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Statistical analysis of low-latitude spread F observed over Puer, China, during 2015–2016

Ting Lan[1*], Chunhua Jiang[1*], Guobin Yang[1], Yuannong Zhang[1], Jing Liu[2] and Zhengyu Zhao[1]

Abstract

Statistical analysis of spread F (SF), recorded at Puer (PUR, 22.7° N, 101.05° E, Dip Latitude 12.9° N) during 2015–2016, was carried out to reveal its characteristics at the northern equatorial ionization anomaly. In our study, SF was categorized into four types, frequency spread F (FSF), range spread F (RSF), mix spread F (MSF) and strong range spread F (SSF). The statistical results presented that FSF and MSF were dominant over Puer. Most types of SF appeared mostly in summer months, except the maximum occurrence of SSF in equinox months. Moreover, observations of SF events also showed that the solar activity and magnetic activity dependence of SF varied with seasons. Compared with observations at other region, the present results suggest that medium-scale traveling ionospheric disturbances (MSTIDs) may play a key role in generation of SF in low-latitude region.

Keywords: Ionosphere, Spread F, Ionosonde, MSTIDs

Key points

- The occurrence rate of SF observed at Puer during 2015–2016 shows obvious dependence on local time and season.
- The dependences of different types of SF on solar activity and geomagnetic activity are varied with season.
- SF observed at Puer could be induced by various mechanisms including ionospheric irregularities at equator or nighttime MSTID.

Introduction

A nighttime ionospheric phenomenon in the equatorial and low-latitude region, known as spread F (SF), has been extensively investigated for many years since it was first observed by Booker and Wells (1938). SF traces on ionograms can be divided into four different types including frequency spread F (FSF), range spread F (RSF), mix spread F (MSF) and strong range spread F (SSF) (Piggot and Rawer 1972; Shi et al. 2011), which are the manifestation of density irregularities with different altitudes and spatial scales from centimeters to hundreds of kilometers.

Statistical characteristics of nighttime SF have been studied over the past several decades. Earlier observational evidences suggested that the occurrence of SF at equator and low latitudes has obvious diurnal, latitudinal, longitudinal, seasonal, solar cycle and geomagnetic activity variations (Abdu et al. 1981, 1985; Li et al. 2010; Upadhayaya and Gupta 2014; Rungraengwajiake et al. 2013; Wang et al. 2010; Dabas et al. 2007; Zhu et al. 2015; Wang et al. 2018). Pezzopane et al. (2013) performed a comparative analysis of equinoctial SF characteristics at different longitude sectors at low latitudes using observations of ionosonde. Their results indicated that features of the occurrence of SF were different at different sites, depending on both the longitude and hemisphere. Li et al. (2007) showed that nighttime *F* region density irregularities in equatorial and low-latitude region have distinct seasonal/longitudinal variations using satellite observations. In addition, their results presented that there were two peaks (minima) of plasma bubble occurrences in the African and Pacific longitude sector during June solstice (December solstice) and there was no significant longitudinal effect on plasma bubble occurrences during

*Correspondence: tinglan@whu.edu.cn; chuajiang@whu.edu.cn
[1] Department of Space Physics, School of Electronic Information, Wuhan University, Wuhan 430072, China
Full list of author information is available at the end of the article

equinoxes. Rangaswamy and Kapasi (1964) reported that the occurrence of SF was anti-correlated with magnetic activity during sunspot maximum, while the negative correlation was indistinctive during sunspot minimum. This inverse relationship between *F* region density irregularity and magnetic activity has also been confirmed by Su et al. (2006) using observations of satellite. Long-term observational results have suggested that there were obvious differences in statistical characteristics of each type of SF. Chandra et al. (2003) analyzed SF phenomena recorded by ionosonde over Ahmedabad (23.0° N, 72.4° E, Dip latitude 14.3° N) and presented that the maximum and minimum occurrences of RSF were, respectively, at equinoxes and summer solstices during high solar activity years. However, FSF occurred frequently in summer solstices of low sunspot years and after midnight. The similar results of RSF and FSF were also shown by Zhu et al. (2015). Wang et al. (2010) showed that the occurrence of MSF, observed before midnight, was maximum in summer months during low solar conditions. However, SSF mainly occurred around midnight at equinoxes during high solar conditions. Moreover, the negative correlations between Kp and RSF, MSF and SSF were also presented in their work, except FSF. On the other hand, Wang et al. (2018), Dabas et al. (2007) and Rungraengwajiake et al. (2013) carried out comparative analysis of SF recorded by ionosondes at different latitudinal regions. Their results showed that RSF was dominant over the stations near equator which occurred mostly in equinoxes and at post-sunset. However, FSF was dominant in low- and mid-latitude region which frequently occurred in summer months and at post-midnight. Observations mentioned above show that there are some discrepancies in the occurrence characteristics of SF at different latitudinal and longitudinal regions.

Many studies proposed that the formation of nighttime SF is generally attributed to the generalized Rayleigh–Taylor instability (GRT) which results from the evening pre-reversal electric field enhancement (PRE), especially at equatorial region (Abdu 2001; Kelly 2009). Madhav Haridas et al. (2018) analyzed nearly two decades of ionosonde observations over Trivandrum (8.5° N, 77° E, Dip latitude 0.1° N) and examined the correlation between the occurrence of SF and the growth rate of GRT. They suggested that occurrence of SF varied exponentially with the growth rate of GRT. However, the statistical characteristics of FSF cannot be fully explained by the GRT instability. Recent studies (Candido et al. 2011; Krall et al. 2011) suggested that medium-scale traveling ionospheric disturbances (MSTIDs) might be a key role for the formation of SF at equatorial and low-latitude region. Candido et al. (2011) presented that the FSF events at non-equatorial region, Cachoeira Paulista (22.7° S, 45.0° W, Dip latitude 25.3° E), during June solstices could be caused by MSTIDs rather than equatorial electrodynamic process. Based on observations from VHF radar at equatorial and low-latitude region during low solar activity period, atmospheric gravity waves (GWs) from lower thermosphere and the uplift of F layer by neutral winds may be also contribute to the formation of post-midnight F layer density irregularities during June solstices (Otsuka 2018; and references therein). Therefore, the statistical characteristics of each type of SF might not be similar due to the different mechanisms.

Although nighttime SF phenomena in the equatorial and low-latitude region have been investigated by many researchers, statistical characteristics of each type of SF might be different due to the different region and their mechanisms. As a result, the statistical characteristics of each type of SF still need to be further investigated. In this work, a statistical study of each type of SF, recorded by the ionosonde at Puer station during the period of 2015–2016, was carried out. This study might provide another view to understand the characteristics and possible physical mechanisms for each type of SF.

Data

An advanced digital ionosonde, Wuhan Ionospheric Sounding System (WISS) (Shi et al. 2009), was installed at Puer (PUR, 22.7° N, 101.05° E, Dip Latitude 12.9° N). WISS is carrying out vertical incidence ionospheric sounding every 5 min to monitor characteristics of the ionosphere since 2013. In this study, about 210,000 ionograms recorded during 2015–2016 were used to investigate the characteristics of SF. All ionograms were manually examined for the statistical analysis of SF, including the occurred time and SF type. In this work, SF traces were categorized into four types: FSF, RSF, MSF and SSF. Moreover, SF data were grouped into three seasons: equinox (March, April, September and October), summer (May, June, July and August) and winter (November, December, January and February). Some typical ionograms with four types of SF are plotted in Fig. 1.

Observations and statistical results

For each type of SF, the occurrence rate of SF was calculated using the following basic formula:

$$\text{Occurrence rate (\%)} = \frac{\text{Sum of SF occurrences}}{\text{Total number of observed ionograms}} \times 100$$

In order to describe the different statistical features of SF, the basic formula of occurrence rate has different forms of expression under different conditions in the following sections.

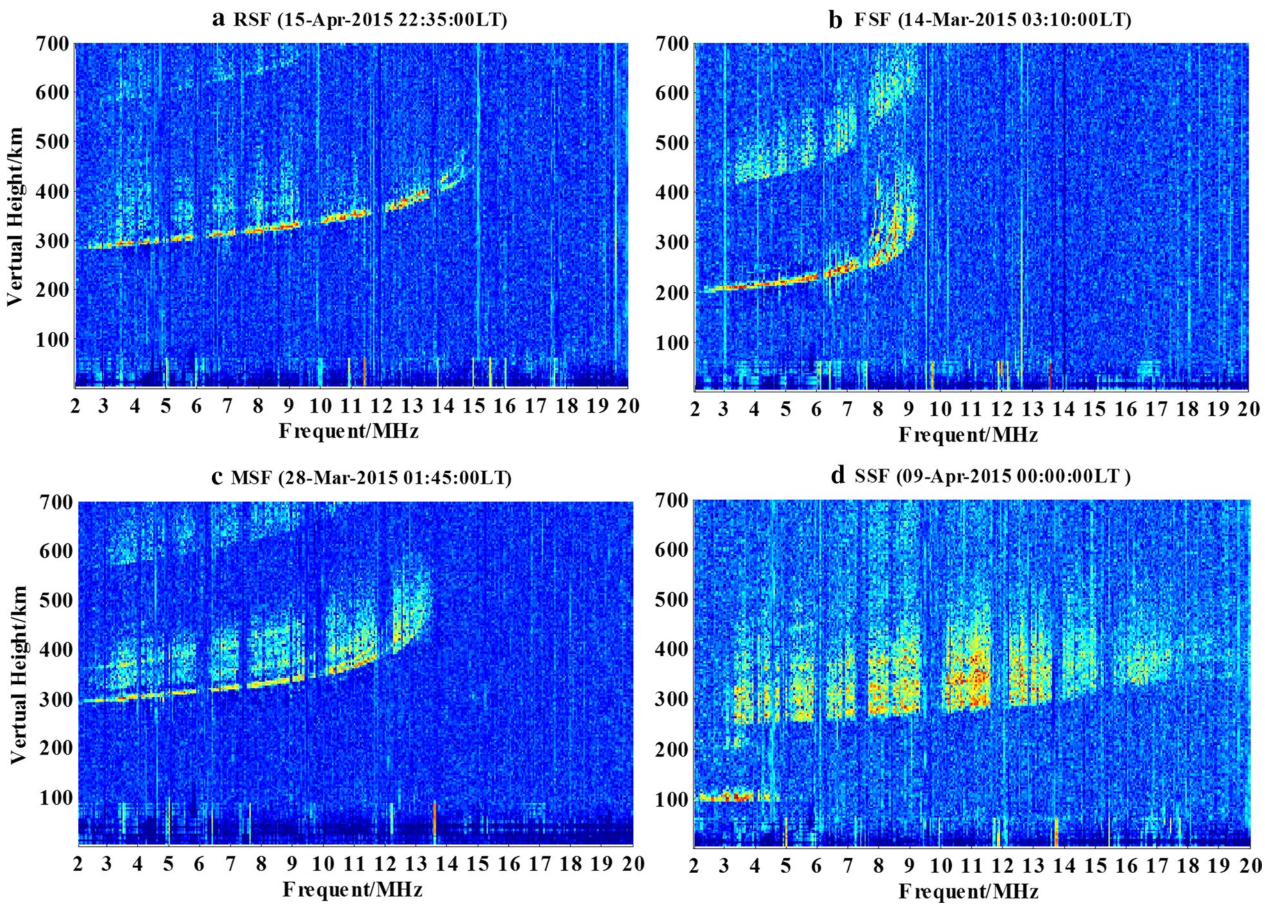

Fig. 1 Four types of SF. **a** RSF, **b** FSF, **c** MSF, **d** SSF

Diurnal and seasonal variations

Figure 2 shows diurnal variation of the occurrence rate of SF during different seasons in 2015–2016. Note that the scale of the occurrence rate is different for different plots in Fig. 2. For each season and each type of SF, the occurrence rate in Fig. 2 is defined as the ratio of the sum of observed SF to the total number of ionograms. It was found that the probability of the occurrence of MSF and FSF was greater than that of RSF and SSF. The maximum occurrences of MSF and FSF were at around

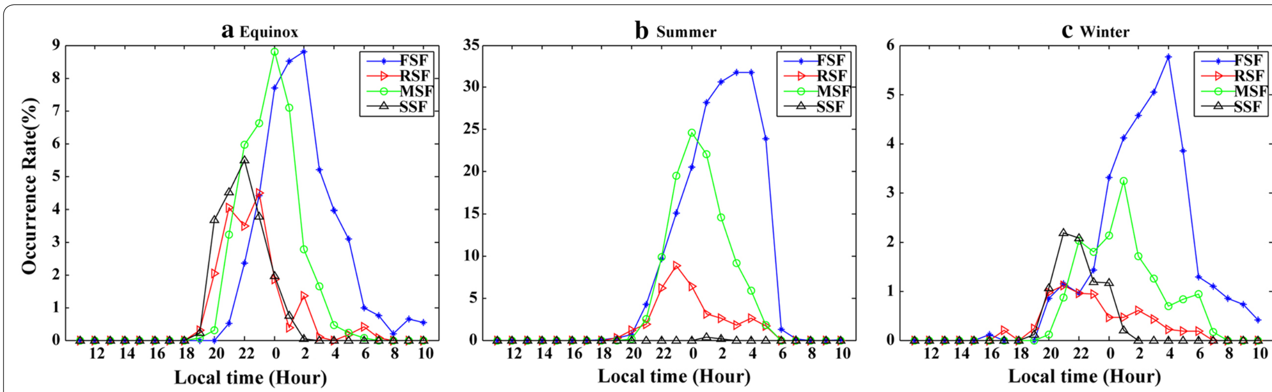

Fig. 2 SF occurrence rates for 2015–2016 as a function of local time (LT) for different seasons

post-midnight, while RSF and SSF mainly occurred around 22:00–00:00 LT. It can be seen from Fig. 2 that the probability of the occurrence rate was greater in summer months than in winter months and equinox months, except of SSF. In contrary, SSF was almost not observed in summer. The maximum occurrence rate of SSF was in spring and autumn equinoxes. The similar statistical results for MSF and FSF were also presented in Amabayo et al. (2011) at mid-latitudes. Figure 3 presents month-local time distribution of the occurrence rate of SF in 2015–2016. Note that the scale of the color is different for different plots in Fig. 3. For each type of SF, the occurrence rate in Fig. 3 was defined as the ratio of the sum of observed SF to the total number of ionograms in a month. It can be seen from Fig. 3 that the minimum occurrence rate of SF was in winter months. It is interesting that the SSF mainly occurred in March equinox. Shi et al. (2011) reported similar characteristics of SSF over low latitudes. Rungraengwajiake et al. (2013) compared the occurrence of spread F observed by two ionosondes located along the similar longitude sector. One is Chumphon (10.7° N, 99.4° E, Dip latitude 3.0° N) located near the magnetic equator, and the other is Chiangmai (18.7° N, 98.9° E, Dip latitude 12.7° N), located near Puer station in this study. In the results presented by Rungraengwajiake et al. (2013), the occurrence of RSF at Chumphon station was evidently higher than Chiangmai station. However, the occurrence of FSF was higher at Chiangmai station than that at Chumphon station. The RSF mostly occurred in equinoctial months at both stations, and note

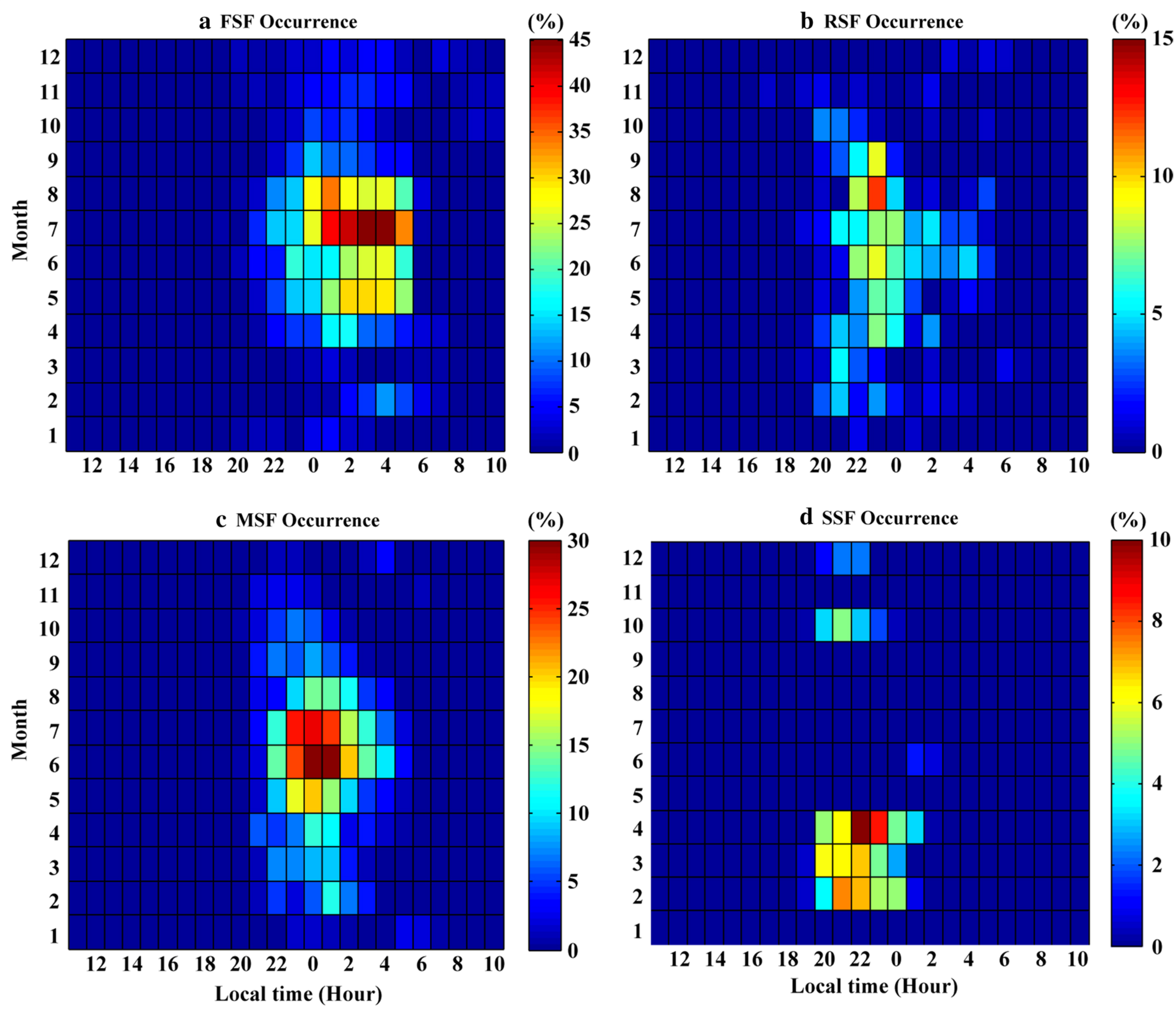

Fig. 3 SF occurrence rates for 2015 and 2016 as a function of local time (LT) and month. Colors represent the occurrence rate

that the RSF was also frequently observed the summer months at Chiangmai station, while FSF mostly occurred in summer months at both stations. The results of Chiangmai station were consistent with our results of RSF and FSF, except that the maximum occurrence of RSF was in summer months in our result. In our study, the occurrence of RSF was lower than FSF in all seasons. It was found that onset time of RSF in summer months was later than in equinoxes in Fig. 3, which is consistent with the results over Sanya (18° N, 109° E, Dip latitude 8° N) presented in Zhu et al. (2015). The sunset time and the occurrence time of PRE were later in summer months, and it is responsible for the later onset time of RSF (Fejer et al. 1999). Compared with the results in Fig. 8 of the study shown by Rungraengwajiake et al. (2013), in equinox months, the RSF onset time was mostly during 18:00 LT–19:00 LT at Chumphon station; nevertheless, the RSF onset time was mostly during 19:00 LT–20:00 LT at Chiangmai and Puer stations. Moreover, the maximum occurrence of SSF at Puer station was in equinoxes which agreed with Hainan (19.5° N, 109° E, Dip latitude 9° N) (Shi et al. 2011).

Dependence of solar activity

To reveal the correlation between SF and solar activity, Fig. 4 shows the occurrence of SF as a function of local time and month during 2015 (Average $F10.7 \approx 118$) and 2016 (Average $F10.7 \approx 89$). It was found that the probability of the occurrence of RSF and SSF was greater in 2015 than in 2016. In other words, there was a strong dependence of solar activity on the occurrence of RSF and SSF in our study. However, we cannot find the similar dependence of solar activity on the occurrence of FSF and MSF from Fig. 4.

Previous studies have suggested that the effect of solar activity on characteristics of SF over equatorial and low-latitude region varied with latitude, longitude and season (Rangaswamy and Kapasi 1964; Wang et al. 2010; Amabayo et al. 2011; Bhaneja et al. 2018). Abdu et al. (1985) analyzed RSF data in equinox months during 1973–1982 from two ionosonde stations over equatorial and low-latitude region in Brazil and found that there was a positive correlation between the occurrence of RSF and solar activity over low-latitude region. Hysell and Burcham (2002) carried out a long-term observation of plasma irregularities by JULIA radar at Jicamarca. From Jicamarca observation near dip equator, Hysell and Burcham (2002) found that the highest occurrence of ESF appears in equinox months in either high or low solar activities, and the occurrence rate of irregularities was greater during high solar activity than that during low solar activity due to the enhancement of PRE. Results mentioned

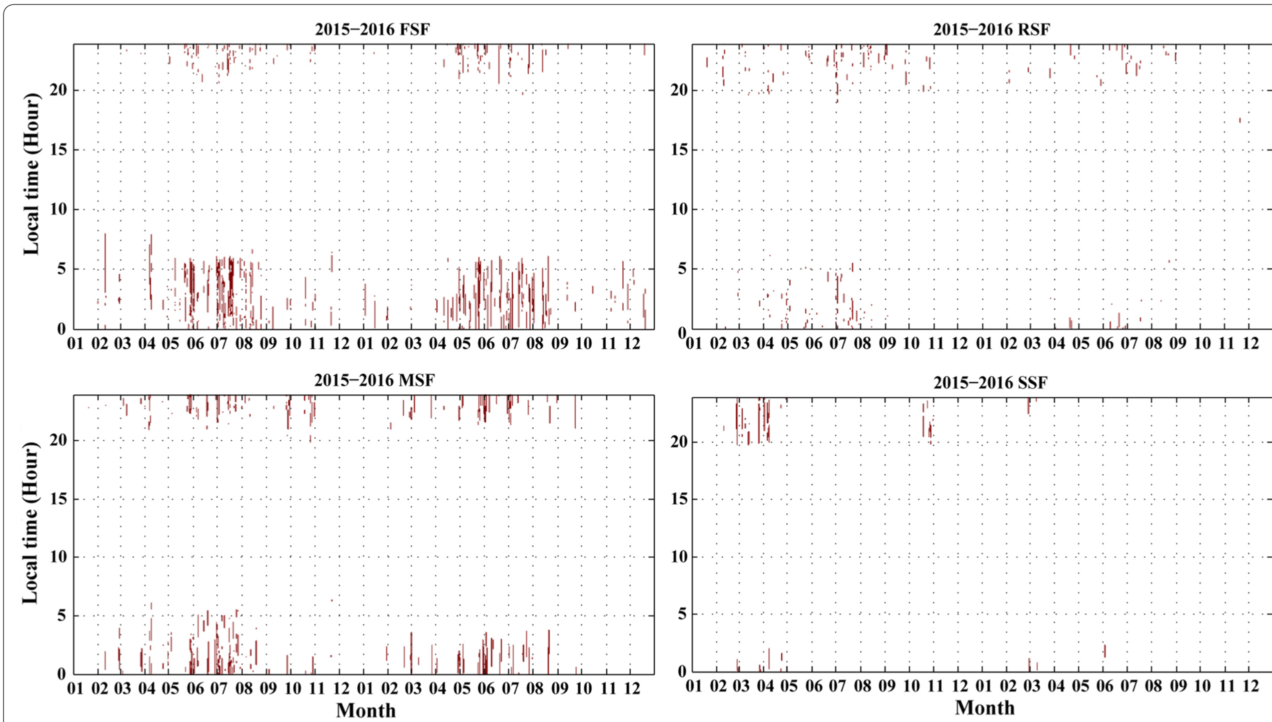

Fig. 4 The variation of SF occurrence time with days during the magnetic quiet conditions (Kp < 3) for 2015 (moderate solar activity year) and 2016 (low solar activity year)

above are consistent with our statistical results for RSF and SSF. Amabayo et al. (2011) showed that the occurrence possibility of MSF and FSF over South Africa during low solar activity was higher than that during high solar activity (inconsistent with FSF and MSF at Puer). However, Chandra et al. (2003) showed that FSF occurrence was independent of solar activity (same as FSF at Puer). Moreover, solar activity dependence of four types of SF also presented in Wang et al. (2010). Wang et al. (2010) shows that the occurrence of FSF was independent of solar activity. However, there was a positive correlation between the occurrence of RSF and SSF and solar activity in Hainan. For the occurrence of MSF at Hainan, it was independent of solar activity in equinoxes but had an inverse correlation with solar activity in summer and winter months. Results shown by Wang et al. (2010) are in agreement with our observations of FSF, SSF and RSF, except MSF observation. As a result, the effect of solar activity on SF has significant differences which varies with different seasons, different latitudes and different types of SF.

Dependence of magnetic activity

Figure 5 shows the occurrence rate of SF with different geomagnetic activities to reveal the effect of geomagnetic activity on the formation of SF. In this study, quiet and storm periods were specified when $Kp < 3$ and $Kp \geq 5$, respectively. Note that the ionograms with Kp index between 3 and 4 were not included in this plot. In this section, the number of ionograms with SF under each geomagnetic activity condition was divided by the total number of ionograms under each geomagnetic activity condition during equinox, summer and winter, respectively. It was found from Fig. 5 that the occurrences of FSF and MSF decreased obviously when Kp increased in summer months. The occurrence of FSF was slightly higher during active geomagnetic condition than quiet condition during equinox and winter months. A positive correlation was observed for all types SF in winter months and for RSF in all seasons. Moreover, the occurrence of SSF showed an inverse correlation with geomagnetic condition during equinox and summer months, while there was a slight increase in its occurrence in winter months when Kp increased.

Many studies investigated the effect of geomagnetic activities on the occurrence of SF. At equatorial region, some studies (Bowman 1998; Sobral et al. 2002; Su et al. 2006; Ray and DasGupta 2007) found that the geomagnetic activity tended to suppress the generation of ESF. However, some researches have suggested that the dependence of magnetic activity varied with latitude, longitude, season and the phase of storm (Sahai et al. 2005; Sobral et al. 2002; Becker-Guedes et al. 2004; Li et al. 2010; Kumar et al. 2016). Whalen (2002) reported that there was an inverse relationship between the occurrence of ESF and Kp index during equinoxes and December solstice, but no correlation in June solstice. Their results are inconsistent with our observations in this work. Becker-Guedes et al. (2004) suggested that the geomagnetic activity acted as an inhibitor during high SF occurrence months and as an initiator during low SF occurrence months. In our study, the summer months were the high SF occurrence months and the winter months were the low occurrence months, the occurrences of SF in summer and winter months at Puer were completely consistent with the results proposed by Becker-Guedes. Sahai et al. (2005) analyzed ionograms recorded at four different stations in both hemispheres and low latitudes as well as equator region in equinox months, and indicated that the geomagnetic storm had different effect on SF at different stations. The salient uplift of F layer at sunset was observed at two stations during storm period and the SF appeared subsequently. Therefore, storm could also act as an initiator for the occurrence of SF during equinoxes.

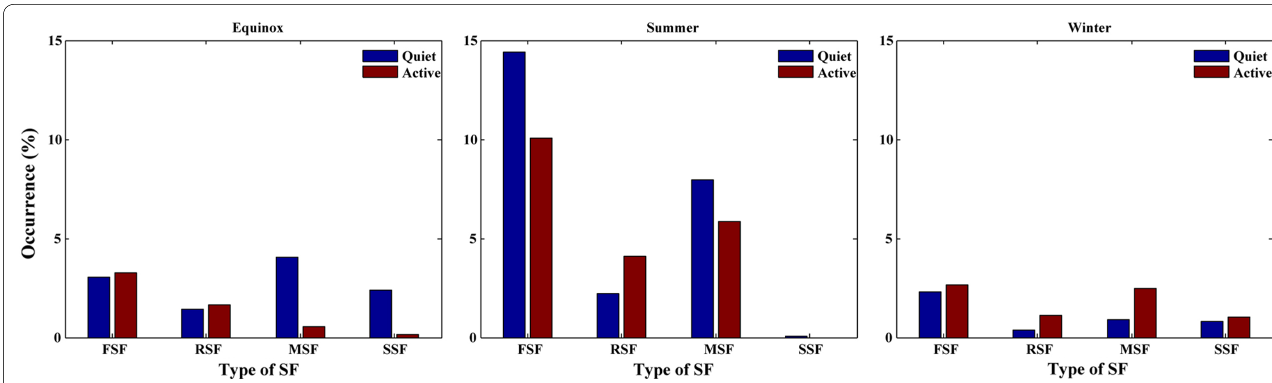

Fig. 5 The occurrence rates of four types of SF under different geomagnetic conditions in 2015–2016

However, the morphology of SF during different magnetic activity period still be not fully understood according to the existing theories. More detailed analysis for the relationship between each type of SF and magnetic activity is needed for further investigation in the future based on long-term observational data over Puer.

Discussion

Previous observational evidences suggested that SF at low latitudes is due to the diffusion of the equatorial plasma bubbles along magnetic field lines (Kelly 2009). Manju et al. (2011) and Wang et al. (2015) also presented some observations which further confirmed this hypothesis that plasma bubbles originated from the equator can propagate to low-latitude and generate SSF or scintillations. As a result, it indicates that plasma bubbles developed from the equator might expand to higher latitude and play an important role in the formation of RSF and SSF at low latitudes. Our results showed that the maximum occurrence rates of RSF, FSF and MSF were in summer months at Puer station (at about 100° E longitude sector). However, Gentile et al. (2006) and Rungraengwajiake et al. (2013) reported that the maximum occurrence rate of the equatorial plasma bubbles/RSF at 100° E longitude sector was in equinox months. Therefore, it was reasonable to think that the irregularities from the equator might not be the only driver for formation of SF at low latitudes. Dabas et al. (2007) studied characteristics of SF at Delhi (28.6° N, 77.2° E, Dip latitude 19.9° N) and proposed that the SF in summer months might be caused by other originated irregularities. Many previous studies have highlight that the MSTIDs might contribute to the generation of spread F in equatorial and low-latitude regions. Fukushima et al. (2012) indicated that nighttime MSTIDs could be classified into two groups. The first group has their origin in GWs which are possibly generated from deep convection. Abdu et al. (2009) presented a study which compared the observational results with the theoretical model calculation results and provided the evidence that the GWs could seed ESF, which agreed well with the results shown by Krall et al. (2013). It is known that TIDs are the manifestation of GWs in ionosphere (Hines 1960) and MSTIDs/GWs could be supposed to be a seeding of SF. Jiang et al. (2019) showed that wave-like structure in the ionosphere, induced by MSTIDs/GWs, also could produce SF on ionograms. Jiang et al. (2016) presented an observational case (daytime SF) at Puer station which was suggested to be induced by MSTIDs/GWs. The second group of nighttime MSTID is related to plasma density irregularities developed at mid-latitudes. Candido et al. (2011) suggested that low-latitude SF could be caused by nighttime MSTIDs. Based on all-sky imaging system observations, Pimenta et al. (2008) proposed that nighttime MSTIDs generated in mid-latitude region could propagate toward low-latitude region and generate nighttime SF. Studies by Miller et al. (2009) and Krall et al. (2011) also suggested the results proposed by Pimenta et al. (2008). In terms of the occurrence of nighttime MSTIDs, studies (Candido et al. 2008; Ding et al. 2011) about nighttime occurrence of MSTIDs showed that there was a maximum occurrence rate of nighttime MSTIDs around midnight in June solstice in the low- and middle-latitude regions. Chen et al. (2019) also investigated the occurrence of MSTIDs in Hongkong (22.2° N, 114.2° E, Dip Latitude 12.5° N) and showed that the nighttime MSTIDs mainly occurred at 22:00 LT–03:00 LT in summer months. As the dip latitude of Hongkong is similar to Puer, the results might be suitable for applying to Puer station. The higher occurrence of nighttime MSTIDs in summer months is also consistent with the maximum occurrence rates of RSF, FSF and MSF in summer months at Puer. Moreover, Seker et al. (2011) proposed that the mid-latitude nighttime MSTIDs and geomagnetic activity had a negative correlation. It can be seen from Fig. 5 that it is consistent with the variation of FSF and MSF occurrences with geomagnetic activity in our work. As a result, we suggested that the nighttime MSTIDs might play a significant role in forming RSF, FSF and MSF at Puer station in the present study.

Conclusions

In this study, ionograms, recorded by ionosonde at Puer, were used to carry out a statistical investigation of SF in 2015–2016. The morphology of four types of SF was presented in our work. The main conclusions are as follows:

1. The occurrence rates of each type of SF were strongly dependent on local time and season. The probability of the occurrence of FSF and MSF was greater than that of SSF and RSF during 2015–2016. The maximum occurrence rates of FSF, MSF and RSF were in summer months, while SSF occurrence was maximum in equinox months. In terms of local time of the occurrence, FSF and MSF mostly occurred at post-midnight, while RSF and SSF tended to occur at pre-midnight.
2. The effect of solar activity and magnetic activity on each type of SF varied with season. Our results presented that the occurrences of RSF and SSF had a positive correlation with solar activity for most seasons, while FSF and MSF occurrences were independent of solar activity. Furthermore, the occurrences of MSF and FSF obviously decreased during higher geomagnetic activity period in summer months; all types of SF had an inverse relationship with Kp during winter months; the occurrence

of RSF slightly increased as the Kp increased during all seasons.

3. Our observational results demonstrate that the occurrence of SF at low latitudes under lower solar conditions cannot be fully interpreted by the characteristics of equatorial plasma bubbles. Our study suggests that nighttime MSTIDs may be a significant role in formation of SF over Puer.

Abbreviations

SF: spread F; FSF: frequency spread F; RSF: range spread F; MSF: mix spread F; SSF: strong range spread F; TID: traveling ionospheric disturbance; GRT: generalized Rayleigh–Taylor instability; PRE: pre-reversal electric field enhancement; GWs: atmospheric gravity waves; MSTID: medium-scale traveling ionospheric disturbance.

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Authors' contributions

TL performed data processing and statistical analysis on spread F and drafted the manuscript. TL, CJ and YG revised the whole manuscript. YZ and CJ elaborated on the processing of SF data and supervised all the work of TL. YG, JL and ZZ participated in the discussion and interpretation of the statistical results obtained. All authors read and approved the final manuscript.

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Availability of data and materials

The data that support the findings of this study are available upon request from the corresponding author.

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare that they have no competing interests.

Author details

[1] Department of Space Physics, School of Electronic Information, Wuhan University, Wuhan 430072, China. [2] Institute of Earthquake Science, China Earthquake Administration, Beijing 100036, China.

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