

A statistical study on the correlation between sporadic Ca⁺ layer and Es in Beijing (40.5°N, 116°E)

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Key Points:

- The sporadic Ca⁺ layers with a maximum density of 5–2200 cm⁻³ distributed at the altitudes ranging from 88 to 120 km.
- The sporadic Ca⁺ layer and the sporadic E layer (Es) are correlated by 61.89% at Beijing (40.5°N, 116°E), which was observed by both lidar and ionosonde at the same time.
- The peak density of the sporadic Ca⁺ layer is directly related to the intensity of the sporadic E layer. During the summer, this correlation becomes more pronounced.

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Abstract: From April 2020 to June 2022, a Ca⁺ lidar with dual-wavelength and narrow-band emitting lasers utilizing all-solid-state technology was employed to conduct observations in Beijing (40.41°N, 116.01°E) for a total duration of 1797.79 hours over 280 nights. A total of 286 sporadic Ca⁺ layers were observed, with heights ranging from 88 to 120 km and densities varying from 5.33 to 2200 cm⁻³. We simultaneously observed the ionosonde, located 28 km from the lidar, and found a correlation of 61.89% between the sporadic Ca⁺ layer and the sporadic E layer. When the sporadic Ca⁺ layer has a downward phase trend, there is a correlation of 76.84%. By excluding the influence of ionosonde sensitivity, we focus only on calcium ions that have a density exceeding 140 cm⁻³, which exhibit a correlation of 82.25%. Above 100 km, the correlation significantly increases, reaching approximately 90%. Furthermore, the correlation between the sporadic Ca⁺ layer and the sporadic E layer is particularly noticeable during the summer season, reaching around 90%. This phenomenon can be attributed to the variations in metal ions that occur during different seasons.

Keywords: the Meridian Project; lidar; sporadic Ca⁺ layer; sporadic E layer

1. Introduction

In the mesosphere and low thermosphere regions of 75–115 km, there are stable layers of metal atoms and ions. These layers are formed due to the ablation and release of cosmic dust (Plane et al., 2015). Since Slipher and Bowman et al. (1969) first observed sodium atoms using resonant fluorescent airglow and lidar in 1929 and 1969, respectively, atoms and ions such as Na, Fe, K, Ni, and Ca have been observed one after another. The fine structures of these atoms and ion layers, including potential effects of meteor injection (Clemesha et al., 1980, 1988), dust release (von Zahn et al., 1987), ion neutralization (Cox and Plane, 1998; Collins

et al., 2002), vertical transport (Chu XZ and Yu ZB, 2017), horizontal transport (Chu XZ and Yu ZB, 2017), and so on, gradually become visible as lidar's detection capability improves. Metal atoms in the thermospheric metal layer are useful tracers for studying atmospheric chemical and dynamical processes.

Due to the resonance absorption wavelengths of other metal ions in the ultraviolet range and being readily absorbed by ozone, Ca⁺ is the only metallic species that can be detected by ground-based instruments. Since 1985, Granier et al. (1985) conducted the first lidar detection of Ca⁺ in Haute Provence, France (44°N, 6°E), and they observed that Ca⁺ was mainly concentrated at a height of 2–4 km. Gardner et al. (1993) observed an irregular Ca⁺ profile of 90–100 km in Urbana, Illinois (40°N, 88°E). Alpers et al. (1996) reported frequent sporadic Ca⁺ layers at 90–120 km in Juliusru (54.5°N, 13.4°E), Germany. Other researchers subsequently confirmed the existence of a sporadic Ca⁺ layer. Gerding et al. (2000) took a comprehensive observation of Ca and Ca⁺ in Kühlungsborn (54°N, 12°E) Germany, found an abrupt density

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enhancement of the Ca^+ layer; [Gerding et al. \(2001\)](#) gave the definition of the sporadic Ca^+ layer, since it cannot be determined whether the observed density variation is caused by local chemical processes or by the transmission of inhomogeneous layers through the lidar field of view. Therefore, the sporadic layer is defined only by its full width at half maximum (FWHM), with a FWHM less than 5 km. Recently, [Raizada et al. \(2020\)](#) first reported that the Ca^+ layer extends to 180 km in the equatorial region (18.35°N, 66.75°W). In 2022, [Jiao J et al. \(2022\)](#) first reported that during the geomagnetic quiet period, the Ca^+ profile in the mid-latitude of Yanqing, Beijing (40.5°N, 116°E) up to 300 km and a complete upward and downward structure accompanied by Es and spread F were seen. Research on the coupling between the middle and upper atmosphere, using calcium ions as tracers, has seen further expansion ([Ejiri et al., 2019](#); [Raizada et al., 2020](#); [Jiao J et al., 2022](#)).

Metal ions are the main component of the sporadic E layer (Es) ([Kopp, 1997](#)). The Es layer has a high electron density, which will absorb and scatter radio waves, seriously affecting satellite communications and navigation that rely on the propagation of radio waves across the ionosphere. Unfortunately, it is still challenging to understand and predict the formation rules of the Es layer.

The correlation between the sporadic Na layer (SSL) and the Es was first discovered by [Clemesha et al. \(1980\)](#) and subsequently reported by many studies ([Von Zahn and Hansen, 1988](#); [Mathews et al., 1993](#); [Nagasawa and Abo, 1995](#); [Dou XK et al., 2009](#)). [Gardner et al. \(1993\)](#) observed a correlation between the Fe_s , Na_s , and sporadic Ca^+ layers alongside the Es layer. They proposed that the neutralization of Fe^+ and Na^+ within the corresponding sporadic E layer generates the sporadic Fe layer and sporadic Na layer above 100 km altitude. [Dou XK et al. \(2009\)](#) conducted statistical analysis and discovered a significant correlation between the seasonal variations of sporadic sodium layers (SSL) and the Es layer. For a long time, research on the correlation between metal layers and Es has focused on the metal atomic layer, mainly through changes of the metal atomic layer to understand the dynamics and composition of the middle and upper atmosphere and ionosphere.

However, there are few reports on the correlation between the metal ion layer and the Es layer. [Gardner et al. \(1993\)](#) proposed that the sporadic Ca^+ layer may be related to the Es layer. [Tepley et al. \(2003\)](#) reported that in a small sample, there is always a good correlation between Ca^+ and electron density, whether it is distributed in narrow tidal ion layers, or as a more diffuse distribution of ionization. Subsequent studies have demonstrated a typical connection between sporadic Ca^+ layers and electrons which were detected by IS radar and lidar from the Arecibo Observatory (18.4°N, 66.8°W) ([Tepley et al., 2003](#); [Raizada et al., 2011, 2012](#)). [Ejiri et al. \(2019\)](#) recently found that the peak density of Ca^+ has a strong positive correlation with the electron density. By using ions to study atmospheric physics, chemical changes, and ionospheric responses, Ca^+ has been recognized as an excellent tracer for coupling between the middle and upper atmosphere and the ionosphere. However, these studies are limited to a single case study ([Ejiri et al., 2019](#); [Raizada et al., 2020](#); [Jiao J et al., 2022](#)).

Recently, we used an OPO/OPA lidar to conduct Ca^+ observations in Beijing, and carried out comprehensive statistics on sporadic Ca^+ layers from April 2020 to June 2022. Furthermore, using concurrent lidar and ionosonde observations, we statistically analyzed the correlation between the sporadic Ca^+ layer and the sporadic E layer (Es) in Beijing. The relationship between metal ions and Es can be shown directly.

2. Sporadic Ca^+ Layer Lidar Observation

The all-solid-state Ca^+ lidar system was built and operated by March 2020 in Beijing (40.5°N, 116°E). The emission system consists of a seed laser, an Optical Parametric Oscillator (OPO), an Optical Parametric Amplifier (OPA), a frequency-doubling crystal, an optical lens and a beam splitter. The laser emission system uses a seed-injected Nd: YAG laser to pump OPO/OPA laser, and injects a 786 nm seed laser into the resonator of the OPO to generate a pulse 786 nm signal laser and idle laser. Wherein the idle laser attenuates the output and the signal laser is further amplified through OPA. Finally, the amplified 786 nm signal laser is converted into a 393 nm emission laser by the SHG module, see Figs. 1 and 2 of [Du LF et al. \(2023\)](#). The 393 nm laser beam excites the resonance fluorescence of Ca^+ with a single pulse energy of the laser reaching 30 mJ. The receiving system is a telescope with a 1.23 m aperture. The Ca^+ data have a raw time resolution of 33 s and a height resolution of 96 m.

We employed Ca^+ data collected between April 2020 and June 2022. This dataset covers 266 nights of observation, totaling 2193.73 hours. We obtained lidar and ionosonde measurements simultaneously on 200 nights, resulting in a total observation time of 1797.79 hours. [Figure 1](#) depicts the distribution of all observation hours by month and hour. According to [Gerding et al. \(2001\)](#), the sporadic metal ion layer is defined as having a full width at half maximum (FWHM) of less than 5 km. This work presents an extension of the sporadic atomic and ionic layers' definition. The sporadic Ca^+ layer is defined by two criteria: its density is twice as high as the average background density of Ca^+ , and the altitude extension (FWHM) is less than 5 km ([Gerding et al., 2001](#); [Dou XK et al., 2013](#)). The average background density of Ca^+ refers to the average density at the non-sporadic layer period for the whole night. We observed a total of 286 sporadic Ca^+ layers from April 2020 to June 2022. The average occurrence rate of the sporadic Ca^+ layers is defined as the ratio of the number of sporadic Ca^+ layers within the total observation hours. The average occurrence rate of the sporadic Ca^+ layers in Beijing is approximately 1 event / 6.29 h.

[Ma ZZ and Yi F \(2010\)](#) found that the occurrence rate of the sporadic Fe layer was 1/11.58 h at (30°N). [Dou XK et al. \(2013\)](#) reported average occurrence rates of approximately 1/46.0, 1/12.3, 1/13.8 and 1/15.0 h, for sporadic sodium atom layers in Beijing (40.2°N, 116.2°E), Hefei (31.8°N, 117.3°E), Wuhan (30.5°N, 114.4°E), and Haikou (19.5°N, 109.1°E), respectively. [Jiao J et al. \(2016\)](#) found that the occurrence rate of the sporadic K layer in Beijing was approximately 1/35 h. In this paper, we found that the sporadic Ca^+ layer occurrence rate in Beijing was approximately 1/6.29 h. The occurrence rate of ions is higher than that of metal atoms.

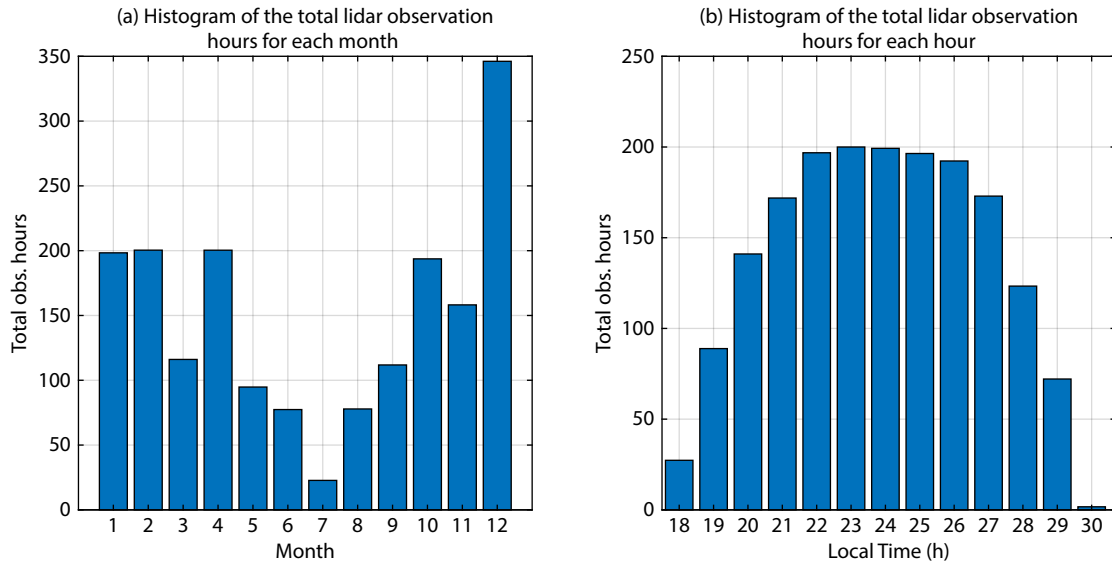


Figure 1. The distribution of all observation hours by month and by hour.

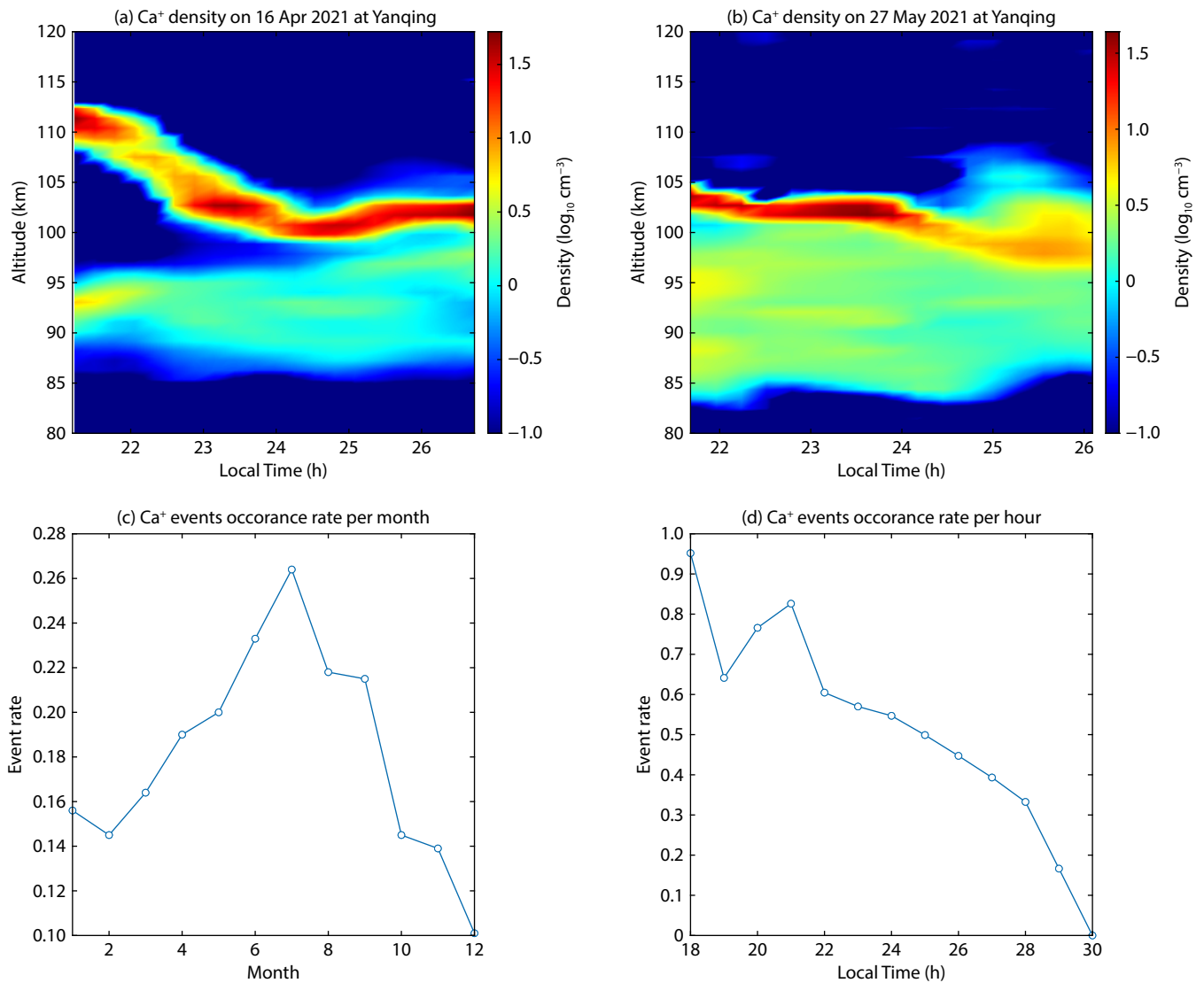


Figure 2. Examples of sporadic Ca⁺ layers at (a) Apr 16 in 2021 and (b) May 27 in 2021. And the (c) monthly and (d) hourly occurrence rates of sporadic Ca⁺ layers.

Figure 2 shows two cases of sporadic Ca^+ layers and the monthly and hourly occurrence rate of the sporadic Ca^+ layer. Figure 2a shows that the sporadic Ca^+ layer began at an altitude of 113.3 km and dropped to 100.8 km between 20:40 and 27:29 LT. The rate of descent was 1.84 m/s. The maximum density observed was 111.7 cm^{-3} at an altitude of 111.4 km at 20:58 LT. In Figure 2b, between 21:08 and 25:58 LT, the sporadic Ca^+ layer began at an altitude of 104.6 km and gradually dropped to 97.92 km at an average rate of 1.38 m/s. The peak density reached its maximum value of 84.71 cm^{-3} at 23:24 LT, at a height of 102.7 km.

Figure 2c illustrates the monthly occurrence rate of sporadic Ca^+ layer formation from January to December. The occurrence rate varies between 0.101–0.264 events/hour, with an average value of 0.181. The sporadic Ca^+ layer's annual occurrence rate peaks at 0.264 in July and reaches a minimum of 0.101 in December. Figure 2d illustrates the frequency distribution of sporadic Ca^+ layer occurrence rate per hour, ranging from 0 to 0.952 events per hour. The sporadic Ca^+ layer exhibits its maximum frequency of 0.952 at 18 LT after sunset, followed by a secondary peak frequency of 0.826 at 21 LT. Afterwards, the occurrence rate of the sporadic Ca^+ layer showed a gradual decrease over time. The sporadic Ca^+ layer consistently occurred at a frequency of 0.547 or higher between 18 and 24 local time.

Figure 3 displays histograms illustrating the distribution of time, height, and peak density of the sporadic Ca^+ layers. Figure 3a displays the temporal distribution of sporadic Ca^+ layers. The sporadic Ca^+ layers are mainly observed between 20–27 LT. Figure 3b shows the sporadic Ca^+ layers are distributed in the range of 88–120 km. And the sporadic Ca^+ layers are mainly concentrated between 92.16 and 100.8 km. The sporadic Ca^+ layer's average height is 99.06 km. The peak density of the sporadic Ca^+ layers in Figure 3c is distributed within the range of $5.33\text{--}2200 \text{ cm}^{-3}$. The majority of the density of the sporadic Ca^+ layer is below 600 cm^{-3} , with an average density of 315.98 cm^{-3} .

3. Correlation Statistics Between the Sporadic Ca^+ Layer and Es

Metal ions play a significant role in the composition of the sporadic E layer, as demonstrated by Kopp (1997). Raizada et al. (2011) conducted a study that demonstrated a simultaneous

increase in the density of Ca^+ and electrons. Then Raizada et al. (2012) observed a declining Ca^+ layer that correlates to electron density. These observations suggest a potential temporal and geographical relationship between the Ca^+ layer and Es. The Shisanling Station (Beijing National Observatory of Space Environment, Institute of Geology and Geophysics Chinese Academy of Sciences, 40.3°N , 116.2°E) carries out a concurrent ionosonde observation simultaneously. The distance between this station and the Beijing lidar station is 28 km. The ionosonde has a 15-minute temporal resolution and a 1-kilometer spatial resolution. In this context, the Es used meets the requirement of having a critical frequency ($f_o\text{Es}$) greater than 1.5 MHz.

We specify two requirements for the correlation between calcium ions and Es: (1) the time interval between the two must be shorter than 15 minutes, and (2) the height disparity between the two must be smaller than 5 km. Figures 4a and 4c depict examples of simultaneous occurrences of the sporadic Ca^+ layer and Es on June 2nd and June 4th, 2021, respectively. The bottom point of the line segment in the diagram represents the virtual height of Es (h'_{Es}), while the length of the line segment represents the crucial frequency ($f_o\text{Es}$) of Es. Figure 4a shows that on June 2, 2021, the sporadic Ca^+ layer persisted from 21:02 LT to 26:31 LT, with a height distribution between 100 and 110 km and a vertical width of about 5 km. The density reaches its maximum value at 407.4 cm^{-3} , and this occurs around 25:51 LT. The Es appears from 21:30 LT to 26:15 LT, with a height distribution between 100 and 111.3 km. The maximum $f_o\text{Es}$ are 7.05 MHz, and the trajectory of Es typically shows a declining pattern, often accompanied by a sporadic Ca^+ layer. Figure 4c shows that on June 4, 2021, the sporadic Ca^+ layer lasted from 21:00 LT to 25:55 LT, with a height distribution between 96 and 120 km and a vertical width of about 5 km. The peak density is 705.3 cm^{-3} , and it occurs at 24:43 LT. The Es appears from 21:15 LT to 26:15 LT, with a height distribution between 97.5 and 121.3 km. The maximum $f_o\text{Es}$ is 6.7 MHz. The sporadic Ca^+ layer often exhibits a downward trend in the trajectory of Es. Figures 4b and 4d show the correlation between the sporadic Ca^+ layer and Es during the observation period. The linear Pearson coefficients for these correlations are 0.7733 and 0.9046 respectively. We found a significant correlation between Es and the sporadic Ca^+ layer.

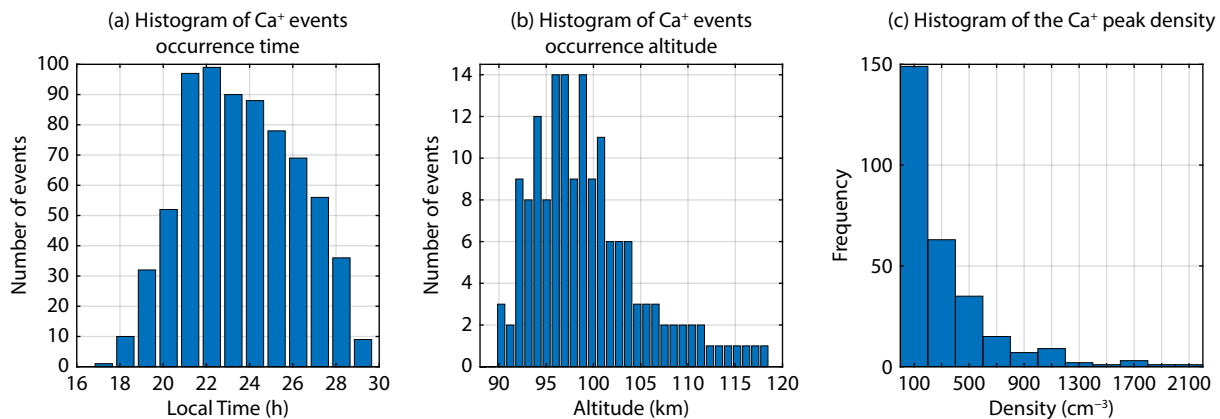


Figure 3. Histogram of occurrence time, height range, and peak density of sporadic Ca^+ layers.

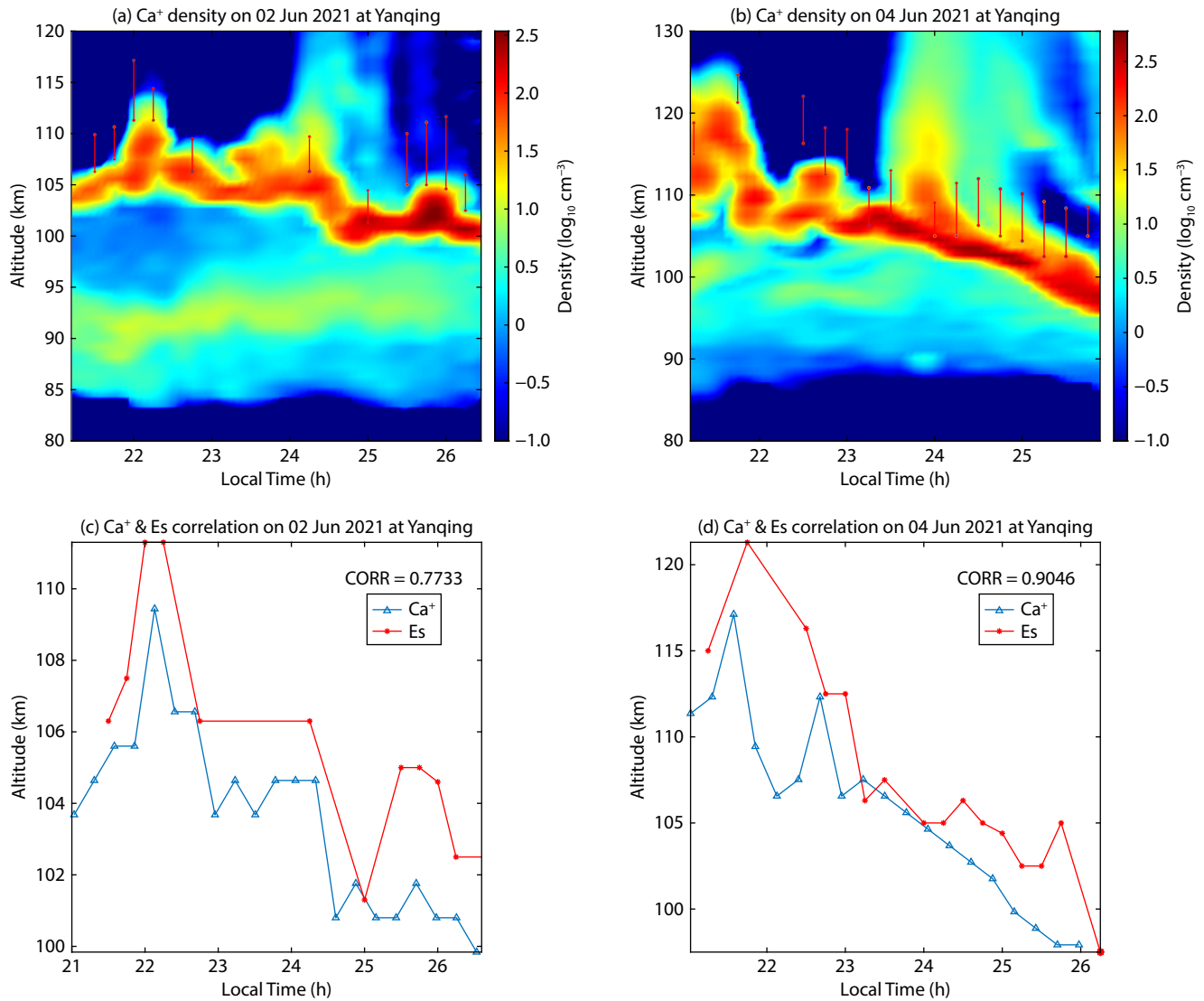


Figure 4. Correlation between the sporadic Ca^+ layer and Es on June 2nd and June 4th, 2021.

These two cases illustrate the temporal and spatial relationship between the sporadic Ca^+ layer and Es. In Figure 5, we statistically calculated and graphed the time and altitude distribution of all sporadic Ca^+ layers and Es together. The Es mainly occurs in the 20–26 LT, which overlaps with the occurrence time of the sporadic Ca^+ layer. And the Es are distributed in the 91.9–129.3 km altitude range, and Ca^+ layers occur mainly in the 101.5–112.1 km altitude range. Generally, the altitude of Es is higher than that of the sporadic Ca^+ layer.

4. Discussion

Over a period of 200 nights between 2020 and 2022, where lidar and ionosonde observations were conducted simultaneously, a total of 286 sporadic Ca^+ layers was observed. There were 177 sporadic Ca^+ layers that were associated with Es, accounting for 61.89% of them. The statistical analysis reveals significant correlations between the Ca^+ layer and Es under certain circumstances, namely when the sporadic Ca^+ layer has a decreasing pattern, the peak density exceeds 200 cm^{-3} , and during the summer season. The correlation between metal atoms and Es is generally consid-

ered to be that metal ions in Es can be neutralized to form metal atoms. This is supported by the theory proposed by Cox and Plane (1998), which suggests that Na^+ is neutralized and the formation of SSL (sporadic sodium atom layers) occurs in the descending Es layer. Therefore, we investigated the correlation of Na, Fe, and K with Es in comparison. Generally, the criteria for determining that metal atoms are correlated with Es in time are that they appear within 2 hours of each other. Dou XK et al. (2013) found that the correlation between SSL and Es in Beijing (40.2°N, 116.2°E), Hefei (31.8°N, 117.3°E), Wuhan (30.5°N, 114.4°E), and Haikou (19.5°N, 109.1°E) was about 64.5%, 45%, 47%, and 51.67%, respectively. Ma Z et al. (2014) found that 49% of Nas occurrences in Qingdao (36°N, 120°E) were related to Es. According to Alpers et al. (1994), they observed that at polar latitudes (above 67°), 23% of Fes events occurred within 2 hours after the Es event. Jiao J et al. (2016) reported in Beijing (40.5°N, 116.2°E) that 15 of 21 Ks events, or 71.43% of the total, were associated with Es. And 14 of these events occurred within a two-hour timeframe, accounting for 66.67%.

The correlation between the sporadic Ca^+ layer and Es is strength-

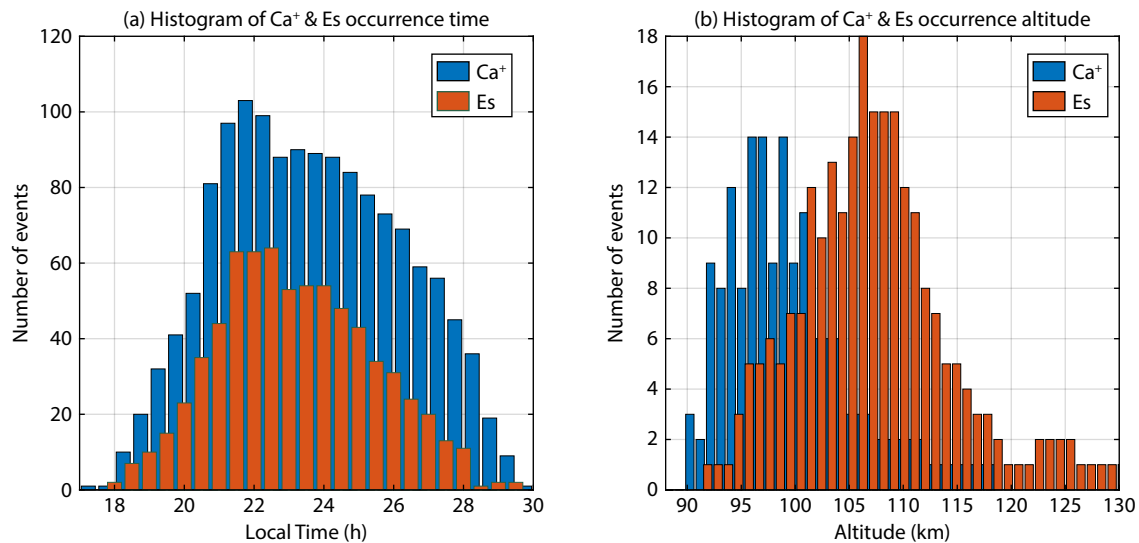


Figure 5. Time distribution, altitude distribution of sporadic Ca⁺ layers and Es.

ened when there is a downward tendency in the movement of the sporadic Ca⁺ layer. We can describe the movement pattern of the sporadic Ca⁺ layer using the following criteria: we classify a rate of height change ranging from -0.139 to 0.139 m/s as "acclinic," indicating a horizontal trend; we classify a rate of height change below -0.139 m/s as "down," indicating a descending trend, and we classify a height change rate above 0.139 m/s as "up," indicating an ascending trend. Shown as Figure 6a, the 286 events, 29 cases showed an "up" trend, 50 cases showed an "acclinic" trend, 199 cases showed a "down" trend, and 8 cases showed no obvious trend (no UAD). We have analyzed a total of 177 sporadic Ca⁺ layers showing excellent correlations with Es. Among them, there were 13 cases exhibiting an "up" trend, accounting for 7.34%. Additionally, 24 cases had an "acclinic" trend, accounting for 13.56%. Furthermore, 136 cases had a "down" trend, accounting for 76.84%. Finally, there were 4 examples that did not show any clear pattern, which accounted for

2.26%. Figure 6b shows the distribution of average height change rate.

Raizada et al. (2012) observed a notable descending in the sporadic Ca⁺ layer. Voiculescu and Ignat (2003) proposed that the observed downward movement may be caused by the interaction between tidal and planetary waves. In addition, Haldoupis (2011) observed a comparable decrease in the Es layer. This fits with Mathews's (1998) study, which indicates that the Arecibo ISR observations demonstrate that diurnal and semidiurnal tides are the primary factors responsible for the formation and subsequent decrease in height of Es layers. Both the Ca⁺ layer and the Es layer exhibit a descending pattern, primarily influenced by waves. The statistical analysis supports the hypothesis that there is a strong association between the sporadic Ca⁺ layer and Es during the descent process.

The ionospheric E-region irregularities observed by VHF radar are

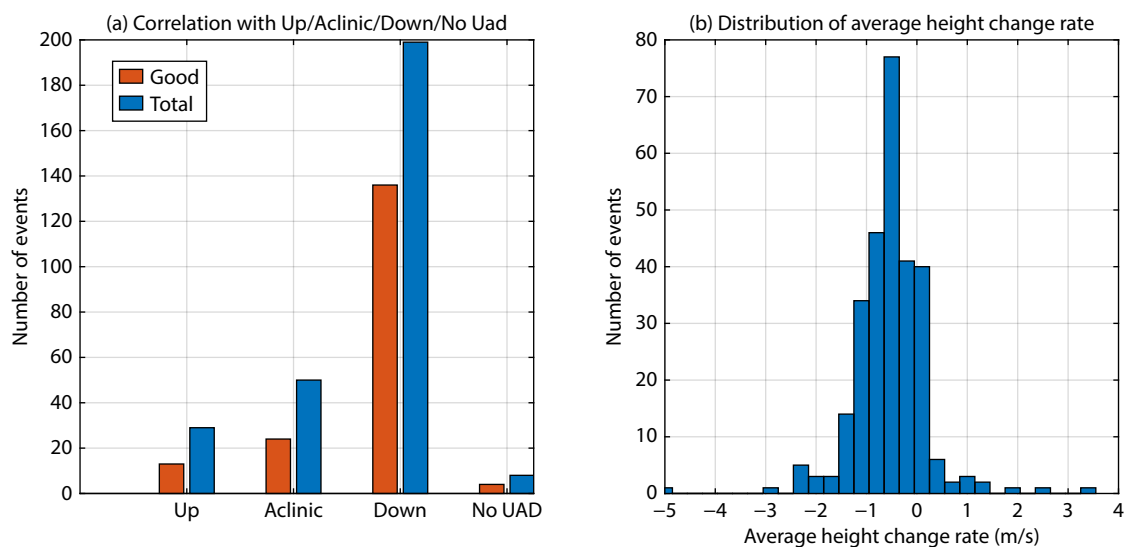


Figure 6. Statistics of the movement trend of the sporadic Ca⁺ layer and the distribution of the average height change rate ("total" represents the overall quantity of a single trend; "good" represents the number of events with high correlation).

mainly of two types: continuous and quasi-periodic. The continuous E-region irregularities mainly correspond to large tidal Es layers over the radar, while the quasi-periodic irregularities correspond to structures that are spatially separated from each other (Yamamoto et al., 1991; Patra et al., 2004). The occurrence of Es is usually accompanied by ionospheric E-region irregularities (Sun WJ et al., 2023a, b). Occasionally, the ionosonde fails to detect Es because of its inhomogeneity. But the Ca^+ lidar is able to detect irregular Ca^+ layers with lower densities. The connection between the falling E-region irregularity layer and the atmospheric tidal wind field is widely acknowledged (Patra et al., 2007). During periods of intense tidal activity, ionosondes are able to more readily detect the presence of the expansive tidal Es layer. So, when the sporadic Ca^+ layer is decreasing, there is a higher correlation with Es.

Gardner et al. (1993) also found that metallic sodium atoms may originate from the neutralization of sodium ions above 100 km. Additionally, Ejiri et al. (2019) noted a downward trend in the Ca^+ layer from high-altitude regions to around 100 km. The stabilization of the Ca^+ layer at around 100 km and subsequent stop of its descent can be attributed to the augmented occurrence of neutral collisions at lower altitudes. Consequently, the correlation between the sporadic Ca^+ layer and Es was calculated at two distinct altitude intervals: 90–100 km, 100–120 km. Figure 7a displays the relevant statistical results. The correlation values for the altitude range of 90–100 km and 100–120 km are 41.91% and 89.15% respectively. The correlation between the sporadic Ca^+ layer and Es is particularly strong at the altitude range of 100–120 km.

Raizada et al. (2011) detected a concurrent variation in the density of Ca^+ and electron density. In addition, Ejiri et al. (2019) observed a notable correlation between the electron density and the peak density of Ca^+ . In the past, Es was considered a "sporadic" phenomenon. However, coherent scattering radar studies have indicated that at mid latitudes and low latitudes, Es are not sporadic in nature, as the term implies, but rather a frequent iono-

spheric event (Haldoupis, 2011). The ionosonde's detection sensitivity influences this phenomenon. The ionosonde's detection sensitivity is roughly 1.5 MHz. The relationship between the $f_o\text{Es}$ and the electron density is provided in Xue XH et al. (2013): $N = 1.24 \times 10^{10} f^2$. The $f_o\text{Es}$ of 1.5 MHz correspond to an ion density of about 140 cm^{-3} as detected by Ca^+ lidar. Therefore, in order to eliminate the impact of detection sensitivity, we calculated the correlation data of the sporadic Ca^+ layer density between $140\text{--}700 \text{ cm}^{-3}$, which is shown in Figure 7b. A total of 169 incidents were recorded with peak densities exceeding 140 cm^{-3} . Out of these, 139 cases showed strong connections, about 82.25% of the total. In further there were 137 cases of Ca^+ layer peak density above 200 cm^{-3} . Of these cases, 120 had a strong association with Es, or 87.59% of the total. Once the density of the Ca^+ layer exceeds 500 cm^{-3} , the correlation achieves a value of 96.61%. The correlation reached nearly 100% when the concentrations exceeded 650 cm^{-3} . Therefore, we believe that the calcium ions not bound to Es might be influenced by the ionosonde's detection sensitivity.

There is a significant correlation between the sporadic Ca^+ layer and Es during the summer. Raizada et al. (2012) presented two cases, one in June and the other in October, showing the density of Ca^+ and its correlation with electron concentrations during summer and winter at Arecibo Observatory. Here, we confirm that the summer season spans from May to August, while the winter season spans from November to February. We identified a total of 60 sporadic Ca^+ layers during the summer, and observed 117 layers during the winter. The incidence rate is 0.22 and 0.13, respectively. During the summer season, the frequency of sporadic Ca^+ layers is approximately 1.69 times higher compared to the winter season.

Prior research conducted by Whitehead (1989) has documented significant latitudinal and seasonal variations in the E region of the ionosphere. Furthermore, it has been observed by other researchers that there is a twofold increase in electron abundance during the summer compared to the winter (Gerding et al., 2000).

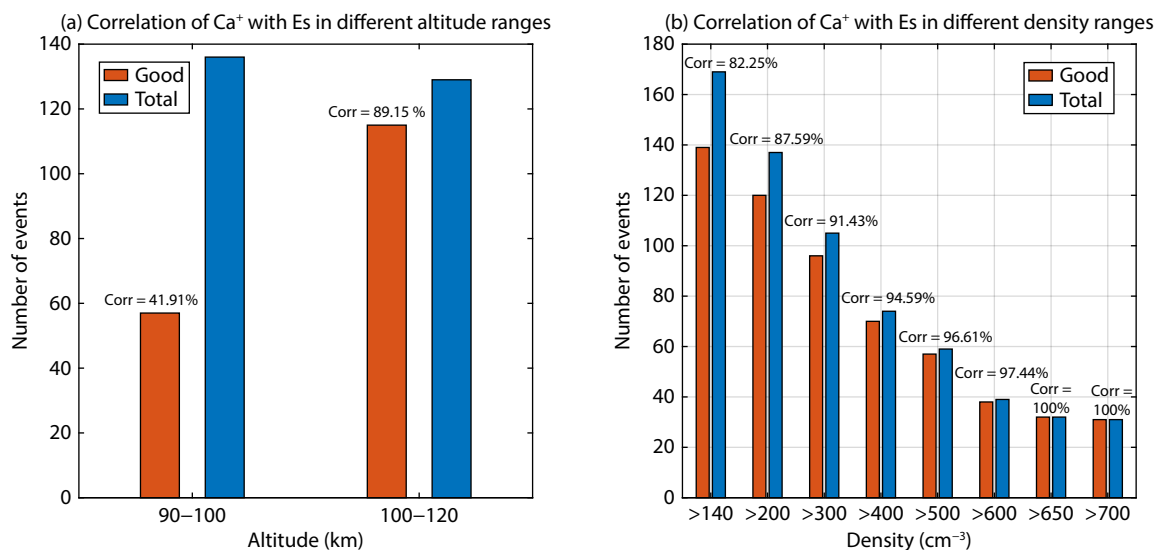


Figure 7. Correlation statistics between the sporadic Ca^+ layer and Es in different altitude ranges and density ranges.

Thus, the highest values of Es during the summer could be attributed to a rise in the concentration of metallic ions (Whitehead, 1989). Later, certain researchers suggested that the occurrence and intensity of Es could be influenced by the seasonal variation of metal ions. The daily meteor count rates exhibit significant seasonal variations, peaking during the summer, similar to the Es layer (Singer et al., 2004; Janches et al., 2004; Lau et al., 2006; Haldoupis, 2011). We conducted a statistical analysis in the summer and winter, respectively. We found that 54 cases were related to Es, accounting for 90% of the 60 sporadic Ca⁺ layers that occurred during the summer. Similarly, we found 59 cases correlated with Es out of the 117 sporadic Ca⁺ layers that occurred during the winter, accounting for 50.43%. The correlation between the sporadic Ca⁺ layer and Es is notably stronger during the summer than in the winter.

The statistical mean peak Ca⁺ concentrations were 265.70 cm⁻³ in winter and 506.05 cm⁻³ in summer. The correlation between the sporadic Ca⁺ layer and Es is contingent upon the ionosonde's detection sensitivity when the Ca⁺ density is low. Furthermore, according to the findings presented in Fig. 11 of Yeh et al. (2014), during the winter season in the northern hemisphere, the convergence of ions to form Es is hindered. Hence, the link between Ca⁺ and Es in the winter of the northern hemisphere is diminished.

5. Conclusion

This research investigates the relationship between the sporadic Ca⁺ layer and Es. From April 2020 to June 2022, a total of 286 sporadic Ca⁺ layers were observed. The altitudes of the sporadic Ca⁺ layer range from 88–120 km, and peak densities vary from 5.33 to 2200 cm⁻³. Concurrent lidar and ionosonde observations reveal a significant correlation between the sporadic Ca⁺ layer and Es. We found a correlation of 61.89% with Es among the 286 sporadic Ca⁺ layer cases. By excluding the influence of ionosonde sensitivity, we focus only on calcium ions that have a density exceeding 140 cm⁻³, which exhibit a correlation of 82.25%. The relationship between the sporadic Ca⁺ layer and Es is further influenced by factors such as season, Ca⁺ density, altitude, and morphological structure.

Lidar serves as a highly sensitive detection technique for identifying Es and other plasma irregularities. The utilization of metal ions as tracers offers valuable assistance in the prediction and comprehension of the dynamic mechanisms and chemical transformations associated with ionospheric anomalies. In addition to ensuring the safety of radios and astronauts, a comprehensive understanding of the ionosphere's shape and its changes over time would stimulate further research into the theory of ionospheric atmosphere coupling and its potential applications in space science. More simultaneous observations across latitudes will help us learn more about the sporadic Ca⁺ layer and Es at different latitudes as Phase II of the Chinese Meridian Project moves forward, which will also help us figure out how Es forms.

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Data Availability Statement

The ionosonde data were provided by Beijing National Observatory of Space Environment, Institute of Geology and Geophysics, Chinese Academy of Sciences through the Geophysics Center, National Earth System Scientific Data Center (<http://wdc.geophys.ac.cn>). We acknowledge the use of data from the Chinese Meridian Project. The data shown in this work, lidar data, can be downloaded from Mendeley Data repository.

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