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Generation of large-scale equatorial F-region plasma depletions during low range spread-F season

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Abstract. All-sky imaging observations of the F-region OI 630 nm nightglow emission allow us to visualize large-scale equatorial plasma depletions, generally known as trans-equatorial plasma bubbles. Strong range type spread-F is the radio signature of these (magnetically) north-south aligned plasma depletions. An extensive database of the OI 630 nm emission all-sky imaging observations has been obtained at Cachoeira Paulista (22.7°S, 45.0°W; dip latitude ∼16°S), Brazil, between the years 1987 and 2000. An analysis of these observations revealed that relatively few large-scale ionospheric plasma depletions occur during the months of May to August (southern winter, June solstice) in the Brazilian sector. Of the few that are observed during these months, some occur in association with geomagnetic storms and some do not. In this paper, a detailed analysis of the events when large-scale ionospheric plasma depletions were initiated and evolved during the June solstice periods are presented and discussed.

Key words. Atmospheric composition and chemistry (airglow and aurora). Ionosphere (equatorial ionosphere; ionospheric irregularities)

1 Introduction

Equatorial spread-F (ESF) irregularities (Booker and Wells, 1938) continue to be a subject of intensive investigations (observational and theoretical), because the ionospheric turbulence created has a strong, deleterious influence on trans-ionospheric radio wave communication. As pointed out by Tsunoda et al. (1982), a unique feature found to play a major role in the equatorial spread-F phenomena is the plasma "bubble", a localized depletion in F-region electron density. Plasma bubbles are aligned magnetic flux tubes and cover north-south distances across the magnetic equator of several thousand kilometers, with east-west dimensions of up to a few hundred kilometers. It appears now that there is a consensus that the plasma bubbles are formed due to the Rayleigh-Taylor gravitational instability process which is operational on the steep upward gradient in the nighttime bottomside F-region at the magnetic equator. As plasma bubbles buoyantly rise upward, they become highly elongated in the vertical direction (Tsunoda and Towle, 1979), sometimes attaining very high altitudes (>1500 km) at the magnetic equator (Mendillo and Tyler, 1983; Sahai et al., 1994) and the depleted regions extend poleward in the flux tubes (Sales et al., 1996), reaching dip latitudes of over ±15° (Rohrbaugh et al., 1989).

The F-region nightglow emissions (e.g. OI 630 nm and 777.4 nm) arising from recombination (dissociative ($O_2^+ + e \rightarrow O + O^*$) and radiative ($O^+ + e \rightarrow O^* + h\nu$), respectively) processes can be used to remotely observe and to study the development and dynamics of the plasma bubbles. The observed column OI 630 nm emission intensity is proportional to the integral of the product of the O_2^+ (charge transfer: $O_2 + O^+ \rightarrow O_2^+ + O$) and e (electron density) concentrations. Weber et al. (1978) were the first to detect quasi-magnetically north-south aligned valleys of intensity depletion bands in the airborne all-sky imaging observations of the OI 630 nm emission, accompanied by strong range type spread-F. These intensity depletion bands are the bottomside optical signatures of low electron density within the plasma bubbles. Also, the OI 630 nm emission intensity shows inverse dependence on the F-region height, with the intensity decreasing when the F-region goes up and vice versa. Moore and Weber (1981) and Sahai et al. (1981) were the first to use the simultaneous measurements of the OI 630 nm and 777.4 nm emissions to study the plasma bubbles with an all-sky imaging system and conventional photometer observations, respectively. Several investigators have used wide-angle imaging of the F-region emissions to study the onset, evolution and dynamics of plasma bubbles (e.g. Weber et al., 1980; Mendillo and Baumgardner, 1982; Rohrbaugh et al., 1989; Sahai et al., 1994; Tinsley et al., 1997; Taylor et al., 1997; Mukherjee et al., 1998; Fagundes et al., 1999; Sinha et al., 2001; Abalde et al., 2001).

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Using a large database (March 1987–January 1998) of the OI 630 nm all-sky imaging observations obtained at Cachoeira Paulista (22.7°S, 45.0°W; dip latitude ∼16°S), Brazil, Sahai et al. (2000) have presented the solar cycle effects on the plasma bubbles. The occurrence of plasma bubbles, as evidenced by the all-sky images of the OI 630 nm emission from C. Paulista, is high between the October to March (range spread-F season) period, but the occurrence is very low during the May to August (low range spread-F season) period in the Brazilian sector. Analyzing the OI 630 nm emission images obtained at C. Paulista during the earlier period of observations between March 1987 and October 1991, Sahai et al. (1998) have shown a high correlation in the occurrence of plasma bubbles and geomagnetic disturbances in the low spread-F season.

In this paper, we present and discuss salient features related to the occurrence characteristics, using the extensive database of the OI 630 nm emission images obtained between the years 1987 and 2000 (possibly the only comprehensive imaging database in existence at the present time), during the low spread-F seasons (May to August).

2 Observations

In a collaborative program between the Center for Space Physics, Boston University, and the Brazilian National Institute for Space Research (INPE), an OI 630 nm all-sky (180° field of view) imaging system (for details, see Mendillo and Baumgardner, 1982) was operational on a routine basis at C. Paulista between March 1987 to October 1991 and September 1994 to September 2000. During the intervening period, the imaging system was not operational due to some technical problems. Briefly, the single-channel OI 630 nm emission imaging system used an interference filter 10 cm in diameter with a bandwidth of 1.35 nm. The intensified (ITT type F 4727 image intensifier) monochromatic images were recorded on 35 mm film with a Nikon SLR camera. The OI 630 nm images were obtained with a 32 s exposure time at 20-min intervals. Figure 1 shows the observing geometry with the imaging system located at C. Paulista and the OI 630 nm emission peak height considered at 300 km altitude (covering an extensive area (field of view 180°) of about 11.5 million square kilometers from the magnetic equator to more than 30° dip latitude). It should be pointed out that the extensive aerial coverage provided by the OI 630 nm all-sky images from F-region height at a low-latitude station is an excellent observational technique to detect the onset, evolution and dynamics of the large-scale F-region irregularities. The complementary Global Positioning System (GPS) data presented in this paper were obtained at Tucuman (26.8°S, 65.2°W; dip latitude ∼13°S), Argentina.

3 Results and discussion

3.1 Observations of plasma bubbles during low spread-F season

The observed seasonal occurrence (1987–2000) characteristics of plasma bubbles detected as quasi-north-south aligned intensity depletions in the OI 630 nm emission all-sky images are very similar to that presented and discussed in detail by Sahai et al. (1994), based on the initial few years of observations (1987–1989), with very small occurrence during the period May to August (generally low range type spread-F season (Abdu et al., 1983; Sastri et al., 1997) and absence of plasma bubbles) and maximizing during the period October to March (high spread-F season). In Table 1, details of the plasma bubble observations on nights during the months from May to August - hereafter referred to as J-months (June solstice)- for the period 1987 to 2000 are summarized. At the outset it should be pointed out that the OI 630 nm emission all-sky imaging from C. Paulista not only allows for detection and tracking of equatorial plasma bubbles (regions of low electron densities), but also permits tracking the F-layer height variations. The onset conditions for the equatorial plasma bubbles (rapid uplifting of the F-layer in the equatorial region) are indicated by decrease in the OI 630 nm emission intensities in the successive all-sky images in the north-west edge (because of about 20°W magnetic declination in this sector), and the area of decreased emission intensities expand towards the south for some time before the plasma bubbles start appearing. In the present study, if the K_p index reached ≥4 for at least three 3-h periods between 15:00–06:00 LT, the night was then considered to be geomagnetically disturbed. It is amazing that for the observational sequence comprising of so many years, there are only 12 nights during the J-months which show the presence of plasma bubbles, and these observations are the subject of study in this investigation. However, it should be pointed out that the airglow observations are limited to only clear nights around the new moon (about 12 nights during a month). A perusal of Table 1 indicates that out of the 12 nights, 7 nights have geomagnetic disturbances, 2 nights have possibly some influence of magnetic disturbances and 3 nights are with relatively quiet geomagnetic conditions.

Kelley et al. (2000) have recently mentioned that it is generally thought, if anything, that solar wind-induced geomagnetic activity tends to suppress ESF. Recently, Whalen (2002) has presented investigations of the dependence of equatorial plasma bubbles and bottomside spread-F on season, magnetic activity and $\boldsymbol{ExB}$ drift velocity during solar maximum, based on a chain of ionospheric sounding stations operational in the western South American sector, during the International Geophysical Year (IGY) of 1958. Results presented by Whalen (2002) indicate that during the equinox (E) months (March, April, September and October) and December (D) solstice months (November to February), plasma bubbles decrease with geomagnetic activity (linear function of K_p), whereas by contrast during the J months

Fig. 1. Spatial coverage at 75° and 90° zenith angles of the OI 630 nm emission (peak emission height 300 km) all-sky imaging from C. Paulista, Brazil. Also, Tucuman, Argentina, the location of the GPS observations is shown.

there is no dependence on K_p. Sastri et al. (1997) have presented 5 case studies (with 4 mild to moderate magnetic disturbances and 1, as a quiet day) of onset conditions of equatorial range spread-F during the post-sunset hours (dusk), using the ionospheric sounding observations obtained at Fortaleza (4°S, 38°W; dip latitude 1.8°S), Brazil, during the June solstice months of high solar activity period (1978–1981). Of the 5 case studies presented by Sastri et al. (1997), only in one case during the magnetic disturbance, range spread-F was observed simultaneously at Fortaleza and Cachoeira Paulista, indicating the development of plasma bubbles. It has been pointed out by Sastri et al. (1997) that the occasional occurrence of range spread-F during the dusk period at Fortaleza in the June solstice seems to be the presence of an anomalously large F layer vertical drift under disturbed as well as quiet conditions.

The present observational database of the OI 630 nm emission all-sky images covers low, medium and high solar ac-

Table 1. OI 630 nm all-sky imaging observations with plasma bubbles during low spread-F seasons (May–August) with/without magnetic disturbances.

Date	Period of obs. (LT)	Period of N-S int. depl. (LT)	Monthly mean sunspot number	3-h K_p between 06:00 to 06:00 LT	Max. $\|D_{st}\|$ between 06:00 to 06:00 LT	SSC (LT)	Tropospheric disturbances (fronts)*	Remarks
28–29 July 1987 (D)	19:00–05:20	02:00–02:20	33.0	4-,5,4+,4+,5+,7-,7,5+	29 July; 06:00;100 nT	28 July; 05:49	No	Post-midnight with onset
25–26 August 1987 (D)	19:00–05:10	04:40–05:10	38.7	5-,6,5+,5+,5-,6-,6,5-	25 August; 19:00; 097 nT	24 August; 06:39	No	Post-midnight with onset
06–07 June 1989 (D)	18:20–05:20	01:20–03:00	196.2	1+,2-,1,1+,5-,6,4+,5-	07 June; 04:00;067 nT	06 June; 20:14	No	Post-midnight with onset
30–31 August 1989 (Q)**	19:40–05:00	21:00–21:40	168.9	3,3+,4,3,3-,2,1+,1	30 August; 14:00;061 nT	-	No	Pre-midnight with onset
26–27 May 1990 (D)	18:40–05:20	19:40 04:40	132.2	3+,5,4-,6-,7+,4-,6+,7-	27 May; 06:00;087 nT	26 May; 17:36	No	Most part of the night with onset
05–06 August 1991 (D)	19:00–05:20	21:00–05:20	176.3	4,4,3-,4+,5+,6,5,4+	06 August; 02:00; 088 nT	05 August; 17:46	No	Most part of the night with onset
01–02 August 1995 (Q)	19:00–05:00	22:00–03:40	14.5	2-,1-,1-,1-,0+,1,1-,1	02 August; 06:00;007 nT	-	No	Most part of the night with onset
13–14 July 1996 (Q)	19:00–04:20	21:40–03:40	8.2	0+,1+,1,3+,3,3-,2-,1-	13 July; 16:00; 013 nT	-	Yes	Most part of the night with onset
16–17 August 1996 (Q)**	20:00–05:00	00:20–04:00	14.4	3,3-,3,3+,2+,4-,3,2+	16 August; 18:00; 023 nT	-	Yes	Post-midnight without onset
08–09 June 1997 (D)	19:00–04:20	22:20–04:20	12.7	3-,2+,4-,3-,4,5+,6-,5	09 June; 01:00; 084 nT	-	Yes	Most part of the night without onset
31 Jul–01 Aug 1997 (Q)	21:40–04:40	00:00–03:00	10.5	3+,2+,2-,1+,2,2-,2,1	31 July; 13:00; 023 nT	-	No	Post-midnight without onset
26–27 August 1998 (D)	19:20–05:00	20:20–05:00	91.7	6-,5-,6-,6-,6+,8,8,8-	27 August; 01:00; 142 nT	26 August 06:53	No	Most part of the night with onset

* Fronts moving from the southern part of the South American continent and reaching about 20°S or less in the Brazilian sector and covering the longitude belt from about 40°W to 50°W.
** Possibly having some influence of geomagnetic disturbances.

tivity periods. A perusal of Table 1 indicates that large-scale ionospheric plasma depletions were observed at different times during the course of a night and under both geomagnetic disturbed and quiet conditions during the J-months. The results are in agreement with Sastri et al. (1997) and Whalen (2002), but cover all levels of solar activity and onsets detected in post-midnight periods as well. Large-scale ionospheric plasma depletions were observed on 4 nights during the post-midnight period with onset conditions (3 disturbed; 1 possibly disturbed), 5 nights during most of the night and onset conditions around the dusk period (3 disturbed; 2 quiet), 2 nights during post-midnight without onset conditions (plasma bubbles are formed west of the observational site and move in the field of view as they drift eastward), (1 possibly disturbed; 1 quiet), and 1 night during most of the night without onset conditions (disturbed). This indicates that the plasma bubbles were observed under a variety of background ionospheric conditions.

In order to investigate the influence of geomagnetic activity on the initiation and development of large-scale ionospheric plasma depletions, Figure 2 shows the time variations of the D_{st} and AE indices (hourly values) for the nights of observations presented in Table 1 (for 1989 and 1996, AE indices are not available). For the geomagnetically disturbed nights (28–29 July 1987, 25–26 August 1987, 06–07 June 1989, 26–27 May 1990, 05–06 August 1991, 08–09 June 1997, 26–27 August 1998), it is observed that the auroral electrojet (AE) indices show large increases ($\gg$500 nT) before the observations of the plasma bubbles. Also, the nighttime $|D_{st}|$ values were high for all the cases studied. As pointed out by Akasofu (1970), AE of the order of 500 nT are rather common and occur frequently. A rapid uplifting of

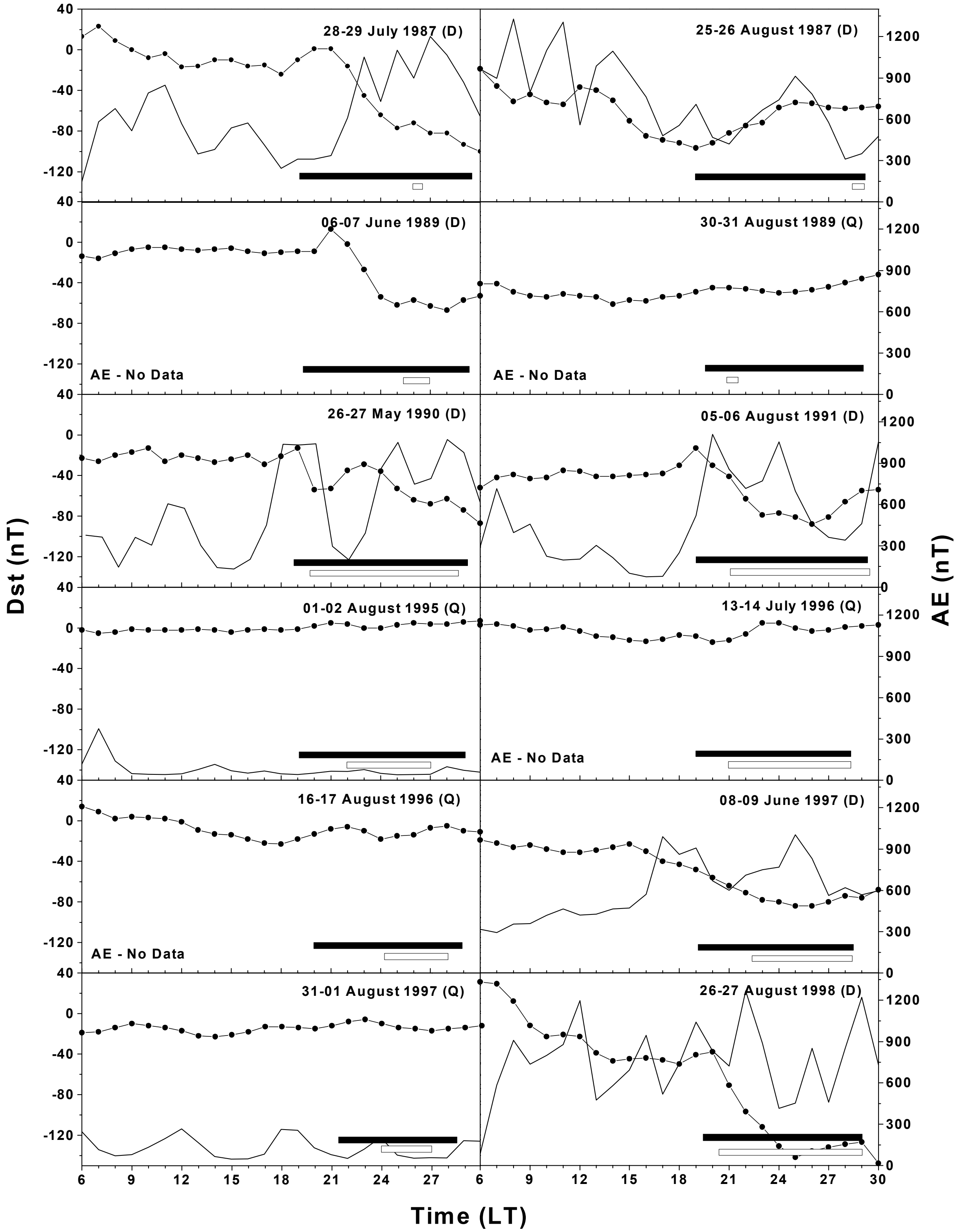

Fig. 2. Time variations of the AE (continuous lines) and D_{st} (lines with dots) indices for the observational nights (geomagnetically disturbed conditions (D); geomagnetically quiet conditions (Q)) when plasma bubbles were detected during the low spread-F seasons (May–August). Filled horizontal bar shows the period of the OI 630 nm all-sky imaging observations, whereas the blank horizontal bar shows the period when the plasma bubbles were detected.

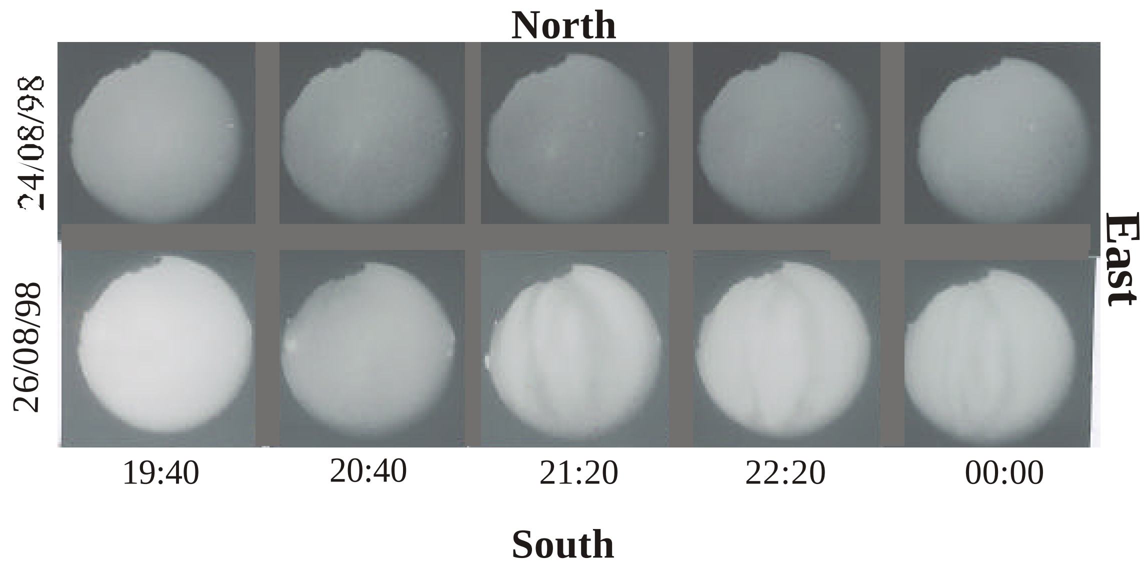

Fig. 3. Sequences of the OI 630 nm emission images observed on the nights of 24 August (quiet geomagnetic conditions) and 26 August (disturbed geomagnetic conditions) 1998. North-south aligned intensity depleted bands are seen on the geomagnetically disturbed night.

the equatorial F-region is an important condition, in conjunction with any other disturbance source, for example, gravity waves and neutral winds (seeding), for the onset of ESF. The plasma bubbles observed during the geomagnetic disturbances presented here, possibly due to prompt penetration of the magnetospheric convective electric fields (high latitude) to the equatorial region (Fejer and Scherliess, 1995), result in large-scale vertical motion of the ionosphere (Ruster, 1965). A detailed case study of the recent observations on 26–27 August 1998 is presented later. It should be pointed out that from the criterion we have utilized, 30–31 August 1989 and 16–17 August 1996 have been considered geomagnetically quiet. However, these two nights do have K_p values of 4 and 4−, respectively, and some geomagnetic activities could have been around those times. Also, 29–30 August 1989 (a day before 30–31 August) was geomagnetically disturbed with $\Sigma K_p = 38-$. For these two nights the AE indices are not available.

As mentioned earlier, we had 3 nights of observations (Table 1; 2 nights with the overhead formation (onset) and 1 night without onset) during the J-months with the presence of plasma bubbles during relatively quiet geomagnetic conditions. Also, these quiet nights (01–02 August 1995, 13–14 July 1996, and 31 July–01 August 1997) had no geomagnetic disturbances for more than a week preceding the night for which observations are reported. Several investigators (e.g. Rottger, 1977, 1981; McClure et al., 1998) have studied the initiation of ESF related to the tropospheric disturbance sources. Also, several investigators (e.g. Bertin et al., 1978; Meriwether et al., 1996; Kelley, 1997; Boska and Sauli, 2001 and Fagundes et al., 2001) have presented studies related to the influence of tropospheric disturbances at the thermospheric/F-region heights. Therefore, an attempt was made to look for the causes below the ionosphere, i.e. possible influence of the tropospheric disturbances. The recent studies of Bosca and Sauli (2001) indicate that strong tropospheric events like a cold front, can affect the electron density profile. Also, Clark et al. (1971) have indicated that wave-like structures resulting from large meteorological phenomenon propagate from the troposphere to thermospheric heights. Table 1 shows the presence or absence of frontal systems on the observational days in this study. The data for the frontal systems were obtained from “Climanálise”, a monthly publication by the Center for Weather Prediction and Climate Analysis, INPE. The data presented in “Climanálise” are for the Brazilian coastal and mainland sections and indicate if frontal systems were detected during 24-h period, on the day of the observations. For the present study, we have considered the presence of the frontal systems, if when moving from the south they attained 20°S or less. A perusal of Table 1 indicates that only three observational nights (viz. 13–14 July 1996 (Q), 16–17 August 1996 (possibly with some disturbance) and 08–09 June 1997 (D)) had the presence of the frontal systems, with only 1 quiet night. Therefore, the influence of tropospheric disturbances (frontal systems) could be limited to seeding only. It should be pointed out that on the night of 01–02 August 1995, there is neither a magnetic nor a tropospheric disturbance. As pointed out by Sastri et al. (1997) the origin of anomalous uplifting of the equatorial F-layer under quiet conditions is intriguing and needs further investigation.

The foregoing discussions related to the present database indicate that, during the low spread-F season, the observations of large-scale ionospheric depletions during magnetic disturbances are possibly associated with prompt equatorial field disturbances related to substorm activity, resulting in an unusual uplifting of the F-layer. However, influences of tropospheric disturbances appear to be possibly limited to

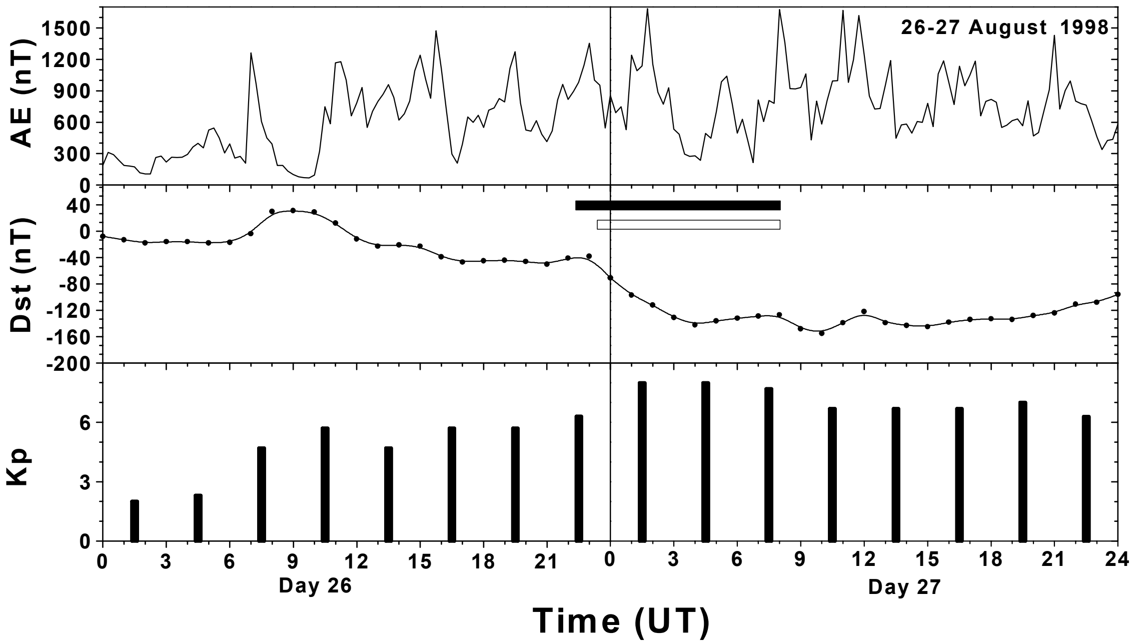

Fig. 4. Geomagnetic indices (AE, K_p and D_{st}) for 26 and 27 August 1998. Filled horizontal bar shows the period of the OI 630 nm all-sky imaging observations, whereas the blank horizontal bar shows the period when the plasma bubbles were detected.

seeding only. Obviously, more F-region nightglow wide-angle imaging or radio (simultaneous ionospheric sounding, GPS, etc., from the equatorial and low-latitude regions) and thermospheric wind observations with the availability of simultaneous meteorological data during the low spread-F season might be important and helpful for studies related to the initiation mechanisms for ESF and large-scale ionospheric plasma depletions.

3.2 26–27 August 1998–A case study

Good weather conditions allowed for the OI 630 nm emission imaging observations on 9 nights during the new moon period in August 1998. However, only one night, viz. 26–27 August showed the presence of plasma bubbles, virtually throughout the night. Figure 3 shows sequences of a few images obtained on the night of 24 August (no plasma bubbles; nearly uniform intensity levels) and 26 August (with plasma bubbles; quasi-north-south aligned intensity depletion valleys). Figure 4 shows the magnetic activity data (K_p, D_{st} and AE) for 26 and 27 August. A sudden commencement geomagnetic storm with SSC at 06:53 UT (UT =LT + 3 h for observations at C. Paulista) was observed on 26 August. Strong intensification of the ring current parameter, D_{st}, was observed after the SSC and the AE index (15 min values) showed intense substorm activity. It is noted that the period during which plasma bubbles were observed on 26–27 August nearly coincides with K_p reaching 8 (21:00 to 06:00 LT).

Figure 5 shows the TEC phase fluctuations, for different satellite signals tracked at Tucuman, obtained from GPS phase differences (1-min samples of TEC) between 1.2 GHz and 1.6 GHz for the nights of 24–25 August (quiet) and 26–27 August (disturbed). The format of the data presentation is similar to that given by Aarons et al. (1996). It is noted that intense ionospheric irregularities were observed on the geomagnetically disturbed night of 26–27 August from observations at Tucuman, a location about 2000 km west of C. Paulista, indicating that the east-west extent of ESF which developed on this night is of the order of several thousand kilometers.

Since the plasma bubbles were observed at C. Paulista on very few occasions during geomagnetic storms, in the low spread-F season, for a series of observations extending close to 11 years, it appears that magnetospheric substorm related transient electric field disturbances in the region of the magnetic equator produce only sometimes the conditions (which normally occurs during the spread-F season) necessary for the generation of the large-scale plasma irregularities (Reddy and Nishida, 1992; Fejer and Scherliess, 1995).

4 Conclusions

In this paper we have presented results from an extensive series (about 11 years) of the OI 630 nm emission all-sky imaging observations (possibly the longest series of F-region nightglow emission imaging observations available at the present time) obtained from C. Paulista, a low-latitude location in Brazil. The main results from this study are summarized below:

1. The observed seasonal pattern of plasma bubbles (quasi-north-south aligned airglow intensity depletion valleys

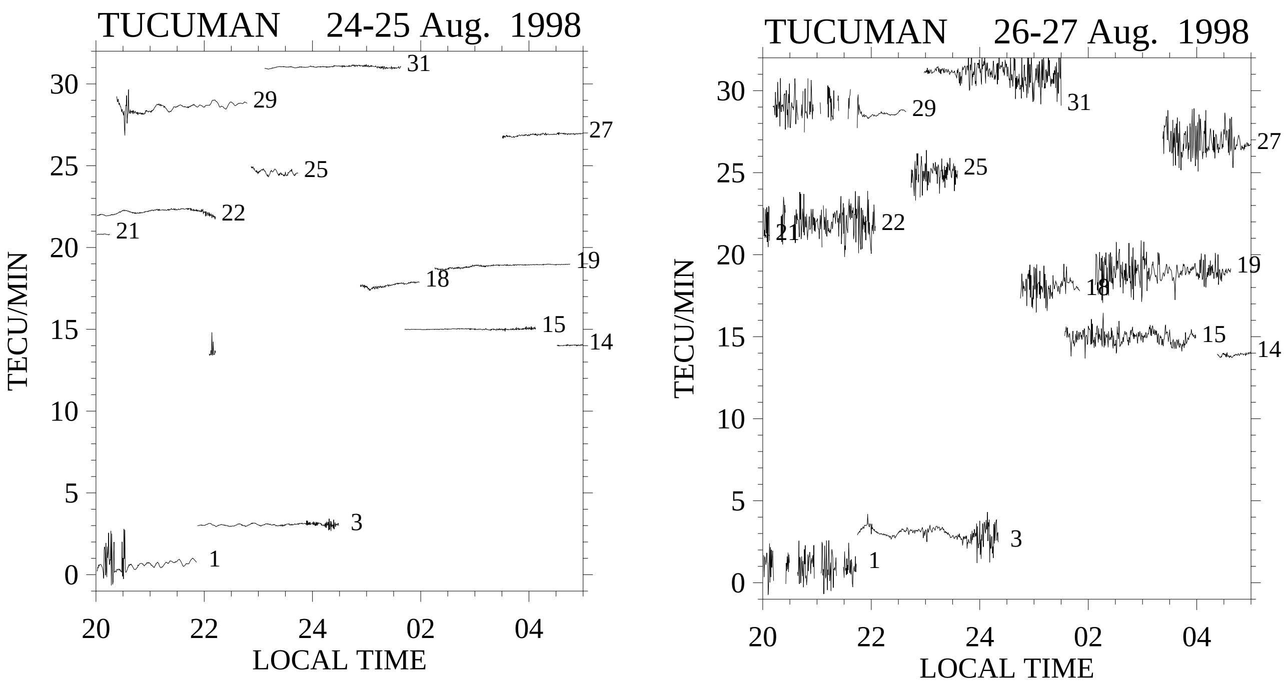

Fig. 5. GPS-TEC phase fluctuations observed at Tucuman, Argentina, on the nights of 24–25 August (geomagnetically quiet; virtually no phase fluctuations with no plasma bubbles seen from C. Paulista) and 26–27 August (geomagnetically disturbed; intense phase fluctuations with plasma bubbles observed from C. Paulista), 1998. The satellite numbers are also shown.

or bands) shows a very small occurrence during the period May–August and maximizes during the period October–March. The present results are very similar to that presented by Sahai et al. (1994) from the earlier few years of observations.

2. During the low spread-F seasons (May–August), the plasma bubbles were observed only on 12 nights (7 nights during geomagnetically disturbed, 2 nights possibly having the influence of geomagnetic disturbances and 3 nights during relatively quiet geomagnetic conditions).

3. The plasma bubbles observed in the low spread-F seasons during geomagnetic disturbances are possibly associated with magnetospheric substorm related prompt penetration of high latitude electric fields into the magnetic equator region, resulting in an unusual lifting of the F-layer.

4. The plasma bubbles observed in the low spread-F seasons during quiet geomagnetic conditions are still puzzling. Sometimes they are associated with intense tropospheric disturbances (seeding). However, the influence of tropospheric disturbances needs further investigation.

Since during the low spread-F season plasma bubbles are normally absent and rarely observed, it will be important to detect and study their occurrence using a multi-instrument (radio, optical and meteorological) approach, for a better understanding of the onset and evolution of the equatorial large-scale ionospheric plasma irregularities.

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References

Aarons, J., Mendillo, M., and Yantosca, R.: GPS phase fluctuations in the equatorial region during the MISETA 1994 campaign, J. Geophys. Res., 101, 26 851–26 862, 1996.

Abalde, J. R., Fagundes, P. R., Bittencourt, J. A., and Sahai, Y.: Observations of equatorial F-region plasma bubbles using simultaneous OI 777.4 nm and OI 630.0 nm imaging: New results, J. Geophys. Res., 106, 30331–30336, 2001.

Abdu, M. A., de Medeiros, R. T., and Nakamura, Y.: Latitudinal magnetic flux tube extension of the equatorial spread F irregularities, J. Geophys. Res., 88, 4861–4868, 1983.

Akasofu, S.I.: Diagnostics of the magnetosphere using geomagnetic, auroral and airglow phenomena, Ann. Geophys., 26, 443–457, 1970.

Bertin, F., Kersley, L., Rees, P. R., and Testud, J.: Meteorological jet stream as source of medium scale gravity-waves in thermosphere–an experimental study, J. Atmos. Terr. Phys., 40, 1161–1183, 1978.

Booker, H. G. and Wells, H. W.: Scattering of radio waves by the F-region of the ionosphere, J. Geophys. Res., 43, 249–256, 1938.

Boska, J. and Sauli, P.: Observations of gravity waves of meteorological origin in the F-region ionosphere, Chem. Earth (C), 26, 425–428, 2001.

Clark, R. M., Yeh, K. C., and Liu, C. H.: Interaction of internal gravity waves with the ionospheric F2-layer, J. Atmos. Terr. Phys., 33, 1567–1576, 1971.

Fagundes, P. R., Sahai, Y., Batista, I. S., Abdu, M. A., Bittencourt, J. A., and Takahashi, H.: Observations of day-to-day variability in precursor signatures to equatorial F-region plasma depletions, Annales Geophysicae, 17, 1053–1063, 1999.

Fagundes, P. R., Sahai, Y., and Bittencourt, J. A.: Thermospheric zonal temperature gradients observed at low latitudes, Annales Geophysicae, 19, 1133–1139, 2001.

Fejer, B. G. and Scherliess, L.: Time dependent response of equatorial ionospheric fields to magnetospheric disturbances, Geophys. Res. Lett., 22, 851–854, 1995.

Kelley, M. C.: In situ ionospheric observations of severe weather-related gravity waves and associated small-scale plasma structure, J. Geophys. Res., 102, 329–335, 1997.

Kelley, M. C., Garcia, F., Makela, J., Fan, T., Mak, E., Sai, C., and Alcocer, D.: Highly structured tropical airglow and TEC signature during strong geomagnetic activity, Geophys. Res. Lett., 27, 465–468, 2000.

McClure, J. P., Singh, S., Bamgboya, D. K., Johnson, F. S., and Kil, H.: Occurrence of equatorial F-region irregularities: Evidence for tropospheric seeding, J. Geophys. Res., 103, 29 119–29 135, 1998.

Mendillo, M. and Baumgardner, J.: Airglow characteristics of equatorial plasma depletions, J. Geophys. Res., 87, 7641–7652, 1982.

Mendillo, M. and Tyler, A.: Geometry of depleted plasma regions in the equatorial ionosphere, J. Geophys. Res., 88, 5778–5782, 1983.

Meriwether, J. W., Mirick, J. L., Biondi, M. A., Herrero, F. A., and Fesen, C. G.: Evidence for orographic wave heating in the equatorial thermosphere at solar maximum, Geophys. Res. Lett., 23, 2177–2180, 1996.

Moore, J. G. and Weber, E. J.: OI 6300 and 7774 A airglow measurements of equatorial plasma depletions, J. Atmos. Terr. Phys., 43, 851–858, 1981.

Mukherjee, G. K., Carlo, L., Mahajan, S. H., and Patil, P. T.: First results of all-sky imaging from India, Earth Planets Space, 50, 119–127, 1998.

Reddy, C. A. and Nishida, A.: Magnetospheric substorms and nighttime height changes of the F2-region at middle and low latitudes, J. Geophys. Res., 97, 3039–3061, 1992.

Rohrbaugh, R. P., Hanson, W. B., Tinsley, B. A., Cragin, B. L., and McClure, J. P.: Images of transequatorial bubbles based on field-aligned airglow from Haleakela in 1984–1986, 94, 6763–6770, 1989.

Rottger, J.: Traveling disturbances in the equatorial ionosphere and their association with penetrative cummulus convection, J. Atmos. Terr. Phys., 39, 987–998, 1977.

Rottger, J.: Equatorial spread F by electric fields and atmospheric gravity waves generated by thunderstorms, J. Atmos. Terr. Phys., 43, 453–462, 1981.

Ruster, R.: Height variations of the F2-layer above Tsumeb during geomagnetic bay disturbances, J. Atmos. Terr. Phys., 27, 1229–1245, 1965.

Sahai, Y., Bittencourt, J. A., Teixeira, N. R., and Takahashi, H.: Plasma irregularities in the tropical F-region detected by OI 7774 A and 6300–A nightglow measurements, J. Geophys. Res., 86, 3496–3500, 1981.

Sahai, Y., Aarons, J., Mendillo, M., Baumgardner, J., Bittencourt, J. A., and Takahashi, H.: OI 630 nm imaging observations of equatorial plasma depletions at 16°S dip latitude, J. Atmos. Terr. Phys., 56, 1461–1475, 1994.

Sahai, Y., Fagundes, P. R., Bittencourt, J. A., and Abdu, M. A.: Occurrence of large scale equatorial F-region plasma depletions during geo-magnetic disturbances, J. Atmos. S-T, 60, 1593–1604, 1998.

Sahai, Y., Fagundes, P. R., and Bittencourt, J.A.: Transequatorial F-region ionospheric plasma bubbles: solar cycle effects, J. Atmos. S-T, 62, 1377–1383, 2000.

Sales, G. S., Reinisch, B. W., Scali, J. L., Dozois, C., Bullet, T. W., Weber, E. J., and Ning, P.: Spread F and the structure of equatorial ionization depletions in the southern anomaly region, J. Geophys. Res., 101, 26 819–26 827, 1996.

Sastri, J. H., Abdu, M. A., Batista, I. S., and Sobral, J. H. A.: Onset conditions of equatorial (range) spread F at Fortaleza, Brazil, during the June solstice, J. Geophys. Res., 102, 24 013–24 021, 1997.

Sinha, H. S. S., Rajesh, P. K., Misra, R. N., and Dutt, N.: Multi-wavelength imaging observations of plasma depletions over Kavalur, India, Annales Geophysicae, 19, 1119–1131, 2001.

Taylor, M. J., Eccles, J. V., La Belle, J., and Sobral, J. H. A.: High resolution OI (630 nm) image measurements of F-region depletions drifts during the Guara campaign, Gephys. Res. Lett., 24, 1699–1702, 1997.

Tinsley, B. A., Rorhbaugh, R. P., Hanson, W. B., and Broadfoot, A. L.: Images of transequatorial F-region bubbles in 630 and 777.4 nm emissions compared with satellite measurements, J. Geophys. Res., 102, 2057–2077, 1997.

Tsunoda, R. T. and Towle, D. M.: On the spatial relationship of 1-meter equatorial spread-F irregularities and depletions in total electron content, Geophys. Res. Lett., 6, 873–876, 1979.

Tsunoda, R. T., Livingston, R. C., McClure, J. P., and Hanson, W. B.: Equatorial plasma bubbles: Vertically elongated wedges from the bottomside F layer, J. Geophys. Res., 87, 9171–9180, 1982.

Weber, E. J., Buchau, J., Eather, R., and Mende, S. B.: North-south aligned equatorial airglow depletions, J. Geophys. Res., 83, 712–716, 1978.

Weber, E. J., Buchau, J., and Moore, J. G.: Airborne studies of equatorial F layer ionospheric irregularities, J. Goephys. Res., 85, 4631–4641, 1980.

Whalen, J. A.: Dependence of equatorial bubbles and bottomside spread F on season, magnetic activity, and $\boldsymbol{E} \times \boldsymbol{B}$ drift velocity during solar maximum, J. Geophys. Res., 107, 10.1029/2001JA000039, 2002.