Triangulation of red sprites observed above a mesoscale convective system in North China

YongPing Wang1, GaoPeng Lu2,3,4*, Ming Ma1, HongBo Zhang2, YanFeng Fan5, GuoJin Liu1, ZheRun Wan1, Yu Wang6, Kang-Ming Peng7, ChangZhi Peng1, FeiFan Liu1, BaoYou Zhu1, BinBin Ni8, XuDong Gu8, Long Chen8, Juan Yi8, and RuoXian Zhou8

1University of Science and Technology of China, School of Earth and Space Science, Hefei 230026, China; 2Key Laboratory of Middle Atmosphere and Global Environment Observation (LAGEO), Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing 100029, China; 3Collaborative Innovation Center on Forecast and Evaluation of Meteorological Disasters, Nanjing University of Information Science and Technology, Nanjing 210044, China; 4State Key Laboratory of Numerical Modeling for Atmospheric Sciences and Geophysical Fluid Dynamics (LASG), Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing 100029, China; 5State Key Laboratory of Severe Weather, Chinese Academy of Meteorological Sciences, Beijing 100049, China; 6Wuhan NARI Limited Liability Company, State Grid Electric Power Research Institute, Wuhan 430074, China; 7Department of Physics, National Cheng Kung University, Tainan 701, China; 8Department of Space Physics, School of Electronic Information, Wuhan University, Wuhan 430072, China

Abstract: The triangulation of red sprites was obtained, based on concurrent observations over a mesoscale convective system (MCS) in North China from two stations separated by about 450 km. In addition, broadband sferics from the sprite-producing lightning were measured at five ground stations, making it possible to locate and identify the individual causative lightning discharges for different elements in this dancing sprite event. The results of our analyses indicate that the sprites were produced above the trailing stratiform region of the MCS, and their parent strokes were located mainly in the peripheral area of the stratiform. The lateral offset between sprites and causative strokes ranges from a few km to more than 50 km. In a particularly bright sprite, with a distinct halo feature and streamers descending down to an altitude of approximately 48 km, the sprite current signal identified in the electric sferic, measured at a range of about 1,110 km, peaked at approximately 1 ms after the return stroke.

Keywords: sprite; triangulation; peak current; hybrid location

Citation: Wang, Y. P., Lu, G. P., Ma, M., Zhang, H. B., Fan, Y. F., Liu, G. J., Wan, Z. R., Wang, Y., Peng, K. M., ... and Zhou, R. X. (2019). Triangulation of red sprites observed above a mesoscale convective system in North China. Earth Planet. Phys., 3(2), 111–125. http://doi.org/10.26464/epp2019015

1. Introduction

The effects of lightning in the near-earth space are substantiated by the observations of transient luminous events (TLEs), such as red sprites. When a cloud-to-ground (CG) stroke rapidly removes substantial charge from thundercloud to ground, an intense transient electric field is generated between the thundercloud and the ionosphere; this intense field can exceed the conventional dielectric breakdown threshold; it can initiate sprites with vertically developing streamers (Cho and Rycroft, 1998; Qin JQ et al., 2012). Sprites usually span an altitude range from 40 to 90 km (Sentman and Wescott, 1993), taking various shapes, such as column-shaped, carrot-shaped, jellyfish-shaped, angel-shaped, etc. (Lyons et al., 2003). Sprites can extend horizontally over several tens of kilometers in the form of clusters (Füllekrug et al., 2001; Soula et al., 2014), or even more than 100 km as sequential luminous emissions called dancing or jumping sprites (Lu GP et al., 2013; Yang J et al., 2015). In general, the duration of luminous sprite elements is limited to several milliseconds, but individual elements have been observed to last more than 100 ms (Lu GP et al., 2013). Sprites are produced mainly by positive CG strokes above stratiform regions of mesoscale convective systems (MCS), but occasionally by negative CG strokes (Lyons, 1996; Li JB et al., 2012). The time delay between causative CG strokes and sprites ranges from a few milliseconds to several tens of milliseconds (Cummer and Lyons, 2005; van der Velde et al., 2006). Lu GP et al. (2013) concluded that prompt sprites (<20 ms) are less horizontally displaced (typically <30 km) from their causative strokes than delayed sprites; delayed sprites often occur more than 40 ms after the parent CG and exhibit large horizontal offsets (>30 km). Most
sprite-producing positive CG strokes (SP+CGs) are initiated in the convective cores of thunderstorm and then propagate horizontally into the stratiform region (van der Velde et al., 2014). In many cases, these sprite-producing flashes develop a horizontal spider or tree structure in the thunderclouds (Lang et al., 2004), which implies that the in-cloud activity of sprite-producing lightning plays an important role in sprite formation (Ohkubo et al., 2005; Marshall et al., 2007).

This study investigates observations of sprites over a mesoscale convective system near Beijing on 8 August 2017. This first triangulation of sprites above mainland of China advances knowledge of the TLE phenomenon and its relationship with lightning and thunderstorms. In particular, by applying the time difference of arrival (TDOA) algorithm with least squares method to electromagnetic signal data recorded during this event at more than four ground stations, and by identifying triggering times manually, we have been able to determine the locations of the sprite-producing CG strokes.

2. Data and Methods

The videos used in this study were recorded with a low-light-level camera (WATEC 902H2, with minimum illumination of 0.0001lux at F1.4) installed at two stations in Xinzhou (38.49°N, 112.94°E) and Jiushan (37.83°N, 118.11°E) (Figure 1). To capture sprites with brightness above a given threshold related to the background brightness, it is operated in the triggered mode by the UFO CaptureV2 software. Each video field of the video streams is inserted according to GPS-based Coordinated Universal Time (UTC) with millisecond precision.

When videos of sprites are available from two or more stations, sprite locations can be triangulated by analyzing the background star field (Peng K-M et al., 2017). In the analysis, the curvature of the Earth is taken into account, because the distance between sprites and observation stations ranges from 250 to 550 km. Knowledge of the latitude, longitude, and altitude of each observation station and the azimuth and elevation of sprites from those stations allows calculation of sprite locations and altitudes. Since sprite images captured by two stations contain a few common features in the corresponding field, the corresponding azimuths of common features are introduced into spherical trigonometry equations to obtain locations, and then altitudes are obtained through locations and elevation. By comparing and checking the altitudes calculated by data from two stations, the error is limited to less than 4 km.

We analyzed data collected during the above-mentioned thunderstorm by several lightning location systems in the studied area. First of these is the World-Wide Lightning Location Network (WWLLN), but since the detection efficiency of WWLLN is low, we also use data from the local lightning detection network (LLDN) operated by the State Grid Electric Power Research Institute. The LLDN records CG stroke characteristics such as latitude, longitude, polarity, peak current, and occurrence times. Our second source of data is from stations of a long-baseline lightning detection system used to detect broadband electromagnetic emissions, including the Xinzhou station (38.49°N, 112.94°E), the Jiushan station (37.83°N, 118.11°E), the Huaibei station (33.98°N, 116.79°E), the Lu’an station (32.21°N, 116.24°E) and the Wuhan station (30.51°N, 114.50°E) (Figures 1). Data came from magnetic field sensors of

Figure 1. Ground observation stations (red squares), magnetic station (cerulean hexagon), electric station (green diamond) and VLF station (blue star).
the Lightning Effects Research Platform (LERP) (Huang AJ et al., 2018), installed at Xinzhou and Jiushan stations, and from electric field sensors of the Jianghuai Area Sféric Array (JASA) (Liu FF et al., 2018), installed at Huaibei, Lu’an, and Wuhan stations.

The structure of this thunderstorm was recorded by an S-band (2.88 GHz) Doppler radar (39.48°N, 116.28°E, 45 m above mean sea level) with detection range of about 340 km; its distance from the center of the MCS was approximately 130 km. The radar operated with a 6 min cycle producing polar volumes. Cloud top temperature (CTT) data were provided by the National Centers for Environmental Prediction (NCEP) and the Climate Prediction Center (CPC). These global infrared (IR) cloud image data are merged from the European, Japanese, and U.S. geostationary satellites. The spatial resolution of this dataset is 4 km x 4 km; its temporal resolution is 30 min (https://disc.gsfc.nasa.gov/datasets/GPM_MERGIR_V1/summary?keywords=cpc). Our analyses also use atmospheric sounding data (Beijing, 54511 ZBAA, 39.93°N, 116.28°E, 55.0 m above sea level) (http://weather.uwyo.edu/upperair/sounding.html).

3. Storm Development and CG Lightning Activity
Southwest flow from the western Pacific subtropical anticyclone causes intense convective precipitation to appear over a large range in Hebei Province, a typical mesoscale convective process in the North China Plain. On 8 August 2017, the southwest flow carried unstable air to northwestern Tangshan and southern Chengde, forming an asymmetric mesoscale convective system. According to atmospheric sounding data from the University of Wyoming, the convective available potential energy value in Beijing, China, at 12:00 UTC on 8 August 2017, was 857.6 J·kg⁻¹, and the precipitable water for the entire sounding reached a high value of 45.21 mm (mean sea level, msl).

The base reflectivity map (Figure 2) shows that the MCS analyzed in this paper began with several small convective cells that first appeared at about 10:00 UTC on 8 August 2017 near Beijing, and then kept growing until a squall line formed over western Tangshan. As the MCS evolved, moving eastward, the leading convective line gradually transformed into a bow-echo structure on the southeastern wing, and the trailing stratiform precipitation area dominated on the northeastern side, giving the MCS an asymmetric structure (Houze et al., 1990). The MCS dissipated at 02:00 UTC on 9 August, having lasted about 16 hour. All sprite events observed in this experiment occurred between 14:10 and 18:29 UTC. Around the time of the sprite occurrences, the area and the horizontal dimension of the MCS were approximately 38,000 km² and 200 km, respectively. The SP+CGs were located within the typical stratiform region (Soula et al., 2009; Lang et al., 2010) and the maximum reflectivity was 30–45 dBZ with a low horizontal gradient (Figure 2).

According to LLDN lightning detection data, negative CG stroke rates overwhelmingly dominated—160 negative CG strokes per minute, compared to just 5 positive strokes per minute—from 13:00 to 20:00 UTC (Figure 3). The occurrences of sprites can be divided into three periods, 14:10 UTC, 15:26–16:13 UTC, and 17:20–18:28 UTC; the locations of strokes are shown in Figure 2. We found that the rate variations of positive and negative lightning strokes are similar and the stroke rate fluctuates before the occurrence of sprites (Figure 3a). Figure 3b shows that the peak current of the positive CG was more discrete than that of the negative CG, and that high peak current is not an indicator of sprite generation. The geometric (arithmetic) mean values of the positive- and negative-stroke peak currents during this period of observation are 18.52 kA (27.49 kA) and −11.53 kA (−15.90 kA), respectively, and their maximum and minimum values are 328.9 kA and −258.3 kA. The number of positive (negative) strokes with peak current beyond 100 kA (−100 kA) is 135 (114), accounting for only 4.5% (0.2%) of the total positive (negative) strokes during the same period, as shown in Figure 3a.

Figure 4 shows that CGs detected by the WWLLN gradually developed from northwest to southeast. During the night, from 14:10 to 18:29 UTC, 20 sprite events were recorded by cameras located at Xinzhou and Jiushan stations. Detected during the three periods mentioned above (i.e., 14:10 UTC, 15:26–16:13 UTC, 17:20–18:28 UTC) were 1 sprite event (1 stroke/sprite pair), 13 sprite events (22 stroke/sprite pairs), and 6 sprite events (12 stroke/sprite pairs), respectively. Figure 5 shows the polarity distribution of CGs recorded by the LLDN. According to the cloud top temperature (CTT) maps at 14:00, 16:00, and 18:00 UTC (Figure 5), three types of CGs are represented by white crosses: small magenta pluses and large red pluses for negative CG, positive CG, and SP+CGs, respectively; the coldest temperature was approximately 218 K. The large concentrations of CGs were located in the intense convective region corresponding to the coldest CTT area. Consistent with results of previous studies, sprites are observed at times when the stratiform region associated with sprites is producing a relatively lower number of strokes. The SP+CGs are more scattered than CGs without sprites in the storm system and these strokes are quite far—as distant as 200 km—from the coldest part of the cloud top.

4. Triangulation of Sprite Observations
The coordinated observation system recorded 20 sprites, of which six were columnar sprites, eight were the dancing sprites and one was the jellyfish-shaped sprite (Soula et al., 2017; Yang J et al., 2018), but there were no clearly visible halos in any of the observed images (Li JB et al., 2012). Of these 20 sprites, eight lasted less than one field (<20 ms) and 12 lasted more than two fields (>40 ms). The temporal resolution of each field is 20 ms, which is much longer than the 1–2 ms timescale associated with streamer initiation, so it is not possible to determine the propagating directions of the sprites. These events had an average top altitude of 82.3 km and bottom altitude of 52.5 km. The electric field measurements indicate that all the sprites were induced by positive CGs. The sprites simultaneously captured at Xinzhou and Jiushan station were labeled as SP1 to SP6 (Figure 6) and listed in Table 1. The remaining 14 sprites were recorded at only one station. It should be noted that the sprite time in Column 2 of Table 1 is the time of the first field with sprite luminosity in the two videos, and that the time delay in Column 5 of Table 1 is the time difference between sprite time and first stroke time.
Figure 2. Radar reflectivity with SP+CGs (red pluses) at 14:06 UTC (Panel a), 16:00 UTC (Panel b) and 18:30 UTC (Panel c), respectively.

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4.1 Triangulation of a Jellyfish-Shaped Sprite

The peak current of SP2 is higher than that of the other sprites recorded; the distance between this sprite and the SP+CG stroke, measured using the great circle path, is about 8.24 km. The sprite matches very well with the SP+CG stroke locations. As shown in Figure 7, the location of the sprite and the SP+CG stroke is re-
Figure 5. CTT with SP+CGs (red pluses) at 14:00 UTC (Panel a), 16:00 UTC (Panel b), and 18:00 UTC (Panel c), respectively. The CGs recorded by the LLDN during 10 min around the time of the scan are plotted with white crosses and magenta pluses for –CG and +CG, respectively.

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Table 1. Details of sprite observations on August 8, 2017. The sprite time gives the earlier time of sprite observation recorded at two stations

| Event | Sprite time (UTC) | First stroke time (UTC) | Sprite duration (ms) | Time delay (ms) (stroke/sprite) | Distance (km) (stroke/sprite) | First stroke peak current (kA) | Shape | Stroke/Sprite pairs |
|-------|-------------------|-------------------------|----------------------|---------------------------------|-------------------------------|-------------------------------|-------|---------------------|
| SP1   | 15:29:11.2815     | 15:29:11.2680           | 20                   | 13.5                            | 21.7                          | 53.1                          | Column | 1                   |
| SP2   | 15:40:19.1388     | 15:40:19.1268           | 20                   | 12.2                            | 8.2                           | 328.9                         | Jellyfish | 1               |
| SP3   | 15:48:58.4567     | 15:48:58.4308           | 380                  | 25.9                            | 44.9                          | 93.3                          | Dancing  | 2                   |
| SP4   | 15:57:27.6660     | 15:57:27.6601           | 200                  | 5.9                             | 49.6                          | 137.2                         | Dancing  | 3                   |
| SP5   | 16:00:28.6739     | 16:00:28.6580           | 340                  | 15.9                            | 35.3                          | 73.3                          | Dancing  | 2                   |
| SP6   | 17:29:50.5918     | 17:29:50.3185           | 640                  | 273.3                           | 44.4                          | 132                           | Dancing  | 4                   |

Figure 6. Sprites detected at two stations on August 8, 2017 for the parent stroke at (a) 15:29:11.2680 UTC, (b) 15:40:19.1268 UTC, (c) 15:48:58.4308 UTC, (d) 15:57:27.6601 UTC, (e) 16:00:28.6580 UTC and (f) 17:29:50.3185 UTC. The upper panel is for the image recorded at station Xinzhou, and the lower panel is for the image recorded at station Binzhou. The altitude is in kilometers.
respectively marked by a blue dot and a blue plus and overlapped on the weather radar reflectivity map. The image times recorded at Jiushan and Xinzhou station are 15:40:19.1388 and 15:40:19.1598 UTC, respectively (Figure 6). Because of the time difference of 21 ms between initial detection at the two stations, the duration of SP2 is greater than 21.0 ms. Figure 8a shows the image captured at Jiushan station. Unfortunately, due to cloud cover, the sprite could not be observed at Xinzhou station. Nevertheless, the strong emission intensity of SP2 allows the location and altitude of the sprite to be determined. The SP2 event was of the jellyfish type; streamer energy was concentrated in the main luminous body and the halo was generated on the top of streamer (Figure 8a). According to the vertical structuring of sprites elaborated by Pasko and Stenbaek-Nielsen (2002), conductivity of the atmosphere is low near the ionospheric boundary, and the size of the streamer increases as air densities decrease. In other words, due to slow air heating at reduced air densities, the up-streamer and down-streamer have different morphologies.

Previous studies have reported that pulse signature waveform is related to the spatial relationship between sprites and parent lightning strokes (Mlynarczyk et al., 2015; Soula et al., 2017). As shown in Figure 8d, the electric field radiated in very low frequency (VLF) band for SP2 is different from that of the other sprites. There is a significant positive hump of about 0.5 ms in the electric field after the positive CG return stroke that can be attributed to sprites, similar to sprite features shown in Cummer and Inan (1997) and Soula et al. (2014). Hager et al. (2012) suggested that the electric field hump is produced by a sprite current that originates in the ionosphere and propagates downward. Such sprite currents can also last a few tens of milliseconds (e.g., Mlynarczyk et al., 2015; Füllekrug et al., 2001).

4.2 Triangulation of Dancing Sprites
Figures 9 and 11 show locations of sprite events and causative strokes overlying the radar reflectivity map. These sprite events were all laterally displaced to the southwest from the associated lightning strokes. Figures 10 and 12 show the time series of lightning signals corresponding to the above dancing sprites. Sprites indicated by open circles (SP5-2 and SP6-2) may have been generated by the \( M \)-component; unfortunately, no pulses were detected. The durations of SP5 and SP6 were, respectively, about 340 ms and 640 ms; in both cases, sprite luminosity lasted roughly 100 ms. Most elements of these two dancing sprites (with the exceptions of SP5-1 and SP6-4) started with delays significantly larger than 40 ms, and can thus be considered long time-delayed (Lu GP et al., 2013). We observe that longer time-delayed sprites are more displaced from their parent strokes than those with shorter delays, and these sprites may contain a sprite produced by \( M \)-component superimposed on a long continuing current. This observation is quite consistent with the analysis of Li JB et al. (2008) on delayed sprites. Lang et al. (2010) showed that the correspondence between a storm’s convective activity and sprite occurrences can depend on the storm’s particular morphology. The radar reflectivity of the large stratiform region in the MCS is less than 50 dBZ. The SP+CGs were detected mainly on the edge of the large stratiform region; very few CG flashes (see Figures 2 and 5) occurred within it. The observed discharges appear to follow the pattern proposed by van der Velde et al. (2014), i.e., a dual discharge phenomenon crosses the stratiform region from a convective region, up to the other end of the thunderstorm system.

Gordillo-Vázquez and Luque (2010) showed that the change of atmospheric conductivity induced by sprites lasts for several minutes and can be detected after optical emissions. This is consistent with previous observation of sprite re-ignition events (Stenbaek-Nielsen et al., 2000). Therefore, the residual plasma originating from SP4 can be expected to be conductive and to allow the SP5 streamers to pass through. We speculate that the existence of residual plasma may be a universal feature in successively
occurring sprite events.

5. Discussion

The initial triangulation of red sprites was based on synchronous observations on the night of August 8, 2017, in North China. Figure 13 shows the spatial relationship between sprites and SP+CG strokes. Soula et al. (2015) propose that the residual plasma of the first sprite decreases the triggering threshold of subsequent sprites and that the following elements of dancing sprites are more displaced from the SP+CG stroke than the first elements. The comparison between triangulated sprites and SP+CG locations shows that sprites usually propagate from the edge of the stratiform area to the inactive lightning region in the MCS, which seems to be due to a response to positive sprites from ionospheric perturbation caused by lightning activity. Multiple sprites can be produced in one lightning flash through distinct strokes or $M$-component during the continuing current (Lu GP et al., 2013). The SP+CGs are usually initiated in the leading convective region and then propagate to the stratiform region, i.e. the behaviors of the bidirectional leaders in the SP+CG strokes. The cor-

Figure 8. (a) The SP2 event captured at Jiushan station at 15:40:19 UTC. The sprite extended between 48.5 and 88.2 km in altitude. (b), (c) and (d) Electric field change versus time for SP2. The red crosses display the triggering times.
The correspondence between the convective activity and sprite occurrences can depend on thunderstorm morphology (Lang et al., 2010).

Hybrid location of electromagnetic signals can provide a new method for lightning location. Computation of triggering times from differences of lightning pulse arrival times, measured within

Figure 9. Weather radar reflectivity at 16:00 UTC with different symbols superimposed for the SP+CGs (blue plus) and the sprite (blue dot and open circle).

Figure 10. (a) and (b) Dancing sprites recorded at 16:00:28 UTC. (c) E-field waveform of the dancing sprite event at 16:00:28 UTC. The red crosses display triggering time.
a detection network, can allow optimal determination of event locations. Figure 14 shows the broadband electromagnetic sferic signals of SP6 recorded at four stations. As the distance between the sprite-producing lightning stroke and the electromagnetic field station increases, the TODA between the ground wave and the (first) ionosphere reflection becomes smaller, and the dominance of the ground wave also declines. As shown in the following figure, at distances of up to 681.6 km (Huaibei station) from the stroke, the sferic peak signal is still dominated by the ground wave. Because the subsequent return stroke signal of a dancing sprite is weak, we give the computed location of only the first stroke. Taking the LLDN location as the ground truth, the location error is 43 km (Huang AJ et al., 2018). This large error is due to the fact that the stations were all on the same side of the thunderstorm system we analyzed. The hybrid location approach can use data from different collection systems to locate the target lightning in instances of malfunction at some of the stations in the detection network.

The iCMC serves as an efficient metric to evaluate the potential of sprite occurrence. Lu GP et al. (2013) showed that if a lightning flash produces a positive CG stroke with iCMC > +300 C·km, it is
90% likely to generate a sprite. For sprite streamers to be initiated, inhomogeneities of the ionosphere/mesosphere are also required (Luque and Ebert, 2010; Liu NY et al., 2012; Kosar et al., 2013). Lightning strokes can cause direct heating and ionization of the lower ionosphere, leading to conductivity enhancement, electron density depletions, etc. (Qin JQ et al., 2014; Liu NY et al., 2015). Recovery of the disturbed ionosphere typically requires many tens of seconds. Salut et al. (2013) suggested that the ionospheric disturbance increases with the peak current intensity of the causative lightning discharge, and that positive strokes are more likely to generate ionospheric disturbance than negative strokes of the same intensity. We propose that the ionospheric disturbance caused by positive (negative) CG strokes might have a promotion (inhibition) effect on the generation of positive sprites. Because of the collection method of VLF/ULF band data, it is impossible to give the iCMC of each stroke. However, there is a correspondence between peak current and iCMC (Cummer et al., 2013). Therefore, we conduct a qualitative analysis of the contribution of peak current: As shown in Figure 15, the three periods in this study, i.e., 14:10 UTC (the CGs detected during 10 min around this time), 15:26–16:13 UTC, and 17:20–18:28 UTC, are dominated by the transfer of negative charges. In addition, plots of the -CG and +CG detected reveal a bipolar pattern (Lyons, 1996). The -CGs were largely associated with the high-reflectivity core along the southeastern of the MCS, while the +CGs were concentrated further to the northwest in the downwind anvil. As described, sprites usually tend to develop toward the region of lightning inactivity (Cummer et al., 2013), which may be because negative CG dis-

Figure 13. Locations of the sprites observed on August 8, 2017. The color plus signs are the SP+CG stroke locations. The color dot and circle signs are the sprite locations.

Figure 14. Broadband electromagnetic sferic signals of SP6 recorded at four stations. The red and blue crosses display triggering time.
We suspect that this may also explain why negative sprites often occur in marine storms (Lang et al., 2013; Boggs et al., 2016; Yang et al., 2018) and that winter thunderstorms in Japan can produce sprites (Hayakawa et al., 2004). The proportion of positive CGs is lower in marine thunderstorms than in those occurring over land, so it is easier to generate the electromagnetic environment required by the negative sprite. However, in Japanese winter thunderstorms, the proportion of positive and negative CGs is similar, so we would expect the influence of positive CGs on the disturbance of the upper atmosphere to be increased. Therefore, when CG strokes are sufficiently strong, sprites can also be generated by small-scale thunderstorm systems.

6. Conclusions

We examined observations of 20 sprites above a mesoscale convective system in North China on August 8, 2017—in particular, we have triangulated six sprites observed at two different stations. The data set includes optical emissions, characteristics (time, location, and peak current) of SP+CGs detected by WWLLN and LLDN, electromagnetic field radiated by lightning discharges, CTT provided by NCEP/CPC, and radar reflectivity. The thunderstorm began at 10:00 UTC near Zhangjiakou, Hebei Province, and then...
moved southeastward during its lifetime (about 16 hours). The positive and negative CG lightning rate of this thunderstorm reached more than 5 strokes/min and 160 strokes/min, respectively, while CTT reached a minimum of 218 K at about 16:00 UTC. The area and the horizontal dimension of the MCS were approximately 38,000 km² and 200 km, respectively. We analyze in detail the complex structure of the thunderstorm and the lightning activity associated with sprite production. The region of the sprite occurrence was roughly 250 to 550 km from the observation stations. The main results derived from our analysis are summarized as follows:

1. All the sprites were produced above the trailing stratiform region of the MCS, and their parent strokes were located primarily in the peripheral area of the stratiform region. The lateral offset between sprites and causative strokes ranges from a few km to more than 50 km.

2. The jellyfish-shaped sprite with distinct halo feature and streamers descended down to an altitude of about 48 km, and the sprite current signal identified in the electric sferic data measured at about 1110 km peaked at approximately 1 ms after the return stroke.

3. The first strokes of the dancing sprites analyzed had stronger pulse currents than those of their subsequent strokes. Most elements of these dancing sprites started with delays significantly longer than 40 ms.

4. Hybrid location of sprite-producing lightning strokes indicated that by using data from different collection systems, we could overcome the inability to locate a specific lightning discharge due to malfunction of individual stations; thus hybrid analysis promises to improve the accuracy and efficiency of location.

This work demonstrates the results of combining optical observations of sprites and remote sensing of broadband electromagnetic fields to study the spatial correlation between sprites and their parent lightning. Because all the sprites examined in this paper were produced by positive CG strokes, we can report no triangulation of a negative sprite. Since it has been revealed that negative sprites occur more often over oceanic than over land thunderstorms (e.g., Lu GP et al., 2017), we recommend further observation experiments in other areas, especially over the sea area of Southeast China.

Acknowledgments
This work was supported by the National Key Basic Research and Development Program (2017YFC1501501), National Natural Science Foundation of China (41574179, 41875006), National Natural Science Foundation for Excellent Youth of China (41622501), and “The Hundred Talents Program” of Chinese Academy of Sciences (2013068). The creation of the original data at NOAA/NCEP is supported by funding from the NOAA Office of Global Programs for the Global Precipitation Climatology Project (GPCP) and by NASA via the Tropical Rainfall Measuring Mission (TRMM). The permanent archive at GES DISC is supported by NASA’s HQ Earth Science Data Systems (ESDS) Program.

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