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Using lightning locating system based on time-of-arrival technique to study three-dimensional lightning discharge processes

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A time-of-arrival (TOA) system based on GPS technology for locating VHF radiation sources from lightning has been developed and used in observation sites in the northern Shandong Province, China. The 3D images of the lightning progression have been obtained successfully for the first time in China. The 3D-channel evolutions of typical negative CG, positive CG and IC lightning flashes have been discussed together with the data of fast electric field change. It was found that significant differences existed between the negative and positive CG lightning flashes in terms of the initiation and propagation of the radiation sources. The preliminary breakdown of a negative CG lightning flash propagated at a speed about 5.2×10^4 m/s. The stepped leader of negative CG lightning flashes was trigged by negative initial breakdown. Thereafter, it propagated downward at a speed of 1.3×10^5 m/s. The initial process of the positive CG lightning flashes was also a propagation process of negative streamer. These streamers propagated dominantly horizontally in the positive charge region and accumulated positive charges at the origin of the lightning, and as a consequence, initiated downward positive streamers. A new type of lightning discharge that was triggered by a narrow bipolar pulse (NBP) is discussed in this study. The NBP was originated at altitude of about 10.5 km in the upper positive charge region. As a distinct difference from normal IC flash, its channels extended horizontally all around and produced a lot of radiation sources. The source power of the NBP could approach 16.7 kW, which is much greater than that of normal lightning discharge ranging between 100 mW and 500 W. The 3D propagation of this new type of lightning discharge was observed and obtained for the first time in China. The possible initiation mechanism of this new type of lightning is discussed here.

time-of-arrival (TOA) technique, three dimensional lightning locating system, discharge process, narrow bipolar pulse, new-type of IC lightning

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Realization of three dimensional (3D) location of lightning radiation process provides a new approach to study meticulously the lightning discharge process, as well as the electrical structure of thunderstorms and their electrification mechanism. Lightning discharges are categorized as cloud-to-ground (CG) and intracloud (IC) flashes. People are more concentrated on the CG flash since CG flash is the cause of most lightning damage, injury, and death. Many meaningful results [1–3] based on the lightning locating technology and

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researches on the cloud-to-ground lightning mechanism have been obtained due to the application of low frequency CG lightning locating system and VHF interferometer system (2D). Recently, technology of lightning detecting has been greatly improved on the precision aspect. Based on the technology of LDAR [4], Scientists at New Mexico Institute of Mining and Technology developed a VHF lightning radiation sources locating system by time of arrival tech (LMA) with GPS system, which is used to study the 3D evolution process of the lightning VHF radiation sources [5–7]. Using the data of this LMA system, Zhang et al. [8–11] made an analysis showing that the charge structure of thunderstorms often presented a normal triple polarity. Meanwhile, he indicated that lightning discharge process inside the cloud not only occurs between the areas of the upper positive charge and negative charge regions, but also exists in the reversed polarity region. Zhu et al. [12] also utilized observation system made by themselves to make statistical analysis on pulse events of dual polarity in thunderstorms. Shao et al. [13] and Qie et al. [14] also made some meaningful study through lightning observation system using TOA tech in low frequency. However, in China, there was still no 3D lightning location system like LMA. Hence, it is impossible to study the thunderstorm charge structure and its electrification mechanism more accurately. In this article, a 3D locating system with high time and space resolution to locate the lightning VHF radiation sources developed by ourselves was utilized successfully in observing the entire evolution images of CG and IC discharge processes. Meanwhile, the lightning discharge character and the peak value of VHF radiation power were analyzed in detail. Preliminary results revealed the channels of lightning discharges, thunderstorms charge structure in 3D varying with time, and especially the structure and the likely mechanism of IC flash initiated with the NBP.

1 Experiment sites and the instrumentation

From June to August in 2007, a comprehensive observational experiment on lightning was made in Binzhou of Shandong, China. As shown in Figure 1, with the Zhanhua (Hengdian)-central station as the center, seven affiliated stations are installed in radial pattern. An experimental site for artificially triggering lightning was located 550 m north-west away from the central station. The central area of experiment field lay in the vicinity of eastern Bohai gulf (50 km away). The topographic feature of the experiment area was relatively flat with altitude from 5 to 10 m. The severe thunderstorm passes over this region frequently in summer season because of the interaction of southern and northern weather systems. Each station was installed with a 3D lightning radiation source locating system (LLR for short) based on TOA technique, and high precision clock (±25 ns) triggered synchronously by GPS. Besides, instruments as

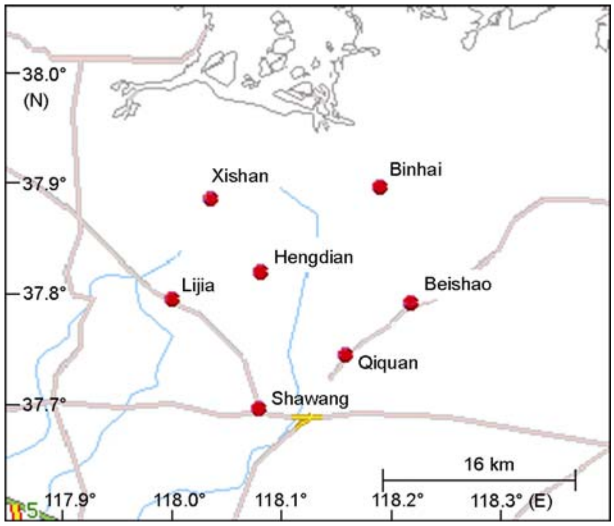


Figure 1 Map of the observation sites.

wideband fast antenna (with bandwidth 0–10 MHz, time constant 100 μs and dynamic range ±3.5 V), fast antenna (with bandwidth 0–5 MHz, time constant 1ms and dynamic range ±10 V), slow antenna (with bandwidth 0–2 MHz, time constant 6 s and dynamic range ±10 V) as well as field mills (dynamic range is ±50 kV/m) were used to measure the electric field changes of lightning discharge with different time resolutions. The signals mentioned above were recorded in computers through A/D converters and synchronized by a fast antenna triggering. At the central station, some additional devices such as a high-speed camera (100000 image/s), Red Sprite Observation System, VHF narrowband interferometer and so forth were equipped. A net was thus composed of these stations by wireless broadband system connection. Data collection can be controlled in the way of triggering by central station or in an independent way. In this article, we stipulate the negative electric field change corresponding to the positive charge reduced over head.

2 3D locating method of radiation sources

2.1 Operation of the hardware

The 3D locating system of lightning VHF radiation sources is composed of seven affiliated observational stations, as shows in Figure 1. Each station synchronously receives peak-values of the VHF electromagnetism radiation pulse signals produced by lightning discharge. The shape of the pulses is shown in Figure 2. The VHF receiver system has its center frequency of 270 MHz with 3 dB bandwidth of 6 MHz. Due to the adoption of logarithmic amplifier, the measurement range has reached up to 100 dB. The time and peak value are recorded in every 25 μs interval when the signal amplitude exceeds the threshold level of noises. The digitized rate of the A/D converter used is 20 MHz, i.e., the

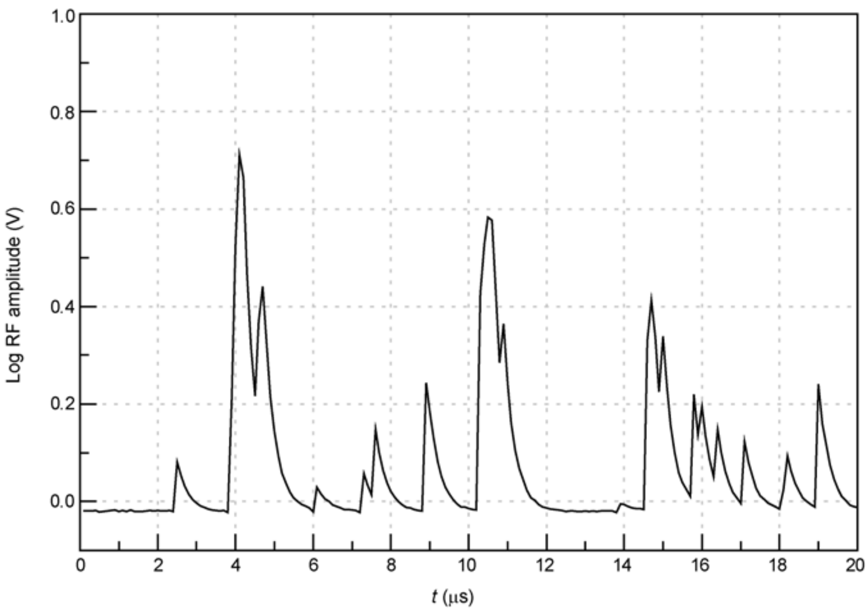


Figure 2 The expanded RF radiation pulses detected by LLR system from lightning discharge in logarithmic RF radiation amplitude (log RF).

signal peak time resolution is 50 ns. The 40 MHz high precision clock was synchronized and calibrated by 1PPS output of a GPS receiver. The 20 MHz signal output by frequency demultiplication was used as benchmark signal of A/D converter sampling clock. The lightning radiation sources can be located in 3D with time by using absolute time of peak value arrival to seven stations. The system deals with one peak value event in every 25 μs window time, with the highest located number up to 40 thousands radiation sources in one second (actual amounts of located radiation points may change according to the number of identified independent pulses from each station), thus describing the entire image of lightning discharge process in detail.

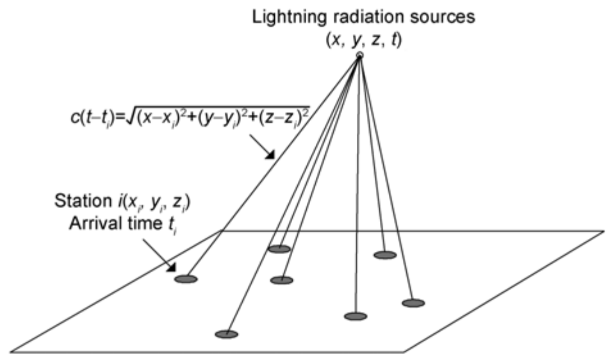


Figure 3 A schematic diagram of the TOA technique.

2.2 Method of locating the radiation sources

From simple geometric considerations (Figure 3), the time of signal arrival at a given station i is simply

$$t_i = t + \frac{\sqrt{(x-x_i)^2 + (y-y_i)^2 + (z-z_i)^2}}{c}, \tag{1}$$

where c is the speed of propagation of the light in vacuum, t is the time the radiation emitted from source location (x, y, z), (x_i, y_i, z_i) is the location of station i, and t_i is the arrival time at station i.

If more than 6 stations were used to measure the arrival time t_i, and by using eq. (1), a set of more than 6 nonlinear equations was constituted. The values of x, y, z, t solved from the set of nonlinear equations mentioned above must minimize the difference between measured t_i and that obtained from the eq. (1). The method of the non-linear least square was used to fit the parameters x, y, z, t in order to minimize the value x^2:

$$x^2 = \sum_{i=1}^{N} \frac{(t_i^{\text{obs}} - t_i^{\text{fit}})^2}{\Delta t_{\text{rms}}^2}, \tag{2}$$

where x^2 is the goodness of fit, which was used to weigh the degree of approximation between the time from the equation solution and from the measurement. An iterative process can be proceeded to finally make the value of x, y, z, t closest to the measurement, thus obtaining the solution needed.

2.3 Error estimate

We use simple geometric method [15] to estimate the error. Assume the location of the source occurred on the baseline of two stations. The distance error of the location on a plane is equivalent to the distance error corresponding to half of the standard deviation of the arrival time difference to the two stations. The error of the height is related to the distance between radiation source and station. The minimum error of the height appears while radiation source occurs right over the station. The error of the height increases while the radiation source is apart from the station. We could estimate the system error in two types, inside or outside the network. If the radiation source occurs inside or near the network, we have

$$\Delta d \approx \frac{1}{\sqrt{2}} c\Delta t, \quad \Delta z \approx c\Delta t\left(\frac{d+r}{z}\right), \tag{3}$$

where Δd is plane error, Δt is the rms error of the time measured at each station, Δz is the rms error of z, the height of the source, d is the horizontal projection distance of the source to the closest station, and r is the distance from the source to the closest station.

There is also synchronization error in the system because a high precision GPS with 1 PPS pulse was used to synchronize 40 MHz clock. In other words, GPS has a timing error of less than 12 ns in average (6 Sigma average). The total rms error of each station is about 18 ns. The sampling period of A/D is 50 ns, the rms of which is $50/\sqrt{12} \approx 14.1$ ns because quantification error [16] exists in the A/D conversion process. With the triggering error etc., the estimated maximum system error is about 50 ns. It is calculated by using the eq. (3) (this equation may properly be used within about 10 km outside the network) that the plane error is less than 11 m and the altitude error is 2–3 times greater, when inside or near the network, and lightning usually occurs at altitude between 4 and 15 km. The altitude error increases while the altitude of the source decreases. Meanwhile, outside the network, we have

$$\Delta r = \begin{cases} 8\left(\dfrac{r}{D}\right)\Delta y, & \Delta y = \left(\dfrac{r}{D}\right)c\Delta T, \\ 8\left(\dfrac{z}{D}\right)\Delta z, & \Delta z = \left(\dfrac{r^2}{Dz}\right)c\Delta T, \end{cases} \quad \Delta T \approx \sqrt{2}\Delta t, \tag{4}$$

where r is the distance from the central station to the radiation source, D is the diameter of model network, z is the altitude of the source from model network plane, ΔT is the arrival time difference of the two stations, Δt is rms error of each station. Calculation shows that the typical horizontal error is 100 m on network plane in the range of 100 km, the altitude error is less than 300 m, and both increase with distance.

From the calibration test with synchronous pulse received in the laboratory by using a 25 ns time resolution clock, the statistical result shows that the typical arrival time error is 50 ns. According to the velocity of light, the distance error is less than 50 m. Further calibration of time and space in field test and error analysis will be discussed elsewhere.

3 Data analyses

3.1 Negative CG lightning

Figure 4(A) shows a 3D structure of a negative CG lightning occurred at 23:55:40 (Beijing Time) on July 9, 2007. The changes of color from blue, green, yellow to purple in the figure indicate the variations of VHF radiation events with time. The small green squares on the plan view indicate the locations of the observation stations. The –CG flash started at about 30 km to the southeast of the central station. Figure 4(B) shows that there was only one stroke in this –CG flash and the whole discharge process lasted about 250 ms. As shown in Figure 4(A), the flash started at a height of 4.5 km in the thunderstorm, corresponding to large positive pulse on the positive change of electric field in Figure 4(B). It indicated that the preliminary breakdown was a downward going negative one. Above the height of 3.5 km, its channel propagated downwards obliquely and scattered with plentiful VHF radiation sources, then suddenly propagated downwards vertically and initiated stepped-leader process when its channel was lower than 3.5 km. The exact time of the initiation of the return stroke was at 23:55:40.5269 (consistent with the recordings from the DFs network of Shandong Province). It can be seen from Figure 4(A) that many new VHF radiation sources occurred in the initial source area of the –CG lightning during the stage of stepped-leader, and the new channels occurred on top of the vertical channel and origin area and expanded towards other direction after the return stroke.

By considering the start point of vertically fast downward going channel process as the beginning of the negative stepped-leader, the preliminary breakdown lasted about 19 ms (above 3.5 km); the stepped-leader lasted about 26 ms (below 3.5 km). The velocity of the preliminary breakdown was 5.2×10^4 m/s and that of the stepped-leader was 1.3×10^5 m/s, similar to the results by Shao et al. [1–3]. The polarity of breakdown was mostly negative corresponding to the positive pulses in the waveform of electric field. But, it can still be seen that with a few negative pulses in the waveform, it indicated that positive breakdown also existed in the negatively dominant preliminary breakdown.

3.2 Positive CG lightning

Figure 5(A) shows the 3D structure of a +CG lightning occurred at 11:01:49 (Beijing Time) on July 11, 2007. There was only one return stroke in this +CG lightning. The charge structure of the thunderstorm was a three-layer one, according to the recordings of the electric field change on the ground. The east-westward vertical projection and plan view in Figure 5(A) show that this +CG lightning started at the height of 4 km, and expanded towards south-south west, then turned upwards into the positive charge region and reached at a height of about 6 km in about 10 ms, meantime

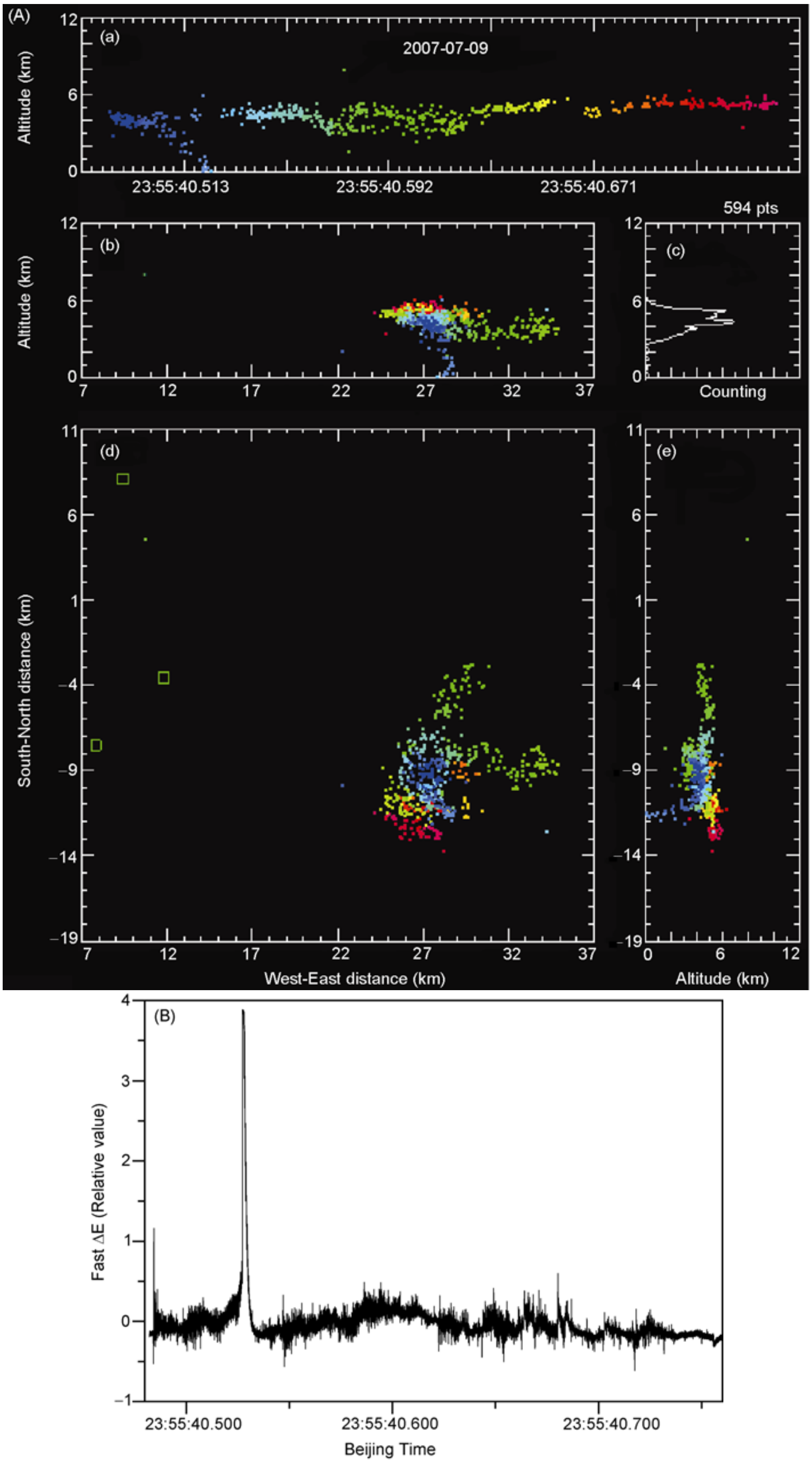


Figure 4 (A) A typical −CG lightning occurring at 23:55:40 (Beijing Time) July 9, 2007. (a) The different panels show height-time plots panel; (b) north-southward vertical projection; (c) height distribution of number of radiation events; (d) plan view; (e) east-westward vertical projection of lightning radiation sources. (B) Time waveform of electric field change (Fast ΔE) for the −CG lightning occurring at 23:55:40 (Beijing Time) July 9, 2007 (from Beishao Station).

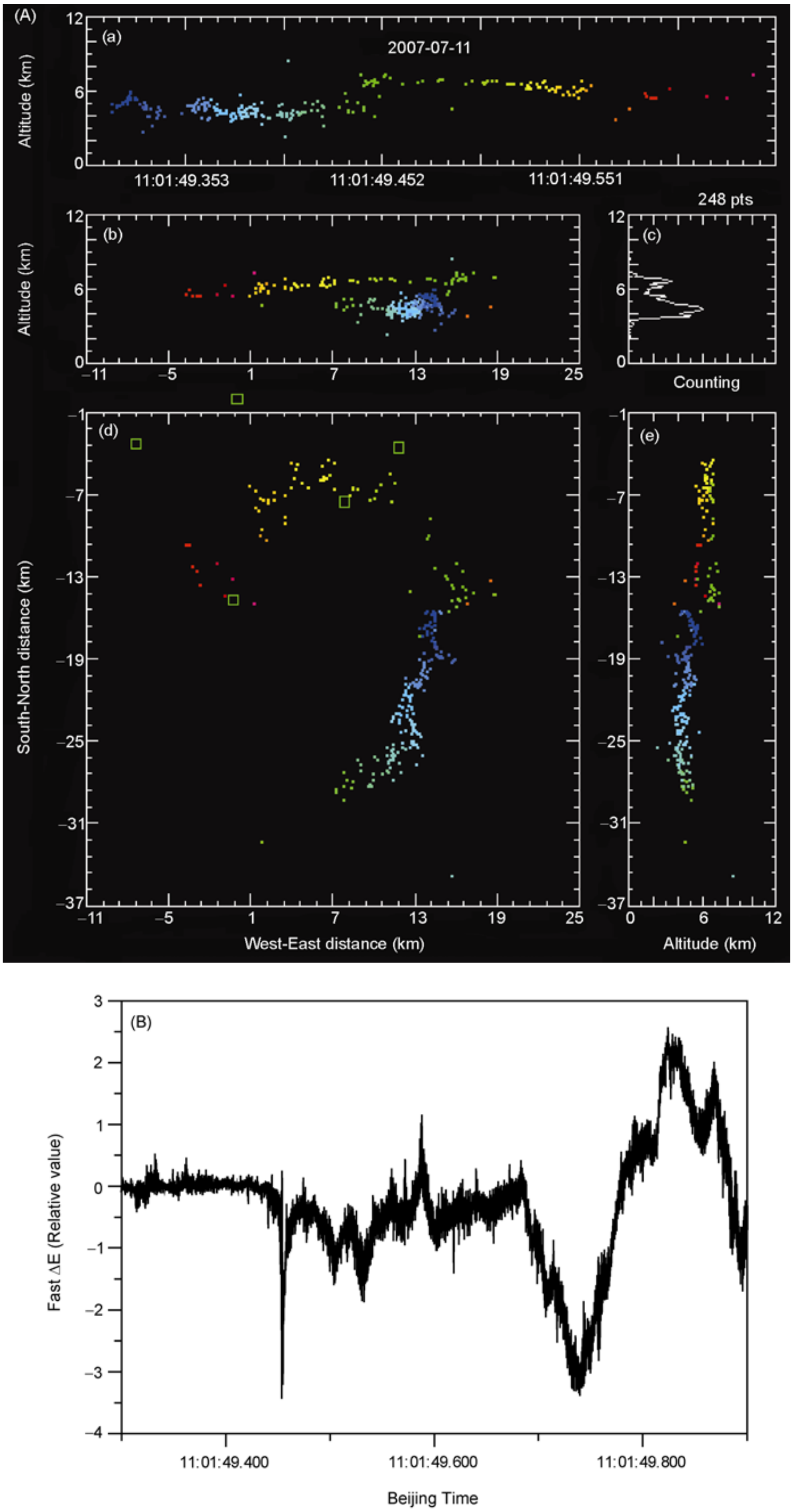


Figure 5 (A) A typical +CG lightning occurring at 11:01:49 (Beijing Time) July 11, 2007. (B) Time waveform of electric field change (Fast ΔE) for the +CG lightning occurring at 11:01:49 (Beijing Time) July 11, 2007 (from Hengdian Station).

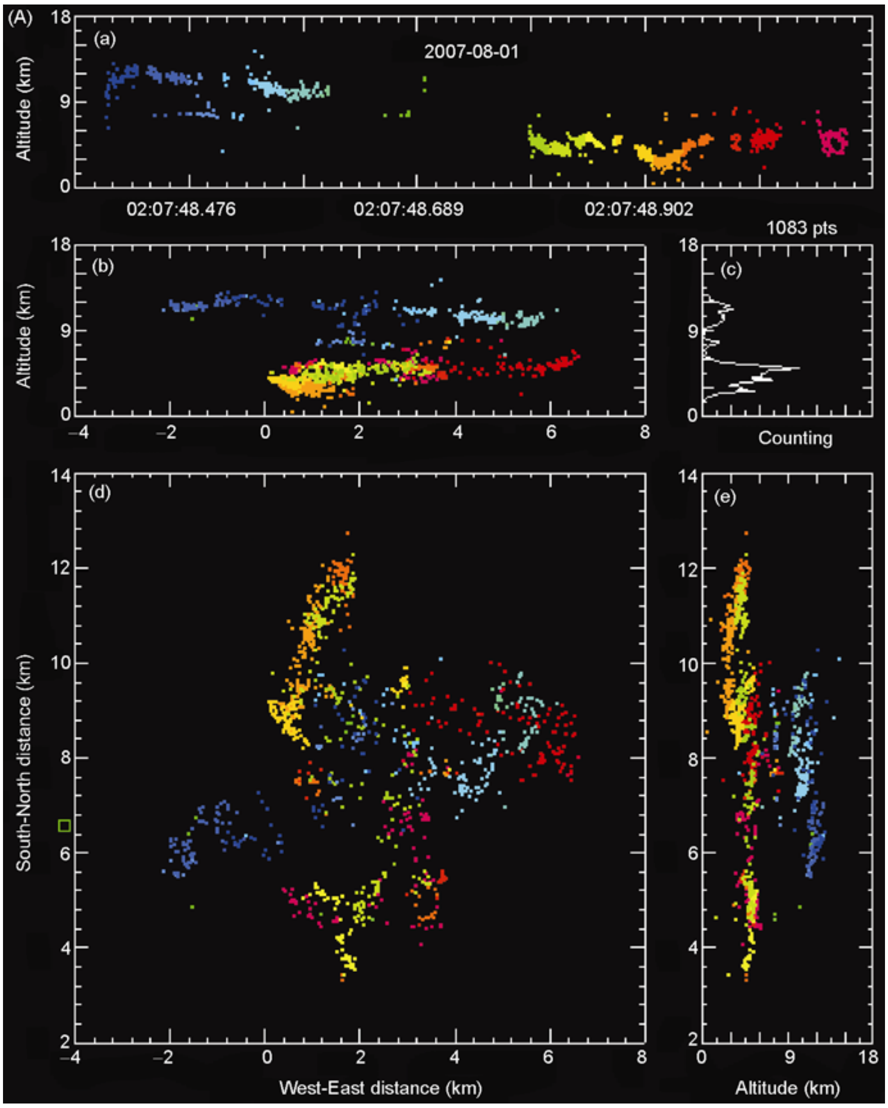
a lot of negative breakdown occurred in the positive charge region. After 11 ms, it stopped at a lower height of about 4 km. Combined with Figure 5(B), it shows that intensive pulses with both polarities superposed on large waveform of negative electric field change, indicating that a great deal of negative charge from electron avalanche in the propagating channel moved toward the positive charge region and wearing down the positive charge. On the contrary, the positive charge propagated toward the initial source area of radiation with a lot of pulses of both polarities. And then lots of negative breakdowns occurred at the height of 4.4 km and expanded about 16 km horizontally. The above mentioned negative breakdowns consumed lots positive charges; meanwhile, lots positive charges were accumulated in the origin region, and drove up the positive potential, then initiated the downward going channel. According to the waveform of the recorded electric field change, the exact time of the initiation of the return stroke was at 11:01:49.453896 (Beijing Time), consistent with the recordings from the DFs network of Shandong Province. After the return stroke, the new channel occurred on the top of the initial source region of lightning and expanded upward about 35 km toward the north-northwest. The duration of the +CG lightning was about 600 ms, and its channel developed symmetrically around the source region. Before the return-stroke, the average velocity of channel expanding was 1.6×10^5 m/s. The radiation sources were relatively concentrated and their average height was 4.4 km. After the return-stroke, the average velocity of channel expanding was 1.4×10^5 m/s, the radiation sources were spread and their average height was 7.2 km. As consistent with Zhang et al. [11], the downward going positive leader was not detected from the sources region because its radiation was too weak. From some comprehensive analysis on this +CG lightning, it could be seen that the charge regions were obliquely and non-uniformly distributed in the thunderstorm.

Based on the above analysis, it was found that the triggering mechanisms of the +CG lightning and −CG lightning were probably different from each other. In the cloud, the −CG lightning was triggered in the environment of negative electric field and then the negative streamers propagated downward as stepped-leader, with no or only a few discharge processes. Whereas in the case of the +CG lightning, the breakdown was triggered in the environment of positive electric field and the negative streamers propagated horizontally for a long time in the positive charge region and with a lot of discharge processes in the cloud. Many positive charges were accumulated at the triggered location and the positive potential was driven up until it could trigger the downward positive streamers. It thus seems that the discharge in the cloud plays an important role in providing energy to trigger +CG lightning.

3.3 Intracloud lightning

Figure 6(A) shows two IC lightning flashes with two layers structure, occurred at about 02:07:48 (Beijing Time) on August 1, 2007. The three layers of radiation sources corresponded to the upper positive charge region (11–13 km), the middle main negative charge region (8–9 km), and the lower secondary positive charge region (3–6 km) in the thunderstorm. Figure 6(B) shows the waveform of the electric field change on the ground obtained at Hengdian Station. The preliminary breakdown started at height of about 8.7 km in the negative charge region, the negative streamer (identified from electric field change) propagated upward into the upper positive charge region, then turned southwestward horizontally and ceased later, subsequently a few radiation sources occurred in the negative charge region, and initiated a second upward propagation. The channel propagated vertically from the negative charge region at the height of about 7.9 km to the positive charge region at about 11.5 km, and then initiated a new horizontal channel to the northeast direction. This discharge processes between the upper positive charge region and the middle negative charge region lasted about 205 ms, and it could be seen from the plan view panel of the figure that the points of the radiation sources were scattered. The second IC flash started at 185 ms after the first IC flash terminated. Figure 6(A) shows that it propagated between the middle negative and the lower positive charge region. The initial negative streamer of this IC flash propagated downwards from the main negative charge region at a height of 6.5 km, and formed a new vertical connecting channel to the lower positive charge region. Several discharge processes occurred downward along this new channel, while still some occurred along the former horizontal channel. The plan view figure shows that the channel of two IC flashes scattered horizontally, and centered at the vertical channel. The propagation direction of the vertical channel was upward going and its velocity was 1.8×10^5 m/s in the 1st IC flash, and it was downward going and the velocity was 2.9×10^5 m/s in the 2nd IC flash. The total number of the recorded radiation sources was 1083, Figure 6((A)-(c)) shows that the density of radiation sources was the highest in the lower positive charge region, while that was the lowest in the middle negative charge region.

Based on the above analysis, it was found that both of the two IC flashes started in the negative charge region and propagated upward or downward. The negative streamer became tilted because of the influence of positive charge when closing to the upper or lower positive charge region. The neutralization process occurred when the streamer got into the positive charge region and created a lot of breakdowns and then formed the horizontal channel. The density of radiation sources was corresponding to that of the charge in the storm. Above results indicated that the density of charge in the lower positive charge region was higher than that in the upper positive charge region. In addition, the three-layer structure of the thunderstorm was clearly seen from the structure of these two IC flashes [10].



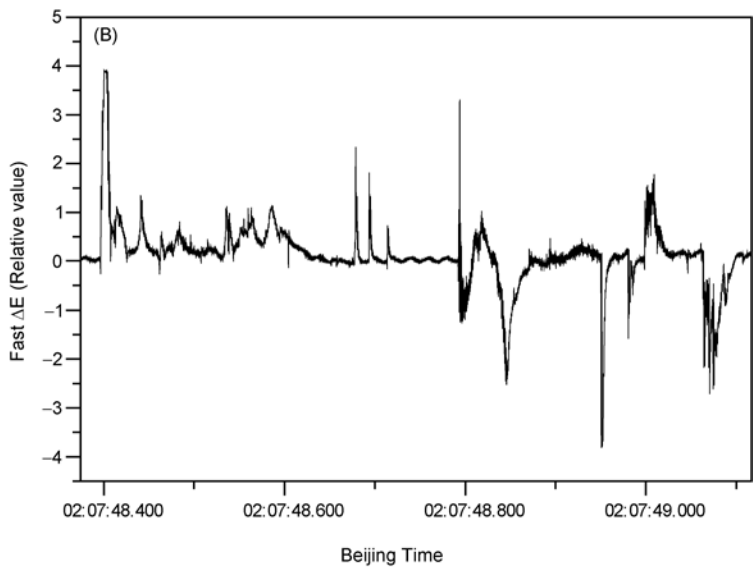


Figure 6 (A) The IC flash occurring at 02:07:48 (Beijing Time) August 1 2007. (B) Time waveform of electric field change (Fast ΔE) for the IC flash occurring at 02:07:48 (Beijing Time) August 1, 2007 (from Beishao Station).

3.4 Narrow bipolar event

The narrow bipolar pulse (NBP) is a discharge event accompanying strong RF radiation during the cloud discharge. Recent observations indicated that the NBP occurred not only in isolated form, but also in the initial stage of a lightning. The amplitudes of RF emissions were approximately 10 times greater than those from normal lightning emissions. Based on the classical concept, IC lightning is initiated in or close to the negative charge region, and then propagates vertically upwards or downwards. Its channel becomes horizontal when it enters the positive charge region. But some observations also show that there could be a long horizontal channel in the initial stage of IC lightning with no obvious vertical channel. In addition, the classic IC lightning has many small pulses in its initial stage, but the first pulse of this type IC lightning is a narrow bipolar pulse with the strongest RF radiation, and then the channel propagates horizontally. It seems that the IC lightning is initiated by an NBP. Many researchers paid attention to its mechanism, but no clear conclusion has been generally accepted at present. It will be discussed in this section through a selected sample.

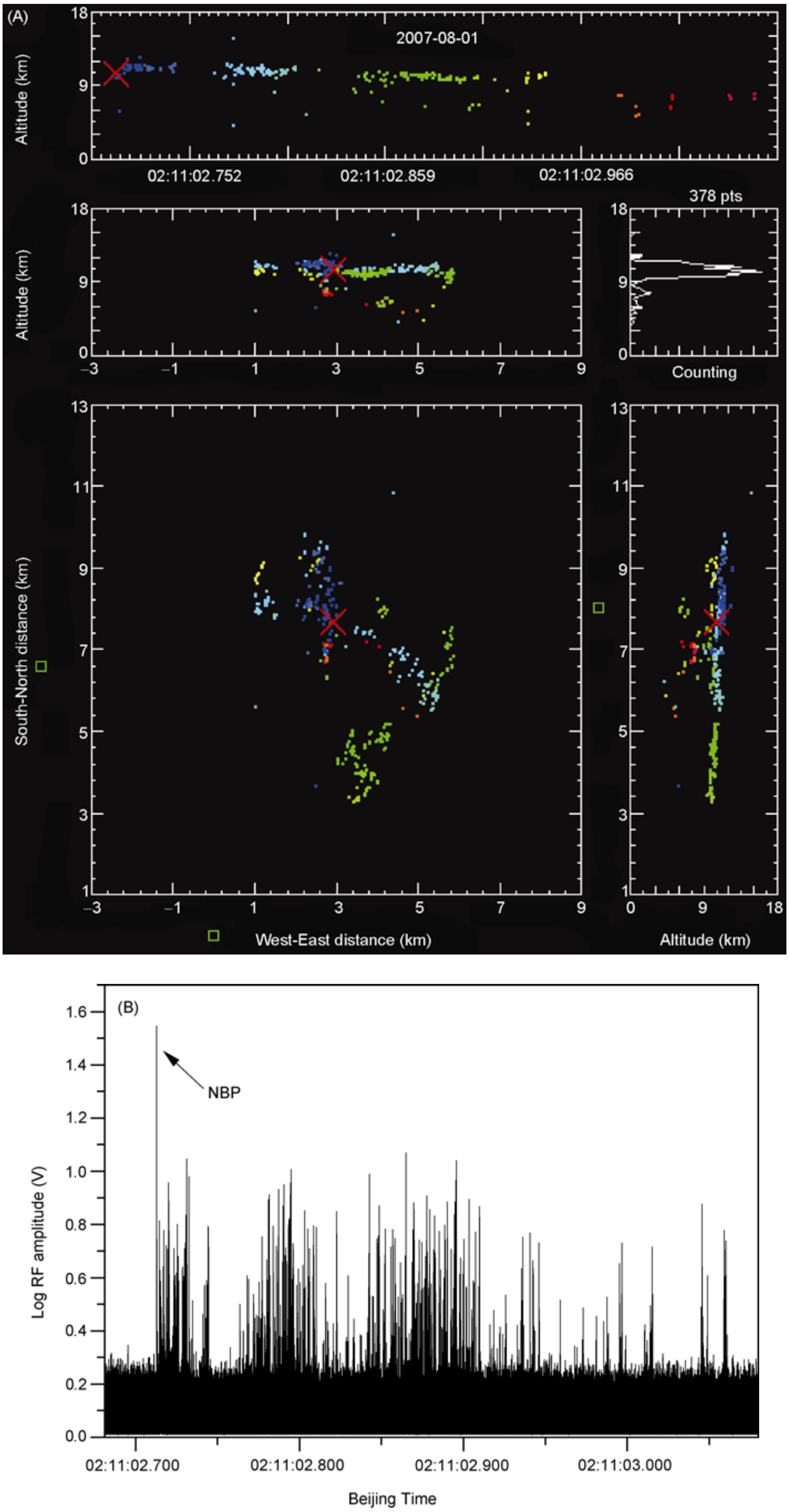
Figure 7(A) shows a new type 3D discharge process of an IC lightning at 02:11:02.712716 (Beijing Time) on August 1, 2007. The first pulse of this IC lightning was an NBP with the strongest RF radiation (center frequency of 270 MHz with its 3 dB bandwidth as 6 MHz). Figure 7(B) shows that the NBP was the first pulse of the IC lightning in the waveform of the RF radiation. The estimated value of the NBP power was higher than that of the classical lightning. The red ‘×’ in Figure 7(A) marks the occurring time and location of the NBP. Figure 7(C) shows the waveform of fast electric field change of this IC lightning. It can be seen that the polarity of the first pulse was negative, and its peak value was larger than that of all the other pulses in this IC lightning.

Figure 7(D) and (E) show the expanded waveform of the fast electric field and RF radiation waveform of the NBP respectively. It is known that the RF radiation comes from the breakdown process during the new channel formation, and only a little comes from the original channel. Figure 7(F) shows the radar echo (CAPPI at the height of 11 km) at 02:12 (Beijing Time) August 1, 2007. Figure 7(G) shows the superposition chart of this IC lightning radiation and radar RHI. The NBP was located at about 8.2 km away from the central station (Hengdian) and its height was about 10.5 km. The radar echo intensity nearby was about 15–25 dBZ. In combination with Figure 7(G), it shows that there were many radiation sources between the region 9–11 km in all echo area, especially around the NBP, but the NBP occurred only in the region that echo intensity between 15–25 dBZ.

Generally, the large bipolar pulses tended to occur in the active stage or later but not in the initial stage of lightning, and there also appeared some bipolar pulses in the initial stage of the IC lightning, but usually its amplitude was low. Thus, large amplitude NBP might be the result of the development of the IC lightning, it might not be the causes to initiate the IC lightning. But this IC lightning seemed to be initiated by the NBP. The question is how the NBP was produced.

Figure 7(A) shows that the NBP occurred at the height of about 10.5 km, corresponding to the positive charge region in the storm. It propagated as an approximate X shape from inside to outside and formed long horizontal channels. From the figure, it could be seen that there were a lot of very concentrated horizontal breakdown processes. Still, there were also a few vertical breakdown processes shown by the radiation points in the vertical channel. The propagating process mentioned above indicated that the initial breakdown of this IC lightning occurred in the positive charge region. It was triggered by the NBP, and then entered into the very active phase directly, without a conventional preliminary breakdown process. Its main channel was horizontal, not vertical; in other words, the channel of this type IC lightning propagated in the positive charge region in the initial stage similar to that of a +CG lightning. From some recent observations, it was found that the triggered point of the +CG lightning might also be in the upper positive charge region (such as the winter thunderstorm in Japan). The positive breakdown was initiated from local high positive potential; meanwhile, the negative streamer propagated and drove up the positive potential of the triggered point then triggered the positive breakdown. The negative streamer would disappear if the positive potential at the triggering point was not high enough to produce positive breakdown. If the positive charges were concentrated enough in some region, it might be possible to trigger a positive breakdown directly and enabled the propagation of the positive streamers in the concentrated positive charge region. If this streamer entered the local negative charge region during its propagation, the NBP was triggered by strong neutralization between positive and negative charges. Because the positive charge in the positive streamers was neutralized, the negative streamers was strengthened and intensive radiation source occurred just as it is shown in Figure 7(A), which was similar to the normal IC lightning. Hence we consider that this type of IC lightning was initiated by the NBP in the positive charge region. It was originated from the extremely high local potential in the positive region.

There are some opposite charge clusters, especially free electron clusters in the upper-atmosphere, because of the ionization by cosmic rays from the outer space [17]. We think that the opposite charge cluster mentioned above in the positive charge region is just accumulated by these free electrons. There are lots of free electrons in the atmosphere, which could even decrease the threshold of breakdown to one tenth. The free electrons are accelerated in the electric field and easy to form electron avalanche and the positive streamers. The NBP may be initiated when the positive


(A)
2007-08-01
Altitude (km)
02:11:02.752
02:11:02.859
02:11:02.966
378 pts
Counting
South-North distance (km)
West-East distance (km)
Altitude (km)
(B)
NBP
Log RF amplitude (V)
02:11:02.700
02:11:02.800
02:11:02.900
02:11:03.000
Beijing Time

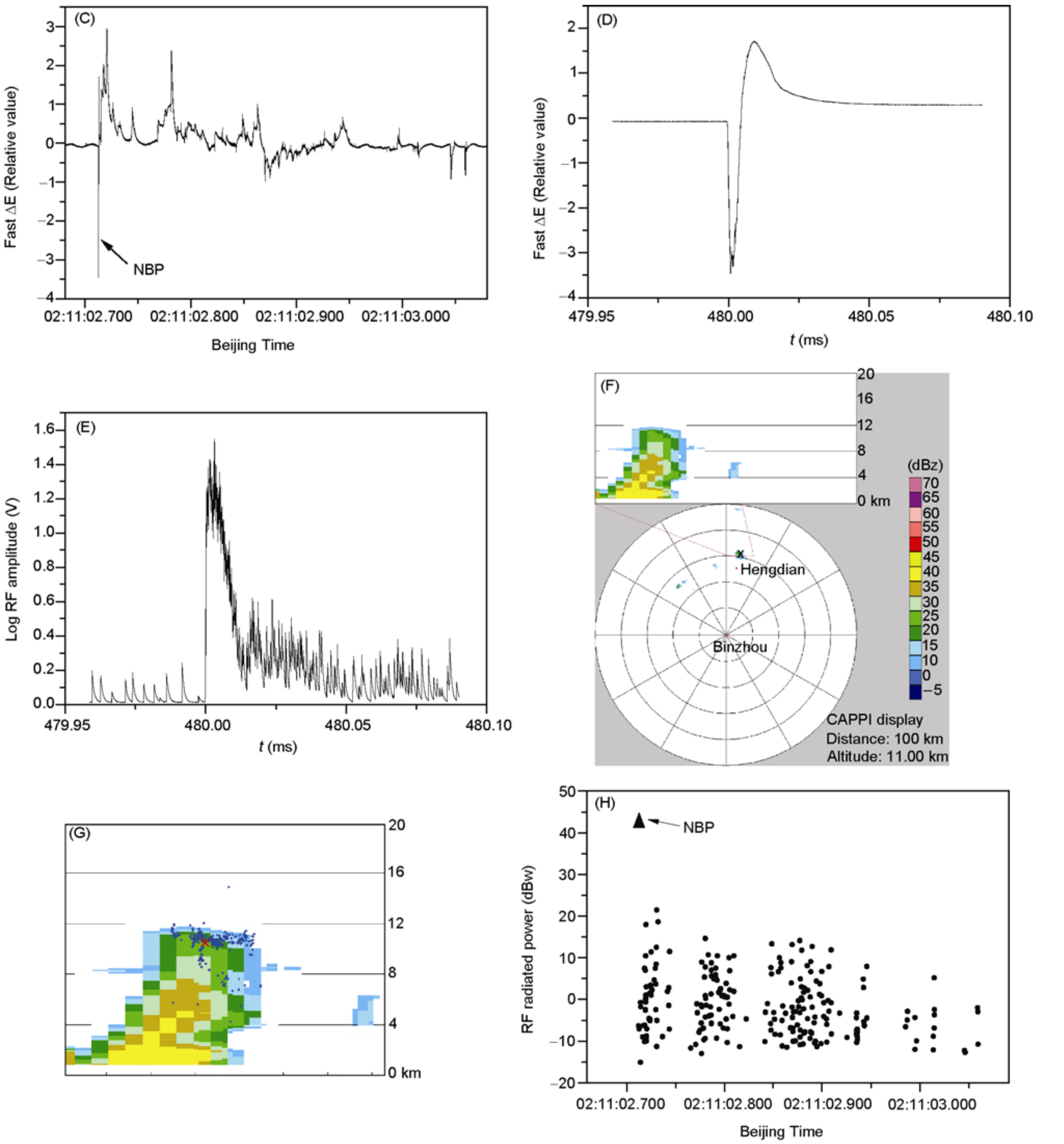


Figure 7 (A) An IC lightning initialed by the NBP occurring at 02:11:02 (Beijing Time) August 1, 2007. (B) The RF radiation waveforms of the NBP and the IC lightning initialed by it (from Hengdian) in logarithmic RF radiation amplitude (Log RF). (C) Time waveform of electric field change (Fast ΔE) from the NBP and the IC lightning initialed by it (from Hengdian). (D) The expanded time waveform of electric field change (Fast ΔE) from the NBP (from Hengdian). (E) The expanded RF radiation waveform of the NBP (from Hengdian) in logarithmic RF radiation amplitude (Log RF). (F) The radar echo of thunderstorm at 02:12 (Beijing Time) August 1, 2007. The CAPPI at height 11 km. (G) The superposition of RHI indicated in (F) and radiation sources. (H) The power distribution of the IC lightning initiated by the NBP from Hengdian station.

streamers meet the free electron cluster. Hence the case of the NBP is related to the opposite charge region, and the radar echo intensity in this region is not so strong according to Figure 7(F). More observation about the NBP and the theoretical calculation about runway breakdown are both needed.

We have estimated the power of this IC lightning radiation sources according to the formula [7, 18]. Figure 7(H) shows the NBP's power is much larger than that of all the other RF radiation sources. The power of all the other radiation sources was from 100 mW to 500 W while the power from the NBP reached 16.7 kW, indicating a typical NBP event. This estimated value of the NBP power is lower than that from Thomas [7, 18], and the reason might be that the receiver's frequency range we used is from 267–273 MHz, which is different from their 63 MHz. Further study needs more data.

4 Conclusions

The paper introduced an independently developed lightning VHF 3D locating system (LLR) and the observed data. The 3D radiation structures of –CG, +CG, and IC lightning flashes including IC lightning initiated by the NBP have been analyzed. Our study leads to the following conclusions:

(1) The –CG lightning was initiated by a downward negative breakdown. The radiation sources scattered around the source area of the radiation, and then became concentrated while propagating downwards as a stepped-leader. According to the 3D structure image, the preliminary breakdown process and the stepped-leader were simply separated. The velocity of the preliminary breakdown was about 5.2×10^4 m/s, and that of the stepped-leader was 1.3×10^5 m/s. Obviously, the velocity of the stepped-leader was faster than that of the preliminary breakdown process.

(2) There was negative streamer propagation in the initial stage of the +CG. Lightning, with long horizontal channel in the positive charge region, and accumulated lots positive charges to drive up the positive potential until the energy accumulated was high enough to initiate the downward going positive leader. This process was different from that of the –CG lightning flash.

(3) Most IC lightning flashes started in the negative charge region and then propagated upwards or downwards with long horizontal channel in the positive charge region. The thunderstorm was mainly a three-layer charge structure, with the middle main negative charge region (at height from 8–9 km), the upper positive charge region (at height from 11–13 km), and the lower positive charge region (at height from 3–6 km).

(4) We proposed that there are a few IC lightning flashes initiated by the NBP in the positive charge region. It propagated horizontally and did not enter the negative charge region. The 3D propagation of this new type lightning discharge process was observed for the first time in China and its possible mechanism of the initiation needs to be further studied.

(5) The power of lightning radiation sources was estimated. The results show that most of the lightning power was between the values from about 100 mW to 500 W. The power of the NBP reached 16.7 kW, much larger than that of other radiation sources in this IC lightning.

(6) The newly developed 3D locating system of lightning VHF radiation sources (LLR) can map the propagating lightning channel in space and time with high resolution, providing an effective means to improve the study on the mechanism of discharge and the NBP events in the storm.

The LLR is a high precision 3D locating system based on time-difference locating technique. Nevertheless, it is hard to locate continuous pulses by using this technique. We think that it could be improved through shortening the baseline of stations, which needs further study in the future.

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