

Gigantic jets with negative and positive polarity streamers

J. K. Chou,¹ C. L. Kuo,^{1,2,3} L. Y. Tsai,¹ A. B. Chen,^{4,5} H. T. Su,^{1,3} R. R. Hsu,^{1,3,4} S. A. Cummer,⁶ J. Li,⁶ H. U. Frey,⁷ S. B. Mende,⁷ Y. Takahashi,⁸ and L. C. Lee²

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[1] The ISUAL gigantic jets (GJs) are categorized into three types from their generating sequence and spectral properties. Generating sequence of the type I GJs resembles that reported previously; after the fully developed jet (FDJ) established the discharge channel, the ISUAL photometers registered a peak that was from a return-stroke-like process. The associated ULF (ultra-low-frequency) sferics of these type I GJs indicates that they are negative cloud-to-ionosphere discharges (-CIs). Type II GJs begin as blue jets and then developed into GJs in ~ 100 ms. Blue jets also frequently occurred at the same region before and after the type II GJs. No identifiable ULF sferics of the type II GJs were found, though an extra event that has +CI ULF signature is probably a type II GJ. The FDJ streamer brightness of the type I GJs is \sim 3.4 times of that of the type II GJs. These evidences suggest that the type II GJs are composed of positive streamers. Type III GJs were preceded by lightning, and a GJ subsequently occurred near this preceding lightning. The spectral data of the type III GJs are dominated by lightning signals and the ULF data have high background noise; thus both cannot be properly analyzed. However, the average brightness of the type III GJs falls between those of the other two types of GJs. We propose that the discharge polarity of the type III GJs can be either negative or positive, depending on the type of the charge imbalance left by the trigger lightning.

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1. Introduction

[2] Jets are members of the transient luminous events (TLEs), and are upward discharges from thundercloud top (~15–18 km) with a cone shape [*Wescott et al.*, 1995]. Characterized by their terminating altitudes, the family of jets includes blue starters, blue jets (BJs), and gigantic jets (GJs). The average terminal altitude is about 20.8 km for the blue starters [*Wescott et al.*, 1996] and about 40–50 km for the blue jets. The cone angle for the blue jets is about 15°, the upward propagating velocity is about 100 km/s, and the luminous duration is ~200–300 ms [*Wescott et al.*, 1995]. GJs are upward discharges that span the cloud top and the lower

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ionosphere, and their luminous period is ~500 ms [*Pasko* et al., 2002; Su et al., 2003; van der Velde et al., 2007; Cummer et al., 2009]. The morphological evolution of the GJ consists of three stages: the leading jet, the fully developed jet (FDJ), and the trailing jet. The leading jet behaves similarly to the stepped leader in the cloud-to-ground lightning (CG). The fully developed jet optically and electrically links the cloud top and the lower ionosphere. The brightest part of the ensuing trailing jet slowly propagates upward from ~50 km to ~60 km, and persists typically for about 300 ms. These previously observed GJs were not associated with CG lightning, and the associated ELF (extremely low frequency; 1 Hz~100 Hz) emissions indicate that this type of GJs were negative cloud to ionosphere discharges (-CI) [Su et al., 2003; Cummer et al., 2009].

[3] From the observational data, *Wescott et al.* [1996, 1998] reported that blue starters and blue jets both were related to the cumulative –CG before the events. From the images of BJs, they further concluded that the branching structure of the blue jets is similar to that of streamers [*Wescott et al.*, 2001]. *Petrov and Petrova* [1999] proposed that blue starters and BJs are the streamer zones of the positive leaders. *Pasko and George* [2002] constructed a three-dimensional fractal streamer model with the charge and current system in thunderstorm to simulate the upward propagating and the branching features of BJs; their simulation results agrees well with the observational data. *Raizer et al.* [2006, 2007] further pointed out that the base trunk of

¹Department of Physics, National Cheng Kung University, Tainan, Taiwan.

²Institute of Space Science, National Central University, Jhongli, Taiwan.

³Earth Dynamic System Research Center, National Cheng Kung University, Tainan, Taiwan.

⁴Institute of Space, Astrophysical and Plasma Sciences, National Cheng Kung University, Tainan, Taiwan.

⁵Plasma and Space Science Center, National Cheng Kung University, Tainan, Taiwan.

⁶Department of Electrical and Computer Engineering, Duke University, Durham, North Carolina, USA.

⁷Space Sciences Laboratory, University of California, Berkeley, California, USA.

⁸Department of Cosmosciences, Hokkaido University, Sapporo, Japan.

 Table 1. Band Passes of the ISUAL Imager and Spectrophotometer

 and the Major Emissions in the Passing Bands

Filter	Wavelength Band (nm)	Emission Band System				
Imager						
1	653–754	N ₂ 1P				
2	762 (758–769)	O_2 A band $(b_1 \Sigma_g^+ \rightarrow X_3 \Sigma_g^-)$				
3	630 (626–633)	OI (1D→3P)				
4	557.7 (555–563)	OI $(1S \rightarrow 1D)$				
5	427.8 (425–432)	N_2^+ 1N				
6	no filter	full wavelength observation				
Spectrophotometer						
SP1	150-280	N ₂ Lyman-Birge-Hopfield (LBH)				
SP2	337 (bandwidth: 5.6)	$N_2 2P(0,0)$				
SP3	391.4 (bandwidth: 4.2)	N_2^+ 1N(0,0)				
SP4	624-750	N ₂ 1P				
SP5	777.4 (773.6–783.4)	OI(1) in lightning				
SP6	244–392	mid-UV band				

a BJ is a leader and the fanning upper branch is the streamer zone of the leader. Because the existence of the leader, the discharge of a BJ could persist about 0.3 s. Krehbiel et al. [2008] proposed a unified model for various types of cloud discharges: downward CG lightning, intracloud lightning, and upward jet events. They suggested that positive blue jets (+BJs) are initiated between the upper positive charge pocket and the negative screening layer at the top of the normally electrified storm after the occurrence of -CGs. From the observed "bolt-from-the-blue" lightning discharges and the nature of the associated ELF sferics of GJs [Su et al., 2003], they speculated that negative gigantic jet (-GJs) are originated from the mid-level negative storm charge and propagate upward to the ionosphere. They further proposed that both negative blue jets (-BJs) and positive gigantic jets (+GJs) could occur in the inverted electrical storm of the opposite polarity. Recently, Kuo et al. [2009] suggested that the fully developed jet stage contains ionized discharge channel that lowered the local ionosphere boundary to ~50 km, and then a return-stroke-like process would occur from that altitude and develop toward the cloud top. Following the return-stroke-like process, continuous current flows upward from the cloud top along the conducting channel and results in the observed trailing jet in the GJs. Such current during the trailing jet stage has been observed by Cummer et al. [2009].

[4] Since 2004, the ISUAL experiment on the FORMOSAT-2 satellite has continuously and globally surveyed TLEs from space [Chen et al., 2008a]. Jet events are readily recorded by ISUAL due to the reduced atmosphere attenuation when observing from space [Hsu et al., 2005; Su et al., 2005a, 2005b; Chou et al., 2007; Chen et al., 2008b; Kuo et al., 2009]. This paper presents the gigantic jets recorded by ISUAL during the first five years of operation. Besides the known class of negative streamer GJs, which we call type I, the data reveal for the first time two other kinds of gigantic jet. Type II GJs start as a BJ then develop into a GJ in a process with details that are clearly distinct from those in type I GJs. On the basis of electromagnetic data, the type I GJs are identified as negative cloud-to-ionosphere-discharge events (-CIs), similar to those GJs observed from the ground [Su et al., 2003; Cummer et al., 2009]. Photometric features also support that type II GJs are composed of positive streamers, though no clear electromagnetic signals were found for these events and thus the charge polarity of the type II GJs yet

to be assigned unambiguously. In a few cases, gigantic jets appeared to be triggered by lightning to create the third type of GJs (type III). The discharge polarity of the type III GJs is expected to vary and depends on the charge imbalance left by the trigger lighting. However, the current available electromagnetic data are contaminated by lighting signals from sources near the Duke radio wave recording station or have high background noise and thus cannot be properly analyzed.

2. Instruments

[5] The Imager of Sprites and Upper Atmospheric Lightning (ISUAL) is the scientific payload of the FORMOSAT-2 satellite, which has a Sun-synchronous polar orbit and uses an eastward side-looking view to capture the TLEs near Earth's limb [Chern et al., 2003]. The orbit altitude of the satellite is 891 km and a typical event distance between the TLE and satellite ranges from ~2300 km to ~4000 km. ISUAL contains an ICCD imager (Imager), a six-channel spectrophotometer (SP), and a dual-band array photometer (AP). The Imager captures the TLE images and their spatial development. The imaging area of the ICCD is 512 pixels \times 128 pixels with a field-of-view (FOV) of 20° (H) \times 5° (V). For each event trigger, ISUAL records six consecutive image frames, and the exposure time for each frame is 29 ms for the TLEs reported in this article. The Imager is equipped with six switchable filters, and the band passes are given in Table 1. The TLE and lightning events discussed in this paper were all recorded through the N₂1P (653–754 nm) band filter. The ISUAL SP consists of six photometric channels that are bore-sighted with the imager and have the same FOV; their band passes is also listed in Table 1. The time resolution of the ISUAL SP is 0.1 ms (10 kHz) which is much higher than that of the ISUAL imager (29 ms). The ISUAL AP contains a blue (370-450 nm) and a red (530–650 nm) modules; each module has 16 vertically stacked photomultiplier tubes with a combined FOV of 22° (H) \times 3.6° (V). The ISUAL AP provides information on the photometric variation along the vertical direction of an ISUAL event. Before and within 10 ms after the event trigger the sampling rate of AP is 20 kHz to better resolve the temporal evolution at the initiation of the event, then the sampling rate drops down to 2 kHz for a total data length of 240 ms.

[6] At Duke University ($35.864^{\circ}N$, $-79.101^{\circ}E$), two pairs of magnetic induction coils recorded the vector horizontal magnetic field from 0.1 Hz to 500 Hz. These signals are used to identify the low-frequency radio signatures of the observed gigantic jets and to determine the source polarity when a signal is sufficiently clear. Using the known gigantic jet locations, we compute the measured azimuthal magnetic field, which is the magnetic field in the azimuthal direction defined by a cylindrical coordinate system with the origin at the jet location. A negative polarity for the initial part of this signal implies either downward motion of positive charge, as in a +CG, or the upward motion of negative charge, as in a -CI. A positive polarity implies the opposite source polarity.

3. Morphological Development and Spectral Features

[7] Between July 2004 and April 2009 ISUAL imager registered 32 GJs. Among them, 20 GJ events taken through

the N_21P filter that were not contaminated by lightning or other types of TLEs are selected for analysis. We classify these 20 GJs into three types according to their morphological development and spectral properties.

3.1. Type I GJs (Eight Events)

[8] The spatial-temporal evolution of this type of GJs is similar to those observed in ground observations. This type of ISUAL GJs triggered on the fully developed jet, as shown in Figure 1a. Hence only the fully developed jet and the trailing jet stage were recorded, and the leading jet was not observed. In the fully developed jet stage, both SP2 and SP6 showed double photometric peaks which separated from each other by ~1.5 ms. The AP data provided auxiliary information that helps to understand the SP reading. From the AP blue module data (Figure 1b), the double photometric peaks in SP2 and SP6 were identified as peaks associated with upward discharge and the ensuing downward return-stroke-like process [Kuo et al., 2009]. The AP red module registered photometric traces with very low S/N ratio for the GJ emissions from ~45 km altitude or lower, thus only the first upward propagating peak was unambiguously resolved. The first photometric peak was seen by all the SP channels except SP5. SP2, SP3, SP4, and SP6 data also show slowly varying continuous emissions following the distinct peaks that are associated with continuing current flow from the cloud to the ionosphere [Kuo et al., 2009; Cummer et al., 2009]. The duration of the continuous current varies from event to event and differs for different event distances. From the AP data, one can clearly discern that the continuous emissions recorded by the SP are emitted by electric current flowing inside the thundercloud [Kuo et al., 2009].

3.2. Type II GJs (Seven Events)

[9] Image sequence in Figure 2a suggests that this type II GJ starts with a jet-like event (frames 2–4) and then slowly propagates upward and finally develops into a fully developed jet (frame 5). Figure 2a indicates that signals in SP2, SP3, and SP6 are only clearly discernible within ~1 ms around the trigger time with sharp rise and slow decay features. The AP blue module registers a jet-like signal that cross \sim 2–3 channels, while the red module signals always have low S/N ratios. All the initiating jets share the same photometric features as those shown in Figure 3 for a typical ISUAL blue jet; the image sequence was also taken through the same $N_2 P$ filter. Therefore it can be concluded with high confidence that the type II GJ starts with a slow upward propagating blue jet and later develops into a fully developed jet. This process typically takes ~110 ms. The fully developed jet appeared in the fifth image frame, and the last image frame seems to contain a trailing-jet-like luminous column that radiated continuously and rose up from the cloud to ~30 km altitude. However, the morphology of this trailing-jet-like column is

very different from that for the type I GJs, and there is no detectable radiation at the cloud deck level. Hence whether the trailing jet feature exists in the type II GJs is an unsettled issue. The corresponding SP emissions for the fully developed jet of the type II GJs are full of noises and cannot be properly analyzed. The brightness of the fully developed jet (frame 5) is distinctly lower than that of the type I GJs. We also found that blue starters and blue jets often occurred in the same general region before and after the type II GJs; another distinct feature that is not shared by the type I GJs.

3.3. Type III GJs (Five Events)

[10] Type III GJs are preceded by bright lightning; after that a GJ occurs near the preceding lightning and extends from the cloud top toward the ionosphere, as shown in Figure 4. The interval between preceding lightning and type III GJ varies widely from ~15 ms to 110 ms. Morphologically, type III GJs can be falsely identified as sprites. However, sprites [Sentman et al., 1994; Pasko, 2007, and references therein] extend from \sim 40 km to 90 km altitudes but do not connect to the cloud top, unlike the type III GJs. Furthermore, sprites always produce clearly recognizable spectral signals in the ISUAL SP [Kuo et al., 2005; Figures 3 and 4] that characteristically are very different from those from lightning/type III GJs. Also, the average brightness of the ISUAL carrot sprites is found to be ~3 MR [Kuo et al., 2008], which is nearly 10 times higher than that for the type III GJs. Hence the type III GJs are unambiguously distinct from the carrot sprites.

[11] After careful examining the image frames 2–4 in Figure 4a, a small luminous column is seen to protrude above the cloud emissions in each frame. During the interval, weak blue emissions are represented in SP2 (337 nm) and SP6 (224–392 nm). This suggests that the small luminous column might be a blue jet-like event. Figure 4b shows that a long luminous column that bridges the cloud top and the ionosphere seems to develop along the discharge channel established by the preceding luminous events, while it emits no recognizable signals in SP and AP. Therefore this clearly is a type III GJ, not a sprite, since both its generating sequence and its spectral features also differ from those for the type I and the type II GJs.

[12] The main characteristics for the three types of gigantic jets are summarized in Table 2. From the spectral data recorded by ISUAL spectrophotometer and array photometer, it is clear that the forms and the spectral properties of type I and type II GJs are very different. The spectral signals from the type III GJs are masked by the emissions of the preceding lightning, so it is extremely difficult to compare them to those of the type I and type II GJs.

[13] The spatial-temporal evolution of the type I GJs is similar to that of the ground-observed GJs, which are known to emit sferics that signifies they are -CI events [*Su et al.*, 2003; *Cummer et al.*, 2009]. Hence it is nature to expect

Figure 1. Type I gigantic jets (GJ) on 28 February 2006 0435:52.993 UTC. (a) The image sequence and the spectrophotometer data for this event. (b) The first image frame and the associated array photometer (AP) data. The fully developed jet (FDJ) occurred in first image, and the corresponding spectrophotometer (SP)2 and SP6 data contain double peaks and a humping continuous luminosity. The trailing jet occurred in frames 2–6. The AP blue module shows signals associated with the upward propagation FDJ and the ensuing downward return stroke-like process. For the red module, only the signal from the FDJ was registered. The continuous cloud emissions of this event manifest themselves as the humping curves in SP2, SP3, SP6, and AP channels 10 and 11.



Figure 1



Figure 2. Type II GJ on 4 April 2009 1627:28.574 UTC. (a) The image sequence and the spectrophotometer data for this event. (b) The second and the fifth image frames and the associated array photometer data for the second frame. The blue jet occurred in the second image frame and then slowly developed into a GJ in the fifth frame. The associated AP data for the fifth frame is very noisy and is not shown here. The AP blue module data contain a clear signature from the blue jet; whereas it was absent from the AP red module data.

that the type I GJs are also consist of negative streamers. Previous observations and theoretical studies [*Wescott et al.*, 1996, 1998; *Pasko et al.*, 1996; *Pasko and George*, 2002] have concluded that blue jets are comprised of positive streamers extending upward from the cloud top. The type II GJ begins as a blue jet and then develops into a GJ; hence its polarity should be the same as the preceding blue jet. The polarity of the type IIIs likely is stipulated by the preceding lightning that creates the charge imbalance to initiate this type of gigantic jets. To verify the above conjectures, magnetic field and photometric signatures of the three types of GJs will be analyzed and compared in the following sections.

4. ULF Signatures of the Gigantic Jets

[14] As shown in Table 2, clear ULF (ultra-low-frequency) magnetic field recordings from Duke University were made for five of the eight observed type I GJs, and all of these were



Figure 3. A blue jet on 14 May 2007 2155:30.258 UTC. (a) The image sequence and the spectrophotometer data for this event. (b) The second image frames and the associated array photometer data for the second frame. The blue jet occurred in frames 2–4 (marked by arrows). The lightning signal at ~40 ms is from a storm outside these cropped images but in the fields of view (FOVs) of the ISUAL sensors. The AP blue module data contain a clear signature from the blue jet that crossed ~2–3 channels, while the blue jet signal was absent from the AP red module.

Figure 4. Type III GJ on 7 August 2005 1454:43.161 UTC. (a) The image sequence and the spectrophotometer data for this event. (b) The fifth and the sixth image frames and the associated array photometer data. The preceding lightning occurred in the first frame. In frames 2–4, luminous columns jutting from the storm are upward discharges (marked by the arrows). The GJ occurred in the last two frames, but the SP data show no double-peaked feature during the FDJ stage. Owing to the low sampling rate (2 kHz) at this time range, the AP signals from this GJ have low signal-to-noise ratios.



Figure 4

Table 2. Characteristics of the Three Types of Gigantic Jets

Туре	Characteristics in Imager, SP, and AP	Trigger Time (UTC)	ULF Data	Leading and Trailing BJs
Ι	The development is similar to those from the ground observations.	2005/10/01 1122:23.898	no data	no
	The FDJ are doubly peaked for SP. SP2, SP3, and SP6 data	2005/12/13 1305:54.688	-CI	no
	show continuous-current characteristics that related to the	2006/02/28 0435:52.993	-CI	no
	in-cloud lightning after complete the discharge channel. AP	2006/03/14 1633:00.609	-CI	no
	signals are corresponding to SP double peaks: the first peak	2007/04/12 1500:54.967	no data	no
	is from the upward discharge, and the velocity is $\sim 10^7$ m/s;	2007/05/28 0634:08.404	-CI	no
	the second peak is from a downward return stroke-like process	2007/11/07 1509:23.326	-CI	no
	[Kuo et al., 2009].	2008/07/03 1825:56.923	no detectable signal	no
Π	The event starts as a BJ and then develops into a GJ. The SP	2006/03/03 1452:13.956	no detectable signal	likely ^a
	emissions are similar to those for BJs; only signals from SP2	2007/05/14 2155:16.469	no detectable signal	ves
	(SP3) and SP6 are clearly discernible. The corresponding	2007/06/01 1835:37.112	no detectable signal	yes
	signal for GJ is buried under noise. Only the blue module	2008/01/03 1508:39.547	no detectable signal	yes
	contained BJ signal, and the red module featured signals	2008/04/10 1321:42.984	high background noise	yes
	with very low S/N ratio.	2008/05/01 1651:26.635	no detectable signal	yes
	·	2009/04/04 1627:28.574	no detectable signal	yes
III	Events are preceded by lightning and then develop into a GJ. The	2005/08/07 1454:43.161	high background noise	no
	SP emissions are dominated by lightning, and the emissions	2006/07/02 0443:12.950	no detectable signal	yes
	from GJ are not discernible.	2006/08/18 1314:15.297	no detectable signal	no
		2008/07/27 1508:02.739	high background noise	no
		2008/10/01 1504:42.651	no detectable signal	likely

accLikely" means that the discharge is similar to the normal blue jets but has an associated SP4 signal (624–750 nm), and we are uncertain about whether the in-cloud lightning exists.

unambiguously consistent with upward traveling negative charge (-CIs). Data were either unavailable or too contaminated by local lightning for the other three type I events. Figure 5a is the associated ULF emission for a type I GJ on 28 February 2006 0435:52.993 UTC, which occurred a relatively short 4500 km from the Duke sensors. It is clear from the signal waveform that this type I event has -CI polarity.

[15] The associated ULF signals for the type II generally are too small to be identified. The type II GJs are generally dim; hence the energy and the current associated with this type of upward discharges are also expected to be low. The ISUAL SP data further indicated that the type II GJs have no return-stroke-like process. ULF emissions in GJs are expected to be radiated by the current flowing in the fully developed jet, the return-stroke-like process, and/or the trailing jet. Since the type II GJs contain only the fully developed jet stage and have dimmer luminosity (implying lower current) comparing with the type I GJs; thus they likely are also weak radio emitters.

[16] The polarity of the type III GJs likely is set by the preceding lightning that creates the charge imbalance to initiate the type III gigantic jets. If the preceding lightning remove negative charges from the thundercloud, the resulting type III GJs probably are +CI discharges, and vice versa. The recorded ULF emissions for this type of GJs are found to be mingled with noises and lightning signals from other sources that may not related to the preceding lightning. Since the available ULF data cannot be analyzed, the polarities of the type III GJs remain undetermined.

[17] While searching for the associated ULF signals for the ISUAL GJs, the observed magnetic field signals are temporally associated with the observed events if they are in the same azimuthal direction and differ in time by less than 100 ms. To further confirm that these signals originate in the observed gigantic jets, we simulated the range-dependent azimuthal magnetic field waveform using an analytical Schumann resonance model [Sentman et al., 1996; Huang et al., 1999]. These simulated signals are overlaid on the



Figure 5. Measured azimuthal magnetic fields from two gigantic jets. (a) –CI Type I GJ event on 28 February 2006, 0435:52.993 UTC. (b) Special +CI GJ event on 11 January 2009, 2143:57.015 UTC. The gray solid curves are the magnetic fields measured at Duke University, and the black dashed curves are the simulated signals corresponding to the observed propagation distances of 4500 km (Figure 5a) and 10,400 km (Figure 5b).



Figure 6. Brightness histogram of the twenty analyzed gigantic jets under 29 ms image frame exposure time. Type I GJs are the brightest and type II GJs are the dimmest, while the brightness of the type III GJs is in between.

observed signals in Figure 5 after time shifting to align the initial pulses. The precise timing and shape of the multiple around-the-world pulses in the simulated waveforms agree well with the same features of the measured magnetic fields. This confirms that the observed signatures originate from sources at the location of the observed gigantic jets and thus that the observed signal polarities reflect the polarity of the charge motion associated with the gigantic jets.

5. Brightness of the Gigantic Jets

[18] As depicted in Figures 1a and 2a, the ISUAL imager-N₂1P brightness of the type I GJs is always greater than that of the type II GJs. To quantify the N₂1P brightness of these 20 GJs, the reading of each luminous pixel in the image frame has to be summed. However, Raizer et al. [2006, 2007] pointed out that GJ is composed of the leader channel extending from the cloud and the streamer zone beyond the leader. With an exposure time of 29 ms per image frame, the fully developed jet and the trailing jet stages of type I GJ are often superimposed, whereas for the type II GJs, only the fully developed jet was observed. Thus a comparison of spatially integrated brightness among the various types of GJs would be invalid. We thus choose to compute the $N_2 P$ brightness the streamer zone of the GJ between about 50 and 90 km altitudes, which is above the luminous region of the trailing jets. A rectangular area that vertically spans the streamer zone of ~50 to 90 km is chosen for a given event. The brightness of the 20 GJs was computed, after the background was properly subtracted. The computation only included image pixels whose brightness exceeds two standard deviations of the mean in this area. The reason for this choice is to avoid picking up the background pixels, as it would be if the threshold is set at 1 standard deviation. Furthermore, if the screening threshold was set at or above 3 standard deviations of the mean, then dimmer events would only have a small number of residual pixels and even have none. The brightness is in units of Rayleighs, 1 Rayleigh equal to $10^{6}/4\pi$ photons/ sr/cm²/s, to remove the distance factor. Figure 6 shows the resulting imager- N₂1P brightness distribution of the GJ streamer zone for the three types of GJs with a 29 ms exposure time. The brightness of the type I and the type II GJs is clearly distinct. The average brightness of the type I GJs is 0.47 \pm

0.13 MR over 29 ms exposure time and that for the type II GJs is 0.14 \pm 0.07 MR. Thus the mean brightness ratio between them is about 3.4. The N₂1P brightness of the type III GJs generally falls between that of the other two types. The average brightness of type III GJs is 0.19 \pm 0.11 MR over 29 ms exposure time.

[19] The leader at the base of a GJ is a good conductor which transmits the voltage from thundercloud to the leader head. The strength of the electric field in the region between the leader tip and the ionosphere plate depends on the leader voltage; higher voltage leaders will produce stronger background electric fields to enable the propagation of streamers. The conductivity of a streamer channel is low and thus a voltage drop builds up across the channel. For a uniform streamer, a higher leader voltage will result in a greater potential at the streamer heads. The streamer head potential is proportional to the product of the electric field of the streamer head and the radius of the charged sphere [Bazelyan and Raizer, 2000, p. 36; Liu and Pasko, 2004; Liu et al., 2009]. Modeling results reported by Liu and Pasko [2004] and Liu et al. [2009] confirm a linear relationship between the streamer head potential and the streamer radius. In addition, the strength of the peak electric field at the streamer head increases with the applied electric field [Liu and Pasko, 2004, Table 3]. A higher leader voltage would induce a higher background electric field, which causes both the radius and the electric field at the streamer head to increase. A larger streamer radius would lead to a larger emission volume and thus a brighter emission. A higher electric field near the streamer head would also produce brighter emissions [Kuo et al., 2005], since the excitation rate and the electron number density are monotonically increasing functions of the reduced electric field (E/N), where E is the magnitude of the electric field and N is air number density; E/N is in units of Td and 1 Td is 10^{-21} V-m²) and the air density is assumed to vary in the same way for each type of GJs. Therefore the higher applied electric field will induce a brighter emission at the streamer zone of the GJs between 50 and 90 km altitudes.

[20] From experiments and theoretical calculations, the minimum electric field needed for the propagation of positive streamers in air at ground pressure is known to be ~4.4 kV/ cm, whereas for the negative streamers the field is $\sim 12.5 \text{ kV}/$ cm that is about 2–3 times greater than that of the positive streamers [Pasko, 2006, p. 261, and references therein]. And from similarity laws [Raizer, 1997, p. 11], although the air density decreases with increasing altitudes, the reduced electric field remains constant throughout. In the point-toplate electrode discharge experiment at different voltages and different polarities [Briels et al., 2008, Figure 2], the positive streamers can develop at a lower voltage than the negative streamers. Also comparing both polarity discharges performed at the same voltage, the positive discharge contains more branching structures and are easier to propagate to the plate electrode. These results consist with the negative spritehalo observation reported by Taylor et al. [2008]; the negative sprite has a relatively short vertical extent and small expansion and is dimmer than the positive sprites with a similar charge moment change.

[21] Since most of the blue jets could not develop into GJs, we suspect that the background electric field set up by the leader of the type II GJs only exceeds the threshold propagation field just enough for this type of GJs to reach the lower



Figure 7. Image sequence and the spectrophotometer data for a probable GJ event on 11 January 2009 2143:57.015 UTC. This event occurred near the front edge of the imager FOV and the lower section is outside the FOV.

ionosphere. In the negative GJ model proposed by *Krehbiel et al.* [2008], the charge source of the type I GJ would be the main negative charge layer in the normal storm. The plentiful negative charge creates a high potential at the leader head, which create a large electric field in the region between the leader head and ionosphere to propagate the negative streamers. Since the average brightness of the type II GJs is ~ 3.4 times lower than that of the type I GJs, if the type II GJs are composed of positive streamers, that have lower threshold propagation fields and lower potentials at the leader heads, they would be consistent with the photometric properties reported in this paper.

[22] The brightness of the type III GJs falls between that for the type I and the type II GJs. It is conjectured that the type III GJs having brightness similar to the type II GJs could be +CI discharges, while those having brightness close to the type I GJs might have been -CI discharge events. Probably due to the influence of the preceding lightning, the spatial-temporal development and the spectral characteristics of the type III GJs differ significantly from the other two categories of gigantic jets.

6. A Probable Type II Gigantic Jet

[23] Figure 5b shows the ULF emission from a special event on 11 January 2009 2143:57.015 UTC with a distance of 10,400 km from the Duke sensor that is not included in the

set of the 20 GJs. Judging from the signal polarity, the special event is clearly having the +CI polarity. The image sequence and the spectrophotometer data for this event are shown in Figure 7. Morphologically, it looks like a carrot-like sprite with branching streamers in the head. This proximity event is 2200 km from the ISUAL/FORMOSAT-2 and its parent thunderstorm is outside the FOVs of the ISUAL sensors. Its spectral signals contain primarily blue emissions (SP2, SP3, and SP6) but differ somewhat from the three types of GJs. For ISUAL sprites with similar event distances, the strong emissions from the unseen causative lightning would reflect off the instrument baffles and produce significant readings in the ISUAL sensors, especially in the SP5 777.4 nm channel. While this mystic event shows no discernible lightning emissions near the trigger time, identifying this event as a negative sprite would be consistent with the polarity of the associated ULF emission. However, negative sprites are known to have bright accompanied halos [Barrington-Leigh and Inan, 1999; Taylor et al., 2008], while this event has none. Also the average brightness of the ISUAL near-edge carrot sprites is $\sim 1.99 \pm 0.95$ MR over 29 ms exposure time, which is much brighter than this 0.35 MR event, while the brightness of this event is similar to that of the 20 analyzed GJs. Consequently, this event cannot be a negative sprite but can be a GJ.

[24] The SP2 (337 nm) signal of this event reveals that there are four emission peaks during the second image frame. The

first peak has a sharp rise feature of a blue starter or a blue jets, though it cannot be discerned whether the slow-decaying feature exists due to the pileup of emissions from the other peaks. However, the SP3 to SP2 intensity ratio of the first peak is ~ 0.08 , which is a typical ratio for blue starters or blue jets. The third SP2 photometric peak of this frame has a small but clear associated peak in the SP1 far-UV channel. Since due to the atmospheric extinction, the TLE far-UV emissions detected by ISUAL are induced by the electron-impact processes near the lower ionosphere [Chang et al., 2010], and this indicates that the mystic event reached the ionosphere. If the first SP2 emission peak was from a blue jet and the third peak was from the fully developed jet stage of a GJ, the evolution of this event is similar to that of the type II GJs but with a faster propagation speed. Because the event is located partially outside the FOV of the ISUAL AP, signals usually used to discern the upward propagation and the downward return-stroke-like processes are not available. Nevertheless, the current evidences indicate that this special event is a probable type II GJ with +CI polarity.

7. Discussions

[25] Krehbiel et al. [2008] suggested that the charge reservoir of the negative (type I) GJs is the main negative charge in the midlevel of the cloud, and gigantic jets are initiated by the charge imbalance following the preceding ICs. They also predicted that there could be positive GJs in the inverted electrical structure for a decaying storm system. The main midlevel charge of such a storm is of positive polarity, while the heights of the charge distributions are similar to the normal storms. Having similar generating environment but with opposite polarity charge in the model, one would expect that the development of the positive GJs is similar to that of the negative GJs. Also the sferics of the positive GJs would be detected as perspicuously since the abundant charge reserve associated with the negative GJs is capable of driving large current. Since most of the type I GJs and the reported gigantic jets have clear sferics from the negative cloud-to-ionosphere discharges [Su et al., 2003; Kuo et al., 2009; Cummer et al., 2009], the normal polarity thunderstorms (positive-onnegative tripoles) would be the dominant variety.

[26] For positive blue jets (+BJs) from the normal thunderstorms [Krehbiel et al., 2008], the charge reservoir of the blue jets is the upper positive charge region. The cumulative preceding -CG lightning successively increase the net discharge in the storm and increases the potential and electric field near the upper level of the storm. When the local field exceeds the breakdown threshold electric field, the discharge occurs and then both the net charge and the E-field decrease. If these processes occur repeatedly, then the positive BJs will appear in succession. ISUAL often recorded blue starters and blue jets in the same region before and after the occurrence of the type II GJs. Therefore the energy and the charge of the +BJ charge reservoir may not accumulate high enough to initiate bright gigantic jets. The upper positive charge in a normal thundercloud is less than the main midlevel negative charge. This may be also another reason why the type II GJs are dimmer than the type I GJs. The minimum field needed for propagation of positive streamers is $\sim 2-3$ times lower than that of the negative streamers. Thus energetically, positive streamers would be easier to propagate than the negative

streamers. For the same in-cloud charge distribution and similar lightning occurrence, but with an inverted charge reserve, -BJ in an electrically inverted electrified storm would be harder to form and/or to develop into a GJ. However, if -BJs do form and develop into GJs, the streamers of these GJs would be brighter than those in the GJs developing from +BJs. Combing the facts that the type II GJs are \sim 3.4 times dimmer than the type I and the probable type II GJ has an associated +CI ULF sferics suggests that the type II GJs are from the upper positive streamers; also these discharges are from the same charge reservoir with the preceding and the trailing BJs.

[27] Kuo et al. [2009] proposed that the local ionosphere boundary could be located at a lower altitude of about 50 km because of the existence of the ionized discharge channel in the fully developed jet stage. Under such conditions, a return stroke-like process would start from the lowered ionosphere boundary and extend toward the cloud top, and the upward surging trailing jet stage would be the luminosity associated with the continuous current that moves charge from cloud upward along the existing conducting channel and persists for 100 ms and longer [Kuo et al., 2009; Cummer et al., 2009]. From the ISUAL AP data of type II GJs, there has appears to be no such in-cloud continuous current after the completion the discharge channel. This would be reasonably since the upper positive charge pocket near the cloud top may not have sufficient charge to supply the upward continuous current, even if the boundary of local ionosphere does drop down. Therefore the trailing jet of the type II GJs may not exist or too dim to be identifiable.

8. Conclusion

[28] From an analysis of 20 gigantic jets recorded by the ISUAL sensors on board the FORMOSAT-2 satellite, the observed GJs can be categorized into three types according to their morphological development and spectral properties. For the streamer region at ~50–90 km altitudes, the ISUAL imager-N₂1P brightness of these gigantic jets ranges from ~0.1 to ~0.7 MR over 29 ms exposure time. The type I GJs are the brightest among the trio with an average imager-N₂1P brightness of 0.47 \pm 0.13 MR. The average brightness of the type II GJs is 0.14 \pm 0.07 MR, which is about 3.4 times dimmer that that for the type I. The average imager-N₂1P brightness of the type III GJs is 0.19 \pm 0.11 MR, which falls between the other two types. For comparison, the typical ISUAL imager-N₂1P brightness for sprites is ~1.99 \pm 0.95 MR.

[29] The photometric evolution of the type I GJs exhibits a return-stroke-like process after the completion of the discharge channel to the ionosphere at the fully developed jet stage and is always followed by a trailing jet. Owing to the charge redistribution, the cloud is illuminated continuously throughout the fully developed jet and the trailing jet stages. ULF magnetic field data available for 5 of 8 observed type I GJs and show that these events have negative polarity and thus are -CI discharges.

[30] Morphologically, the type II GJ begin as a BJ then slowly develops into a GJ over many tens of ms. The corresponding GJ signals in the ISUAL SP and AP have low S/N ratios. We also noted that lower-altitude blue jets frequently occurred from the same region before and after the type II GJs. Thus the energy and the charge may not accumulate high enough to initiate a bright gigantic jet. The corresponding ULF signals for the type II GJs generally are too weak to render an unambiguous determination of the event polarities. However, current evidences suggest that a possible type II GJ event, which was not included the 20 detailed analyzed GJs, has a clear +CI ULF signature but with faster propagation speed than the typical type II GJs. Also from comparing the positive blue jets model and the negative blue jets model proposed by Krehbiel et al. [2008], and from the minimum field needed for the propagation of positive streamers is $\sim 2-3$ less than that of negative streamers, we concluded that the type II GJs might be composed of the positive streamers. Since the positive blue jet model assumes that the event charge reservoir is in the upper level of a normal thundercloud, and this can be explained naturally why the type II GJs might not have sufficient charge to supply the continuous current and thus have no clear trailing jets.

[31] The type III GJs appear to be triggered by lightning, which is very different from the other two types of GJs. Hence due to the lightning emission contaminations, the spectral features of the type III GJs are very different from those of the type I and type II GJs and cannot be compared. Also the ULF signal for the type III GJs was mingled with noises and lightning signals from other sources; hence the discharge polarity cannot be resolved. However, it is expected that the polarity of the type III GJs will depend on what kind of charge imbalance in the cloud was left by the preceding lightning and thus can either be -CI or +CI discharges.

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- H. U. Frey and S. B. Mende, Space Sciences Laboratory, University of California, Berkeley, CA 94720, USA.
- L. C. Lee, Institute of Space Science, National Central University, Jhongli, 32001 Taiwan.

J. Li and S. A. Cummer, Department of Electrical and Computer Engineering, Duke University, Durham, NC 27708, USA.

Y. Takahashi, Department of Cosmosciences, Hokkaido University, Sapporo, 060-0808, Japan.

A. B. Chen, Institute of Space, Astrophysical and Plasma Sciences, National Cheng Kung University, Tainan, 70701 Taiwan.

J. K. Chou, R. R. Hsu, C. L. Kuo, L. Y. Tsai, and H. T. Su, Department of Physics, National Cheng Kung University, Tainan, 70701 Taiwan. (rrhsu@energy.phys.ncku.edu.tw)