Beta-type stepped leader of elve-producing lightning

H. U. Frey,[1] S. B. Mende,[1] S. A. Cummer,[2] A. B. Chen,[3] R.-R. Hsu,[3] H.-T. Su,[3]
Y.-S. Chang,[4] T. Adachi,[5] H. Fukunishi,[5] and Y. Takahashi[5]

Received 29 March 2005; revised 8 May 2005; accepted 7 June 2005; published 15 July 2005.

[1] The Imager for Sprites and Upper Atmospheric Lightning (ISUAL) on the Taiwanese FORMOSAT-2 (formerly ROCSAT-2) spacecraft is the first global observatory of transient luminous events (TLEs). During the first 4 months of operation a large number of elves were observed. Elves are obvious with their far ultraviolet (FUV) signature that is less attenuated by atmospheric O_2 at their emission altitude compared to emission from sprites or lightning at lower altitude. About half of all elves were produced by lightning that shows a three-step signature in the photometer signal: (1) An initial brightening in all except the FUV channels, (2) a slow brightness decrease for the next 2–5 milliseconds, and (3) an impulsive increase of signal in all channels. We interpret this specific signature as the initial breakdown with a beta-type stepped leader followed by the bright return stroke of a negative cloud to ground (−CG) lightning. In contrast, sprites follow positive cloud to ground lightning (+CG) without a signature of initial breakdown and stepped leader. Many sprites are associated with the continuing current and can be delayed up to 100 ms after the lightning. **Citation:** Frey, H. U., S. B. Mende, S. A. Cummer, A. B. Chen, R.-R. Hsu, H.-T. Su, Y.-S. Chang, T. Adachi, H. Fukunishi, and Y. Takahashi (2005), Beta-type stepped leader of elve-producing lightning, *Geophys. Res. Lett.*, *32*, L13824, doi:10.1029/2005GL023080.

1. Introduction

[2] The Imager for Sprites and Upper Atmospheric Lightning (ISUAL) is the first instrument that is dedicated to observe transient luminous events (TLEs) from space in a global and long-term sense [*Chern et al.*, 2003]. The major goals are the observation of characteristics, occurrence frequency, and global distribution of TLEs and lightning. Additional tasks are the characterization of the spatial, temporal, and spectral properties of TLEs, especially in the far ultraviolet where observations from the ground are impossible due to atmospheric absorption.

[3] During the first 4 months of operation, ISUAL observed a surprising large number of elves. Elves are lightning-induced TLEs around 90 km altitude with a duration of less than 1 ms and a horizontal scale of 100–300 km [*Boeck et al.*, 1992; *Fukunishi et al.*, 1996]. The rapid lateral expansion of the elve is consistent with a model in which elves are produced as a result of electron heating by the electromagnetic pulse (EMP) from a lightning discharge [*Inan et al.*, 1996, 1997]. The upward traveling EMP heats ionospheric electrons at 90–95 km that in turn can excite and ionize ionospheric atoms and molecules [*Inan et al.*, 1991]. The physics of elves is generally well explained by the model. However, there are still open questions about the number of elves that are on average created and their importance for the total nighttime ionization of the lower ionosphere [*Inan et al.*, 1991; S. B. Mende et al., D region ionization by lightning induced EMP, submitted to Journal of Geophysical Research, 2005]. In addition, the properties of the parent lightning should be investigated. We distinguish between negative cloud to ground (−CG) and positive (+CG) lightning on the basis of the polarity of the charge that is lowered to the ground [*Rakov and Uman*, 2003]. Almost all sprites were so far described as initiated by +CG [*Boccippio et al.*, 1995; *Lyons et al.*, 2003]. In contrast, elves can be initiated by both +CG and −CG [*Barrington-Leigh and Inan*, 1999]. One goal of ISUAL is to combine space- and ground-based observations in order to find out why not every lightning stoke creates an elve or sprite. This paper will address this question by showing a specific group of lightning that is likely to create an elve, in contrast to lightning strokes that create sprites.

2. Instrumentation and Data Analysis

[4] ISUAL observes a limb-area of about 1100 km in latitude and 900 km in longitude before midnight local time. It consists of an image intensified CCD camera with a filter wheel, a six-channel Spectrophotometer (SP), and a two-channel Array Photometer (AP). Only images with the N_2-1P filter (633–751 nm) are used in this study. All instruments cover approximately the same field of view of 20° × 5°. The photometers of the SP integrate over the field of view. The AP contains 16 vertically stacked anodes over 3.6° that integrate horizontally, but distinguish the altitude profile in about 10 km steps at 2500 km distance. The AP has two channels in the red (N_2 1P) and blue (N_2 2P) part of the visible spectrum. The six SP channels and major TLE emissions in their pass bands are:

[5] 1. 150–290 nm, N_2 LBH

[6] 2. 333–341 nm, N_2 2P (0–0)

[7] 3. 387–394 nm, N_2^+ 1N (0–0)

[8] 4. 609–753 nm, N_2 1P and N_2^+ Meinel

[9] 5. 774–785 nm, OI

[10] 6. 228–410 nm, N_2 2P and N_2^+ 1N

[11] ISUAL runs continuously, but data collection only happens in a burst mode when pre-programmed trigger criteria are met. These criteria were changed many times during the first months of operation and may thus impose some selection on the recorded data. Most notably, only

[1]Space Sciences Laboratory, University of California, Berkeley, California, USA.
[2]EE Department, Duke University, Durham, North Carolina, USA.
[3]Physics, National Cheng Kung University, Tainan, Taiwan.
[4]NSPO, Hsinchu, Taiwan.
[5]Geophysics Department, Tohoku University, Sendai, Japan.

0094-8276/05/2005GL023080$05.00

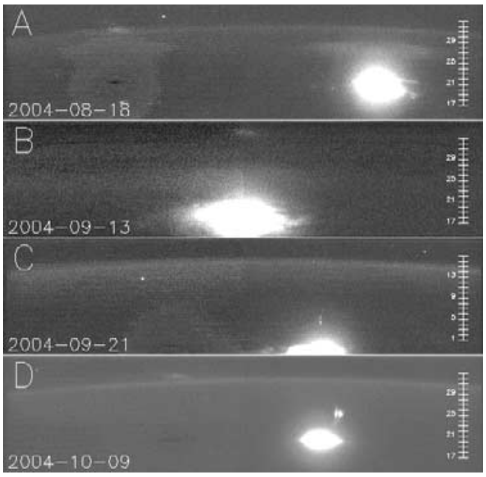

Figure 1. Examples of images with lightning and elve (A + B) and lightning followed by a sprite (C + D). The scale in the images indicates the pointing of the AP channels. Slightly brighter areas diagonally opposite to the bright lightning are caused by reflections within the imager and should be ignored.

bright events were recorded. Therefore, the ISUAL data may not be a statistically representative sample of all lightning and TLEs. All further given percentages have therefore to be considered with some care.

[12] During July-October 2004 Duke University operated a set of sensors in the VLF/ELF (50 Hz–30 kHz) range. The sensors recorded the azimuthal and radial components of the radiated magnetic field and allow for a determination of the polarity and arrival direction of lightning. In order to correlate the VLF signal with the ISUAL observations the VLF signal was shifted in time to account for the travel delay and a systematic 20–25 ms mismatch with the ISUAL time. The reason for this mismatch is most likely a problem with the ISUAL internal clock.

3. Observations

[13] Figure 1 shows representative examples of lightning with an elve and lightning with a sprite. The airglow layer, most likely OH at 90 km altitude, is barely visible. The hard Earth limb is located at approximately the center of the frames. We classify these TLEs as elves because of their fast brightening after the lightning and their expansion signature in the AP channels in contrast to time-delayed halos at lower altitude [*Bering et al.*, 2004].

[14] Figure 2 shows the photometer observation on August 18, 2004. All photometers except the FUV channel show an increased signal about 3 ms before the sharp increase at 67 ms. After the initial increase the signal slowly decreases, but does not return to the pre-event level. This kind of three-step process (initial brightening, slow brightness decrease, strong brightening in all channels) is the characteristic of a large group of lightning signatures that were accompanied by an elve. Two selected AP traces are added in the lowest panels. The lowest channel (Ch-21) tracks the brightness at the lightning altitude and shows the three-step feature. The other channel (Ch-28) tracks the brightness at the elve altitude and does not show a similar feature. The azimuthal component of the radiated magnetic field (third panel from bottom) shows a typical strong pulse at the time of the return stroke. But it also shows a broadband burst composed of a series of individual pulses that begins 3 ms before the return stroke and that occurs at the same time as the initial brightening seen by the photometers.

[15] One more example is given in Figure 3 corresponding to the image in Figure 1b. Here again we see the three-step signature in all except the FUV channel and the high altitude AP trace. The VLF data also show the variation of the magnetic field at the main lightning preceded in this case by the variations 4 ms earlier. In both cases the VLF data (2200 km range) confirm −CGs with charge moment changes of 91 C km and 184 C km, respectively.

[16] Of all 593 elves that were observed between July and November 2004, 294 or almost 50% showed the three-step signature in the photometer traces. When we analyzed the 3231 lightning records that were recorded in August and September only, we found 161 (5%) of them showed the three-step signature. Only 84 of the 161 lightning records (52%) were followed by an elve, though. However, this may be a sensitivity issue. We required for elve identification an indication of the elve in the image, and an obvious high-altitude signature in the AP data. If the elve was not bright enough, the lightning could have shown the three-step

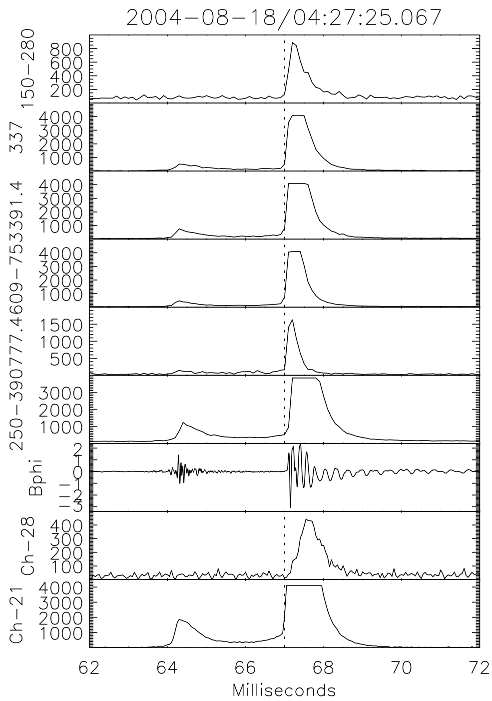

Figure 2. Photometer observations during the elve observed on August 18, 2004 (Figure 1a). The top six panels show the SP data in instrument counts with their pass bands. The following panel gives the azimuthal (Bphi) component of the VLF radiated magnetic field. The bottom two panels give two selected AP-channels with Ch-21 centered at the low-altitude lightning, and Ch-28 centered at the high altitude elve.

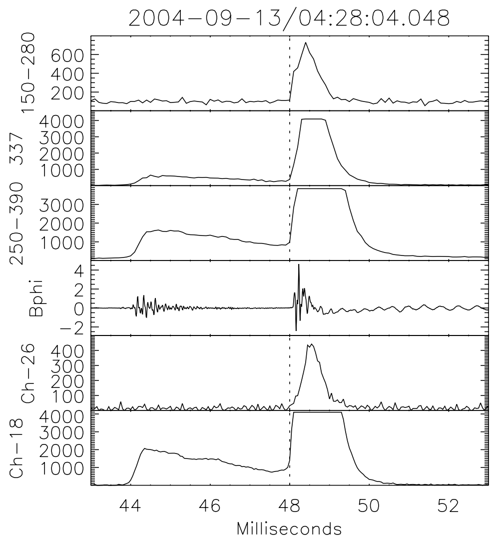

Figure 3. Same as Figure 2 for the elve observation on September 13, 2004 (Figure 1b) with only 3 SP channels.

signature, but the elve signature in the image and AP may have been too weak for a positive identification.

[17] The other approximately half of lightning with an elve (299 of 593) do not show the three-step feature. There is only the sharp increase in output signal from all SP channels simultaneously. We don't show an example because of space limitations.

[18] The lightning that produced the sprites in Figures 1c and 1d shows a totally different behavior. There is no signature of the three-step process before the lightning (Figure 4a). From a dark background level all photometer signals increased at the same time as the main lightning stroke. The VLF data (2600 km range) also do not show the preliminary variation and they identify the lightning as a +CG with an impulsive charge moment change of 115 C km in the first 2 ms. After the lightning the brightness of the emissions did not drop to the pre-lightning level within 1–2 ms. Instead, the brightness first decreased for about 10 ms, but steadily increased again over the following 30 milliseconds, except for the FUV channel and the high altitude AP channel. The sprite was detected in the image that was recorded 36–66 milliseconds after the lightning.

[19] In the other case (Figures 1d and 4b) the sprite was even longer delayed from the lightning by 85 milliseconds. VLF data for this event is not available. The SP and AP traces show again the major lightning without the preceding brightness, and the long lasting signal in all SP channels except the FUV channel. In this case, the brightness of the sprite was sufficient to create a signal in the high-altitude AP channel (Ch-24) and even a weak signal in the FUV.

4. Discussion

[20] Several processes comprise a full −CG lightning stroke [*Rakov and Uman*, 2003]. Following the initial breakdown the stepped leader propagates toward the ground. During the attachment process, a streamer from the ground connects to it, and initiates the upward propagating return stroke. Stepped leaders are organized in two groups, alpha-type and beta-type. The average speed of the alpha-type stepped leader is 2×10^5 m/s which gives an average delay of about 20 ms between the initial breakdown and the return stroke. The speed of beta-type stepped leaders is much larger, of the order of 1×10^6 m/s which reduces the time delay to about 2–5 milliseconds. The alpha-type stepped leaders are more frequent (55–70%), while the beta-type leaders are optically brighter [*Rakov and Uman*, 2003].

[21] Our observations of the three-step process for the elve initiation is consistent with the beta-type stepped leader, and is not with the alpha-type. The time delay of only 3–4 ms is a characteristic of the high speed of the beta-type stepped leader. Also their much greater brightness may explain the considerable signal in the photometers from the initial breakdown and the stepped leader until the huge brightness of the return stroke. In contrast to −CGs, positive +CGs generally do not show an initial breakdown and a stepped leader but are rather preceded by a continuously moving positive leader [*Rakov and Uman*, 2003]. Therefore, our beta-type scenario is only valid for −CG and may indicate, that all our elves that were initiated by a lightning with a three-step photometer signature may have been created by −CG strokes. We want to note that *Heavner et al.* [2002] reported unusually fast stepped leaders that

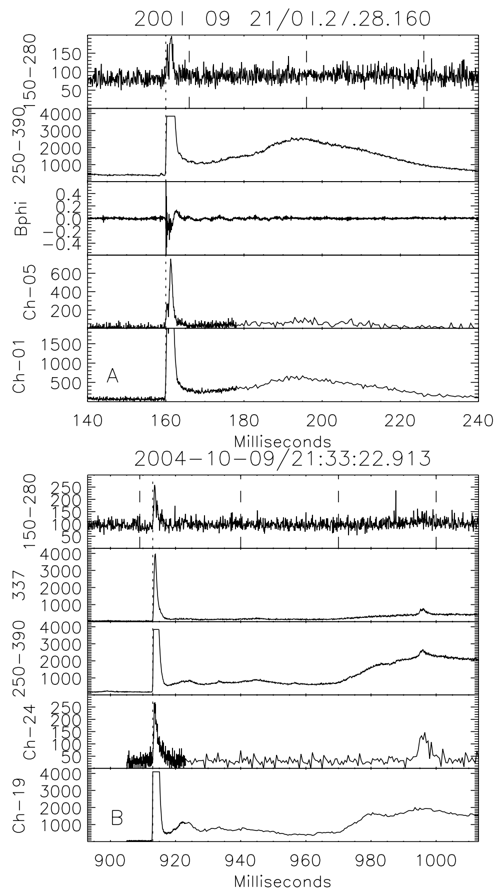

Figure 4. Same as Figure 3 for the sprite observation on September 21, 2004 (A) and on October 9, 2004 (B). There are no VLF data for this event.

preceded the return stroke by less than 6 ms. These could have been beta-type stepped leaders.

[22] The large portion (≈50%) of beta-type stepped leaders that were followed by an elve may be explained by a more efficient ionization compared to the alpha-type. If the brighter and faster beta-type stepped leader is capable of a more efficient ionization in the lightning channel, the following return stroke will be accompanied by a stronger current and a more powerful EMP, which in turn is capable of efficient elve production.

[23] It could be argued, that only the brightest lightning flashes create elves, are accompanied by bright stepped leaders, and are therefore more likely to show the three-step signature. We investigated all bright lightning strokes of September 2004 taking the brightness of the OI 777.4 nm line as an indicator of the peak current that may flow during the return stroke. Of the 138 brightest lightning strokes, only 16% also created an elve. This criterion is therefore not sufficient to classify the likelihood of an elve creation compared to the 50% likelihood if there is an obvious three-step signature.

[24] Positive cloud to ground lightning is much less frequent (only 10%) than −CGs. Almost all sprites were so far described as initiated by +CG [*Boccippio et al.*, 1995; *Lyons et al.*, 2003]. One of our examples is certainly, the other one likely, initiated by a +CG. Therefore, we don't see any signature of the preliminary breakdown, as this process does not happen in +CG. Furthermore, +CG often show a long continuing current which is responsible for the long lasting signal in our photometer tubes [*Rust et al.*, 1981, 1985]. The continuing current has been demonstrated as a possible mechanism of sprite initiation with long time delays [*Cummer and Füllekrug*, 2001].

[25] Both elves were created over salt water, and both sprites were created over land. This is consistent with a previous report of more elves over water [*Lyons et al.*, 1998]. The statistical significance of our preliminary result will be investigated in future work. It will also include VLF data to determine if the lightning without three-step signature is −CG with a dim alpha-type stepped leader or possibly +CG.

5. Conclusions

[26] About half of all elves in the ISUAL data were created by lightning with a three-step brightness signature in the photometer data. The brightness and the time delay fit the description of the initial breakdown and beta-type stepped leader of −CG [*Rakov and Uman*, 2003]. Given the much lower likelihood of beta-type stepped leaders compared to the alpha-type, they seem to be more efficient in producing a lightning stroke that creates an elve. The occurrence or absence of an initial breakdown and stepped-leader signature in photometer data may therefore indicate the most likely lightning polarity. If the other half of elves were created by +CGs or by dimmer −CGs with an alpha-type stepped leader will be further investigated.

[27] It is not surprising that sprite producing lightning does not show the three-step signature since those stokes have a +CG positive polarity. However, +CG tend to create long continuing currents that are very effective in producing a sprite with time delays up to 100 ms after the return stroke.

[28] **Acknowledgments.** S.A.C.'s contribution was supported by NSF Physical Meteorology Program Grant ATM-0221968. This work was supported by research grant 93-NSPO(B)-ISUAL-FA09-01.

References

Barrington-Leigh, C. P., and U. S. Inan (1999), Elves triggered by positive and negative lightning discharges, *Geophys. Res. Lett.*, *26*, 683.
Bering, E. A., et al. (2004), Observations of transient luminous events (TLE) associated with negative cloud to ground (−CG) lightning strokes, *Geophys. Res. Lett.*, *31*, L05104, doi:10.1029/2003GL018659.
Boccippio, D., et al. (1995), Sprites, ELF transients, and positive ground strokes, *Science*, *269*, 1088.
Boeck, W. L., et al. (1992), Lightning induced brightening in the airglow layer, *Geophys. Res. Lett.*, *19*, 99.
Chern, J. L., et al. (2003), Global survey of upper atmospheric transient luminous events on the ROCSAT-2 satellite, *J. Atmos. Sol. Terr. Phys.*, *65*, 647.
Cummer, S. A., and M. Füllekrug (2001), Unusually intense continuing current in lightning produces delayed mesospheric breakdown, *Geophys. Res. Lett.*, *28*, 495.
Fukunishi, H., et al. (1996), Elves: Lightning-induced transient luminous events in the lower ionosphere, *Geophys. Res. Lett.*, *23*, 2157.
Heavner, M. J., D. A. Smith, A. R. Jacobson, and R. J. Sheldon (2002), LF/VLF and VHF lightning fast-stepped leader observations, *J. Geophys. Res.*, *107*(D24), 4791, doi:10.1029/2001JD001290.
Inan, U. S., T. F. Bell, and J. V. Rodriguez (1991), Heating and ionization of the lower ionosphere by lightning, *Geophys. Res. Lett.*, *18*, 705.
Inan, U. S., W. A. Sampson, and Y. N. Taranenko (1996), Space-time structure of optical flashes and ionization changes produced by lightning-EMP, *Geophys. Res. Lett.*, *23*, 133.
Inan, U. S., et al. (1997), Rapid lateral expansion of optical luminosity in lightning-induced ionospheric flashes referred to as elves, *Geophys. Res. Lett.*, *24*, 583.
Lyons, W. A., M. Uliasz, and T. E. Nelson (1998), Large peak current cloud-to-ground lightning flashes during the summer months in the contiguous United States, *Mon. Weather Rev.*, *126*, 2217.
Lyons, W. A., et al. (2003), Characteristics of sprite-producing positive cloud-to-ground lightning during the 19 July 2000 STEPS mesoscale convective systems, *Mon. Weather Rev.*, *131*, 2417.
Rakov, V. A., and M. A. Uman (2003), *Lightning*, Cambridge Univ. Press, New York.
Rust, W. D., D. R. MacGorman, and R. T. Arnold (1981), Positive cloud to ground lightning flashes in severe storms, *Geophys. Res. Lett.*, *8*, 791.
Rust, W. D., D. R. MacGorman, and W. L. Taylor (1985), Photographic verification of continuing current in positive cloud-to-ground flashes, *J. Geophys. Res.*, *90*, 6144.

T. Adachi, H. Fukunishi, and Y. Takahashi, Department of Geophysics, Tohoku University, Sendai, Miyagi, 980-8578, Japan.
Y.-S. Chang, National Space Program Office, Hsinchu, Taiwan.
A. B. Chen, R.-R. Hsu, and H.-T. Su, Department of Physics, National Cheng Kung University, Tainan 70101, Taiwan.
S. A. Cummer, EE Department, Duke University, Durham, NC 27708, USA.
H. U. Frey and S. B. Mende, Space Sciences Laboratory, University of California, Berkeley, CA 94720, USA. (hfrey@ssl.berkeley.edu)