Long-delayed bright dancing sprite with large Horizontal displacement from its parent flash

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\textbf{Abstract}

We reported in this paper the observation of a very bright long-delayed dancing sprite with distinct horizontal displacement from its parent stroke. The dancing sprite lasted only 60 ms, and the morphology consisted of three fields with two slim dim sprite elements in the first two fields and a very bright large element in the third field, different from other observations where the dancing sprites usually contained multiple elements over a longer time interval, and the sprite shape and brightness in the video field are often similar to the previous fields. The bright sprite was displaced at least 38 km from its parent cloud-to-ground (CG) stroke and occurred over comparatively higher cloud top region. The parent flash of this compact dancing sprite was of positive polarity, with only one return stroke (approximately $+24$ kA) and obvious continuing current process, and the charge moment change of stroke was small (barely above the threshold for sprite production). All the sprite elements occurred during the continuing current stage, and the bright long-delayed sprite element induced a considerable current pulse. The dancing feature of this sprite may be linked to the electrical charge structure, dynamics and microphysics of parent storm, and the inferred development of parent CG flash was consistent with previous very high-frequency (VHF) observations of lightning in the same region.

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1. Introduction

Transient luminous events (TLEs) are brief light emissions that could be observed over both summer and winter thunderstorms (Lyons, 1996). So far, the known types of TLEs include sprite, elves (Emissions of Light and VLF perturbation due to EMP Sources), halos, blue jet/blue starter, and gigantic jet. Among the TLE family, sprites are most commonly observed in ground-based observations, and most sprites fall into the shape of column or carrot. In addition to columniform or carrot-shape sprites, dancing sprites (Lyons, 1994, 1996; Winckler et al., 1996; Hardman et al., 2000) were occasionally documented. An obvious feature of dancing sprites is that sequential sprite elements often appear horizontally displaced from the preceding elements and the location of the sprite cluster center changed. Since dancing sprites jump above the storm, they can span a large horizontal distance, and the events in some observations even reach up to 200 km (e.g., Lyons, 1996; Winckler et al., 1996).

Early observations of dancing sprites have been reported by Lyons (1994, 1996), Winckler et al. (1996) and Hardman et al. (2000). Recently, the comprehensive analysis of several dancing sprites in the central United States have been reported by Lu et al. (2013), and the results show that dancing events associated with a single flash could be produced either by distinct cloud-to-ground (CG) strokes of the flash, by a single CG stroke through a series of current surges superposed on an intense continuing current, or by both; the displacement of sprite element from the parent stroke is because of that the charge removed by individual strokes is often from a displaced cloud region. It has also been suggested that the horizontal displacement could be connected to the local plasma inhomogeneity in the lower ionosphere (Qin et al., 2014). Nevertheless, in comparison with tens of thousands of columniform or
carrot-shape sprites that have been documented (e.g., Lyons et al., 2003; Lu et al., 2013), dancing sprites are relatively infrequent although they might act as a unique agent to study the electrodynamic coupling between troposphere and mesosphere. In this paper, an unusual dancing sprite was fortunately captured in north China, and the detailed comprehensive analysis of the parent storm and associated lightning activity is reported by using multidisciplinary data from Doppler radar, lightning location network, and ultra-low frequency (ULF) magnetic field sensor. Relationship between sprite dancing property and storm characteristics, parent CG discharge process is examined.

2. Observations and data

In order to investigate the TLEs and their parent storms and lightning discharges, TLEs observation has been conducted in mainland China since 2007 (Yang et al., 2008). In 2012, another TLE station was installed in Dongying, Shandong province. The camera used in this station is a Watiec 902H2 Supreme low-light-level video camera (equipped with a Computar 12-mm/F0.8 lens) with minimum illumination of 0.0003 lx. The observation system can record the static images at a rate of 25 frames/s. Two kinds of lightning location networks are used to provide lightning characteristics. One was provided by Shandong Province Lightning Detection Network, which consists of 10 very low-frequency/low-frequency sensors and one data processing center, and uses the combined time-of-arrival (TOA) and magnetic-direction-finding (MDF) technology (e.g., Cummins et al., 1998). Data from this network were used for characterizing the lightning activity in the storm of particular interest. Additional lightning data are obtained from the World Wide Lightning Location Network (WWLLN), which were used for real time locating the center of electrical activity and for determining the pointing azimuth of camera.

In addition to lightning location networks, the magnetic field data obtained at Lulin Observatory have been used to identify the polarity of parent lightning. The magnetic ultra-low frequency (ULF) station (0.3–500 Hz) of National Cheng Kung University (NCKU) is located at the Lulin Observatory, which is on the central mountain ridge of Taiwan. The system consists of a pair of EMI-BF4 magnetic induction coils to record the horizontal magnetic field emitted by the source discharges (Lee et al., 2012). The coil orientations are parallel and perpendicular to the geomagnetic field. The recorded signals can be used to infer the polarity of lightning discharges, the vertical current moment and the time-integrated charge moment change (CMC) of TLEs and lightning (Huang et al., 2011). The thunderstorm evolution and structure are given by Doppler radar data. The radar has two scanning ranges, 230 and 460 km (a resolution of 1 km is obtained with a scanning range of 230 km). The radar image is updated every 6 min.

3. Results

3.1. Features of dancing sprite

During the storm evolution, a total of three sprites have been captured. The first two sprites were recorded at 00:23:24 (it was a negative one and will be reported in another study) and 00:27:33 on 5 August 2012 (Beijing time). The third sprite occurred at about 01:21:33, almost one hour after the first two sprites; this sprite includes three fields and its first two fields were very dim elements (as shown in Fig. 1a and b), but the third field was very bright (shown in Fig. 1c) and displaced horizontally from first two elements. This sprite morphology was defined as dancing events by Lyons (1996) and Hardman et al. (2000).

The dancing sprite in this paper was unusual in several aspects. It lasted three fields and the total duration was only about 60 ms, much shorter than that (about 200 ms) reported by Hardman et al. (2000). This dancing event consisted only three elements, less than results obtained by Lu et al. (2013), and even less than the cases (sprite may contain > 30 elements) reported in Hardman et al. (2000). The dancing sprite analyzed in detail by Hardman et al. (2000) consisted of at least > 10 elements. On the other hand, the shape and brightness of preceding sprite elements in Fig. 1a and b are substantially different from that shown in Fig. 1c. However, the dancing sprite elements in previous studies usually have similar shape and brightness, as shown by an example in Fig. 9 of Hardman et al. (2000), which is different from the case reported in this study. Sprite elements in Fig. 1a and b did not change their location during evolution. The bright sprite in Fig. 1c was clearly displaced from two previous fields and was much brighter and closer to the observation site.

The parent CG for the dancing event was unambiguously registered by both of the local lightning location networks and ULF magnetic field sensor at Lulin Observatory (23.4686°N, 120.8736°E). The parent CG location, obtained by local lightning location network, was about 38.33°N, 117.50°E, almost north of the magnetic field sensor. The distance between the parent CG and the observation site was only about 145 km, and the image shows that a large portion of the dancing event was not captured by the camera. In addition, the bright sprite occurred at least 38 km away from its parent flash. The horizontal displacement between the bright sprite and the parent CG would be 43 and 90 km, respectively, assuming that the sprite occurred at the two ends (intersections between Lines L1, L2 and sprite azimuth shown in Fig. 2a) along the sprite azimuth. On the other hand, since there is only one station in the observation, and the dancing event could not be triangulated, the horizontal displacement between the bright element and its adjacent dim element would be at least 6 km based on the 2D image. It should be noted that the actual displacement may be larger than 6 km in three dimension.

Fig. 1. Sequential images of the dancing sprite recorded on the early morning of 5 August 2012.
3.2. Relationship between storm structure and dancing sprite

In this section, the relationship between the thunderstorm structure and the dancing sprite will be investigated. The sprite-producing storm was a squall line and lasted more than ten hours. The parent storm developed at 15:00 on 4 August, moving from southeast to northwest, with strong convective cells weakened and new small cells developed. No sprites were recorded until in the early morning on 5 August, two sprites were recorded at 00:23 and 00:27. The bright dancing sprite analyzed in this paper occurred at 01:25, almost an hour later after the first two sprites.

In order to demonstrate the storm structure and lightning activity clearly around the dancing sprite moment, the overlap of radar reflectivity with CG flashes within ten minutes centered around the time shown in each figure is shown in Fig. 2a. The red “+” stands for positive CGs, and black “−” for negative CGs. Fig. 2b is the enlarged region of the most interested area. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

The positive CGs located in the large stratiform region with radar reflectivity of 20–35 dBZ, consistent with observations of Lyons et al. (2003) and van der Velde et al. (2006). Fig. 2b shows the most interested region over which the dancing sprite occurred, and the sprite azimuth is also overlapped. The +CG occurring farther to the sprite azimuth was the parent CG for the dancing sprite, and its return stroke peak current was about 24 kA. Fig. 2b more clearly shows the large stratiform region around the dancing sprite moment, especially the region with radar reflectivity of 20–35 dBZ, showing a typical characteristics of sprite-producing storms.

Vertical cross section along line AB (passing through parent CG, almost the sprite jumping direction) is shown in Fig. 2c, and parent CG and sprite elements azimuth were also indicated. It shows that the positive charge of parent CG may locate around 6 km storm region. The bright dancing sprite occurred over storm region with higher cloud top (about 11 km) than that of the first two dim elements, indicating that the altitude of the source charge for the dancing sprite may be higher. Why is this? A concept model of the discharge process of parent CG is shown in Fig. 2d, indicating that positive leaders (red line branch with source charge region) developed toward the ground and then a return stroke initiated. Based on the bidirectional leader of lightning propagation, another branch (blue line in Fig. 2d) would go upward to a higher storm region (the higher, the smaller particles). Then advection of snow particles along the sloping lightning pathway initiated, and induced a continuing current (all sprite elements occurred during this time period, see next section) (Carey et al., 2005). The concept model of tripole charge structure was consistent with VHF observation (SAFIR3000) (Liu et al., 2013),
3.3. Lightning activity analysis of the sprite-producing storm

The parent lightning flash for the dancing event was detected by both of the local lightning location network and ULF magnetic field sensor at Lulin Observatory (WWLLN did not detect the parent flash). The parent flash was considered by both of the lightning sensors as one single stroke positive CG. In order to further investigate the parent flash characteristics, the ULF magnetic field (predominated by the east–west component because the sprite-producing stroke was nearly due north of Lulin Observatory) recorded at a distance of 1653 km at Lulin Observatory has been used and the results are shown in Fig. 3. Because the parent stroke of this sprite event was almost due north of the magnetic sensor at Lulin Observatory, and therefore we only present the analyses of associated magnetic deflection in east–west direction.

As shown in Fig. 3a, the main stroke generated a 2-ms magnetic pulse that peaks at about 0.58 nT, which is equivalent to an impulse charge moment change of $+240 \, \text{C km}$ using the de-convolution method described by Lu et al. (2012), roughly the threshold for the sprite production by parent CG strokes (Huang et al., 1999). The low-passed filtered waveform (with cut-off frequency of 100 Hz), as shown in Fig. 3b, further indicates the presence of a long continuing current (with duration of about 120 ms) following the sprite-producing stroke, as well as an enhancement that is most likely attributed to the current flowing in the body of a bright sprite element (Cummer et al., 1998; Pasko et al., 1998). All sprite elements occurred during the continuing current period.

The lightning activity of sprite-producing storms could be characterized by some distinct features, such as a reduced rate of negative CG flashes while the positive CG increases during the sprite time period (Soula et al., 2009; Yang et al., 2013). In order to see the lightning characteristics most relevant to sprite production, the flash evolution in the storm area shown in Fig. 2b is analyzed specifically and the result is shown in Fig. 4a. The grouping algorithm used here is 0.5 s and 10 km, respectively. Fig. 4a indicates that sprite at 01:21 occurred at the time with overall trend of decreasing negative CG rate and increasing positive CG rate. As a matter of fact, the negative CGs reached a discernible valley at 01:20 just before the sprite at 01:21.

Since the grouping algorithm used above may be subject to some uncertainty, the return strokes are analyzed in detailed. The results show that only 23 positive CGs were found in addition to 2661 negative strokes, which indicates the overwhelming dominance of negative CGs. The peak current of most positive strokes ranged between 10 and 30 kA (Fig. 4b), and the mean value was about 29 kA. Analysis also indicates that peak current of $-40$ to $-50$ kA negative return strokes accounted for more than half (56%) of the total negative return strokes during the sprite time period (Fig. 4c), and the maximum negative CG peak current was only about $-60$ kA. Detailed analyses on sprites and parent lightning strokes by Lu et al. (2013) showed that most sprite-producing strokes had peak current larger than $60$ kA with the maximum about $274$ kA, indicating the maximum peak current of $60$ kA in the parent storm of dancing sprite in this study was relatively weak and this storm was not as energetic as the mesospheric convective systems prevailing in the middle-western United States. The maximum peak current of negative CGs is this study is also $-60$ kA, which was much smaller than that ($-120$ to $-218$ kA) reported in Li et al. (2012). The discussions above indicated that peak current of CGs in this study was weak, and the continuing current played a critical role in the formation of dancing sprite.

4. Conclusion

Three sprites have been obtained during the observation night in the early morning on 5 August 2012, and one of them is an unusual dancing event. The dancing event has been analyzed in detail by using multiple data including optical images, Doppler radar reflectivity, lightning location network and ULF magnetic
field data. The dancing sprite consisted of three elements with two dim elements in the first two fields, but a very bright element displaced horizontally from the preceding fields occurred in the third field. The horizontal displacement between the bright sprite element and the adjacent dim one was estimated to be at least 6 km, and the bright element occurred over higher cloud top region. Both of the dancing sprite morphology and duration were different from previous observations. The parent storm was a summer squall line and lasted more than ten hours showing a typical characteristics of sprite-producing storms.

The dancing sprite had a displacement at least 38 km from its parent flash, and the displacement would be even larger considering the sprite location uncertainty. The ULF magnetic field data indicate that the parent flash for the dancing event was a positive CG, with only one return stroke, which is different from the dancing sprites in Lu et al. (2013). The charge moment change of the parent CG return stroke was about 240 C m, roughly the threshold for sprite production. All of the sprite elements in the dancing event were produced during the parent CG continuing current process. Analysis of the low-passed magnetic field waveform indicates that the enhancement during the continuing current is most likely attributed to the current flowing in the body of the bright sprite element. The sprite dancing features may be linked to the electrical charge structure, dynamics, and microphysics of parent storm, and the inferred development of parent CG flash was consistent with previous VHF observations of lightning in the same region (Liu et al., 2013). It has also been suggested that the horizontal displacement may also be related with the local plasma inhomogeneity in the upper atmosphere (Qin et al., 2014), in which the solid evidence has been found from the connection between pre-existing plasma irregularities and sprite streamer initiation in the D-region. Therefore, it is desired that the future study of physical connection between sprites and parent lightning flashes should incorporate the complementary observations of plasma structure in the lower ionosphere.

The parent lightning for the dancing event was a positive cloud-to-ground flash with only one return stroke, and the peak current about 24 kA. The positive peak current during sprite period mostly ranged between 10 and 30 kA. The lightning evolution shows that the positive CGs flash rate during the sprite time period was similar to previous results reported by Yang et al. (2013); however, the negative CG flash rate was almost 10 times larger, leading to a very low POP, although POP was usually high during sprite time period.

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