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Study on the charge structure in thundercloud at LHAASO observatory

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Abstract: Thunderstorms, accompanying with lighting flashes, are frequent phenomena at high altitudes. The intensity and polarity of thunderstorm electric field will change dramatically. The charge structure in thundercloud is one of the hottest topics in atmospheric electricity. To know more about the thunderstorm effects on the variation of cosmic rays detected by ground-based experiments, the thunderstorm activity at LHAASO observatory and the charge distribution in thundercloud are studied in this work. The diurnal variations of thunderstorms are analyzed. We find the thunderstorms are most active in late afternoon to evening, even a few of them occurring at midnight. Based on disk model, the near-earth electric field is calculated with different charge structures in thundercloud.At the same time, using the electric field data from two ground observation stations, an inversion method is proposed to study the charge distribution in thundercloud. The evolution of several typical thunderstorm processes at LHAASO observatory are analyzed in detail. Our results will be helpful in understanding the acceleration mechanism of secondary cosmic rays caused by an atmospheric electric field,the cosmic ray variation detected by LHAASO during thunderstorms, and also be useful in the study of atmospheric physics.

Keywords: Thunderstorm, Charge Structure, LHAASO observatory

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1. Introduction

The charge structure in thundercloud is one of the hottest topics in atmospheric electricity. Thunderstorm is a common natural phenomenon with strong current, high voltage, and strong electromagnetic radiation, which has great hazards. By studying the charge structure in thundercloud, we can understand the structure and characteristics of thunderstorm and improve the efficiency of thunderstorm prevention and disaster-relief work, which is of great significance to avoid the great casualties and financial losses. At the same time, Many studies have shown that thunderstorms have great influences in the intensity and velocity of cosmic rays[1, 2, 3, 4, 5, 6, 7, 8, 9], so it is also necessary to know the charge distribution in thunderclouds to study the variations of cosmic rays in LHASSO experiments during thunderstorms.

However, this is complicated, because the structure of thunderclouds will be different for different thunderstorms, or different development stages of the same thunderstorm. The electrical charge structure of thunderstorms has long been believed to be either a vertical dipole, with positive charge above negative charge, or a tripole, with a lower positive charge region added below the dipole. These models are ubiquitous both within the atmospheric electricity community and beyond it in more general literature. As such, the classical dipole and tripole models are the paradigm for thunderstorm charge structure. At present, more and more observations show that the thunderclouds have a more complex charge structure.

To further understand the influence of thunderstorms on the ground cosmic ray intensity variations, the thunderstorm activity and the charge distributions in thunderclouds over the LHAASO observatory was analyzed in this paper. It can be found that the thunderstorms are frequent in the late afternoon and evening by studying its daily activity, sometimes occur at midnight. Furthermore, we propose an inversion method to study the charge distribution of thunderclouds using the data from only two different ground-based detectors, and analyze the evolution of several typical thunderstorm processes at the LHAASO observatory in detail. Our results will contribute to the understanding of the mechanism of secondary cosmic ray acceleration due to atmospheric electric fields and the cosmic ray variations detected by LHAASO during thunderstorms, and have important implications for atmospheric physics research.

2. Thunderstorm activity at LHAASO site

To observe and study more about thunderstorms, two atmospheric electric field monitors (Boltek EFM-100) were installed at LHAASO Observatory. One of them (here, we call it EFM-1) was installed at the roof of WCDA-2 pond in September 2019, with a saturation value of ±270 V/cm. Another one (here, we call it EFM-2) was installed on the ground in October 2021, with a saturation value of ±1000 V/cm. The EFM-100 is a low cost, high quality atmospheric electric field monitor which can be directly connected to the exhibition computer to display and record data. The polarity and intensity of the near-earth electric field can be recorded in real time. In this work, we use the value of EFM-2.

In order to facilitate our study of the electric field variation in thunderstorm weather, we specify a criterion as the basis for judging thunderstorm weather: the atmospheric electric field exceeds 100 V/cm for more than 8 min or above 200 V/cm at least 4 min. Based on these criteria, we analyzed

60 thunderstorms that occurred from April to September 2022.

Fig. 1 shows the daily distribution of thunderstorm activities. We can see the thunderstorms at LHAASO site are frequent in the late afternoon and evening, with the largest number of thunderstorms occurred at 18:00, accounting for about 23% of the total number of thunderstorms occurring throughout the day. Instead, only a smaller number of thunderstorms occurred at night, and almost no thunderstorms occurred in the dawn and morning.

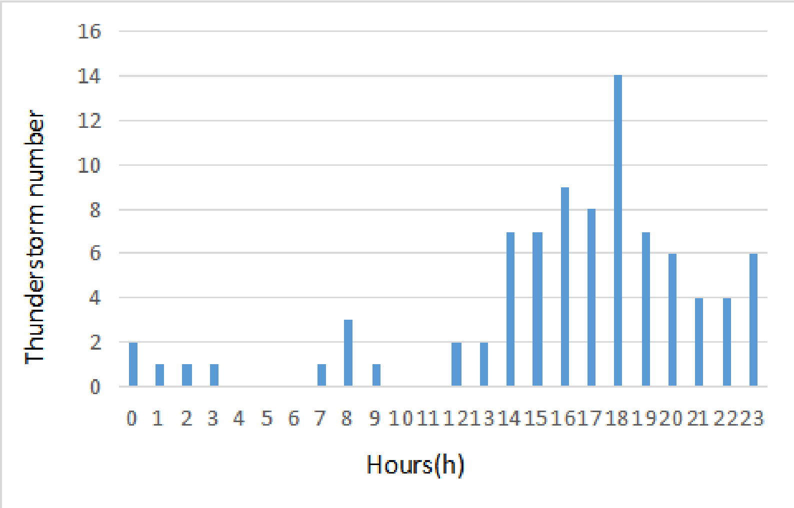

Fig. 1. Daily activity of thunderstorms in April to September

3. Two-station inversion method

3.1 The disk model of the charge structure in thundercloud

The three-polar disc model was constructed as shown in Fig. 2.

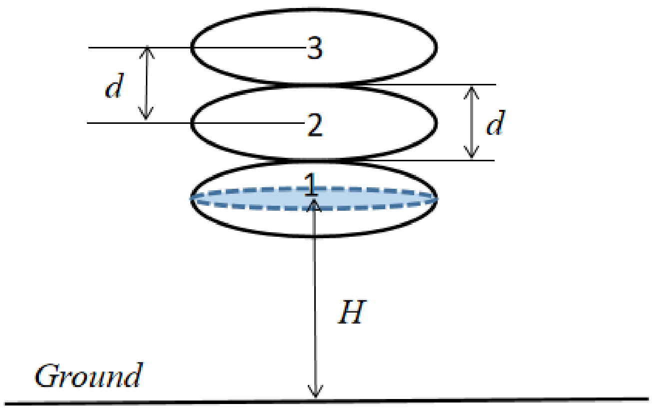

Fig. 2. The three-polar disc model

In this model, the thunderclouds are considered as three layers of uniform charged discs, and the ground electric field produced by each layer of charged discs E_i can be given by the image method as follows[10]:

$$E_i = \frac{1}{\pi \epsilon_0} \frac{Q_i H_i}{R_i^2 r_i} (1 - \frac{r_i}{\sqrt{R_i^2 + r_i^2}}) \tag{1}$$

where Q_i is the charge carried by the i-th layer disc; H_i is the vertical height of the i-th layer disc center from the ground; R_i denotes the radius of the i-th layer disc; r_i denotes the distance of the i-th layer disc center from the observation point; ϵ_0 is the vacuum permittivity; the equation takes the Z-axis negative direction as positive.

According to the vector superposition principle, the value of electric field generated by the three-polar disc model at each place on the ground can be found as:

$$E = \frac{1}{\pi \epsilon_0} [\frac{Q_1 H}{R_1^2 r_1} (1 - \frac{r_1}{\sqrt{R_1^2 + r_1^2}}) - \frac{Q_2 (H + d)}{R_2^2 r_2} (1 - \frac{r_2}{\sqrt{R_2^2 + r_2^2}}) + \frac{Q_3 (H + 2d)}{R_3^2 r_3} (1 - \frac{r_3}{\sqrt{R_3^2 + r_3^2}})] \tag{2}$$

where H is the height of the center of the first layer of discs from the ground; d is the thickness of the thundercloud or the distance between the centers of the discs.

3.2 The introduction of two-station inversion method

In recent years, there are many methods for the inversion of the charge structure in thunderstorm clouds, such as least square method[16], genetic algorithms, the hybrid inversion method of multiple intelligent algorithms [17, 18, 19], and so on.

Nowadays only two EFM-100 detectors have been installed at the LHAASO observatory, so it is theoretically impossible to do an accurate inversion of the parameters of thunderstorm clouds. Hence we propose a two-station inversion method to perform an approximate inversion for this situation, and find that the method has good results.

This method is based on an "obvious" theorem: The thunderstorm which was detected by two adjacent detectors at the same time should be the same one, which mains the electric field values recorded by the two detectors corresponding to the same thunderstorm's parameters.

Firstly, we take some values which reflect the spatial scales of thundercloud(such as H, R, d) in a reasonable range[20], and then substitute them with the electric field data E_0 and the lightning distance value r at one moment recorded by an EFM-100 into the Eq.2. If Q_1, Q_2, Q_3 are expressed by Q by given a general ratio, we can derive the approximate order of magnitude of Q at this moment.

In this work, we make the ratio of Q_1, Q_2, Q_3 equals to 1:5:6, thus obtaining the approximate range of each parameters as $Q_1 \in [40, 100]$, $Q_2 \in [150, 300]$, $Q_3 \in [150, 300]$, $H \in [1, 12]$, $R_1 \in [1, 4]$, $R_2, R_3 \in [2, 8]$, $d \in [0.5, 2.5]$.

Then we use a small-step to take all the Q_i, H, R_i, d and substitute them into the Eq.2 with the recorded lightning distance values. The two groups of electric field values we obtained named E_1 and E_2 respectively. Compare E_1, E_2 with E_0, choose the combination in which the difference is 0, and construct a deviation function δ according to the theorem we mentioned above. In this work, in order to get stable charges, we strengthen the constraint of charges, using the exponential form:

$$\delta = e^{|Q_{11}-Q_{12}|} + e^{|Q_{21}-Q_{22}|} + e^{|Q_{31}-Q_{32}|} + |H_1-H_2| + |d_1-d_2| + |R_{11}-R_{12}| + |R_{21}-R_{22}| + |R_{31}-R_{32}| \quad (3)$$

Then, we average the first 50/100 groups after arranging each group of δ values in ascending order. The obtained average value can be considered as the parameters of the thundercloud charge structure at this moment.

There are three special things need to be noted.

I. In the process of forward and inverse, we use km instead of m for the length scale to play a role of "amplifying the electric field", in the km system, the difference of the electric field will be reflected in the thousandth part or more, so it is possible to get the same combination with the E_0 value in the process of forward without taking the deviation value.

II. After sorting the δ values in ascending order, we only took the first 50/100 combinations for average, which does not affect the results. By comparison, it can be found that the Q_i average value obtained by choosing different groups of numbers is almost stable .

III. Although the method is used to invert the parameters of the point charge model, the method itself does not depend on any assumptions of the charge structure model, so it is also applicable to other models besides the point charge model.

3.3 The correctness of two-station inversion method

Song et al[19] used a hybrid inversion method to strictly invert the ground electric field data for a day in the Jiangnan area to obtain the thunderstorm cloud parameters under the point charge model. In this part, we will use the two-station inversion method in 4.1 to invert the thunderstorm clouds parameters which at 15:30 and 15:50 moments in the point charge model in the Song's paper, and also use the disc model proposed in this paper to invert the thunderstorm clouds parameters at 15:50, so as to provide a better interpretation of the transition conditions proposed in 2.

The data from two stations of electric field meters in the literature can be arbitrarily selected. For the convenience of calculation, in this paper, we choose the electric field data recorded at stations E and F. Inversion results are shown in the table1, where T means' two-station inversion method', while S means' Song's method'.

Table 1: Results of double station inversion and hybrid inversion

		$Q_1(C)$	Q_2(C)	Q_3(C)	H(km)	d(km)
15:30	T	8.694	-22.712	20.372	1.684	0.574
	S	7	-20.3	18.4	1.86	0.71
15:30	T	8.633	-22.278	29.884	1.645	0.733
	S	8.5	-26.4	32.8	1.744	0.895

It can be seen that the two-station inversion method proposed in this paper has certain correctness and can better reflect the parameter values of thunderclouds.

Using the disk model mentioned in part 2, we obtained each thunderstorm cloud parameters (Q_1, Q_2, Q_3, R_1, R_2, R_3, H, d) under the disk model at 15:50 is (8.68 C, -25.87 C, 21.63 C, 4.86

km, 11.81 km, 9.54 km, 1.81 km, 0.92 km), where Q_i is similar to but not exactly the same as the result under the point charge model, which is because the distance of the thunderstorm center from the ground electric field meter in this case is 10.07 km and 15.42 km respectively, is closer to the ground, which also indicates that for the near-ground thunderstorm, the point-charge model tends to produce big discrepancy. Furthermore, using the disk model, we can also better obtain the scale and coverage of the thunderstorm cloud, which is more instructive for the understanding of lightning protection and cosmic ray acceleration/deceleration mechanisms.

4. Charge structure in thundercloud above LHAASO observatory

A thunderstorm occurring from 18:30 to 19:30 on June 12, 2022 was taken as an example to explore the evolution of the charge structure of the thundercloud, wherein only lightning smaller than 10 km is counted. It can be described in three stages according to Fig.3: formation, maturation and dissipation. And the pulse jitter of the electric field was caused by the lightning.

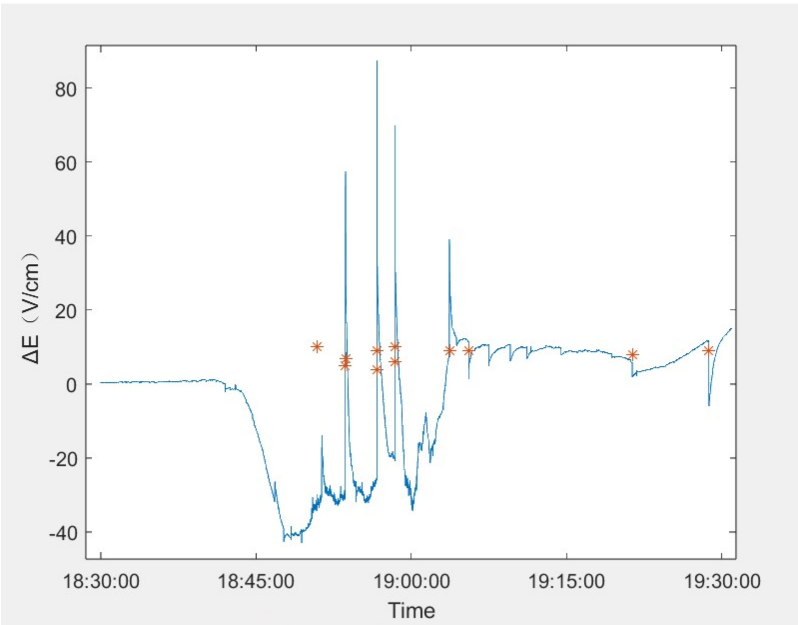

Fig. 3. The lightning events and the changes of electric field

We inverted the charge structure of thunderstorms and made a schematic of the evolution of it. It can be seen from the inversion results that the amount of charge in the negative charge region of the thunderstorm cloud decreased after a lightning. Because the total amount of negative charge was still large, the near-earth electric field was negative polarity. At 19:21, the height of the thunderstorm cloud at was closer to the ground than that at the mature stage, and the positive charge region at the bottom of the thunderstorm cloud further enhanced its effect on the near-earth electric field, so the near-earth electric field was positive. Through this method, we can obtain a more clear change process of the charge structure of the thunderstorm cloud through the inversion analysis of more moments.

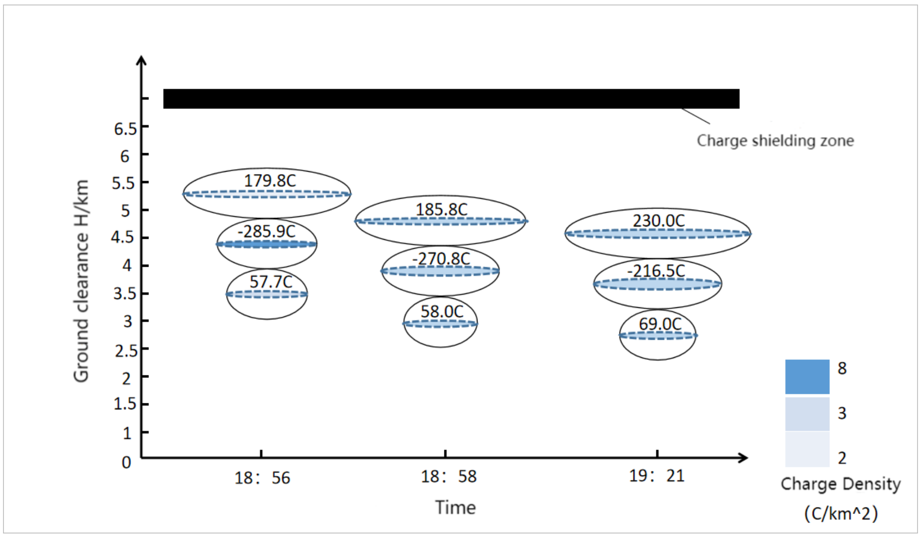

Fig. 4. The evolution of the charge structure of thundercloud above LHAASO Observatory at June 12

5. Summary

The charge structure of thunderclouds has a great significance in the research of the cosmic rays idensity variation. In this work, we first conducted an analysis of the daily activities of the LHASSO Observatory for thunderstorms from April to September, and we can see that the thunderstorms are frequent in the late afternoon and evening, sometimes occur at midnight.

Then we use a new inversion method, double station inversion, to study the charge structure of the thundercloud the LHASSO observatory. We explore the evolution of the charge structure of thunderstorms occurring from 18:30 to 19:30 on June 12, 2022. From the inversion results, we can see that the amount of charge in the negatively charged area of the thunderstorm cloud decreases after lightning occurs. Since the total amount of negative charges is still large, the near-ground electric field is negative polar. Through this method, the charge structure change process of thunderstorm clouds can be obtained.

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