Ionospheric N_e disturbances before 2007 Pu'er, Yunnan, China, earthquake*

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Abstract

Selecting three half orbits near the epicenter of Pu'er earthquake, we analyzed the N_e data recorded in their revisited orbits during a year before this earthquake, and extracted N_e precursors. The results show that: ① There are significant seasonal variations of ionospheric N_e in night time, which exhibit different shapes respectively in four seasons; ② There are three main shapes of N_e : single-peak, saddle-shaped and even-shaped, all of which may occur in four seasons, but each season with its typical shape relatively; ③ Spatial images of N_e showed high values near the epicenter in 30 days before the earthquake, and there is a good correlation between anomaly and distribution of earthquake in space and time, which reflects that these spatial anomalies were indeed concerned with the earthquake; ④ There shows a certain similarity of the N_e curves among revisited orbits, which can provide background information for distinguishing and identification of seismic anomaly.

Key words: Pu'er earthquake; DEMETER satellite; electron density (N_e); seasonal variations; earthquake-related anomaly

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Introduction

At Beijing Time: 2007-06-03 05:34:56.8 (World time: 2007-06-02, 21:34:56), an earthquake of $M_s 6.4$ occurred in Ning'er County, Pu'er City, Yunnan Province (23.0°N, 101.1°E). Due to the relatively shallow depth of the earthquake epicenter (only 10 km), the earthquake caused very serious damage on the ground, bringing a series of heavy losses such as communication disruption, traffic disruption, casualties. This paper uses the observations of French DEMETER satellite to analyze the precursor phenomena related to this earthquake possibly, and explore new technique and method of extracting earthquake precursor by analyzing the ionospheric observations of satellite.

DEMETER (Detection of Electro-Magnetic Emission from Earthquake Regions) satellite was launched by France on June 29, 2004, having a quasi-sun-synchronous circular orbit, obliquity 98.3°, weight 130 kg, height 710 km (reduced to 660 km in mid-December, 2005), which is the first satellite specially services in earthquake monitoring so far. Its main payloads include IMSC, ICE, IAP, ISL and IDP, and the detailed description of these observation parameters refer to Berthelier *et al* (2006a, b), Lebreton *et al* (2006), Parrot *et al* (2006a), Sauvaud *et al* (2006). This paper mainly bases on the data of N_e surveyed by ISL, and researches its own change characteris-

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tic in the background and the disturbed phenomena of N_e in many orbits before Pu'er earthquake.

The previous research on the relationship between earthquake precursors and N_e mainly focuses on using GPS observations to deduce TEC, having found abnormal disturbance of TEC before many earthquakes (Calais and Minster, 1995; Zaslavski *et al*, 1998; Liu *et al*, 2002, 2004; Trigunait *et al*, 2004; Lognonné *et al*, 2006), which are not introduced in detail here. In the analysis of satellite observation, Isaev and Serebryakova (2001) researched the Iran earthquake on January 17, 1989 and the aftershock of the Spitak earthquake on January 20, 1989 and found the disturbance extent reached to about 5% using the data of N_e recorded by Cosmos-1809 satellite. Parrot *et al* (2006b) found a significant increase in N_e observed by DEMETER satellite when two earthquakes occurred on September 5, 2004 in the region of Kii-Peninsula. At DEMETER International Conference, Parrot *et al*^① gave specific cases of N_e disturbance before the major earthquakes based on the data of N_e surveyed by ISL, and made a statistical research using the data at the same time. The statistical data included 2 718 earthquakes of magnitude larger than 4.8, epicentral depth less than 40 km from August 2004 to April 2006, whose orbital data included ascending orbits and descending orbits, magnetic latitude less than 50° and K_p less than 4. The result showed that N_e increased 17~25 h before the earthquake, had a small decrease 8~16 h before the earthquake, and decreased rapidly 22~26 h after the earthquake. When ascending orbits and descending orbits were separated, the descending orbital data showed that N_e decreased rapidly 22~26 h after the earthquake, and the ascending orbital data showed that N_e increased 17~25 h before the earthquake, had a small decrease 8~16 h before the earthquake. The result from randomly selected data showed that the whole change is homogeneous, inexistence of the phenomena of unusual increase and decrease in N_e . Sarkar *et al* (2007) observed the N_e disturbances three times in mid-latitude regions before earthquake using the data of N_e surveyed by ISL on DEMETER satellite, and considered the biggest change extent reaching to 20%. At present, the research on N_e parameters adopts the method of space adjacent orbits contrast generally, lack of study on the physical space background information of N_e and the trace of long-term time. This paper's work makes up for this deficiency, and gives a new analysis idea for extraction of space earthquake-related anomalies.

1 Data analysis of N_e background

1.1 Disturbance image of N_e before earthquake

Many disturbances are observed by the DEMETER microsatellite before Pu'er earthquake (ZHU *et al*, 2008), and these disturbances appear in multi-parameters simultaneously in general. But from the images of physical parameters recorded in orbits, we can see that, the amplitude of disturbance is smaller. Relative to the big extent variety of each parameter which is along with latitude; it is undistinguishable at times, which increases prodigious difficulty for extracting earthquake-related anomaly. From the contrast of many images of physical parameters recorded in different orbits, we find that N_e in ionosphere have a better response to earthquake-related anomaly. We select a few typical orbits which are closer to the epicenter in Figure 1 (the blue line indicates the boundary of 1 800 km). These orbits have appeared between 13 UT and 16 UT, which is around 22:00 LT, that is at night in Beijing. We can see that the amplitude of N_e variety in the entire orbit is particularly obvious, and N_e decline rapidly at the south area of 40°S , which are out of

^① Parrot. 2006. Statistical study of the variation of the electron density observed by the ionospheric satellite DEMETER during seismic activity. Report of international conference on DEMETER satellite.

the range of images settings in several orbits. The variety of N_e is also not steady at the north area of 40°S , but fluctuant disturbed as several groups, so the natural variety of N_e is very complex. Combining the disturbance enhanced phenomenon of power spectrum of the VLF electric field at

Figure 1 Images of power spectrum of the VLF electric field and N_e recorded by DEMETER satellite before Pu'er earthquake

low frequency, we can see that the corresponding disturbance can be observed from N_e curves, but some disturbances increased rapidly (15572_1), some decreased rapidly (15542_1), some change relatively flat (15440_1) and, of course, some variety is not obvious (15484_1), which can be said it have different patterns, so for a given earthquake, there is no uniform characteristics, which reflects the complexity of the variety of N_e in ionosphere. So we need understand the background variety fully of the region before the judgment of earthquake-related anomalies.

1.2 N_e data collection of revisited orbits

According to the statistical results analyzed by the physical images of the orbits one month before and after the Pu'er earthquake, almost all orbits which indicate disturbance signal concentrate in ascending orbits over the epicenter around 22:00 at night (that is, from south latitude to north latitude). The whole orbit span the entire three hours from the perspective of LT, however, all of which distribute between 20:00LT and 23:00LT. In order to compare expediently, three orbits have been selected to do further analysis, two of which appear disturbance before the Pu'er earthquake, and the other one is natural. The characteristics of the orbits are showed in Table 1. Figure 2a shows the spatial distribution of three orbits; it can be seen that they relatively close to the epicenter of Pu'er earthquake, within the 1 500 km. Because the satellite observation is the measurement results of rapid movement in space, it is different from the ground fixed-point observation, and it is difficult to get continuous time series of a fixed point. The distance between adjacent orbits is more than 2 000 km, and 1 h around interval of the time; neither space nor time is convenient to compare directly. According to the orbit design feature of DEMETER satellite, we find that the satellite orbit have the characteristic of 16 days revisited cycle after a period of accumulation of information, which means the satellite will return to the same orbit at the same time every 16 days. Although the interval is relatively long, it provides the basis information for comparing with the data of the same point and the same time. The three selected orbits back forward one year, the amount of the revisited orbits should be 24 (including the jumping-off point orbit itself), but some orbital data missed in the DEMETER Microsatellite Scientific Mission Center. Table 2 shows available data of the revisited orbits. Figure 2b, 2c and 2d show all the revisited orbits of the three orbits; it has a good overlap, smaller difference between the latitude and longitude as shown in the figure. This method can be used to compare the observation results of the same geographical location.

Table 1 The characteristics of the orbits

No.	No. of orbit	Date of orbit	Time from the earthquake	Disturbed orbits or no
1	15440_1	2007-05-24	9 days before	Yes
2	15484_1	2007-05-27	6 days before	No
3	15572_1	2007-06-02	About 6.5 hours before	Yes

Table 2 Available data of the revisited orbits

No. of orbit	Tracking date range	No. of theoretic revisited orbits	No. of missing orbits	No. of available revisited orbits
15440_1	2007-05-24~2006-05-21	24	1	23
15484_1	2007-05-27~2006-05-24	24	2	22
15572_1	2007-06-02~2006-05-30	24	7	17

1.3 Seasonal variation character of N_e

For three selected orbits and their revisited orbits, we plot all N_e curves in one figure, finding

that the change shapes of these curves are very complex. To make the analysis easier, we classify these curves according to different seasons. The method to sort different season is based on the ancient classified law of seasons and Chinese conventional habit. The ancient classified law of

Figure 2 Relative location of the epicenter and the orbits

(a) The relative location of the epicenter and the orbit 15440_1, 15484_1 and 15572_1; (b), (c) and (d) indicate the relative location of the epicenter and the orbit 15440_1, 15484_1 and 15572_1 and their revisited orbits respectively

seasons make spring begins (February 4 or 5), summer begins (May 5 or 6), autumn begins (August 7 or 8) and winter begins (November 8 or 9) as the start of every season; In Chinese civil society, they take January~March of lunar calendar as spring, corresponding April~June as summer, July~September as autumn and October~December as winter. So we classify the orbits of February~April as the observations in spring, the orbits of May~July as observations in summer, the orbits of August~October as observations in fall and the orbits of November~January as observations in winter. With the actual records of the orbits, we find the morphology of N_e curves is more unified after this division. So it can be proved that this method to sort different season is rational. Now we analyze N_e curves of three orbits and their revisited orbits.

1) N_e variation character for the orbit 15440_1 and its revisited orbits

From all the N_e curves which repeatedly pass through this orbit in Figure 3, we can see N_e curves appear the character that it changes along with the change of latitude except some jumping points in the ends of the curve (high latitude area). There is N_e peak value in the low latitude area and near the equator, and N_e decreases with the increased latitude. This character is very typical in all seasons except summer. The minimum of curves distribute near 60°N and 50°S. The curve is different in summer, N_e increased clearly in the northern hemisphere in this season; N_e keeps on a

high value with the increased latitude.

Comparing the figures of four seasons, we can see most curves are saddle-shaped in spring; the change shapes of the whole curve in northern and southern hemispheres are symmetrical to a certain extent; N_e achieves the maximum near the equator, which is between $20\,000\text{ cm}^{-3}$ and $30\,000\text{ cm}^{-3}$; The high value area of N_e distributes in $0\sim 20^\circ\text{N}$; N_e changes smoothly almost at $15\,000\text{ cm}^{-3}$ between $0\sim 20^\circ\text{S}$ and $20^\circ\text{N}\sim 40^\circ\text{N}$; N_e declines rapidly to high latitudes whenever northern or southern hemisphere. In summer, the change shapes of N_e present double-peak, but the two peak values are not very high; One is located near 20°S , another is located near 10°N ; N_e reaches vale of change near the equator; N_e declined more rapidly in high latitude in southern hemisphere; The situation is opposite in northern hemisphere. In autumn, most N_e curves are similar to those in spring, whose peak value appear at $0\sim 20^\circ\text{N}$. In winter, the change trend of N_e is: N_e increased gradually from 50°S ; the maximum is near 10°S ; most minimum less than $30\,000\text{ cm}^{-3}$ except very few curves; the change of N_e is smooth at $0\sim 40^\circ\text{N}$ and it decrease fast higher than 40°N .

Figure 3 Seasonal variations of N_e for the orbit 15440_1 and its revisited orbits

From the change situation of N_e in four seasons, we can see the peak value of N_e is high in winter, whose maximum can reach $45\,000\text{ cm}^{-3}$. However, the peak value is low in summer, almost $23\,000\text{ cm}^{-3}$ on average, and change very smoothly. The area of peak value distribute near $0\sim 20^\circ\text{S}$ in winter; $0\sim 20^\circ\text{N}$ in autumn and spring; there are two peak values in summer, and the area of peak values in southern hemisphere move to south compared with those in winter, which appears near 25°S ; this peak value also emerges in spring and autumn, but it is not obvious comparing with the high value in northern hemisphere.

2) N_e variation character for the orbit 15484_1 and its revisited orbits

The overall seasonal variations of N_e for the orbit 15484_1 in Figure 4 is similar to those in Figure 3, revealing that the peak value locates south in winter, but in the other three seasons it locates north. Most of N_e curves are symmetrical "convex" shape in spring; the peak value of one curve appears in south, departing from other curves greatly. All the curves in summer can be divided into two types; one type is that the higher value appears near 20°N, and another type is that the value changes smoothly from 30°S to north; the phenomenon that value increases rapidly never turns out in northern hemisphere. In autumn, the peak values of two curves migrate to south, and the other two keep "convex" shape. In winter, the change shapes of all the curves are similar; most concentrate in a certain range, and the peak values distribute near 10°S.

Figure 4 Seasonal variations of N_e for the orbit 15484_1 and its revisited orbits3) N_e variation character for the orbit 15572_1 and its revisited orbits

As the same, the location and magnitude of the maximum and minimum in four seasons in Figure 5 is similar to those in Figures 3 and 4. As the missing data of the revisited orbits is so many, so the sample of spring is few. Seen from the figure, one of these curves has a higher value, and the other two do not have obvious high value. In summer, there is a peak value at 25°S, and the peak values of all the curves superpose very well hereon; there is a minimum near the equator, but between 15°N and 20°N, some curves arrive at higher value, reaching $45\,000\text{ cm}^{-3}$; some curves locate vale of the change, and the comparability between curves is bad. The curves of this orbit and its revisited orbits change smoothly in autumn; the maximum is only $20\,000\text{ cm}^{-3}$ and the symmetrical character of "convex" shape is also ruined. The level of peak value in southern hemisphere corresponds with that in northern hemisphere; at the same time, N_e in high latitude

area of northern hemisphere did not decrease rapidly. In winter, the change of peak value is outstanding in low latitude area of southern hemisphere.

Because ionosphere is also influenced by the sun and some other space activities, we consider the corresponding geomagnetic disturbance situation for all the revisited orbits. There are

Figure 5 Seasonal variations of N_e for the orbit 15572_1 and its revisited orbits

Figure 6 K_p index of the orbit 15440_1, 15484_1 and 15572_1 and their revisited orbits

K_p indices of three orbits and corresponding revisited orbits in Figure 6. Figure 6a indicates the K_p indices of 15440_1 and its revisited orbits, from left to right is K_p index of the orbit 15440_1 as a start to the revisited orbits in last year; Figure 6b corresponds to the orbit 15484_1 and its revisited orbits; Figure 6c corresponds to the orbit 15572_1 and its revisited orbits. From the figure, we know there are only two orbits that the K_p index larger than 4, only 3% in all the 62 orbits. Besides, comparing the two orbits with others, we do not find obvious abnormal change. So we can consider the data we used in this research can reflect the rule of N_e background in general.

1.4 Summary of three change shapes of N_e

Based on the above curves and their characteristics, we can divide those changes into three categories: single-peak, saddle-shaped, and even-shaped. The change shapes of electron density of three orbits and their revisited orbits are summarized in the Table 3, Figure 7 is a sketch map of three shapes; Figures 7a, 7b and 7c are single-peak, saddle-shaped and even-shaped respectively. Table 3 indicates that the main change shape of electron density is saddle-shaped in spring for 15440_1 and its revisited orbits, and the following shape is single-peak; and the main change shape of electron density in summer is even-shaped while saddle-shaped in autumn and single-peak in winter. The main change shape of electron density is saddle-shaped in spring for the 15484_1 and its revisited orbits, and the next shape is single-peak; and the main change shape of electron density in summer is even-shaped and autumn is saddle-shaped but all the change shapes of electron density are single-peak in winter. The main change shape of electron density is saddle-shaped in spring for the 15572_1 and its revisited orbits; the main shape in summer is even-shaped; all shapes in autumn are even-shaped but main shape is single-peak in winter.

Table 3 Number of various shapes belonging to each season

	15440_1 and its revisited orbits				15484_1 and its revisited orbits				15572_1 and its revisited orbits			
	Spring	Summer	Autumn	Winter	Spring	Summer	Autumn	Winter	Spring	Summer	Autumn	Winter
Single-peak	2	1	0	4	2	2	1	5	1	2	0	3
Saddle-shaped	4	0	3	0	4	1	2	0	2	0	0	2
Even-shaped	0	6	2	1	0	4	1	0	0	3	3	0

Figure 7 Variation style of N_e for the orbit 15440_1 and its revisited orbits

From the above, we can know that there are certain rules of seasonal variations of ionospheric N_e in night time. In spring and autumn, the change shape of N_e is saddle-shaped or "convex" in dominance, with the peak value in the north region. In winter, the single-peak is dominant and its peak value appears in the south region, and the maximum of one year often appears in this season. In winter, the location and magnitude of the minimum and maximum value of N_e is extremely similar. In summer, there are two main shapes, one is gently change, namely, no obvious peak values in both southern and northern hemisphere; the other is the emergence of a larger peak value in northern hemisphere, and the location lean to north comparing to the peak value in spring and autumn. Therefore, we can see that all three orbits reflect the seasonal characteristics of N_e , the migration of the peak value relatively close to the location of the Sun and the Earth. As the sun deviated from the northern hemisphere in winter, the N_e peak value lean to south region, and the entire average level of N_e in the southern hemisphere is higher than that in the northern hemisphere; and since the beginning of spring, the peak value moves to the northern hemisphere, parts of high-value even more incline to north in summer, and the overall level of N_e in the northern hemisphere increase; In autumn, there are two peak values located in the low-latitude regions of northern and southern hemispheres respectively, reflecting the characteristics of N_e peak value migrate to the south. Therefore the change patterns of N_e fully reflect the changes of the relative position of the Sun and the Earth, meaning that it still retains significant seasonal features even at altitude of satellite, that is, the change of N_e in night time does not attenuate with height in the ionosphere of 660 km. So this most direct observation fulfills the knowledge of the N_e changes at night in the ionosphere of 660 km.

2 Extraction of earthquake-related information

2.1 Comparison of revisited orbits

Though the interval of the revisited orbits is long, the locations of these orbits are very close, so these data have relatively strong comparability. Furthermore, from the above analysis we can see that despite there are seasonal changes among orbits, the curves are of very good similarities, which provide a certain basis for extraction of abnormal disturbance relatively. Putting all pictures of three orbits since 2007 together, we find N_e value is significantly higher at 15440_1 than at the other orbits in 20°N~50°N (Figure 8a). When we focus on this, as is shown in Figure 8b below, the average value of N_e is around $23\ 000\ \text{cm}^{-3}$ at 15440_1 orbit. At other orbits, the minimum

Figure 8 Variation style of N_e for the orbit 15440_1 and its revisited orbits in 2007
(a) N_e curves of the integrated orbits; (b) N_e curves in the range of 20°N~50°N

value is about $10\,000\text{ cm}^{-3}$ and the highest value is about $16\,000\text{ cm}^{-3}$ with the average value of about $13\,000\text{ cm}^{-3}$. From this view, N_e value is higher at 15440_1 than at other orbits by around 77%, increasing to $10\,000\text{ cm}^{-3}$. Since the data of 15440_1 recorded in May, that is summer in which the overall value of N_e in northern hemisphere increases, so 77% of the changes may not be only compatible with earthquake-related information, but also contain some changes in the background. The anomaly at the other two orbits is not obvious.

2.2 N_e temporal-spatial evolution image

We divide the data of three months before earthquake per 10 days, take the scope near the epicenter about 20° as study area, and make N_e of all the orbits across the study area into a contour map (Figure 9). Figures 9a, 9b and 9c are maps from March 14 to May 3, which are of two months before earthquake, could be regarded as normal maps of this region. Figures 9d, 9e and 9f are

Figure 9 N_e temporal-spatial evolution image

Red circle: the epicenter of Pu'er; red triangle: the epicenter of Laos; red rectangle: the area of anomaly. "2007-03-14~2007-03-23" represents the interval of data from 2007-3-14 to 2007-3-23, and the others are similar; the period of all maps is 10 days.

maps one month before earthquake, and 9g is a map after earthquake. We can see that in March and April, 2007, N_e is relatively high at low-latitude on the whole, the higher latitude, the lower N_e . This is in line with the rule of N_e in spring: a maximum value is near the equator, the higher latitude, the lower value. 9d, 9e, 9f and 9g are also in line with the rule of N_e in summer generally: the value is lowest in the region of $10^\circ\text{N}\sim 15^\circ\text{N}$; from about 20°N to north, N_e changes at a higher level. From Figure 9 we can see that at about 20°N it shows even color, which means the value is closer. More obvious changes appear in Figures 9d and 9e, representing abnormal high-value around the epicenter; especially in Figure 9e, N_e in the region of epicenter is highest in the whole area. The abnormal value of Figures 9d and 9e is different from that of Figures 9a~9c, and the latter in the $10^\circ\text{N}\sim 20^\circ\text{N}$ region shows high-value, reflects the large space background change. The high-value of Figure 9d and 9e concentrates over the region of epicenter clearly, reflecting the local change characteristics of N_e , so it may be related to the disturbance caused by the earthquake. According to the earthquake catalog, there is an earthquake (World time: 2007-05-16, 08:56:17, $M_s 6.3$) in Laos near Pu'er earthquake in this period (Figure 9e), so N_e changes of Figures 9d and 9e may be resulted from the combined effect caused by the two earthquakes. Figure 9f is of 10 days before Pu'er earthquake. The abnormal high-value migrates to the southeast of the epicenter, no longer over the region of epicenter, and the amplitude decreases. Post-earthquake of Figure 9g shows that all abnormal high-value disappears in the region of $10^\circ\text{N}\sim 25^\circ\text{N}$ and N_e changes smoothly. It can be shown that there is disturbance of ionospheric N_e in the preparation process of earthquake. In addition, from the use of all data, the sum of K_p index is 33_- on April 1, 32_+ on April 28, 34_- on May 23, 32_0 on May 24, the average of K_p less than 4_0 in other days. The disturbance days (the average of $K_p > 4_0$) are only up to 5% in 70 days. We can consider that the period of this study is not affected by the geomagnetic disturbance significantly.

3 Conclusions

We analyzed the N_e data recorded in their revisited orbits during a year before Pu'er earthquake surveyed by ISL onboard DEMETER satellite, and studied on N_e background information and extracted N_e precursors. We have conclusions as follows:

In the region of $70^\circ\text{E}\sim 120^\circ\text{E}$, there are significant seasonal variations of ionospheric N_e in night time of 20:00~23:00 at the height of 660 km. In winter, N_e of southern hemisphere is wholly higher whose peak value distributes in the low-latitude of southern hemisphere. In spring and autumn, the shape of N_e is symmetrical whose peak value distributes in northern hemisphere. In summer, N_e of northern hemisphere is wholly higher whose peak value moves to about 20°N generally.

There are three main shapes of N_e : single-peak, saddle-shaped and even-shaped. The changes are very complex, but there is a certain rule to follow each season, having its typical shape relatively.

N_e temporal-spatial images of two months before earthquake show that a high-value anomaly begin to appear near the epicenter region one month before earthquake, reach to maximum 10~20 days before earthquake, and there is a drift phenomenon of abnormal region and weakened amplitude in impending 10 days. After the earthquake, anomalies disappear. Therefore, there is a good correlation between ionospheric anomalies and the development of earthquake process either in space or in time.

We extract significant N_e precursors by comparison of the revisited orbits, finding the ampli-

tude of anomaly increase to around 77%. But there may be certain background information here, which is not entirely caused by the earthquake. This method can provide a background basis for extracting anomalies.

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