10A.1 ELECTRICAL DISCHARGES FROM THUNDERSTORM TOPS

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1. INTRODUCTION

Since 1989, more than 10,000 low light television (LLTV) images of sprites, elves and blue jets have been obtained by various research teams (Franz et al., 1990; Lyons, 1996; Sentman et al., 1995; Wescott et al., 1995; Lyons et al., 2000). Even after acknowledging their amazing variety of shapes and sizes, especially of sprites, these phenomena exhibit a recognizable morphology. Numerous reports, however, simply do not fit our current understanding of the phenomenology of these events (Vaughan and Vonnegut, 1989; Lyons and Williams, 1993; Heavner, 2000). A sample includes:

"…vertical lightning bolts were extending from the tops of the clouds…to an altitude of approximately 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…"
"…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 Graff generator...clearly saw several bolts of lightning going upwards…dissipating in the clear air above the storm…all in all 5 or 6 occurrences …"

Staff of the Yucca Ridge Field Station (YRFS) have on three separate occasions made eyewitness observations of unusual lightning-like channels, all emanating from overshooting convective domes of very active storm cells. They all appeared bright white to yellow in color, were relatively straight, did not flicker, extended upwards for at least the height of the depth of the cloud (10-15 km) and were notably long lasting (~1 second). Two of the three were observed during *daylight*. It is difficult to understand how these might represent the blue jet phenomenon as reported by Wescott et al., (1995).

Amazingly, several events evoking the above descriptions have been captured by chance on film during time exposure storm photography. Upward extending white channels topped by blue flame-like features were captured near Darwin, Australia (Lyons, 1997) and over the Indian Ocean (Wescott et al., 2001) This latter event reached a height of ~35 km. But these images were not the first of their kind. Welsh geographer Tudor Williams, who in 1968 was residing near Mt. 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 minute period. In Mr. Williams 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." Figure 1 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). It is not possible from time-exposed photographs to determine whether the bright channel precedes, follows or is coincident with the blue flame.

2. MORE THAN SPRITES DURING STEPS

The STEPS campaign, conducted during the summer of 2000, was a multi-organization field program investigating the co-evolving 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 3-D Lightning Mapping Array (LMA), which was centered near Goodland, KS (Krehbiel et al., 2000). This provided a unique opportunity for the LLTV cameras at YRFS (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. The charge moment changes for the sprite parent +CGs were found to be exceptionally large (~1000 C km) (Hu et al., 2002)

On 22 July 2000, cameras were imaging sprites above northwestern Kansas when a small supercell storm initiated at 0600 UTC, approximately 60 km southeast of Yucca Ridge. It drifted into the field of view of a new GEN III ultra blue sensitive (350-890 nm) LLTV system. The storm grew rapidly and developed a classic overshooting convective dome structure by 0610 UTC. Ten minutes later it reached its peak reflectivity (57 dBZ) and radar altitude (13.7 km). During the first 20 minutes, 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 minute period. Seventeen of these appeared as brief (33-136 ms duration), upward propagating lightning-like channels (Fig. 2). 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 can not be precisely determined, but are estimated to be no more than 10^4 m s^{-1}. While showing some similarities with the blue jets (Wescott et al., 1995), they also appeared to be much brighter, more solid and more compact. Furthermore, we are unable to ascertain their color from the monochrome LLTV 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 minute period, a series of 83 distinctive, very small but intense dots of light appeared, also scattered about upon the surface of the convective dome. These pinpoints of light are estimated to be on the order of 100 meters in size. None persisted beyond a single field of video (16 ms). Again, their intrinsic color can not be determined from the video record. Since it is even less clear that these might represent some form of blue jet, we will provisionally refer to this class of illuminations as "pixies."

A field by field LLTV video analysis of the duration of all detected cloud illuminations in the storm during this 20 minute interval was prepared (Fig. 3). There are few statistics of lightning discharge durations in the literature. Defer et al. (2001) noted a bimodal distribution of supercell discharge durations in which most events where > 50 ms or < 1 ms. The disproportionately large number of very short [<16 ms] flashes shown in Fig. 3 (83 of which were pixies visible on the surface of the convective dome) suggest the possibility of a second population of electrical discharges distinct from "regular" lightning. In common with blue jets, neither the gnomes nor pixies were closely temporally or spatially associated with CG or IC lightning flashes.

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 U.S., always at heights above 8 km, near storm cores with reflectivities of 47 - 58 dBZ. They appear to be vertically oriented, with a spatial extent of <1000 meters. 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 3-D 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 (<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?

3. A CONNECTION TO THE IONOSPHERE

On 15 September 2001, a team of scientists familiar 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). It was recommended that they deploy the same GEN III low-light cameras system used in STEPS to watch the space above rapidly growing tropical thunderstorms. At 0325.00.872 UTC, above a relatively small (~2500 km^2) storm cell 200 km northwest of Arecibo, the LLTV video captured an amazing upward discharge, one frame of which is shown in Fig. 4 (see the full animation at http://pasko.ee.psu.edu/Nature). 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 (~$0.5x10^5$ m s^{-1}) and then accelerated to >$2x10^6$ 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 re-brightenings. 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 upwards beyond the previously documented altitudes. This case marks the first hard evidence of a direct 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.

4. SUMMARY

A growing variety of storm top electrical discharges have been observed using several types of LLTV imagers, film and the human eye. The variety of 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 ~100 m to several km. Vertical extents vary from 100 m to 70 km. Shapes include "points" of light, upward flaring trumpets, narrow vertically oriented lightning-like channels, often topped with blue, flame-like 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 streamer-like channels. Sometimes a blue flame occurs within which a brilliant white channel appears, although when the later 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 of 0.5 s to 2.0 s or more). The events were generally not triggered by a known 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 (Petrov and Petrova, 1998). 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 the regions atop rapidly growing convective storms, including supercells, as opposed to the stratiform regions of large MCS which 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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Figure 1. One of several upward discharges (out of about 15) photographed during time exposures above a nocturnal thunderstorm during March, 1968, near Mt. Isa, 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 2. One of the 17 upward propagating discharges ("gnomes") arising out of the convective dome of a High Plains supercell storm during a 20 minute period (0612-0633 UTC) on 22 July 2000. The bright spot above the anvil is a star.

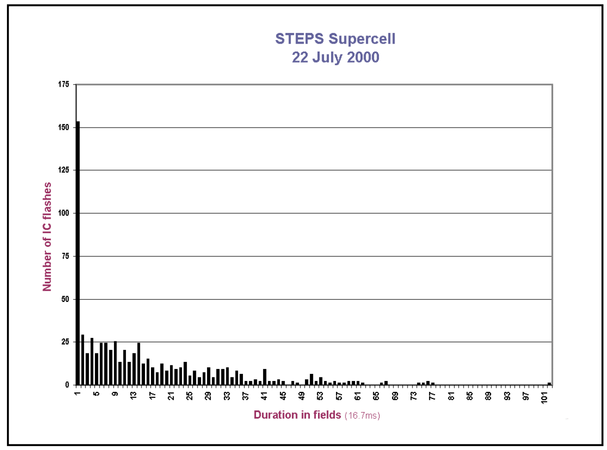

Figure 3. Distribution of the length of the cloud illuminations during the 20 minute period in which the 101 "gnomes" and "pixies" occurred on the convective dome. One video field lasts 16.7 ms, thus the longest flash is about 1.6 seconds. More than half of the illuminations lasting only a single field were cloud top "pixies."

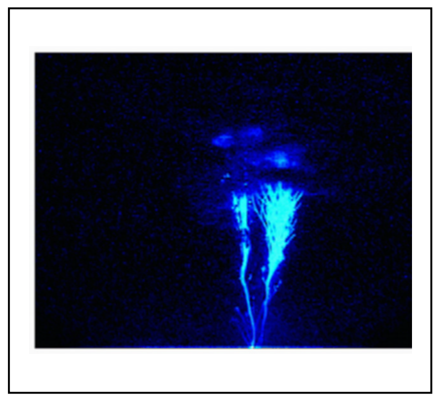

Figure 4. Image of an upward discharge propagating from a cumulonimbus cloud top (just below bottom of image) to an altitude of about 70 km, taken from Arecibo Observatory, Puerto Rico at 0325 UTC 15 September 2001, from a distance of about 200 km. Reprinted by permission from Nature (Pasko et al., 2002), copyright 2002, Macmillan Publishers, Ltd.

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