Study on the distribution characteristics of the plasma irregularities inside the mid-latitude ionospheric trough based on Swarm in situ measurements

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November 23, 2022

Abstract

A large number of studies have confirmed the frequent occurrence of plasma irregularities in the mid-latitude ionospheric trough, but there is little understanding of the distribution characteristics about this feature. Based on Swarm in situ plasma measurements from 2014 to 2020, the diurnal, seasonal, solar activity and geomagnetic activity variations of the occurrence rate of mid-latitude trough region irregularities are analyzed. The results show that for the irregularities with scale size of 7.5-75 km: (1) Both of case and statistical analysis indicate that geomagnetic activity has an obvious inhibitory effect on the formation of irregularities in the mid-latitude trough region, whether on the dayside or nightside. (2) The occurrence rate of mid-latitude trough region irregularities during the day is significantly higher than that at night, and the difference between day and night is significantly greater than the difference between the two walls at the same local time section. (3) On the dayside, the highest and lowest occurrence rate appears in winter and summer, respectively; but on the nightside, the highest and lowest occurrence rate appears in equinoxes and winter, respectively. (4) On the nightside, it shows lower occurrence rate under high solar activity conditions, but no obvious solar activity effect is shown on the dayside occurrence rate.

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Key Points:

- Both of solar activity and geomagnetic activity may inhibit the occurrence rate of trough region irregularities.
- The occurrence rate of mid-latitude trough region irregularities on dayside is significantly higher than that on nightside.
- Obvious seasonal dependence is found on the occurrence rate of trough region irregularities.

Abstract

A large number of studies have confirmed the frequent occurrence of plasma irregularities in the mid-latitude ionospheric trough, but there is little understanding of the distribution characteristics about this feature. Based on Swarm in situ plasma measurements from 2014 to 2020, the diurnal, seasonal, solar activity and geomagnetic activity variations of the occurrence rate of mid-latitude trough region irregularities are analyzed. The results show that for the irregularities with scale size of 7.5-75 km: (1) Both of case and statistical analysis indicate that geomagnetic activity has an obvious inhibitory effect on the formation of irregularities in the mid-latitude trough region, whether on the dayside or nightside. (2) The occurrence rate of mid-latitude trough region irregularities during the day is significantly higher than that at night, and the difference between day and night is significantly greater than the difference between the two walls at the same local time section. (3) On the dayside, the highest and lowest occurrence rate appears in winter and summer, respectively; but on the nightside, the highest and lowest occurrence rate appears in equinoxes and winter, respectively. (4) On the nightside, it shows lower occurrence rate under high solar activity conditions, but no obvious solar activity effect is shown on the dayside occurrence rate.

Plain Language Summary

Early scintillation observational analysis and theoretical studies revealed that the plasma irregularities usually occurred on the equatorward wall and poleward wall of the mid-latitude trough. Our last work provided the direct high resolution observation evidence of the existence of mid-latitude trough region plasma irregularities by using the Swarm 2 Hz electron density measurements, and indicated that the particle precipitation is the dominant mechanism for the dayside trough region irregularities, while the nightside trough region irregularities are mainly controlled by the temperature gradient drift instability (Liu et al., 2021). In the current study, the distribution characteristics of the mid-latitude trough region irregularities under geomagnetic disturbance conditions and geomagnetic quiet times are further analyzed. The results show that both geomagnetic disturbance and high solar activity may inhibit the occurrence of the mid-latitude trough region irregularities, for the scale size of 7.5-75 km irregularities discussed in this paper. In addition, significant magnetic local time dependence and seasonal dependence are also found on the occurrence of the trough region irregularities. This work will promote our understanding of the plasma irregularities inside the mid-latitude trough.

1 Introduction

Ionospheric irregularities are inhomogeneous structures of ionization density in the ionosphere, which were discovered as early as from 1930s (Eckersley, 1932; 1937; Appleton and Piddington, 1938; Booker and wells, 1938). After decades of research, it has been found that ionospheric irregularities mainly occur in two regions, one is around the magnetic equator, and the other is at high-latitudes including auroral oval, cusp and the polar cap (Aarons,1982; Basu, Mackenzie, & Basu, 1988). In addition, some studies had shown that irregularities also occur frequently inside the mid-latitude trough at the sub-auroral region. By using simultaneous 137-MHz amplitude scintillation and TEC observations obtained from the Application Technology Satellite 3 (ATS-3) at a mid-latitude station, Basu (1974) identified the existence of two regions of scintillations, one on the equatorward wall of the mid-latitude trough, and the other on the poleward wall of the mid-laitude trough. Hudson and Kelley (1976) proposed that the so-called temperature gradient instability (TGI), which is characterized by the antiparallel direction of temperature gradient and density gradient in the equatorial side wall of the mid-latitude trough, is possible to cause plasma instability and form irregularities at subaurroal region. Using the scintillation observations of VHF and UHF frequencies at auroral and subauroral stations, together with in situ measurements by International Satellite for Ionospheric Studies 2 (ISIS-2) in 1971-1972 and Air Force Satellite S3-2 (S3-2) in 1975-1976, Houminer et al. (1981) showed that the mid-latitude trough separates two regimes of electron density irregularities during magnetic storm. The two regions are related to the plasmapause and to the auroral oval and straddle the trough minimum area. They also showed that the auroral irregularities are closely related to field-aligned currents. Rodger et al. (1992) summarized that the irregularities in the equatorward edge of the mid-latitude trough is mainly related to the TGI, while the trough poleward wall possesses various possible instability mechanisms, such as the gradient drift instability, current convection instability, Kelvin Helmholtz velocity shear process, structured precipitation, and so on. However, the relative importance of these mechanisms is not clear. Based on joint measurements by the Millstone Hill incoherent scatter radar (ISR) and the Super Dual Auroral Radar Network (SuperDARN) HF radar located at Wallops Island, Virginia, Greenwald et al. (2006) reported that the irregularities are excited on the equatorward wall of the mid-latitude ionospheric trough in a region of opposed density and temperature gradients. Eltrass et al. (2014) computed the time series of both perpendicular and meridional density and temperature gradients. Their comparison showed that the TGI is the most likely the generation mechanism for the irregularities observed on the equatorward wall of the midlatitude ionospheric trough, and the GDI is recognized to play a relatively minor role in irregularity generation. But so far, we have little understanding of the distribution characteristics of the irregularities in this region, mainly due to the lack of high-resolution observation data that can distinguish the fine structure inside the mid-latitude trough.

Recently, using the Swarm in situ plasma measurements, Liu et al. (2021) provided for the first time the magnetic latitude and magnetic local time distribution of irregularities within the mid-latitude trough. The results suggested that the dayside irregularities are mainly caused by the auroral particle precipitations, while the nightside irregularities are related to the TGI. For the nightside irregularities within the trough, they further suggested that the TGI not only dominate the irregularities on the trough equatorward wall, but plays also a role for generating plasma irregularities at trough poleward wall. Nevertheless, there is still a lack of research of the distribution characteristics of mid-latitude trough region irregularities, such as seasonal distribution, solar activity dependence, geomagnetic activity effect and so on.

In this paper, the high-resolution (2 Hz) measurements of electron density from the Langmuir probe (LP) of Swarm satellites will be used to study the distribution characteristics of the occurrence rate of irregularities in the mid-latitude trough from the perspective of space weather, such as seasonal distributions, solar activity dependence and geomagnetic activity dependence.

2 Data and Method

2.1 The *Ne* Measurements from Swarm Satellite

The Swarm mission comprises of three satellites, with two satellites (Swarm A and C) flying side by side at about 460 km (separated by 1.4^{o} of geographic longitude in the east-west direction, corresponding to about 150 km at the equator), while the third satellite (Swarm B) flies at a higher altitude (about 510 km). All three satellites fly in near-polar, circular orbits, and the orbits drift slowly in local time (LT), which takes 133 days for Swarm A/C and 141 days for Swarm B to cover all 24 LT hours, respectively.

The statistical research of this paper is based on the 2 Hz LP electron density measurements, which can be obtained online from ESA Swarm data service website (https://swarm-diss.eo.esa.int/#).

2.2 Method to Identify the Irregularities

So far, there is no consensus on the identification method of ionospheric electron density irregularities. In previous studies, researchers mainly used two kinds of methods, one is relative fluctuation method (ΔNe/Ne) (e.g., Kil & Heelis, 1998; Huang et al., 2001; Su et al., 2008), the other is absolute fluctuation method (ΔNe) (e.g., Xiong et al., 2010; Huang et al., 2014). The main argument is that the relative fluctuation method may miss the irregularities for the high density area, while the absolute fluctuation method may miss the irregularities for the low density area. It means that both of the two methods may lead to misjudgment or judgment leakage under certain condition.

In order to minimize the above situation, we recently proposed a dynamic threshold method to identify the plasma irregularities. The specific approach is that whether we adopt relative fluctuation or absolute fluctuation, the thresholds are dynamically determined according to the background level of Ne. The thresholds are obtained by following equations (Liu et al., 2021):

$$\begin{aligned} Threshold_S &= median(S) + 1.5 \times mad(S) \\ Threshold_{\Delta Ne} &= median(\Delta Ne) + 1 \times mad(\Delta Ne) \end{aligned} \qquad (1)$$

where mad() is the median absolute deviation, S and ΔNe are obtained according to the following equations (Kil & Heelis, 1998; Huang et al., 2014):

$$\begin{aligned} S(\%) &= 100 \times \frac{\left[\frac{1}{10} \sum_{i=1}^{10} (\log Ne_i - \log Ne_{oi})^2 \right]^{1/2}}{\frac{1}{10} \sum_{i=1}^{10} \log Ne_{oi}} \\ \Delta Ne &= \left[\frac{1}{10} \sum_{i=1}^{10} (Ne_i - Ne_{oi})^2 \right]^{1/2} \end{aligned} \qquad (2)$$

where Ne_i and Ne_{oi} are the original Ne and low-pass filtered Ne (with cut-off period of 10s) at i-th data point.

As mentioned in Liu et al. (2021), the comparison results show that applying dynamic thresholds to the relative or absolute fluctuations can identify the irregularities well, for both the high and low level Ne profiles. In this study we will also only give the results derived by the relative fluctuation method, since it has been proved in Liu et al. (2021) that no essential difference between relative fluctuation method and absolute fluctuation method with dynamic threshold. In addition, in the previous work of Liu et al. (2021), the identification of mid-latitude trough structures in Swarm Ne data from 2014 to 2020 was completed, and their minimum positions and the two exterior boundaries were also determined.

Figure 1 shows an example of the plasma irregularities inside the midlatitude ionospheric trough identified from Swarm A satellite Ne data at about 16.38 UT on February 22, 2014. In the top panels of Figure 1, the blue line shows the original 2 Hz Ne profile, the red line shows the filtered (cut-off period of 10 s) Ne profile, and the black solid circles mark the positions of trough minimum and two boundaries. The bottom panel of Figures 1 shows the curve of S derived by equation (2), and the black dotted line shows the threshold level derived by equation (1). It can be seen from the original Ne profile that plasma irregularities extends from high latitudes to near the equatorial boundary of the mid-latitude trough. Through the curve of S and the threshold determined by the S curve, all the irregularities inside the mid-latitude trough area can be well identified (as shown by the yellow shadow area).

3 Results and Disscussion

3.1 Geomagnetic Activity Dependence

Following a coronal mass ejection (CME) event, a strong magnetic storm occurred on 17 March 2015. Figure 2 shows a case of the evolution of mid-latitude trough region irregularities during this storm. As shown in Figure 2 (a), the sudden storm commencements (SSC) with a 56 nT increase in Dst index occured at about 0500 UT on 17 March 2015. The storm main phase lasted for about 17 hours, and the Dst minimum reached -223 nT at about 2300 UT on 17 March 2015. During the storm main phase, the Kp index reached 8-, and remained above 3 in the next two days.

Figure 2 (c) - (g) show five electron density profiles of different development stages during this magnetic storm, and their occurrence times (UT) are marked by black arrows in Figure 2 (a). The positions of the mid-latitude troughs are marked by gray shaded areas. The case in Figure 2 (c) occurs on quiet day before the SSC, in which the mid-latitude trough minimun appears at about 66 °S. The mid-latitude troughs in Figure 2 (d) and 2 (e) occur during storm main phase, and the trough minimun appears at about 54 °S and 49 °S respectively. The cases in Figure 2 (f) and 2 (g) occur during storm recovery phase, in which the mid-latitude trough minimun appears at about 57 °S and 59 °S respectively. During the main phase of this storm, the position of the mid-latitude trough rapidly moves to lower latitudes, and the width of the trough also increases significantly. More importantly, it can be clearly seen that the mid-latitude trough is embedded with many small-scale irregularities in the cases on quiet day of March 16 before the magnetic storm and on March 18-19 during the strom recovery phase (as shown in Figure 2c, 2f, and 2g). However, during the storm main phase, the Ne profiles of the trough structure are very smooth, and there are no discernible inhomogeneous structures (as shown in Figure 2d and 2e).

In addition, statistical analysis is also made on the variation of the occurrence rate of mid-latitude trough region irregularities with Kp index, and the results are shown in Figure 3. Figure 3 shows that the occurrence rates of mid-latitude trough region irregularities decreases significantly with the increase of Kp index, whether on the dayside or nightside. Therefore, it can be concluded from both case analysis and statistical analysis that geomagnetic activity has an obvious inhibitory effect on the formation of irregularities in the mid-latitude trough region.

Above results are the first direct evidences about the effect of magnetic storm on the occurrence rate of mid-latitude trough region irregularities. Previously, Basu (1974) and Houminer et al. (1981) also gave case studies of the behaviour of irregularities in the mid-latitude trough region during magnetic storm times. Using the VHF and UHF band amplitude scintillation observations, they found that during the magnetic storm, the amplitude scintillation indices of the equatorward wall and the poleward wall of the mid-latitude trough increased significantly, while the trough minimum region showed very low activity of scintillation. Thus they pointed out that the trough minimum separates two regions of irregularities during the magnetic storm (Houminer et al., 1981). And the storms seem to have a profound influence on the formation of irregularities at such latitudes (Basu, 1974). However, the results shown in this study shows that the storms have an obvious inhibitory effect on the formation of irregularities in the whole mid-latitude trough region. It should be noted that VHF and UHF scintillations are mainly affected by kilometer-scale irregularities (with fresnel scale of about 1.3 – 0.9 km for signals from 137 MHz to 250 MHz), but the scale-size of plasma irregularities considered here is between 7.5 km and 75 km (Liu et al., 2021). We believe that the inconsistency of conclusions may be related to the scale difference of irregularities discussed.

However, it is still very difficult to discuss the inhibition mechanisms of the trough region 7.5-75 km irregularities during storm main phase, because the related instability mechanisms of the trough region irregularities on the dayside and nightside are quite different. We speculate that the significant reduction of the dayside mid-latitude trough region irregularities during the storm main phase is related to the rapid equatorward movement of the mid-latitude trough structure. Previous studies proved that the dayside mid-latitude trough region irregularities is mainly caused by the particle precipitation, as the dayside mid-latitude trough is completely wrapped in the aurora active area (Houminer et al., 1981; Liu et al., 2021). With the development of the storm main phase, the mid-latitude trough structure rapidly moves out of the aurora active area towards the equator, and the instability process related to the auroral particle precipitation in the mid-latitude trough area disappears completely, resulting in a sharp reduction in the occurrence rate of trough region irregularities during the storm main phase. Then, as the magnetic storm enters the recovery phase, the mid-latitude trough gradually moves back to high latitudes and re-enters the aurora active region, resulting in a restorative increase in the occurrence rate of trough region irregularities during the storm recovery phase.

Nevertheless, the above speculation cannot explain the reduction on the nightside, because the irregularities in the nightside mid-latitude trough area is mainly caused by the TGI (Liu et al., 2021). For the nightside ,we conjecture that several possible processes may lead to the reduction of the trough region 7.5-75 km irregularities during the storm. One is that the width of the mid-latitude trough may increases during the main phase of the magnetic storm according to Figure 2 (d) and 2(e), resulting in the reduction of the density gradient in the mid-latitude trough area (especially near the minimum), which then suppresses the TGI and reduces the occurrence rate of nightside trough region irregularities. The second possible process is that under geomagnetic disturbance condition, the irregularities with scale size of tens of kilometers becomes smaller scale size (such as kilometer-scale irregularities or even smaller), and the observation resolution of Swarm satellite data is insufficient, which makes it impossible to distinguish the irregularities.

3.2 Distributions under Geomagnetic Quiet Conditions

3.2.1 Diurnal Variation

Figure 4 gives the diurnal variation of the occurrence rate of the mid-latitude trough irregularities under geomagnetic quiet conditions (Kp≤3). It can be seen that the total occurrence rate of dayside trough region irregularities is obviously higher than nightside, and the occurrence rate of irregularities in the trough poleward wall is generally higher than that in the trough equatorward wall.

Figure 4 (b) shows that the mean occurrence rate of irregularities in trough equatorward wall on the dayside (about 0600-1800 MLT) is about 45%, and about 32% on the nightside (about 1800-

0600MLT). Figure 4 (c) shows that the mean occurrence rate of irregularities in trough poleward wall on dayside is about 60%, and about 39% on the nightside. It means that the diurnal difference of the occurrence rate of irregularities in the trough equatorward wall is quite smaller than that in the poleward wall, which is about 13% and 21%, respectively. And the difference between the poleward wall and equatorward wall on the nightside is lower than that on the dayside, which is about 7% and 15%, respectively. On the whole, the difference between day and night is significantly greater than the difference between the two walls at the same local time section. The difference of the occurrence rate of irregularities between the poleward wall and equatorward wall reaches the lowest of about 2% during times between midnight and dawn.

Early studies have shown that the ionospheric irregularities around the magnetic equator mainly occur in the postsunset period, the ionospheric irregularities in the auroral oval mainly occur at night, the ionospheric irregularities in the cusp region mainly occur during the day, and the ionospheric irregularities in the polar cap occur at all local times (Basu, Mackenzie, & Basu, 1988). Obviously, the local time dependences of the irregularities in the mid-latitude trough region is quite different from that at other latitudes. This is mainly because the location of the mid-latitude trough changes greatly with local time, which usually appear 'V-shape' diurnal distribution pattern, characterized by usually occurring at higher latitudes on the dayside, and migrates to lower latitudes on the nightside, reaching to the lowest latitude in the pre-dawn sector (Werner & Prölss, 1997; Krankowski et al., 2009; Le et al., 2017; Aa et al., 2020). Our recent work (Liu et al., 2021) fully discussed the reasons for the diurnal differences of higher occurrence rate on the dayside than that on the nightside, that is, the dayside MIT structure resides well inside the aurora/cusp region, but the nightside MIT structure is almost completely outside the auroral oval.

Moreover, on the dayside, the mid-latitude trough region irregularities is mainly caused by the particle precipitation, and the intensity of the particle precipitation decreases with the decrease of latitude, so the occurrence rate of dayside trough equatorward wall irregularities is lower than that of the poleward wall. On the nightside, the irregularities of the walls on both sides of the mid-latitude trough are mainly caused by the TGI (Liu et al., 2021). However, the TGI seems more stronger on the poleward wall, because the steepness of trough poleward wall keeps almost twice the value of trough equatorward wall from midnight to dawn (Liu & Xiong, 2020). Therefore, the occurrence rate of nightside trough poleward wall irregularities shows higher than that of the equatorward wall. It is also speculated that the lower difference between the poleward wall and equatorward wall on the nightside than that on the dayside is mainly caused by different instability mechanisms on the two walls.

3.2.2 Seasonal Variation

Figure 5 shows the seasonal distribution of the occurrence rate of the trough irregularities under geomagnetic quiet conditions. Figure 5 (a) and 5 (b) show the 2-D distribution of the occurrence rate of trough region irregularities as a function of month and magnetic local time in the northern and southern hemisphere, respectively. The results are calculated on a scale of 1 hr (MLT) $\times$ 15 days (Month). It can be seen that there are obvious seasonal dependences on the occurrence rate of the trough region irregularities, and there are significant diurnal differences in seasonal effects. It seems that the maximum occurrence rate on the nightside mainly occurs in equinox seasons, while the maximum occurrence rate on the dayside mainly occurs in winter.

Besides, the results of Figure 5 (a) and 5 (b) show that for all seasons the dayside occurrence rate is generally greater than the nightside, which is consistent with the results of Figure 4. Therefore, we further make statistics on the seasonal variation of the occurrence rate of trough region irregularities according to the dayside (06-18MLT) and nightside (18-06MLT) respectively, and the results are shown in Figure 5(c) - 5(f). In fact, we also made statistics on the trough equatorward wall and the poleward wall respectively, but no discernible difference was found, so only the statistical results of the total occurrence rate are given here. As can be seen from Figure 5 (c) and 5 (d), on the dayside, the occurrence rate is the highest in winter and the lowest in summer in both the northern and southern hemisphere. However, on the nightside, the occurrence rate is the highest in equinoxes and the lowest in winter in both northern and southern hemisphere (Figures 5e and 5f).

Our previous work indicates that the irregularities inside the mid-latitude trough on the dayside are mainly related to the auroral particle precipitation (Liu et al., 2021). Park et al. (2012) reported that the occurrence probabilities of plasma irregularities in the high-latitude is smallest around June solstice and largest around December solstice. The seasonal effect of the occurrence rate of dayside trough region irregularities in Figure 5 is quite consistent with the results derived by Park et al. (2012). They suggested that the higher occurrence rate in winter is due to the shortest sunlight duration, while the lowest occurrence rate in summer is due to the longest sunlight duration. It is noted that the auroral region irregularities show same seasonal effect in both the dayside and nightside (Park et al. 2012). However, on the nightside, the seasonal effect of occurrence rate of the trough region irregularities shows the highest in equinoxes and the lowest in winter. This difference is probably because the nightside mid-latitude trough is completely outside the aurora oval, and the irregularities are mainly caused by the TGI (Liu et al., 2021). We suggest that many processes may affect the seasonal effect of the nightside subauroral irregularities, because the subauroral irregularities is the result of the interaction of the two events of electron temperature enhancement and mid-latitude trough. The location, intensity and driving forces of the two events are dynamic. The identification of the importance of these processes needs further research.

3.2.3 Solar Activity Dependence

Figure 6 shows the yearly averaged occurrence rate of irregularities in the mid-latitude trough under geomagnetic quiet conditions (Kp≤3), as well as the yearly averaged F10.7 index. As can be seen from Figure 6 (a), there is no obvious solar activity effect on the dayside occurrence rate curves. On the nightside, as shown in Figure 6 (b), it can be seen that the occurrence rate of the trough region irregularities during high solar activity years is smaller than that during low solar activity years. This indicates that high solar activity may inhibit the nightside trough region irregularities. In addition, on the nightside, the pole side occurrence rate during high solar activity years is nearly twice as the equator side, but they are roughly equal during low solar activity years.

Previous studies had shown that the occurrence rate of irregularities in low latitude region, polar cap region and auroral oval region increases with the increase of solar activity (Basu et al., 1988; Park et al, 2012). But we would like to remind again that the irregularities discussed here is quite different from that of Basu et al. (1988) and Park et al. (2012). Basu et al. (1988) analyzed the kilometer-scale irregularities in high latitudes and equator-low latitudes. Park et al. (2012) focused on the irregularities (which is commonly characterized by electron density enhancements) with scale sizes below some hundred kilometers at high latitudes. Most importantly, the nightside mid-latitude trough region irregularities can be regarded as the product of the interaction between the mid-latitude trough and the subauroral electron temperature enhancement. Under the geomagnetic quiet conditions, the dynamical and morphological evolution characteristics of the mid-latitude trough are mainly affected by the processes in the ionosphere and thermosphere, such as ionospheric high latitudes plasma convection, neutral wind, electric field, and so on (Rodger et al., 1992; Liu & Xiong, 2020). However, the subauroral electron temperature enhancement is mainly controlled by processes in magnetosphere and plasmasphere, such as high thermal conductivity of electrons, soft particle precipitation, wave activity and so on (Prölss, 2006). There may be differences in the level, mode and speed of the response of these processes to enhanced solar activity, which makes it difficult to satisfy the temperature gradient instability conditions $\nabla \ln Ne \times \nabla \ln T_e < 0$ (or weaken the instability), resulting in the reduction of the occurrence rate of the nightside mid-latitude trough irregularities in high solar activity years.

5 Conclusions

A research on the distribution pattern of the mid-latitude ionospheric trough region irregularities with scale sizes of 7.5-75 km is carried out by using the Swarm A satellite in situ measurements from 2014 to 2020. The occurrence rate distribution characteristics of the trough region irregularities under geomagnetic disturbance conditions and geomagnetic quiet times are analyzed separately. For the geomagnetic storm effect, both the case and statistical analysis reveal that geomagnetic activity has an obvious inhibitory effect on the formation of irregularities in the mid-latitude trough region, whether on the dayside or nightside.

The features of diurnal, seasonal, and solar activity variations of the trough region irregularities occurrence rate are statistically analyzed under geomagnetic quiet conditions. Firstly, the occurrence rate of dayside trough region irregularities is obviously higher than nightside, and the the occurrence rate of irregularities in the trough poleward wall is generally higher than in the trough equatorward wall at same time section. On the whole, the difference between dayside and nightside is significantly greater than the difference between the two walls at same time section. Secondly, obvious seasonal dependence is found on the occurrence rate of trough region irregularities, and there are significant diurnal differences in seasonal effects. On the dayside, the highest occurrence rate appears in winter and lowest in summer, but the highest occurrence rate appears in equinoxes and lowest in winter on the nightside. Finally, on the nightside, it shows smaller occurrence rate under high solar activity conditions, which indicates that high solar activity may inhibit the nightside trough region irregularities. And there is no obvious solar activity dependence on the dayside occurrence rate of the trough region irregularities.

Acknowledgments

We greatly acknowledge the European Space Agent (ESA) for providing the high-resolution (2 Hz) Swarm Ne data (https://swarm-diss.eo.esa.int/#). This work is supported by the National Natural Science Foundation of China (42164010, 42104169), the Postdoctoral Science Foundation of Jiangxi Province (2020KY35), the Science and technology project of Jiangxi Provincial Department of Education (GJJ201722), the China Postdoctoral Science Foundation (2020M6830265), the Education Reform Project of Shangrao Normal University (JG-19-12), and the Fundamental Research Funds for the Central Universities, Sun Yat-sen University(2021qntd29).

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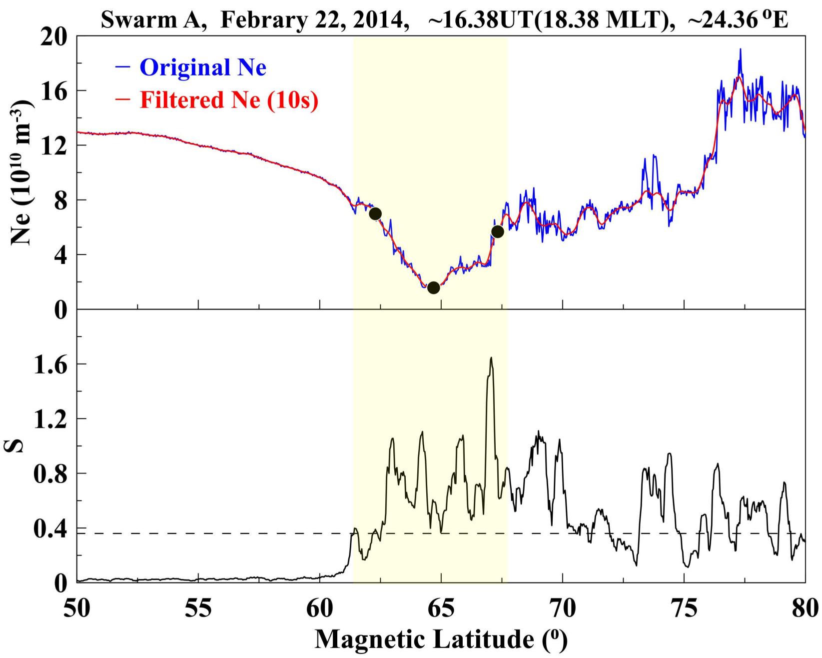

Figure 1. Examples of observed MIT structure and trough region plasma irregularities from Swarm Ne measurements at about 16.38 UT on February 22, 2014.

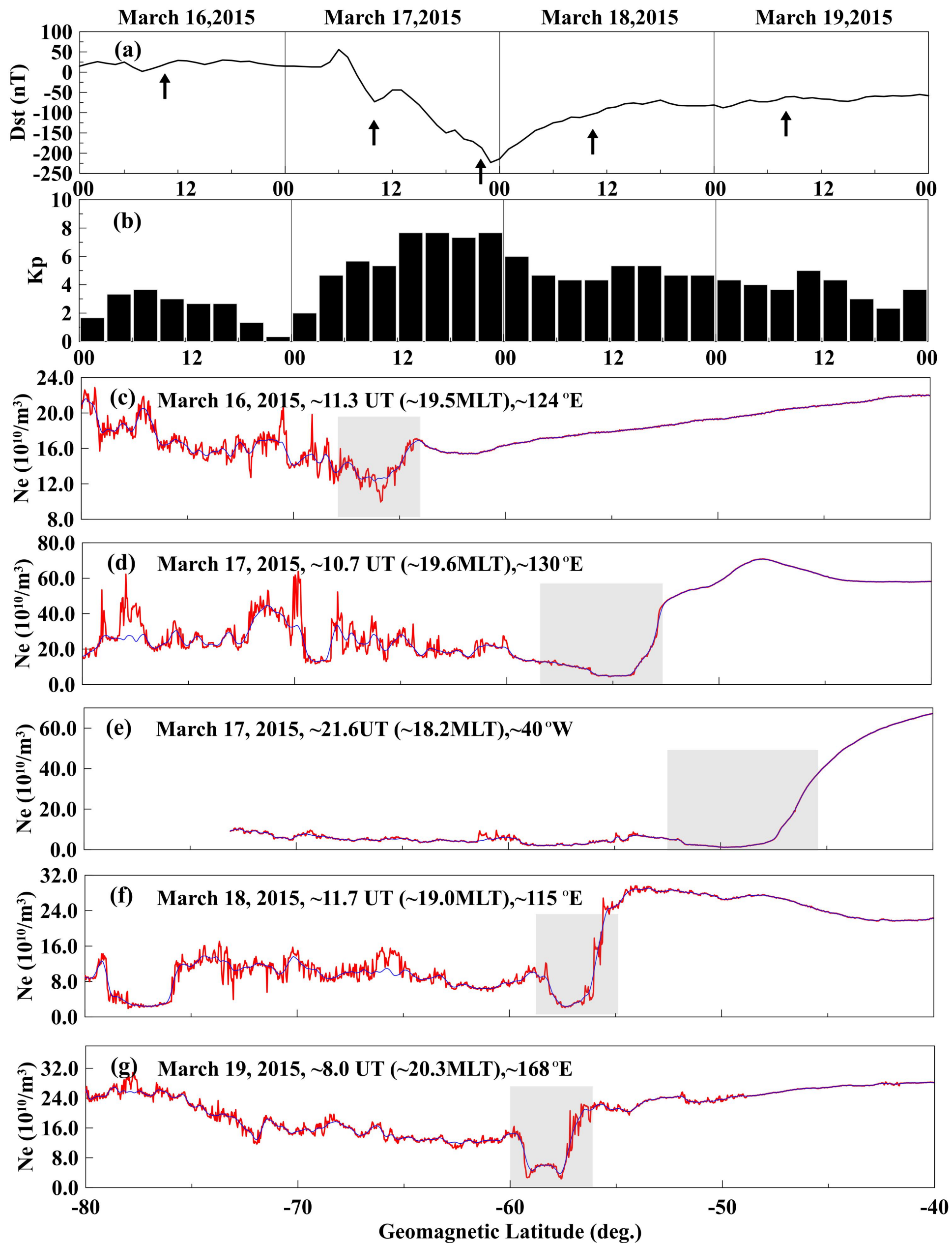

Figure 2. An example of the evolution of mid-latitude trough region irregularities during the strong magnetic storm on 17 March 2015.

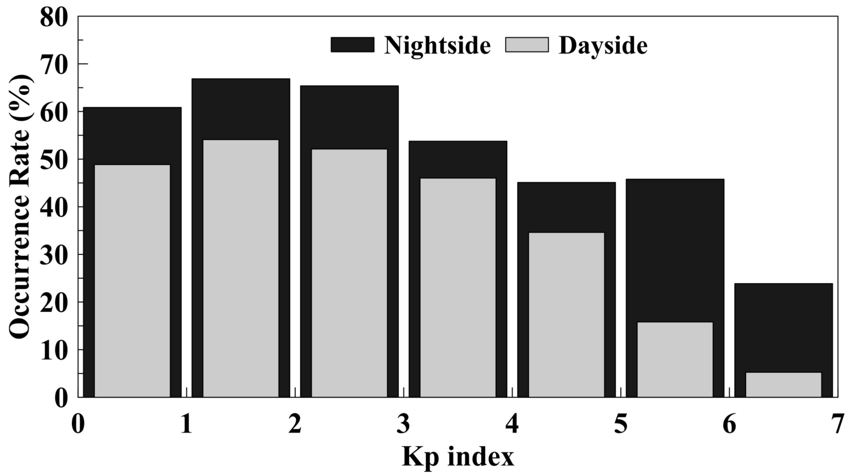

Figure 3. Variation of the occurrence rate of irregularities in the mid-latitude trough area with Kp index.

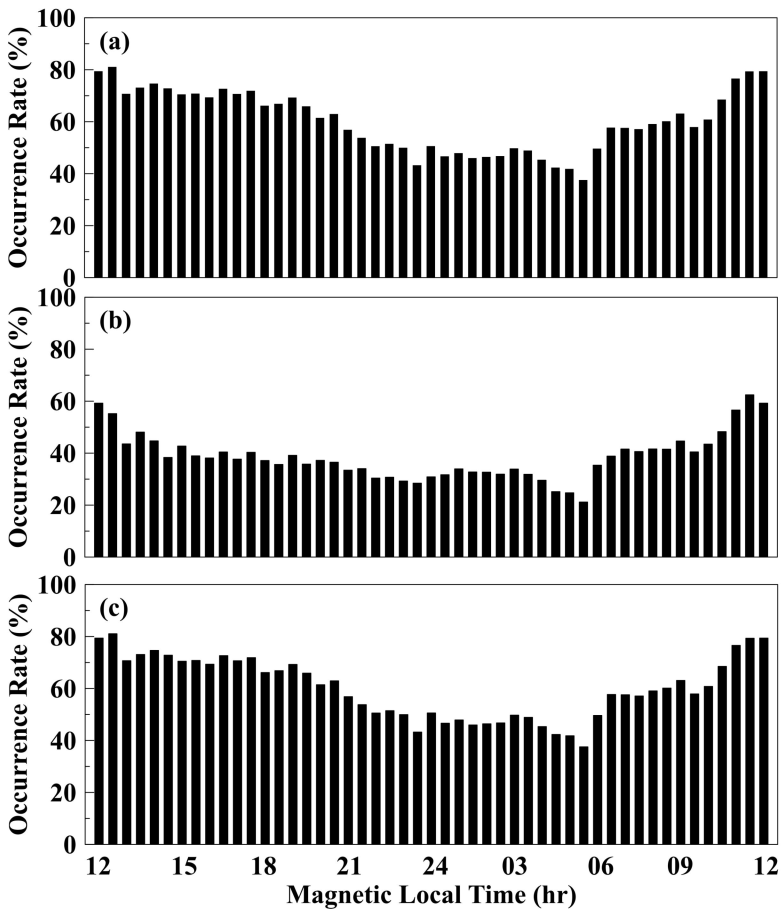

Figure 4. Occurrence rate of mid-latitude trough irregularities as a function of magnetic local time under geomagnetic quiet conditions, (a-c) represent the total occurrence rate, the occurrence rate in the trough equatorward wall, and the occurrence rate in the trough poleward wall, respectively.

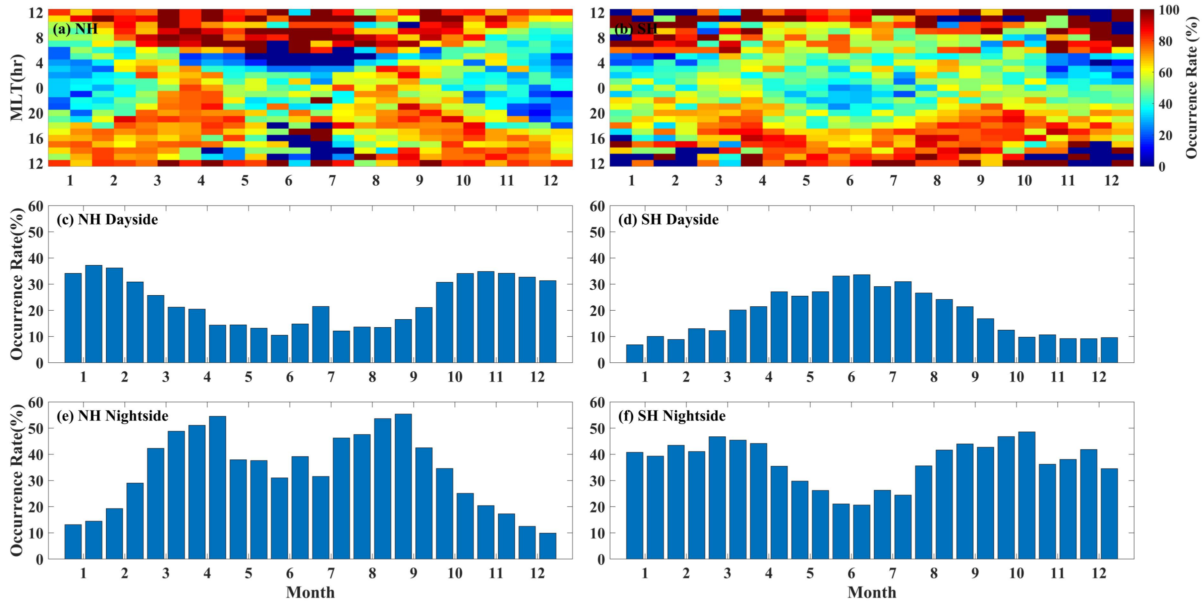

Figure 5. The seasonal versus magnetic local time distributions of the occurrence rate of irregularities in the mid-latitude trough area under geomagnetic quiet conditions.

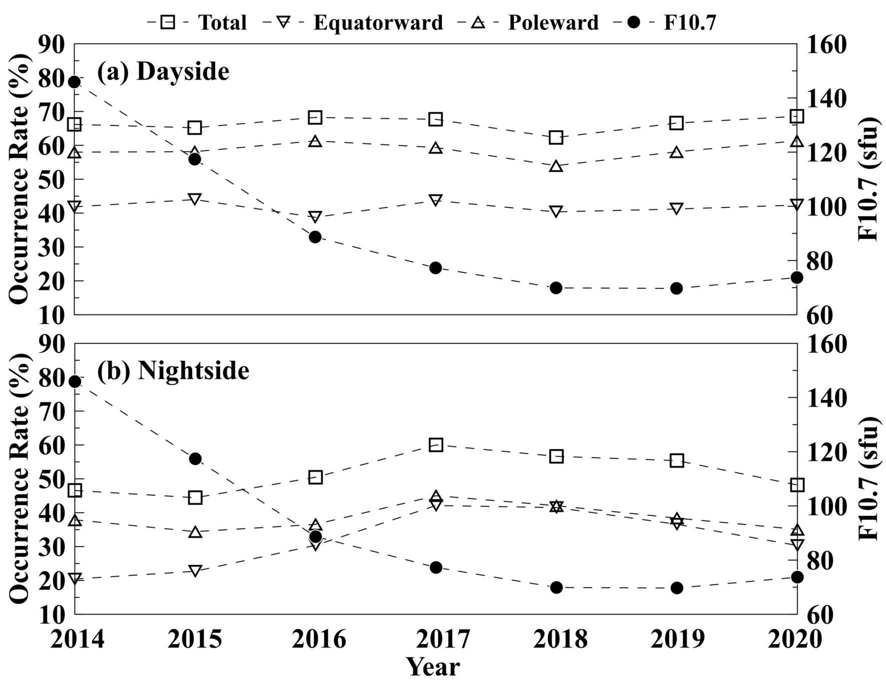

Figure 6. Variation curves of the yearly averaged occurrence rate of irregularities in the mid-latitude trough, as well as curves of the yearly averaged F10.7 index, on (a) dayside and (b) nightside, respectively.