

The relation between magnetospheric state parameters and the occurrence of plasma depletion events in the night-time mid-latitude F-region

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Abstract. Studies using all-sky imagers have revealed the presence of various ionospheric irregularities in the night-time mid-latitude F-region. The most prevalent and well known of these are the Medium Scale Traveling Ionospheric Disturbances (MSTIDs) that usually occur when the geomagnetic activity is low, and mid-latitude spread-F plumes that are often observed when the geomagnetic activity is high. The inverse and direct relations between geomagnetic activity (particularly Kp) and the occurrence rate of MSTIDs and mid-latitude plumes, respectively, have been observed by several studies using different instruments. In order to understand the underlying causes of these two relations, it is illuminating to better characterize the occurrence of MSTIDs and plumes using multiple magnetospheric state parameters. Here we statistically compare multiple geomagnetic driver and response parameters (such as Kp, AE, Dst, and solar wind parameters) with the occurrence rates of night-time MSTIDs and plumes observed using an all-sky imager at Arecibo Observatory (AO) between 2003 and 2008. The results not only allow us to better distinguish MSTIDs and plumes, but also shed further light on the generation mechanism and electrodynamics of these two different phenomena occurring at night-time in the mid-latitude F-region.

Introduction

MSTIDs and spread-F plumes (or plasma bubbles) are the two most common irregularities observed with all-sky imagers at mid-latitudes. Although it is not always easy to distinguish one type of depletion from the other in the airglow images, MSTIDs and plumes each have several distinct characteristics as listed in **Table 1** and demonstrated in **Figure 1**. For example, the MSTIDs typically appear as periodic bands whereas the plumes usually appear as a single structure with fractal-like fingers. Furthermore, at mid-latitudes in the northern hemisphere, MSTIDs usually appear from the north to northeast as opposed to the plumes which usually appear from the south.

Although a number of theoretical models have been proposed for these ionospheric phenomena, most notably the Perkins instability (**Perkins, 1973; Zhou et al., 2006**) for MSTIDs and the Rayleigh-Taylor instability (**Makela, 2006**) for spread-F plumes, how the actual physical mechanisms may operate under different geomagnetic activity levels have not yet been firmly established. Finally, and perhaps most importantly, it has been tentatively found that, at mid-latitudes, the MSTIDs usually occur during geomagnetically quiet times (**Saito et al., 2002; Whalen, 2002; Shiokawa et al., 2003; Kotake et al., 2006; Tsugawa et al., 2007; Candido et al., 2008; He and Ping, 2008; Seker et al., 2008**) whereas the plumes usually occur at mid-latitudes when the geomagnetic activity is high (**Garcia et al., 2000; Sahai et al., 2000; Seker et al., 2007**).

Saito et al. (2002) found using the MU radar and GPS network in Japan that the occurrence of the traveling ionospheric disturbances (TIDs) is anti-correlated with solar activity. Using sounders, **Whalen (2002)** found a similar inverse relation, the strength of which depends on season. **Shiokawa et al. (2003)** reported the inverse dependence of the MSTID occurrence with solar activity at mid-latitudes. After the analysis of 3 years of GPS-TEC data, **Kotake et al. (2006)** revealed a similar inverse relation between solar and MSTID activities only at night-time over Japan and Australia but not during the day and not over North/South America or Europe. **Tsugawa et al. (2007)** reported the seasonal dependence of the inverse relation of the MSTID occurrence with solar activity. After analyzing 7 years of data and 28 MSTID events from an all-sky imager in Brazil, **Candido et al. (2008)** reported that there were no occurrences of dark bands during high solar activity (HSA), 3% during medium solar activity (MSA), and 11% during low solar activity (LSA). **He and Ping (2008)** found a similar relation using Kp and radar data from 2000.

On the other hand, there are only a few studies on the relation between the low-latitude plumes and solar activity and we have found no statistical studies on the relation of mid-latitude plumes and geomagnetic/solar activity. The statistical study of transequatorial plasma bubbles by **Sahai et al. (2000)** using an all-sky imager in Brazil ($\sim 16^\circ\text{S}$ dip latitude) revealed that the plumes occur more frequently at HSA (55% vs. 33%) and reach very high apex (above equator) altitudes more often (66% vs. 34% of plumes) as compared with LSA. They found no difference in the seasonal dependence of plume occurrence between LSA and HSA. The plumes that reach higher altitudes over equator are expected to reach higher latitudes following the field lines, meaning that the plumes would be expected to reach mid-latitudes more often during HSA than LSA which agrees with our observations. **Garcia et al., 2000** studied a mid-latitude plume event which occurred during a geomagnetic storm using allsky imager, GPS, and digisonde observations. They called it “mid-latitude spread-F”. Here, we prefer to call it “mid-latitude plume” to emphasize the distinct shape of these plasma depletions.

In summary, most studies focused on the inverse relation between geomagnetic activity and MSTIDs and used K_p as the only indicator of solar or geomagnetic activity. There are a few studies on mid-latitude plumes but they are based on a few events and do not provide any statistics. Here, we attempt to statistically characterize both MSTIDs and mid-latitude plumes using 5 years of all-sky imager data and multiple magnetospheric state parameters instead of K_p only.

Figure 1. (a) An intense MSTID event consisting of parallel depletion bands. (b) An intense spread-F plume event illustrating its fractal plume-like shape. (c) A moderately intense MSTID event. (d) A moderately intense plume event. The bright (dark) regions indicate enhanced (depleted) density regions. Plumes (MSTIDs) are observed at mid-latitudes usually when the geomagnetic activity is high (low).

Table 1. The different properties of MSTIDs and plumes.

Property	MSTIDs	Plumes
Structure	Parallel bands	Single plume
Appearance	Extending from north	From south
Alignment	Northwest-southeast	North-south
Propagation	Toward southwest	East-West
Wavelength & period	100-300 km, ~ 1 hr	Not periodic
Theory	Perkins Instability	Rayleigh-Taylor
Occurs when K_p is	Low	High

Methodology

In order to better understand the relation between the geomagnetic activity and occurrence of MSTIDs and plumes at mid-latitudes, the data from the Penn State All-sky Imager (PSASI) at Arecibo Observatory (AO) from 2003 to 2008 were categorized and analyzed according to solar wind and geomagnetic conditions. The type, intensity, and start/end times of the F-region events observed using a 630 nm filter during 2003-2008 were recorded. The event type is either MSTID or plume. The event intensity is based on the intensity of depletion in the airglow images and consists of three levels: weak, moderate, intense. For this study, the weak events have been discarded since it is more difficult to distinguish between MSTIDs and plumes unless the depletion is strong. Although the event start and end times often depend on the duration of the event itself, they can also be influenced by other factors which prevent airglow observations such as cloud coverage and moonrise/moonset or sunrise/sunset times. Nevertheless, the start and end times always correspond to a time during which an event occurs.

To determine the relationships between geomagnetic activity and the occurrences of MSTIDs and plumes, we obtained the magnetospheric state parameters by using the NASA Magnetospheric State Query System (MSQS) (**Fung, 2004; Fung and Shao, 2008**). The parameters chosen in this study are K_p , Dst, AE, solar wind (SW) magnetic field (B), SW Bz, SW electric field (E), SW velocity (V), and SW flow pressure (P). For each MSTID and plume event, each parameter is plotted from ~ 10 hours before sunset (10 am or 10 LT)

to ~10 hours after sunrise (4 pm next day or 40 LT). In each plot, the durations of the observed events are highlighted with thick lines which always fall between 7 pm (19 LT) and 6 am (30 LT) local time since the imager can operate only at night.

Results

The relation between various magnetospheric state parameters and the occurrence of MSTIDs and plumes observed with PSASI between 2003 and 2008 can be visually seen from the plots given in **Figure 2** which shows the results only for intense MSTIDs and plumes. The durations of each MSTID or plume event observed is highlighted with a thick line. The average values for each parameter for both moderate and intense plumes and MSTIDs are listed in **Table 2** quantitatively revealing the relationships between the magnetospheric state parameters and these ionospheric events. These values are found by averaging each parameter first over the time duration of each event observed with the all-sky imager and then over all MSTID or plume events.

Figure 2. Magnetospheric state parameters (a) Kp, (b) AE, (c) Dst, (d) SW V, (e) SW E, (f) SW B, (g) SW Bz, (h) SW P for the most intense plumes and MSTIDs. All parameters are averaged over 1 hr except Kp which has a 3 hr time resolution. The durations of each airglow event is highlighted with a thick line.

Table 2. Average values of each geomagnetic state parameter for plumes and MSTIDs. These values correspond to the thick lines in **Figure 2**.

Type	Plume		MSTID		
Intensity	high	moderate	moderate	high	
# of events	11	11	70	30	
Parameter					Units
Kp	4.79	2.97	1.84	1.75	
AE	654	203	182	144	nT
Dst	-86	-30	-15	-8	nT
SW V	542	506	451	458	km/s
SW E	3.9	0.5	-0.1	-0.5	mV/m
SW B	15.1	5.9	5.3	5.8	nT
SW Bz	-5.9	-0.8	0.2	0.9	nT
SW P	4.1	2.28	1.97	1.87	nPa

Figure 2 results suggest that although individual plume events tend to occur during geomagnetic storms, they might also rarely occur during quiet times. Interestingly, among the 11 intense plume events, by far the lowest average Kp (1.82) and highest average Dst (3 nT) occurred on 25-26 December 2003 when a depletion plume turned into a brightness plume and MSTID bands appeared afterwards. This inversion event has been recently investigated in detail by **Martinis et al. (2009)**, however no information on geomagnetic activity was provided. This example suggests that the inversion plumes might occur only during low Kp. On the other hand, the results clearly show that MSTIDs hardly occur during storms (e.g., Kp > 4) further confirming the previous studies mentioned earlier.

These relations become more significant when the parameters are averaged over all MSTID or plume events as illustrated in **Table 2**. For example, the average Kp, AE, and Dst for the 11 intense plume events are 4.8, 654 nT, and -86 nT, respectively, as compared to 1.8, 144 nT, and -8 nT for the 30 intense MSTID events, a significant difference. As expected, the average Kp, AE, and Dst values for moderate MSTIDs and moderate plumes fall between the average values for intense MSTIDs and intense plumes. For example, for moderate plumes (11 events) and moderate MSTIDs (70 events), the average Dst values are -30 nT and -15 nT, respectively. The average Kp, AE, and Dst values for moderate plumes are higher (in magnitude for Dst) than for moderate MSTIDs, as also expected. Similar trends are observed for the other (solar wind) parameters shown in **Table 1** although the strength of the relation varies for each parameter.

Conclusions

In this study, we have investigated, for the first time, the relation between multiple magnetospheric state parameters and the occurrence of mid-latitude plumes and MSTIDs in the night-time F-region. The results given in **Table 2** and **Figure 2** suggest that there is a direct and inverse relation between the occurrences of mid-latitude plumes and MSTIDs, respectively, and the geomagnetic activity. However, it was found that this relation applies to a set of events rather than individual events. Based on these results, it can be concluded that, in general, plumes tend to occur at high Kp, low (highly negative) Dst, and at high solar wind velocity, pressure, magnetic/electric field (in magnitude) whereas MSTIDs tend to occur when the magnitude of these parameters are low. It seems that this empirical relation is especially valid for Kp, AE, and Dst. Accordingly, it can be concluded that although it is impossible to define a single event just by looking at the geomagnetic parameters, it might be possible to define the likelihood of the occurrence of a plume or MSTID event under certain conditions, and inversely, to tell whether an ambiguous depletion event in the all-sky data is likely a plume or MSTID. Most importantly, these results suggest a relation (although somewhat stochastic) between the state of the magnetosphere and ionospheric phenomena such as plumes and MSTIDs. So, it can be concluded that even if these F-region irregularities are seeded at lower altitudes by gravity waves as suggested by various studies (**Nicolls and Kelley, 2005; Shiokawa et al., 2006; Tsugawa et al., 2007; Vadas, 2007; He and Ping, 2008**), their occurrence in the F-region and intensity are certainly affected by the condition of the magnetosphere and solar wind.

Several possible physical causes of the inverse relation between geomagnetic activity and the occurrence of MSTIDs have been proposed. **Saito et al. (2002)** attributed this relation to Perkins Instability, the growth rate of which anti-correlates with the solar activity as **Kelley and Fukao (1991)** first showed. **Whalen (2002)** suggested that the decrease of the pre-reversal eastward electric field during solar maximum suppresses the MSTID occurrence. **Kotake et al., 2006** also attributed this inverse relation to enhanced Perkins Instability due to lower neutral density during low solar activity. After analyzing ionosonde data from 1957 to 1990, **Risbeth and Mendillo (2001)** concluded that the F2 layer variability is mostly caused by the geomagnetic activity. They found that the variability is much higher at night and attributed this to enhanced auroral energy input and lack of the strong photochemical control of the F2-layer at night.

The only statistical study on the relation of (low-latitude) plumes with geomagnetic activity by **Sahai et al. (2000)** found that the equatorial spread-F bubbles reach higher altitudes at high solar activity due to stronger F-region vertical plasma drift. More specifically, around sunset at the magnetic equator the F-layer rises due to pre-reversal enhancement and this process is greatly enhanced during geomagnetic storms due to prompt penetration of high latitude electric fields. The rise of equatorial plumes enables them to reach mid-latitudes following the geomagnetic field lines. We think this is currently the most plausible explanation for the high rate of occurrence of mid-latitude plumes during geomagnetically active periods. On the contrary, **Garcia et al., 2000** refuted this mechanism and suggested that the mid-latitude spread-F might be caused by enhanced Perkins instability due to the expansion of the equatorial anomaly region upward and northward in response to the polarization by a penetrating eastward electric field.

Recent studies using satellite data also suggest that there might be a connection between the quasi-periodic MSTIDs and the periodicities observed in the solar wind (**Huang et al., 2000; Livneh et al., 2009**). So, it might be very interesting to study in more detail the relation between the magnetospheric state parameters and various properties of these events (such as wavelength, orientation, scale, speed, and period). This requires higher resolution satellite data and is going to be the topic of a future study.

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