Lightning development associated with two negative gigantic jets

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[1] We report observations of two negative polarity gigantic jets sufficiently near very high-frequency (VHF) lightning mapping networks that the associated lightning characteristics and charge transfer could be investigated. In both cases the gigantic jet-producing flash began as ordinary intracloud lightning with upper level channels attempting to exit the cloud, and then produced the upward gigantic jet. Neither flash had developed channels to ground, confirming that the major charge transfer during gigantic jets occurred between the cloud and ionosphere. The leader progression of one event was detected at altitudes above 20 km, demonstrating the possibility of detecting and tracking the propagation of negative jets above the cloud with VHF techniques.
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1. Introduction

[2] Lightning discharges occasionally emanating from the tropospheric cloud tops [*Wescott et al.*, 1995; *Lyons et al.*, 2003] may develop up to the base of the ionosphere [*Petrov and Petrova*, 1999], forming gigantic jets (GJs) [*Pasko et al.*, 2002; *Su et al.*, 2003], and transfer electric charge there that originally resided in clouds [*Cummer et al.*, 2009; *van der Velde et al.*, 2010]. The details of lightning morphology and associated charge transfer during GJs remain the subject of ongoing investigations. *Krehbiel et al.* [2008] suggest that intracloud (IC) flashes rooted in the main negative cloud region of normally electrified thunderstorms may escape the cloud top when the upper positive region is depleted, for instance, by mixing with the uppermost negative screening layer. Numerical simulations support this scenario and also show that the GJ-favorable storm condition can be reflected by the occurrence of 'bolt-from-the-blue' (BFB) discharges [*Riousset et al.*, 2010], which typically begin with an upward intracloud channel that continues to progress laterally out of the storm and downward to ground as a negative stroke [*Rison et al.*, 1999; *Thomas et al.*, 2001].

[3] Here we report observations of two negative GJs transferring negative charge upward to the ionosphere, both within the detection range of ground-based networks that resolve three-dimensional lightning evolution by locating sources of impulsive very high-frequency (VHF) emissions [*Rison et al.*, 1999]. Broadband lightning signals were also recorded with multiple magnetic sensors near Duke University, making it possible to assess lightning discharge events on time scales from a few μs to >100 ms. Some of these events were reported by the National Lightning Detection Network (NLDN) [*Cummins and Murphy*, 2009]. All the lightning measurements have been synchronized using GPS time.

[4] Although the two GJs differed substantially in the amount of charge they transferred to the ionosphere, as estimated from the ultra low-frequency (ULF, <1–400 Hz) magnetic fields, the lightning development leading to each was remarkably similar. Both occurred as part of flashes that began as ordinary IC lightning and then attempted to exit the upper part of the storm, indicative of a depleted upper positive cloud region relative to the mid-level negative region, one condition that would favor upward negative GJs [*Krehbiel et al.*, 2008]. This specific lightning evolution would have further depleted the upper positive charge, making conditions more favorable for the subsequent upward negative leader to escape the cloud vertically rather than horizontally. Neither flash developed a ground stroke, as evidenced by the VHF mapping results and by the low-frequency (LF, 30–300 kHz) magnetic fields, constraining the GJ-associated charge transfer between the cloud and ionosphere. Significantly, one of the GJs produced VHF sources of high credibility at altitudes as high as 36 km, suggesting the GJ propagation as a negative leader up to this altitude. This observation raises the feasibility of observing jet-like events with VHF techniques that predominantly detect negative breakdown [*Shao and Krehbiel*, 1996]. Below we present the detailed measurements for each event.

2. Florida Gigantic Jet Near the 4DLSS

[5] The first gigantic jet was recorded with a Watec 902H2 camera at 205 km range from Sebring, Florida (27.52°N, 81.52°W) at 11:01 UTC, 28 September 2010. Observed 16 minutes before local sunrise at sea level (msl), this is the first GJ known to ascend into the daytime ionosphere. The video was not recorded with GPS time, but comparisons with

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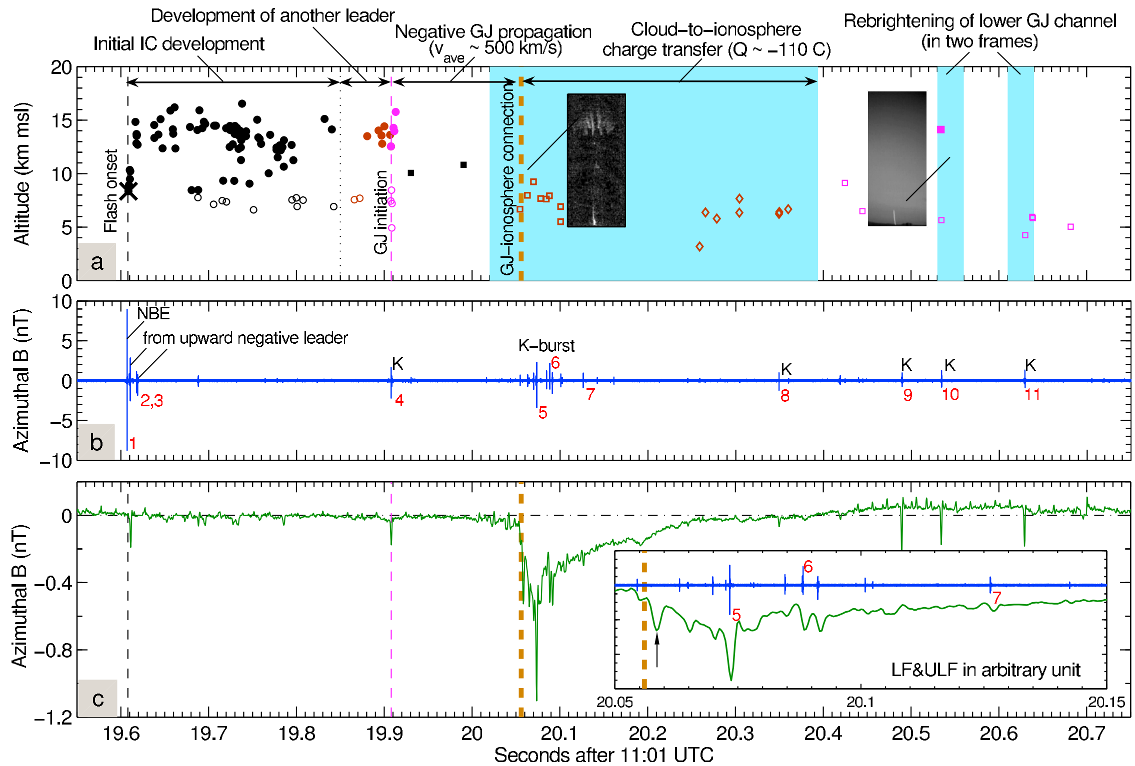

Figure 1. (a) Observations of the Florida GJ (visible in the shaded intervals) and 4DLSS mapping results of the flash (from http://trmm.ksc.nasa.gov/). VHF sources of negative leaders (solid symbols) and *K* processes (open symbols) are color coded to show the annotated lightning progression. (b) Low-frequency (LF) magnetic fields, with red numbers indicating the NLDN events. (c) Ultra low-frequency magnetic fields, with an inset showing the LF impulses during the early GJ-associated excursion.

sprites occurring earlier constrained the absolute timing accuracy to ±20 ms. WSR-88D NEXRAD radar scans indicate that the GJ emanated from an oceanic convective cell ~70 km north of the Four-Dimensional Lightning Surveillance System (4DLSS) of the Kennedy Space Center [*Roeder*, 2010]. The cell reached near the tropopause altitude (16.2 km msl) inferred from radiosonde ascents. Figure 1a compares the GJ observations with the parent flash shown by the 4DLSS VHF sources. The first inset shows the brightest image of the fully developed GJ, which remained visible during the long shaded interval of ~370 ms duration. By comparing with the star field [e.g., *van der Velde et al.*, 2007], the GJ developed a forked top that reached ~80 km altitude, appearing as a 'tree' jet [*Su et al.*, 2003]. The second inset shows a clear rebrightening of the GJ channel below 25 km, and a possible second rebrightening is also indicated.

[6] The 11 NLDN-detected events of the flash are indicated by red numbers in Figure 1b that mark their respective LF impulses, all with short durations (<0.2 ms) indicative of intracloud events within 15 km of the first VHF source ('×' in Figure 1a). Most of these events were also associated with millisecond-scale slow magnetic pulses in the ULF signal (Figure 1c), which were distinct from the large amplitude excursion longer than 200 ms partway through the flash. The slow pulses and the long excursion are both of negative polarity indicating upward negative current flow, and the associated charge moment change (ΔM_q, defined as the product of the charge amount and the altitude range over which the charge is displaced) is estimated with a deconvolution method used by *Cummer et al.* [2009].

[7] Like other flashes around the same time in the storm, the GJ-producing flash was initiated by a narrow bipolar event (NBE), one type of compact intracloud discharge with short durations (10–20 μs) that can be the initial event of ordinary IC flashes [*Rison et al.*, 1999]. The initiating NBE (event 1) radiated the largest LF impulse of the flash and was detected by the NLDN as having a +56-kA peak current. The subsequent upward negative leader generated a slow pulse and several LF impulses (e.g., events 2–3), typical of the breakdown early in normal-polarity IC flashes [*Shao and Krehbiel*, 1996].

[8] The 4DLSS detections in the first 250 ms show the bi-level structure of ordinary IC flashes between two primary charge regions of a normally electrified thundercloud [*Coleman et al.*, 2003]. Most of the VHF sources were associated with the negative leader (solid black circles) propagating in a positive cloud region above 11 km msl; the rest portray *K* processes (open black circles) that traveled backward along positive leaders expanding in a compact negatively charged region of the cloud [*Rison et al.*, 1999]. Figure 2a shows the projection of two types of VHF sources onto a west-east vertical plane. The spatial distribution of these sources is also compared with radar scans at two different altitudes through the convective cell (Figures 2b and 2c). The negative leader declined in altitude while propagating to the edge of the storm (indicated by red arrows), similar to the initial development of a BFB discharge, but stopped short of exiting the storm.

[9] During the 80 ms interval after the initial leader stopped extending, *K* processes (open brown circles) injected a neg-

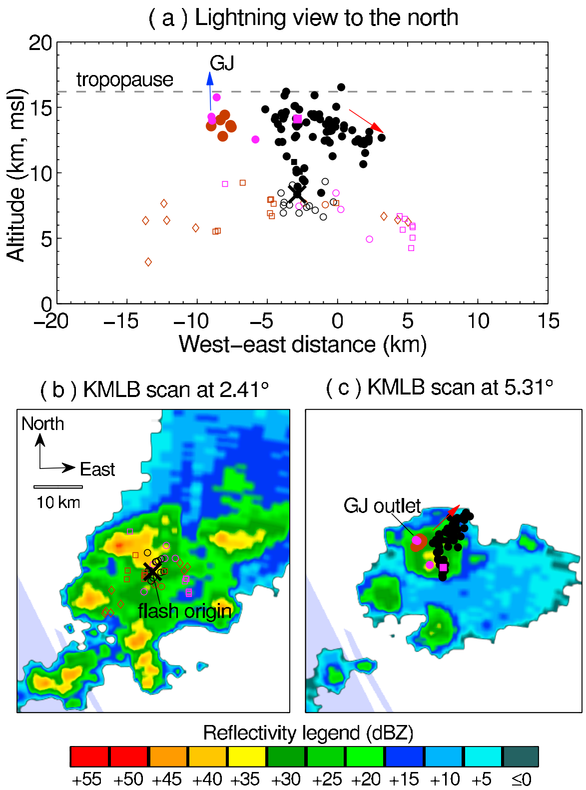

Figure 2. (a) Projection of VHF sources in Figure 1a onto a west-east vertical plane (distances relative to the 4DLSS origin). Comparing the spatial distribution of VHF sources from negative leaders (solid symbols) and *K* processes (open symbols) with NEXRAD radar scans (at 11:00 UTC) from Melbourne, Florida (KMLB) at two elevation angles corresponding to the (b) 6–7 km and (c) 12–13 km altitude in the convective cell.

ative leader (solid brown circles) into a positively charged cloud region not tapped by the earlier activity. The pink dashed line in Figure 1a indicates a *K* process (event 4, open pink circles down to 5 km msl) that generated a slow pulse with a ΔM_q of +40 C-km in 2 ms, with the positive sign indicating negative charge being raised. This *K* process developed a second negative leader (solid pink circles) that, we infer, successfully penetrated the cloud top, and continued ascending at a mean velocity of ~500 km/s to 80 km altitude. The upward propagation caused a modest slow ULF variation as reported before [*Cummer et al.*, 2009], without detectable LF radiation during a 140 ms interval. Meanwhile, other than two VHF sources (solid black squares) likely related to breakdown near existing in-cloud lightning channels, there was little noticeable VHF radiation reflecting positive leader expansion in the negative cloud region that was feeding the upward-moving GJ.

[10] As shown in the inset of Figure 1c, the ULF variation enhanced substantially at 20.056 s, beginning with a slow pulse (indicated by an arrow) not with any LF impulses. We attribute the slow pulse to electrical connection of the jet with the ionosphere (bold brown dashed line). The jet-ionosphere connection, similar to the return stroke of ground flashes, initiates an ionizing wave moving downward along the GJ channel as inferred from space-borne photometric observations [*Kuo et al.*, 2009]. The relative slowness (a few ms) of this connection may result from the lower conductivity of the ionosphere compared to the ground, and also the electrical properties of jets in comparison with conventional lightning leaders [*Pasko and George*, 2002]. This connection initiated a cloud-to-ionosphere continuing current that dominated the long negative excursion in the ULF magnetic field. The early stages of this current were also accompanied by additional millisecond-duration slow pulses that were all associated with in-cloud *K* processes (open brown squares, such as events 5–7), suggesting a rejuvenation of positive leader expansion during the initial charge transfer to the ionosphere. Similar processes could account for *M* components during continuing currents to ground [*Mazur et al.*, 1995]. During the ~160 ms quiescence in *K* processes when the GJ channel remained visible due to the ongoing cloud-ionosphere charge transfer, positive leaders continued passing through negatively charged regions of the cloud, as evidenced by *K* processes (open brown diamonds) recurring in regions farther from the flash origin. Without generating distinct slow pulses, these *K* processes probably did not ascend into the GJ channel that was fading away.

[11] The gigantic jet became invisible 330 ms after reaching the lower ionosphere. By this moment the steadily decreasing cloud-ionosphere current had accumulated a ΔM_q of +8000 C-km, or removal of an estimated 110 C of negative charge from a cloud region centered at 7 km msl if all the charge was deposited at 80 km altitude. However, positive leaders and associated *K* processes (pink open squares) remained active. The last three *K* processes (events 9–11) each caused a ΔM_q of +50 to +60 C-km and were all classified by the NLDN as ground strokes, but their short LF impulses reveal intracloud events. *K* event 10 probably ascended to higher altitudes, producing a VHF source (solid pink square) at 14 km msl, and rebrightened the GJ channel. The second possible rebrightening may have occurred following the final *K* event 11.

[12] Throughout the flash, the LF and VHF data do not imply any channels to ground, confirming that the observed charge transfer was inside the cloud or between the cloud and ionosphere. In addition to the cloud-ionosphere current, other parts of the flash discharged the negative cloud region by an additional 20 to 40 C, and thus the total negative charge removal was 130 to 150 C from a 20-km diameter disk based on the extent of VHF sources below 10 km. On this basis we estimate the mean density of negative charge depleted in an assumed 2 km deep region to be –0.22 nC/m^3, not larger than typical charge densities found in active thunderstorms [*Marshall and Stolzenburg*, 1998].

3. Oklahoma Gigantic Jets Near the LMA

[13] An almost identical lightning evolution to that described above produced one of the two GJs observed at ~500 km range between 07:20 and 07:30 (UTC) on 9 September 2010 from Hawley, Texas (32.66°N, 99.84°W). The exact GPS time was stamped to video fields recorded by a system identical to that capturing the Florida GJ. The storm cell producing these GJs was embedded in the remnants of Tropical Storm Hermine and reached above 15 km msl, about 200 km east of the Oklahoma Lightning Mapping Array (LMA) [*MacGorman et al.*, 2008].

[14] Here we focus on the brighter GJ at 07:28 UTC that remained visible for 300 ms after developing to near 90 km

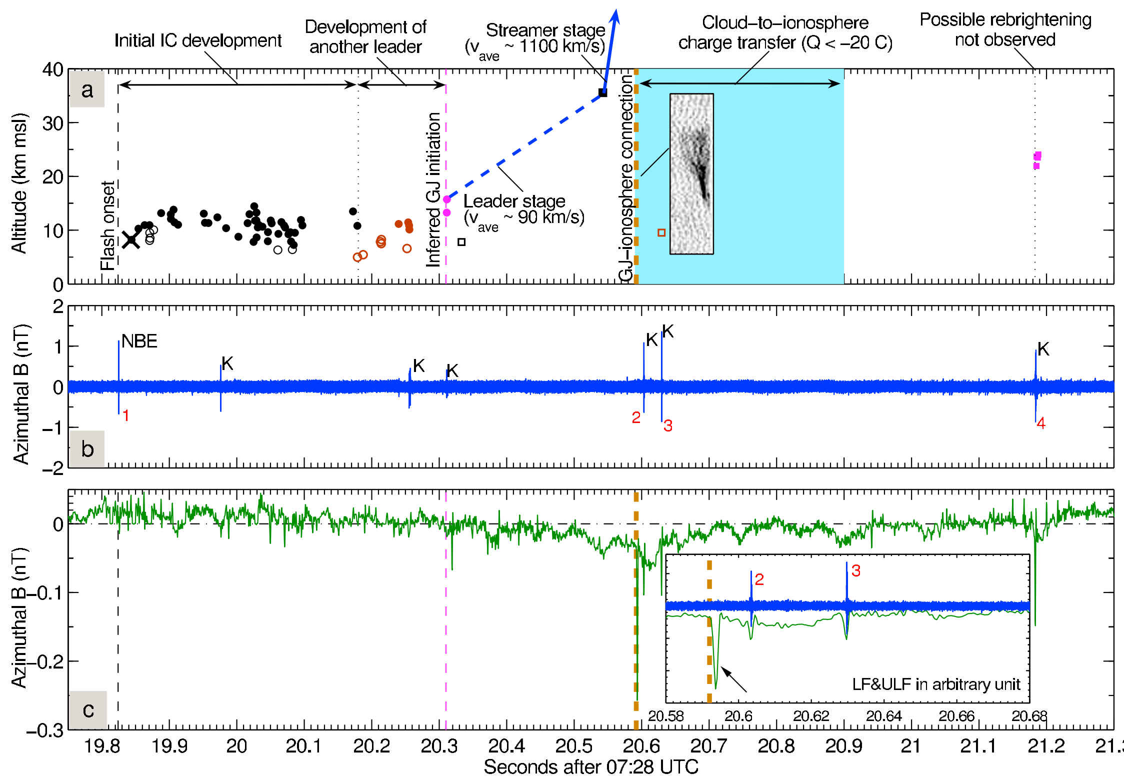

Figure 3. (a) Observations of the Oklahoma GJ in comparison with the LMA mapping results of the flash. VHF detections are color coded as in Figure 1a. (b, c) LF and ULF magnetic fields, organized as in Figures 1b and 1c.

altitude. The inset of Figure 3a shows the first and brightest image (inverted) of the GJ appearing at the right edge of the video field. In addition to the Duke measurements, the associated LF magnetic field was recorded with a closer sensor in New Mexico. The data from this sensor indicate an NBE (event 1 in Figure 3b) simultaneous with an energetic VHF source that, although located in error, was almost certainly associated with the flash onset [*Rison et al.*, 1999]. This NBE and three stronger *K* processes of the flash were reported by the NLDN.

[15] Figure 3a shows the flash evolution as depicted by reliable LMA detections (omitting those with reduced chi-squared values above 1.0 and those with obvious radial errors at the edge of the system) [*Thomas et al.*, 2004], including the second VHF source used here as the flash origin ('×' in Figure 3a). The location uncertainty of most of the plotted VHF sources, mainly in altitude, is ~2 km [*Lang et al.*, 2010]. The spatial flash development is shown in vertical projection and compared with radar scans (Figure 4). Most VHF sources were from the initial negative leader (solid black circles) that ascended relatively slow in this case, without causing noticeable deflections in the ULF magnetic field (Figure 3c). Owing to the large distance to the storm and the increased altitude uncertainties, the bi-level structure of early flash development is less distinct, with only a few detectable *K* processes (open black circles). However, Figure 4 shows that the initial negative leader ascended possibly as high as 14 km and then appeared to descend to ~8 km msl in cloudy air (indicated by red arrows), exactly as observed for full-fledged BFBs but not reaching ground.

[16] After a pause of ~80 ms in the negative leader progression, the LMA detected a few *K* processes (open brown circles) and associated leader development (solid brown circles) near the flash origin. Although it is not possible to resolve the exact jet initiation, two VHF sources (solid pink circles aligned with the pink dashed line) appeared near the cloud top in coincidence with a weak *K* process at 20.310 s. We associate these VHF sources with a negative leader escaping the cloud top and eventually developed into a gigantic jet, as was seen for the Florida GJ. The actual jet onset might have been earlier but this uncertainty does not affect the conclusions. This GJ was similar to the Florida case in that there was an apparent lull in the in-cloud activity during its upward propagation which, again, caused a slowly building magnetic variation (Figure 3c).

[17] Interestingly, the LMA detected a VHF source (solid black square) of a small chi-squared value at 36 km msl during the GJ ascent. This detection likely reflects the leader-to-streamer transition, which occurs between 35 and 42 km in other observations [*Pasko et al.*, 2002; *Su et al.*, 2003], and certainly occurred below this transition in this case. Assuming a transition at 36 km altitude, the mean velocity of the leader stage of the Oklahoma GJ is ~90 km/s (20 km over 230 ms), comparable to typical speeds of conventional stepped leaders [*Shao and Krehbiel*, 1996]. The subsequent streamer stage of GJ development extended at a mean velocity of ~1,100 km/s (55 km over 50 ms), in agreement with the estimates of *Su et al.* [2003] for two events at the 'leading jet' stage. The overall upward propagation speed (~270 km/s) before reaching 90 km altitude is about half of (but comparable to) the Florida GJ.

[18] As shown in the inset of Figure 3c, the inferred GJ-ionosphere connection (bold brown dashed line) caused the largest slow pulse (indicated by an arrow), again, not

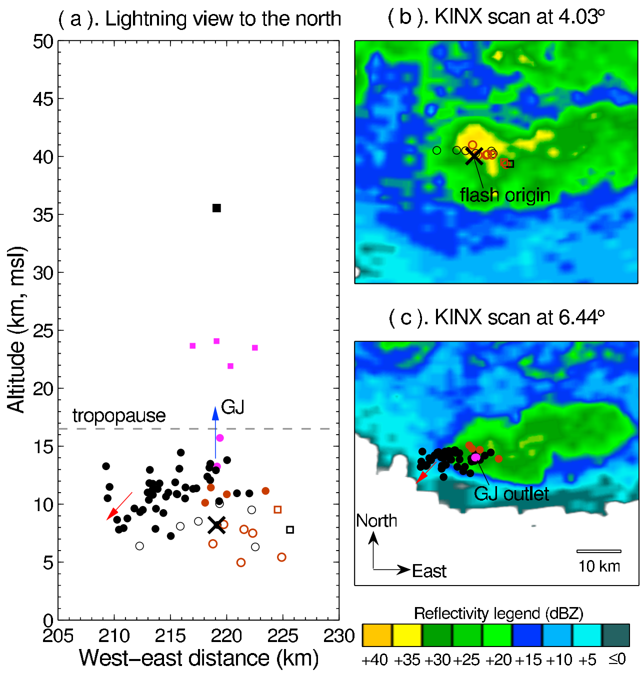

Figure 4. (a) Projection of the VHF sources in Figure 3a onto a west-east vertical plane (distances relative to the LMA origin). Comparing the spatial distribution of in-cloud VHF sources from negative leaders (symbols) and *K* processes (open symbols) with NEXRAD scans (at 07:28 UTC) from Tulsa, Oklahoma (KINX) toward the (b) 7–9 km and (c) 11–14 km altitude in the convective cell.

associated with distinct LF radiation. The subsequent two smaller pulses were related to *K* events 2–3, implying the rejuvenation of positive leaders in the negative cloud region. About 280 ms after the GJ faded away, the NLDN detected a final *K* event 4 that was followed by four VHF sources (solid pink squares) of good reliability at 21–25 km msl. These high altitude VHF emissions reflect negative breakdown that probably ascended high (to generate a slow pulse) and rebrightened the GJ channel, as was seen in the Florida case. The relatively long range in this case, however, may have prevented the optical observation.

[19] The LMA detected similar high altitude VHF sources for the less bright GJ at 07:22 UTC, including one at 35 km msl during the GJ ascent and at least six between 21 and 26 km associated with possible rebrightenings. This GJ was also preceded by long (~400 ms) in-cloud activity, but more spatial features are not clear due to insufficient VHF detections. For both Oklahoma GJs, the overall negative charge transferred to the ionosphere was 10 to 20 C. As the VHF sources of *K* processes were rather sparse, we evaluate the size of the negatively charged cloud region by means of the 35-dBZ contour [*Shao and Krehbiel*, 1996], and compute the negative charge density removed from a 2-km deep region to be less than -0.2 nC/m^3.

4. Conclusions

[20] We have examined two lightning flashes that produced negative gigantic jets near lightning mapping systems in Florida and Oklahoma, respectively. In both cases, the GJs were observed when the storm was actively producing normal-polarity IC flashes, indicating an abundance of negative charge in the mid-level of deep convective cells reaching above 15 km. The parent flashes of both GJs began as ordinary IC lightning and attempted to exit the storm cell, indicative of a depleted upper positive cloud region. Neither flash developed channels to ground. These observations are in good agreement with the hypothesis that negative gigantic jets result from an upper level charge imbalance [*Krehbiel et al.*, 2008]. The lightning development prior to the GJ occurrence could have depleted more upper positive charge to lower the potential well that otherwise inhibits the escape of a subsequent upward negative leader from the cloud top.

[21] After the initial development, both flashes became relatively inactive for about 80 ms until *K* processes initiated a new negative leader. In the Florida case, the leader entered a pristine positively charged region of the cloud and was followed by another leader that made its way out of the cloud top, forming the gigantic jet. The mean speeds of upward propagation in the two cases are comparable (5×10^5 m/s and 2.7×10^5 m/s for the Florida and Oklahoma GJs, respectively). During the upward propagation of both GJs, there was no noticeable LF or VHF radiation reflecting possible positive leader extension in the negative cloud region.

[22] In both cases, the inferred GJ-ionosphere connection generated a millisecond-scale slow pulse not associated with LF radiation. We interpret this as resulting from the lesser conductivity of the lower ionosphere relative to the ground and the different conductivity of low- and high-altitude breakdown. The ensuing cloud-ionosphere continuing current contained *M*-component-type variations linked to *K* processes originating from a rejuvenation of positive leaders in the negative cloud region. The *K* processes remained active after the GJ faded away, which is more distinct in the Florida case where some *K* processes ascended to high altitudes and rebrightened the lower GJ channel. The Florida GJ ultimately transferred five times more negative charge to the ionosphere than the Oklahoma GJ, but neither had significantly discharged an extensive negative region of the cloud.

[23] The Oklahoma LMA detected VHF sources at ~35 km msl during the upward propagation of two GJs, suggesting a leader-streamer transition at or above this altitude. Both GJs also produced VHF sources at 21 to 26 km msl associated with possible rebrightenings of their lower channel. These observations suggest VHF techniques are applicable to resolve jet propagation above the cloud.

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