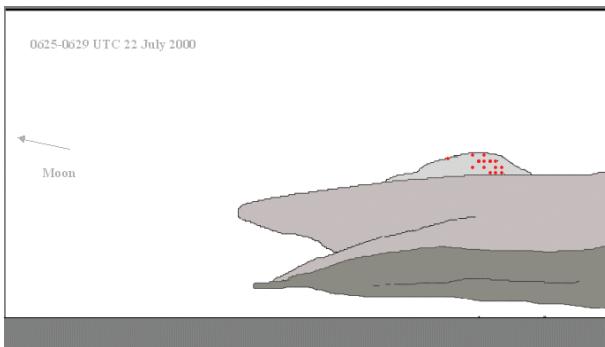


FIG. 6. The location of the brief (< 16 ms) points of light, termed “pixies,” that appeared on the same convective dome as produced the gnomes in Fig. 5. Eighty-three such events occurred during a 20-min interval. This sample shows the events between 0625 and 0629 UTC.

also scattered about upon the surface of the convective dome. Difficult to see in reproduction, some are shown schematically in Fig. 6. These pinpoint of light are estimated to be on the order of 100 m in size. None persisted beyond a single field of video (16 ms). Again, their intrinsic color cannot be determined from the video record. Since it is even less clear that these might represent some form of blue starter, we will provisionally refer to this class of illumination as “pixies.”

A field-by-field LDTV video analysis of the durations of all detected cloud illumination in the storm during this 20-min interval was prepared (Fig. 7). There are surprisingly few statistics of lightning discharge durations in the literature. Brook and Kitagawa (1960) show data from several thunderstorms (based on electric field measurements) that suggest that total discharge durations are generally 100 ms or longer. Defer et al. (2001) noted a bimodal distribution of supercell discharge durations in which most events were $> 50 \text{ ms}$ or $< 1 \text{ ms}$. The disproportionately large number of very short ($< 16 \text{ ms}$) flashes shown in Fig. 7 (83 of which were pixies visible on the surface of the convective dome) suggests the possibility of a second population of electrical discharges distinct from “regular” lightning. Using the LDTV video, the gnomes and pixies could neither be temporally nor spatially associated with specific CG or intracloud (IC) lightning flashes. The relationships between the IC and National Lightning Detection Network (NLDN) CG flash rates, the storm’s radar intensity and altitude, and the occurrence of the gnomes and pixies are displayed in Fig. 8.

Though the GEN III imager was blue sensitive, we could find no evidence of any “flame” extending above the lightning-like channel as in the photographic images. The scattered light from the full moon (just to the left of the field of view) did reduce background contrast. However, using the MODTRAN atmospheric radiance and transmission code, the computed blue sky brightness at that point due to lunar scatter was only approximately 22 kR. This is more than an order of magnitude less than the brightness of reported blue jet optical emissions (Wescott et al. 2001). Thus the lack of the blue “flame,” which could be considered a potential common link between blue jets and the “upward lightning” film images presented here, is puzzling, suggesting other phenomena may be involved.

It could be argued that the STEPS events are merely how blue starters would appear when imaged at relatively close range using a next generation LDTV imager. Alternatively, they may represent new phenomena. Several recent remote sensing studies have

presented observations possibly relating to our LLTV images. Smith (1998) analyzed radio frequency (RF) data from the *ALEXIS* satellite, uncovering a unique broadband RF signature associated with some thunderstorms. Termed Compact Intracloud Discharges (CIDS), they are singular, of sub-millisecond duration, and very powerful intracloud electrical discharges occurring in bursts near the intense region of certain thunderstorms. They are distinct from other known types of thunderstorm electrical processes. CIDs have been detected within nocturnal thunderstorms over the United States, always at heights above 8 km, and near storm cores with reflectivities of 47–58 dBZ. They appear to be vertically oriented, with a spatial extent of < 1000 m. CIDs are temporally isolated from all other lightning-related RF emissions and occur at somewhat regular intervals separated by seconds to minutes. Smith (1998) speculated that CIDs should produce optical emissions, but no confirming data were available. In addition, two 3D lightning mapping systems have reported very localized, extremely short bursts of radio emissions from the upper portion of active thunderstorms. Krehbiel et al. (2000) found small, intense, and very brief electrical emissions within supercell convective domes. Defer et al. (2001) noted numerous, very short duration RF emissions ($\ll 1$ ms) in the upper portion of a vigorous high plains supercell. How might these observations be related, if at all, to the cloud-top events of 22 July 2000? Simultaneous LLTV video, photometric, LMA, and RF observations of storm tops would advance research in this area.

A CONNECTION TO THE IONOSPHERE.

On 15 September 2001, a team of scientists familiar

STEPS Supercell 22 July 2000

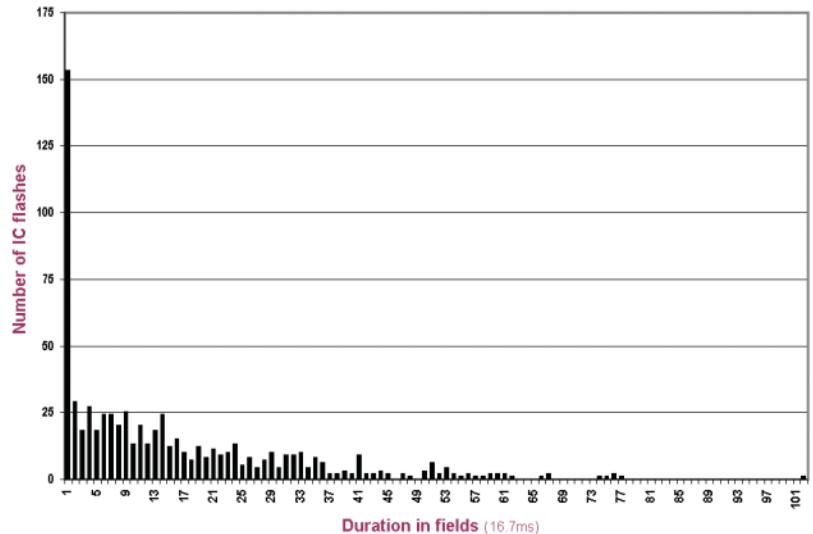


Fig. 7. Distribution of the length of the cloud illuminations during the 20-min period in which the 101 gnomes and pixies occurred on the convective dome. One video field lasts 16.7 ms; thus, the longest flash is about 1.6 s. More than half of the illuminations lasting only a single field were cloud-top pixies.

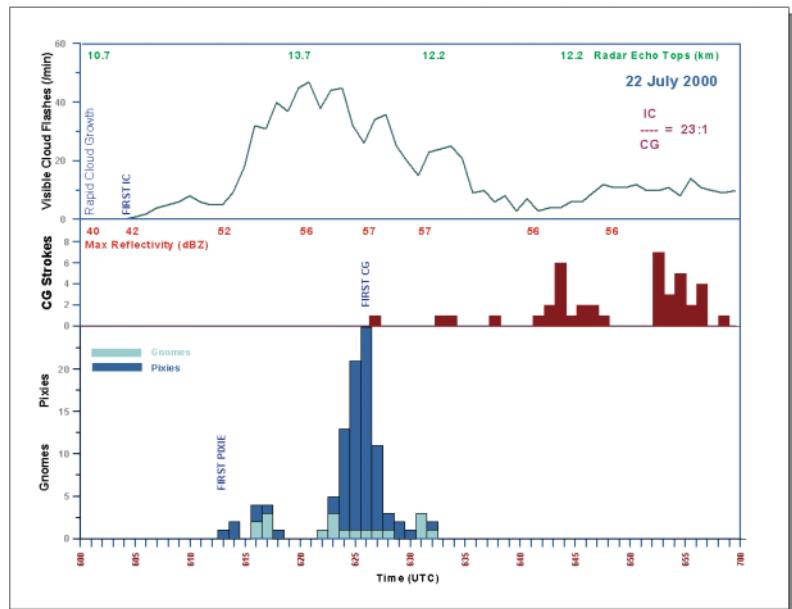


Fig. 8. The life cycle of the small supercell on the bottom that formed at 0600 UTC 22 Jul 2000. The top portrays the intracloud flash rate, while the middle bar shows the NLDN-detected CG lightning flashes (all but one of negative polarity). The rate of gnomes and pixies is shown.

with sprites and blue jets were investigating the effects of lightning on the ionosphere at the Aricebo Observatory in Puerto Rico (Pasko et al. 2002). They deployed the same GEN III low-light camera system

used during STEPS to monitor the space above rapidly growing tropical thunderstorms. A convective system with an anvil cloud dimension of $\sim 2500 \text{ km}^2$ (from infrared satellite imagery) was located 200 km northwest of Arecibo. The LLTV noted an unusually high flash rate for oceanic convection. The LLTV video then captured an amazing upward discharge, one frame of which is shown in Fig. 9 (see <http://pasko.ee.psu.edu/Nature> online for the full animation). Clearly seen as brilliant blue to the naked eye, it appeared as a series of upward and outward expanding streamers which rose from the storm top (16 km), first at relatively slow speeds ($\sim 0.5 \times 10^5 \text{ m s}^{-1}$) and then accelerated to $> 2 \times 10^6 \text{ m s}^{-1}$. The event reached a terminal altitude of 70 km, the estimated lower ledge of the ionosphere. The event lasted almost 800 ms, including several rebrightenings. Since the initial stage of the observed phenomenon closely resembled the general geometric shapes and propagation speeds of previously documented blue jets, the authors speculated that it could be classified as a blue jet, which propagated upward beyond the previously documented altitudes. This case marks the first hard evidence of a direct conductive current electrical link between a tropospheric thunderstorm cell and the ionosphere. If such events are common, they likely influence the global electrical circuit and atmospheric chemistry in ways currently unaccounted for. [Several more events of this type recently

have been reported by Taiwanese researchers (H.-T. Su 2002, personal communication).]

Whether all the cases discussed here are various manifestations of the positive streamer/leader process, perhaps modulated by pressure, that has been represented in blue jet theoretical models, is an open question. It is possible these observations portray several distinct classes of phenomena. One intriguing observation noted at least 10 bolts of lightning shooting out of the top of a 18-km-tall thunderstorm near Guaymas, Mexico, at 2200 LT by a commercial airline pilot flying at 39,000 ft (Gales 1982). Notable was that a blue shaft of light (a blue jet?) would form an instant before the bright, white, lightning-like channel would emerge and penetrate up the shaft some 3–5 km, or about 75% of the height of the pre-existing blue “flame.” This suggests that the blue streamer phenomenon may, under some circumstances, precondition the discharge path to produce much brighter, white colored, lightning-like leaders. It is possible that all of these observations can be described by a more comprehensive theory treating a wider range of physical parameters than those initially proposed for “classical” blue jets.

SUMMARY. A growing variety of storm-top electrical discharges have been observed using several types of LLTV imagers, film, and the human eye. The differences in the sensors employed makes direct comparison of these observations difficult; yet it is clear there is great variability in the morphological features of these events. Horizontal dimensions can range from $\sim 100 \text{ m}$ to several kilometers. Upward extents vary from 100 m to $> 50 \text{ km}$. Shapes include “points” of light, upward-flaring trumpets, narrow, vertically oriented lightning-like channels, often topped with blue, flamelike features. Some, such as the Puerto Rico event, appear to develop considerable upward branching structure. Visual appearances include brilliant, white, lightning-like fingers, granular jets of dim blue light, or bundles of blue, streamerlike channels. Sometimes a blue flame occurs within which a brilliant white channel appears, although when the latter occurs during the sequence is uncertain. A few reports suggest the dim blue “flame” precedes the bright, lightning-like channel.

The classical blue jet is at the lower limit of human night vision whereas some upward discharges have been seen during full daylight. The cloud-top “pixies” last no longer than 16 ms, whereas the upward lightning-like channels are often characterized as unusually long lasting (order 0.5–2.0 s or more). Within the limitations of optical observations, the



FIG. 9. Image of a presumed blue jet propagating from a cumulonimbus cloud top (just below bottom of image) to an altitude of about 70 km, taken from Arecibo Observatory, Puerto Rico, at 0325 UTC 15 Sep 2001, from a distance of about 200 km. The original monochrome image from Pasko et al. (2002) is reproduced in false color. Reprinted by permission from *Nature* (Pasko et al. 2002).

events appear not to be triggered by a specific IC or CG discharge. There is a strong tendency for such events to occur above the convective domes of rapidly developing, intense thunderstorms.

It is possible that the great diversity of forms taken by these discharges illustrates the complexity inherent in the upward leader process as modulated by atmospheric pressure and other factors. It is also possible that the basic blue jet is only one of several distinct classes of discharges from highly electrified storm cloud tops.

Future research will need to focus on rapidly growing convective storm tops, especially in supercells and intense oceanic thunderstorms, as opposed to the stratiform regions of large MCSs that has characterized sprite observation campaigns to date. The implications of these findings for aerospace safety, stratospheric chemistry, and the global electrical circuit remain to be explored.

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