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Key Points:

- Conclusive evidence for EMSTIDs as one of the sources of postmidnight VHF radar echoes in low and equatorial latitudes
- EMSTIDs are shown to contribute to the occurrences of late night spread *F* in equatorial ionograms during solar minimum periods
- EMSTID signatures are seen to occur very close to the dip equator

Supporting Information:

- Supporting Information S1
- Movie S1
- Movie S2

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Coincident Airglow, VHF Radar, and Ionosonde Observations of Electrified Medium-Scale Traveling Ionospheric Disturbances in the Equatorial Latitudes

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Abstract The occurrence of late night spread *F* in the low and equatorial latitude regions during solar minimum is not properly understood. Radar observations have revealed occurrence of postmidnight echoes at low and equatorial latitudes during solar minimum periods. This work discusses the coordinated airglow, VHF radar, and ionosonde observations of nighttime electrified medium-scale traveling ionospheric disturbances (EMSTIDs) made from the low and equatorial latitude Indian region. Two nights of observations are discussed in detail in which EMSTIDs are seen to coexist with spread *F* in ionograms and VHF backscatter. These observations reveal that the EMSTIDs propagate to latitudes very close to dip equator at times and they can be responsible for a reasonable portion of the postmidnight radar echoes and spread *F* events observed at low and equatorial latitudes during low solar activity period.

Plain Language Summary The low-latitude and equatorial *F* region ionosphere is susceptible to the formation of plasma instabilities affecting radio wave propagation. They are commonly referred to as equatorial spread *F*. Generally, they are known to form soon after the sunset. However, during solar minimum periods, spread *F* is often observed in ionosonde and coherent backscatter VHF radar observations in the later hours of the night including postmidnight period. The cause of such instabilities is not properly understood. In this work, using airglow imaging of OI 630.0-nm redline, VHF radar, and ionosonde observations, we show evidence for the existence of midlatitude-type instabilities causing the spread *F* over low and equatorial latitudes in later hours of the night. These observations ascertain that a portion of the late night spread *F* events observed during solar minimum period are caused directly by midlatitude-type electrified medium-scale traveling ionospheric disturbances propagating into the low latitudes.

1. Introduction

Radio wave propagation is affected in the night over low and middle latitudes due to plasma instabilities in the *F* region ionosphere (Makela & Otsuka, 2012). Mechanisms of these nocturnal instabilities are found to be different for low and middle latitudes. The low-latitude instabilities are often attributed to the growth of the Rayleigh-Taylor instability over the dip equator, which lead to large-scale plasma depletions called equatorial plasma bubbles (EPBs) (Ossakkow & Chaturvedi, 1978; Makela, 2006). From the dip equator, the EPBs map to low latitudes along the geomagnetic field lines. Spread *F* occurring at low and equatorial latitudes is usually attributed to the EPBs. On many occasions, VHF radars receive strong echoes arising from the coherent backscattering from meter-scale field-aligned irregularities (FAIs) associated with EPBs and the echo morphology usually consists of erected plumes with trailing structures (Patra et al., 1997; Woodman & La Hoz, 1976). In airglow images, the EPBs manifest as dark bands extending approximately in the north-south direction (Makela, 2006; Weber et al., 1978).

The midlatitude instabilities are believed to be sustained in the *F* region ionosphere owing to the Perkin's instability mechanism (Perkins, 1973) and are referred to as nighttime medium-scale traveling ionospheric disturbances (MSTIDs) in the past studies (Garcia et al., 2000; Otsuka et al., 2004; Shiokawa et al., 2003). However, the calculated growth rate for Perkin's instability is quite small and, hence, theories based on coupled *E* and *F* region electrodynamics in the presence of sporadic *E* layers were proposed to explain such features (Cosgrove & Tsunoda, 2004; Tsunoda & Cosgrove, 2001; Yokoyama et al., 2009). Experimental

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studies appear to support such theories as well (Chen et al., 1972; Kelley et al., 2003; Narayanan et al., 2018; Otsuka et al., 2007, 2008; Saito et al., 2007). Hence, we refer to the midlatitude instability features as electrified medium-scale traveling ionospheric disturbances (EMSTIDs).

The EMSTIDs are seen in the airglow images as alternating dark and bright bands propagating equatorward and westward (southwestward in the Northern Hemisphere and northwestward in the Southern Hemisphere) with phase front alignments along the northwest to the southeast in the Northern Hemisphere (southwest to northeast in the Southern Hemisphere) (Shiokawa, Ihara, et al., 2003; Narayanan et al., 2018). In many of the cases the dark bands are more prominent and occasionally, the EMSTIDs occur as single dark bands as well. The dark bands are caused by plasma moving in the up-northwest direction, while the bright airglow regions are associated with plasma moving in the down-southeast direction (Shiokawa, Otsuka, et al., 2003). Such plasma movements are due to the $\boldsymbol{E} \times \boldsymbol{B}$ drifts caused by the polarization electric fields of the EMSTIDs. VHF radars in the midlatitudes have observed FAIs associated with EMSTIDs, which often show descending echo patterns with striations (Fukao et al., 1991; Otsuka et al., 2009). Since the FAIs are observed by radars in directions perpendicular to the slanted geomagnetic field lines, up-north and down-south Doppler velocities are measured alternatively corresponding to the depleted and enhanced airglow regions (Kelley et al., 2000; Otsuka et al., 2009). The midlatitude spread *F* in ionograms is believed to be associated with such EMSTID features (Bowman, 1990; Bowman & Monro, 1988).

The EMSTIDs are observed typically at midlatitudes, and their occurrences are higher during solar minimum (Narayanan, Shiokawa, et al., 2014; Pimenta et al., 2008; Takeo et al., 2017). Typical low-latitude limit of EMSTIDs is expected to be at ~15°–20° dip latitudes. Shiokawa et al. (2002) suggested that enhanced ion drag in the ionization anomaly crest dissipates the wave perturbations propagating across the crest. Narayanan, Shiokawa, et al. (2014) found that in addition to the equatorial ionization anomaly crest, equatorward propagation of EMSTIDs are often restricted due to the poleward propagating perturbations occurring around the midnight hours, probably associated with the midnight pressure bulge. However, on rare occasions, the EMSTIDs were observed at further lower latitudes during solar minimum periods (Makela et al., 2010). Such occurrences in lower latitudes are interesting and need further detailed study, as it is not clear whether the theories based on coupled *E* and *F* region electrodynamics work in the equatorial region.

The occurrence of late night spread *F* in the ionograms during solar minimum periods is well known at low and equatorial latitudes (Candido et al., 2011; Narayanan, Sau et al., 2014; Niranjan et al., 2003; Sastri, 1999). Recently, the VHF radar observations from low-latitude sites have revealed the occurrence of late night/postmidnight backscatter echoes during low solar activity periods, in concurrence with earlier ionosonde observations (Miller et al., 2010; Otsuka et al., 2012; Patra et al., 2009; Yokoyama et al., 2011). The exact cause of the irregularities producing backscatter echoes is still under debate. Some mechanisms that could produce EPBs in the late night hours were proposed (Dao et al., 2017; Yizengaw et al., 2013), besides allowing for the possibility of EMSTIDs themselves causing such radar echoes (Yokoyama et al., 2011). In this work, we conclusively show that at least a part of such postmidnight radar echoes and spread *F* in the ionograms is caused by midlatitude-type EMSTIDs that might have propagated down to latitudes very close to the dip equator.

2. Results and Discussion

All-sky airglow imaging observations discussed herein were made from Panhala (16.8°N, 74.1°E geographic; 11.1°N dip latitude), India, in campaign modes during January–March 2008. The details of the instrument, information on the campaigns, and observational routines were already discussed in previous works (Narayanan et al., 2009, 2013). In this work, images of OI 630.0-nm airglow with peak emission altitude at ~250 km are utilized. We follow the standard practice of using the percentage perturbation images (I_P) to intensify the EMSTID features in the images. Percentage perturbation images are obtained by subtracting 2-hourly running average images (I_A) centered at each image (I) and normalizing them along with conversion to percentages (i.e., $I^P=(I - I_A)/I_A*100$). Since the peak of the OI 630.0-nm emission occurs around 250 km, we make unwarped projections of the images at that altitude following Narayanan et al. (2009). Coincident VHF radar observations were made from Gadanki (13.5°N, 79.2°E, geographic; 6.5°N dip latitude). In order to orient the radar beam perpendicular to the magnetic field lines at *F* region altitudes, the

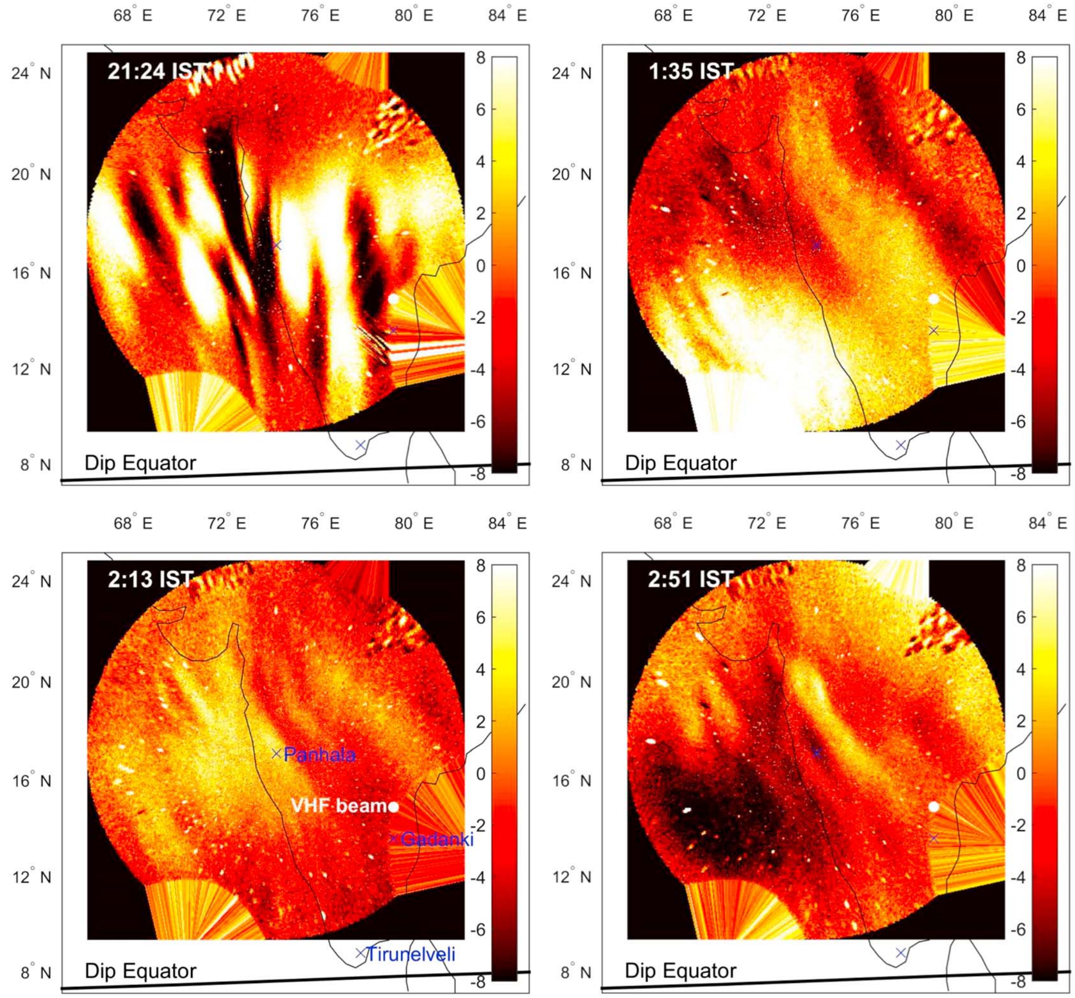

Figure 1. Airglow images on 3 February 2008 showing EPBs and EMSTIDs. The blue X marks show Tirunelveli, Gadanki, and Panhala in the order of increasing latitudes (see lower left image of 02:13 IST). The white dot indicates VHF radar beam intersection at 250 km. Dip equator is also shown. A movie showing the EMSTID event is provided as Supporting Information.

beam is tilted approximately to about 15° toward north from the zenith. This radar is being utilized to study different types of ionospheric irregularities over the past two decades (Rao et al., 1997; Patra et al., 1997, 2009; Patra & Phanikumar, 2009). In addition, we have used two ionosondes, respectively, from Gadanki and Tirunelveli, (8.7°N, 77.8°E; 1.1°N dip latitude), the latter being dip equatorial site in the Indian sector. The ionosonde at Gadanki was IPS-42 digital ionosonde (Titheridge, 1994), while the Canadian Advanced Digital Ionosonde (Gao & MacDougall, 1991) has been operating from Tirunelveli for more than a decade (Narayanan, Sau, et al., 2014). The ionograms were obtained at 15-min cadence from both the stations. The results are presented in Indian Standard Time (IST), which is ahead of universal time by 5.5 hr.

From the all-sky imaging data at Panhala, we have identified 9 nights (out of 37 nights of observations) during which EMSTID-like features were observed. However, most of the cases showed their presence only in the northern portions of the images. In 2008, the VHF radar at Gadanki was operated for 64 nights among which on 34 nights backscatter echoes were observed from *F* region heights. On 25 nights, postmidnight echoes occurred. Only on 3 and 7 February 2008, all the instruments were operated simultaneously when EMSTIDs were seen to occur in all-sky airglow images. In this work, we utilize data from these two nights of simultaneous radio and optical observations.

Figure 1 shows four airglow images obtained on the night of 3 February 2008. The locations of airglow imaging, VHF radar, and ionosondes are indicated by blue crosses. The white dot indicates VHF radar beam

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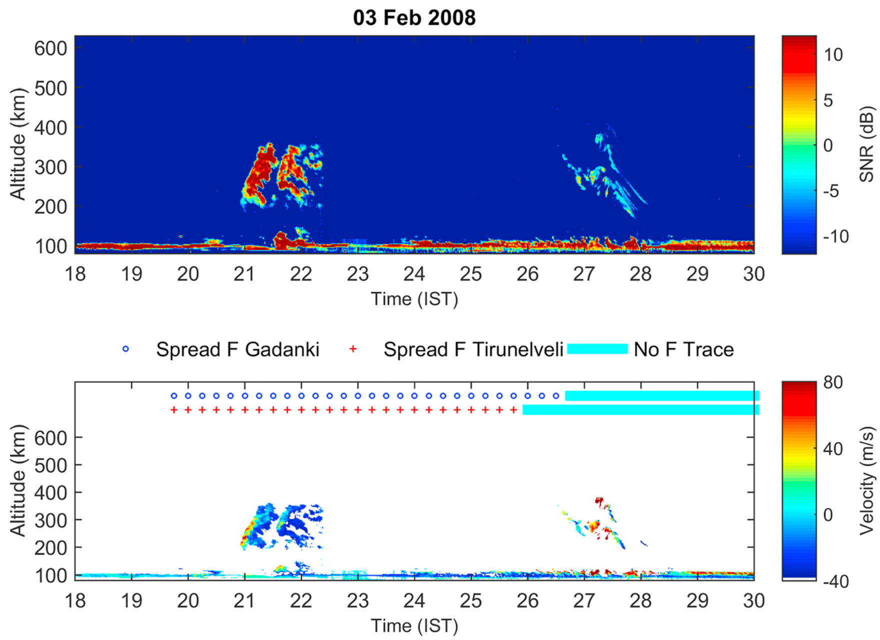

Figure 2. VHF radar observations, showing SNR in the top panel and range-time-Doppler velocity in the bottom panel made on 3 February 2008. Bottom panel includes times of spread *F* occurrences in the ionosonde observations over Gadanki (circles) and Tirunelveli (plus marks). The cyan bar shows times when *F* region trace is not present in the ionograms.

intersection, and the dip equator is also shown. The lower left image of Figure 1 contains these details for easy identification. Figure 2 shows the range-time-intensity of signal-to-noise ratio (SNR) in the top panel and range-time-Doppler velocity in the bottom panel based on VHF radar observations for the same night. The bottom panel also shows the times of occurrence of spread *F* in the ionograms over Tirunelveli and Gadanki, respectively. The blue circles represent times when spread *F* was observed over Gadanki, while red plus symbols mark spread *F* observed over Tirunelveli. The thick cyan-colored bar adjacent to the spread *F* indicators shows the times when *F* region trace could not be seen in the ionograms.

During premidnight hours of this night, north-south elongated depleted features were seen in the airglow images (see the top left image in Figure 1) that were also observed to drift eastward. They were signatures of the EPBs. Two vertical plumes were noticed in the VHF radar measurements before 22:30 IST, and they corresponded to two EPBs on the rightmost corner of the image at 21:24 IST in Figure 1. Spread *F* started appearing in the ionograms over both the sites at 19:45 IST and continued till the disappearance of *F* trace at 01:45 and 02:45 IST over Tirunelveli and Gadanki, respectively.

During the postmidnight hours starting from about 01:30 IST, some dark band features appeared in the images from the northeast direction with phase front orientation along the northwest to the southeast (see the images except for 21:24 IST in Figure 1). Those features clearly showed a southwestward propagation in concurrence with the characteristics of EMSTIDs typically observed at midlatitudes. There were some bright bands as well along with the dark band features indicating alternating phases of the EMSTIDs. The EMSTID event was still in progress when airglow observation was stopped at 03:00 IST on this night due to clouds. A movie showing the propagation of the EMSTIDs on this night is provided as Supporting Information to this article. From about 02:30 IST, the backscatter echoes reappeared in the VHF radar plots. However, their morphology was different when compared to the premidnight echoes in that the echoes started appearing at higher altitudes and they showed a descending pattern with two broadly separated band-like features. Most of the velocities were up-north directed supposedly linked to the depletions in airglow. These early morning echoes were similar to those often observed in the midlatitude regions (Fukao et al., 1991; Otsuka et al., 2009). It is noteworthy that the morphology of VHF radar echoes was different, while airglow images also clearly revealed the EMSTID features in such low geomagnetic latitudes.

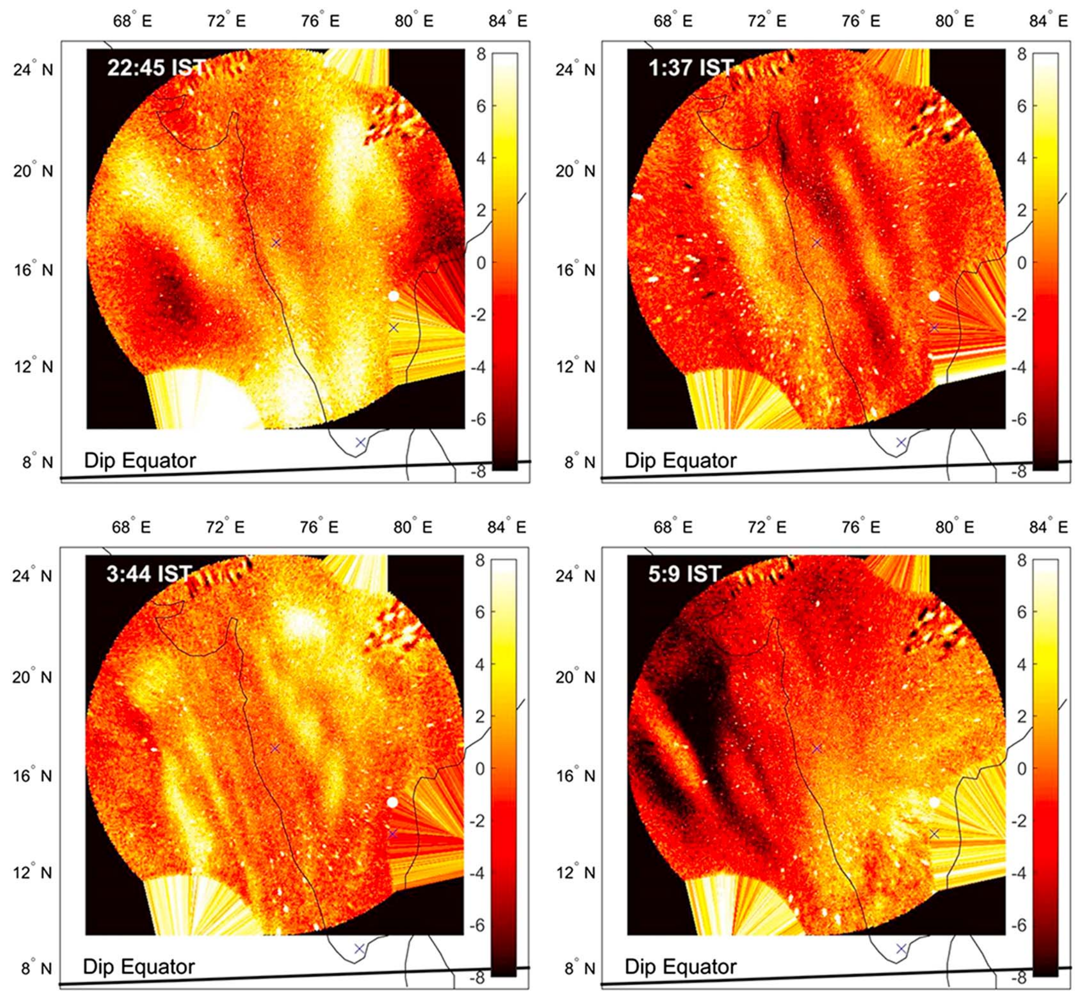

Figure 3. Airglow images on 7 February 2008 showing EMSTIDs in the same format as in Figure 2. A movie showing the EMSTID event is provided as Supporting Information.

The ionosonde observations showed spread *F* till 01:45 and 02:30 IST at Tirunelveli and Gadanki, respectively, as can be seen from the bottom panel of Figure 2. The spread *F* echoes observed during postsunset hours were certainly due to EPBs. However, the spread *F* in the postmidnight hours, at least after 01:30 IST, were likely be due to EMSTIDs. Airglow images clearly show passage of EMSTIDs around Gadanki then. No EPBs were seen in airglow images after 00:25 IST. Unfortunately, there was a gap in the acquisition of airglow images due to power problems between 00:45 and 01:25 IST on this night. Because of the absence of airglow data, we are unable to attribute the spread *F* observations between 00:30 and 01:30 IST conclusively to either EPBs or EMSTIDs. However, it is clear with the aid of the airglow images acquired from 01:34 IST that the spread *F* observed after 01:30 IST was due to EMSTIDs and not EPBs. It may be noticed that the *F* region traces disappeared while spread *F* was still being recorded at both the sites as indicated by the cyan-colored bars in the bottom panel of Figure 2.

To summarize the observations on 3 February 2008, the all-sky airglow images clearly showed the arrival of EMSTIDs from the northern part of the imager field of view (FoV). The VHF radar echoes revealed a descending pattern of striations similar to the midlatitude-type FAIs during the postmidnight hours when the EMSTID features passed the region. Spread *F* was observed over both the locations, Gadanki and Tirunelveli, during the period when EMSTIDs passed over this region.

Figure 3 shows some airglow images observed on 7 February 2008. Right from 22:42 IST, alternate dark and bright features covering the whole extent of FoV with their phase fronts aligned along the northwest-southeast directions and propagating toward southwest were observed in the images. Their morphologies

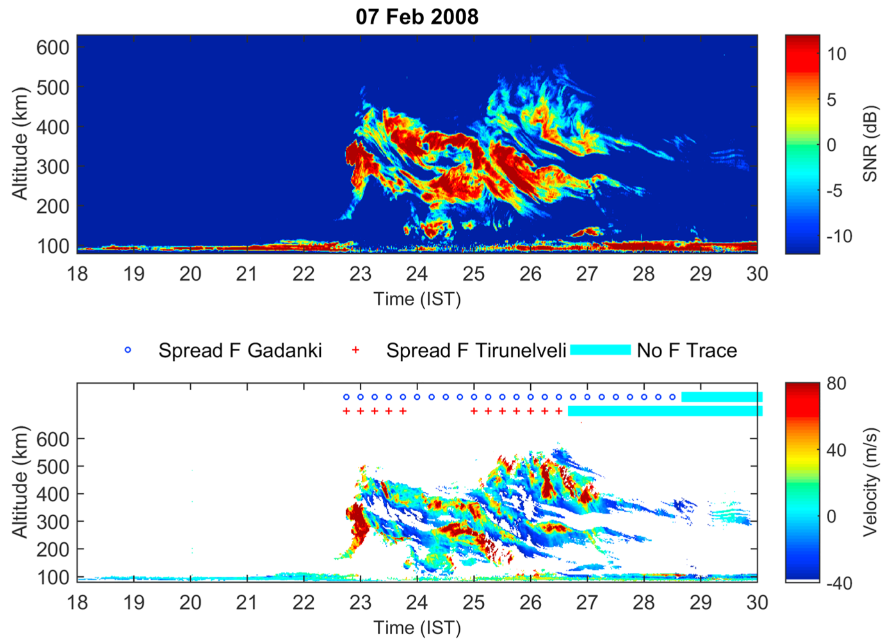

Figure 4. VHF radar and ionosonde observations made on 7 February 2008, shown in the same format as that of Figure 3.

and propagation toward the southwest are very similar to those known for the EMSTIDs. Such features were seen till 05:10 IST when the imaging observations ended for the night. However, after 03:15 IST, the direction of movement of the features reversed toward east-northeast. Movie showing the EMSTID features observed on this night is provided as Supporting Information to this article. On this night, relatively intense echoes were observed by the VHF radar from about 22:45 IST as shown in the top and bottom panels of Figure 4. The echoes reveal descending pattern with multiple striations. Also, the Doppler velocity measurements reveal alternating up-north and down-south movement of the irregularities that were likely to be associated with the alternating phases of the EMSTIDs.

Similar to Figure 2, the spread *F* occurrence times are shown in the bottom panel of Figure 4 along with the Doppler velocity measurements of VHF radar. Ionosonde measurements showed onset of spread *F* at 22:45 IST over both the sites in coordination with airglow features and VHF radar echoes, as can be seen from Figure 4. Spread *F* was continuously present till early morning hours when the *F* region traces disappeared at 02:30 and 04:30 IST over Tirunelveli and Gadanki, respectively. There was data gap between 00:00 and 00:45 IST over Tirunelveli. Spread *F* occurrence in this case was clearly due to the EMSTIDs as revealed by the concurrent observations of airglow and VHF radar measurements.

The reversal of the propagation direction and weakening of radar echoes after 03:00 IST might be associated with the decay phase of the EMSTIDs. When the polarization electric fields associated with the EMSTIDs decay, they would not generate smaller-scale irregularities resulting in a weakening of the radar backscatter echoes. It may, however, be noted that the cause of the southwestward propagation of EMSTIDs is still under debate (Kelley & Makela, 2001; Yokoyama et al., 2009). However, if the polarization electric fields decay, the remnant fossil features are supposed to drift along with the background ionospheric plasma, which is toward the east. Since the features are tilted, they might appear to drift toward east-northeast direction in airglow images, in case they tend to drift along with the background plasma.

In summary, on 7 February 2008, the EMSTIDs were observed in airglow images for the whole observation duration covering about 6.5 hr. VHF radar echoes also occurred concurrently for about 7 hr displaying descending striations resembling the midlatitude-type radar echoes. Spread *F* was observed over both Gadanki and Tirunelveli concurrent with airglow and VHF radar observations.

The observations reported here reveal that the EMSTIDs propagate very close to the dip equator. Narayanan, Shiokawa, et al. (2014) showed that equatorward propagation of EMSTIDs are restricted by equatorial

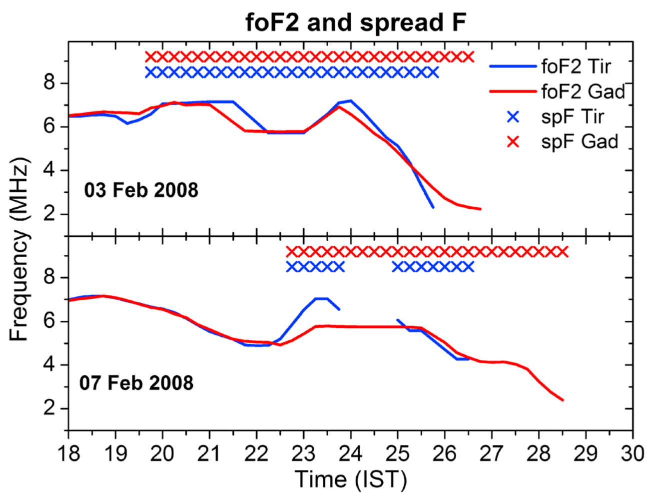

Figure 5. Ionosonde measurements of foF2 (curve) and occurrence of spread F (X marks) over Tirunelveli and Gadanki on 3 and 7 February 2008.

ionization anomaly (EIA) or higher plasma density regions associated with poleward propagating perturbations. This indicates that if the background plasma density is low or devoid of any relatively high plasma density structures, the EMSTIDs might reach further lower latitudes. The fact that the *F* region traces in the ionogram disappeared during early morning hours on both the locations indicates that the plasma density was relatively low on the nights so that they decayed to levels below the sensitivity of the ionosondes. The EIA occurrence in airglow images during the period of observations reported here was already studied in detail in Narayanan et al. (2013). In the airglow images, the EIA crest was observed only on 3 February 2008 during the premidnight hours approximately till 23:30 IST. No presence of EIA crest was noticed during the postmidnight hours when the EMSTIDs entered imager FoV on 3 February 2008. On 7 February 2008, no signature of EIA crest was seen in the airglow images. To further check the background ionospheric plasma density, we show foF2 measured by the ionosondes in Figure 5 along with the duration of spread *F*. It has to be noted that the foF2 values obtained during the presence of spread *F* echoes may not represent the real background plasma density of the ionosphere. Nevertheless, we may check the variation of foF2 on these nights. On 3 February 2008, the foF2 values were decreasing rapidly during the time of occurrence of EMSTIDs in the postmidnight period. On 7 February 2008, the foF2 values were showing a decreasing trend over both the locations until the occurrence of spread *F* associated with EMSTIDs (see the decrease up to 22:30 IST). The enhancement in foF2 values after 22:30 IST coincided with the onset of spread *F* associated with the EMSTIDs on this night. It is quite possible that this enhancement was associated with the higher plasma density regions of the EMSTIDs. Therefore, based on observation of EIA and measured foF2 values, it can be seen that the EMSTIDs entered the low and equatorial zone when there was lack of identifiable EIA crest and when the plasma densities were apparently getting weaker.

The results presented above provide direct evidence for the role of EMSTIDs in causing the postmidnight VHF radar echoes and spread *F* in ionograms during low solar activity period. Further, simultaneous onset of spread *F* over Gadanki and Tirunelveli implies that the EMSTIDs might have propagated almost up to the dip equator during these nights. The role of EMSTIDs in the equatorial ionosphere needs further study as there are theories supporting the seeding of EPBs caused by EMSTIDs (Miller et al., 2009; Takahashi et al., 2018). In our observations, no EPBs appeared after the passage of the EMSTIDs. Instead, the EMSTIDs themselves caused meter-scale irregularities and spread *F* in the cases shown here. This is further substantiated by lack of vertical plume-like structures in the VHF radar backscattering observed during the postmidnight hours.

3. Summary

The observations on 3 February 2008 reveal clear differences in the structure of airglow features and morphology of VHF radar echoes that were respectively caused by EPBs and EMSTIDs. Significantly, for the first time, the EMSTIDs are inferred to occur very close to the dip equator as indicated by the simultaneous spread *F* occurrences over Gadanki and Tirunelveli while airglow images reveal presence of EMSTIDs within about 3° of the dip equator. The events presented here provide direct evidence for the contribution of EMSTIDs to the formation of postmidnight VHF radar echoes and spread *F* in ionograms during solar minimum conditions at low and equatorial latitudes. The present observations when linked with the earlier reports (Patra et al., 2009; Sastri, 1999; Takahashi et al., 2018; Yokoyama et al., 2011) imply that the EMSTIDs are also important components responsible for the onset of ionospheric irregularities in the tropical locations.

Acknowledgments
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