Spread F occurrence over a southern anomaly crest location in Brazil during June solstice of solar minimum activity

C. M. N. Candido,[1] I. S. Batista,[1] F. Becker-Guedes,[1] M. A. Abdu,[1] J. H. A. Sobral,[1] and H. Takahashi[1]

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[1] We present a study of Spread F occurrence over a location under the southern crest of the equatorial ionization anomaly (Cachoeira Paulista 22.7°S, 45.0°W, mag. Lat.: 16°S, dip angle: −32.3°, Brazil) during the last solar cycle, which presented an extended solar minimum activity. After analyzing hundreds of ionograms obtained with a digital ionosonde DGS 256, between 2001 and 2010, we verified high Spread F occurrence around midnight-postmidnight during June solstice (Southern Hemisphere winter) with a peak occurrence between 2006 and 2009, when the solar flux has reached very low values (<70 SFU). At the Brazilian sector the occurrence of Spread F is known to be associated with equatorial plasma bubbles (EPBs) and is observed mainly between September and March. On the other hand, EPBs are rarely observed over Cachoeira Paulista (hereafter referred as CP) during June solstice because of the weak magnitudes of the equatorial electric field prereversal enhancement, an essential condition to the development of the large-scale irregularities at the equatorial region. Despite the rarity of EPBs, we observed several strong Spread F events occurring under low plasma densities conditions which can extend for several hours. We have found evidences that the Spread F events over CP during June solstices of low solar activity can be caused by ionospheric disturbances that are unrelated to equatorial processes. Finally we present a statistical analysis of the events and we suggest that traveling ionospheric disturbances could be one of the main sources of these nonequatorial Spread F events.

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1. Introduction

1.1. Brazilian Low-Latitude Spread F

[2] The Spread F phenomenon generally refers to ionosonde radio pulse echo traces spread in range and frequency mainly attributed to the presence of ionospheric plasma density irregularities and was first reported by *Booker and Wells* [1938]. The Spread F is globally observed from the low latitudes and the equatorial region to auroral latitudes, over all the longitudinal sectors of the Earth and their occurrence depends on several factors. In classical description, the Spread F is divided in two main types: the frequency Spread F and the range Spread F. The former is observed at the higher-frequency end of the ordinary and extraordinary traces in the ionograms, being associated to plasma density irregularities near the F layer peak. The later is usually interpreted as the spread of multiple echoes coming from oblique directions out of zenithal region, also often associated with the presence of large-scale plasma bubbles/irregularities known as equatorial plasma bubbles (EPBs), or equatorial Spread F (ESF)/plumes. Generally, in the presence of EPBs the ionograms present an extended frequency and flat range spread echoes pattern and can extend for a large period after sunset. At midlatitudes, the extensively studied Spread F is mainly related to the presence of large wave-like structures at F layer heights [*Bowman*, 2001; *Bowman and Mortimer*, 2002]. At Brazilian low latitudes the occurrence of Spread F is well known to be associated with EPBs, which begins at postsunset times, when complex dynamical processes at equatorial region become most prominent. At these times the global wind circulation system with the thermospheric wind blowing eastward, in the presence of the abrupt decay of the *E* region conductivities and the quasi horizontal geomagnetic field, produces a prereversal enhancement in the evening zonal electric field (PRE) resulting in a sharp vertical **E** × **B** drift of F layer. The rapid vertical drift of the postsunset F layer, in presence of seeding processes, can result in instability growth (Rayleigh-Taylor instability) leading to large-scale field aligned plasma depletions, known as equatorial plasma bubbles with associated cascading irregularities

[1]Instituto Nacional de Pesquisas Espaciais, São Paulo, Brazil.

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constituting a Spread F event. As these depletions vertically develop to higher altitudes over the equator (attaining altitudes of one or two thousand kilometers) they map along the magnetic field lines to higher (low) latitudes. The most favorable conditions for these events occur during high solar activity periods, between September and March, presenting its lowest occurrence rate of ~10% during June solstice according to *Sobral et al.* [2002] and to *Koga et al.* [2011]. At Cachoeira Paulista (CP) region, located under the southern equatorial anomaly crest, the Spread F/EPB is observed by a variety of instruments, such as ionosondes, optical imagers, photometers, etc. [*Abdu et al.*, 1983, 2006; *Batista et al.*, 1986; *Sobral et al.*, 2002; *Fagundes et al.*, 1997]. An essential condition for the EPBs to be observed over CP is that they should reach high apex altitudes over the magnetic equator, above 1000 km [*Sahai et al.*, 1994], which depends on the strength of equatorial evening $\mathbf{E} \times \mathbf{B}$ drift (due to PRE) and other ionosphere background conditions. However, during June solstice, the equatorial electric field prereversal enhancement is weaker over the South American region [e.g., *Fejer et al.*, 1995; *Batista et al.*, 1996]. So, the unusual occurrence of EPBs during the June solstice over the low-latitude Brazilian region (such as CP) is essentially related to geomagnetic disturbed conditions [*Becker-Guedes et al.*, 2004]. In this manner, the EPBs/plumes are rarely observed during June solstice in this latitudinal region, especially during solar minimum.

1.2. June Solstice Spread F

[3] Regarding the June solstice Spread F, several authors have pointed out its occurrence around midnight hours, at several longitudinal sectors principally over equatorial regions. *Abdu et al.* [1983] reported that while there is a maximum of frequency Spread F, the range Spread F presents a minimum over Fortaleza, Brazil. *Chapagain et al.* [2009] reported the very low occurrence of Spread F/plumes over Jicamarca during June solstice using coherent and incoherent scatter radar data. In Indian equatorial zone, several works have been reported an occurrence peak of Spread F during June solstice at solar minimum activity, which occurs around midnight hours [see *Sastri*, 1999; *Patra et al.*, 2009; and references therein]. Additionally, *Bowman* [1990], has extensively studied the midlatitude Spread F over Australian sector, and verified high occurrence rate in June solstice of solar minimum activity.

[4] Finally, despite the absence of EPBs over CP we have observed that the low-latitude ionosphere is not quiescent during the June solstice. *Sobral et al.* [1997] showed 630.0 nm depletions associated with intense gravity wave activity after sunset during the Southern Hemisphere winter, without Spread F. On the other hand, we observed high Spread F occurrence during the low solar activity years around midnight-postmidnight hours. The low solar flux and geomagnetic quiet conditions during the studied period suggest the existence of other ionospheric disturbances over low latitudes, not primarily influenced by equatorial processes. Possibly a variety of the ionospheric phenomena observed during low solar activity are associated with the upper atmosphere-ionosphere coupling processes over this region.

2. Instrumentation and Method

[5] We used data from a digital ionosonde (DGS 256) operated at CP and analyzed hundreds of ionograms obtained during the solar cycle 23–24, when the solar activity presented a prolonged minimum period. The average solar flux index, F10.7, is shown in Table 1. The number of quiet to moderately disturbed nights ($\sum$Kp < 24) for each period of four months (May to August), where the symbol $\sum$ represents throughout this paper an UT day sum of the 3 h Kp indexes, is also shown in Table 1. We have used the following criteria in the statistical analysis: (1) first we restricted the analyzed period between May and August, when the EPBs are very rare over CP (this would minimize the ambiguity of the Spread F being caused by TIDs or EPBs); and (2) we established as a Spread F event the well known cases of range Spread F or mixed Spread F (simultaneous frequency and range Spread F). The frequency Spread F types were excluded from the statistics because they were inexpressive in occurrence and duration time in comparison with the other observed events. Also, we excluded the ionograms which presented some doubts principally due to the presence of sporadic E layer (Es) and the Spread F events undoubtedly caused by EPBs (which present higher top critical frequencies). (3) The Spread F occurrence rate was calculated by two ways: as the number of nights of Spread F occurrence under quiet conditions ($\sum$Kp < 24) divided by the total number of nights of ionospheric data (Figure 2, full columns) and as the number of nights of Spread F occurrence under quiet conditions ($\sum$Kp < 24) divided by the total number of quiet nights with data (Figure 2, white columns), from 1 May to 31 August.

[6] The Spread F onset time and duration was analyzed considering the initiation and the end of the entire event during the night without interruptions. In order to seek a probable cause of Spread F over CP analyzed here, we selected one Spread F event and examined the evolution of the F layer parameters from 18:00 LT to 06:00 LT, by plotting the ionospheric parameters: h′F (virtual F layer height, in km), hmF2 (F layer peak height, in km), and foF2 (plasma critical frequency, in MHz). Also, we present the monthly average of hmF2. Moreover, as there were airglow data available for this case, we present one sequence of airglow images (OI 630.0 nm emission) obtained from an all-sky imaging system. The OI 630.0 nm emission comes from recombination processes between O_2^+ and electrons, and has a volumetric emission rate peak at about 250 km. The imaging of this emission have been used extensively in the study of ionospheric irregularities in the F region such as EPBs [*Sobral et al.*, 2002; *Abalde et al.*, 2009; *Chapagain et al.*, 2011], TIDs, brightness waves, etc. [*Martinis et al.*, 2006; *Pimenta et al.*, 2008; *Candido et al.*, 2008, *Martinis et al.*, 2010].

3. Results

[7] We observed an unexpected and frequent occurrence of Spread F over CP during June solstice during solar minimum activity. Figure 1 shows some examples of these

Table 1. Some Important Information About the Studied Period

Year	Annual Average F10.7 (SFU)	May–August Average F10.7 (SFU)	Number of Quiet Nights for May–August (∑Kp < 24)	Number of Disturbed Nights for May–August (∑Kp ≥ 24)	Total Number of Nights of Data in the Period	Number of Spread F Events During Quiet Nights (May–August)
2001	183.50	159.34	108	15	123	6
2002	180.20	180.74	90	18	108	1
2003	130.0	128.65	50	72	122	12
2004	107.03	109.90	107	16	123	18
2005	94.60	101.41	76	29	105	42
2006	80.51	79.75	102	13	115	68
2007	73.01	74.09	112	07	119	70
2008	68.99	68.4	118	05	123	58
2009	70.44	70.52	121	02	123	103
2010	79.13	78.33	110	11	121	43

premidnight and postmidnight Spread F. Figures 1a and 1b show Spread F events over CP during a disturbed night (ΣKp ≤ 61) and during a quiet period (ΣKp < 24), respectively. Both examples are associated with the occurrence of EPBs and show a flat pattern of range Spread F, common during EPBs occurrence. Figures 1c and 1d present two examples which are classified as mixed Spread F (simultaneous frequency and range Spread F occurrence), as proposed by *Piggott and Rawer* [1972]. In Figures 1e and 1f we can see other common type of Spread F, which show Spread F echoes traces at regions above the foF2 curve and at altitudes higher than the bottomside F layer (>h′F). These traces are classified as "spur" trace according to the U.R.S.I. Handbook of Ionograms [*Piggott and Rawer*, 1972] and they are usually present at the same time as frequency or mixed Spread F. In this work we observed that the most common Spread F patterns were the Spread F starting as frequency Spread F and latter evolving to range or mixed

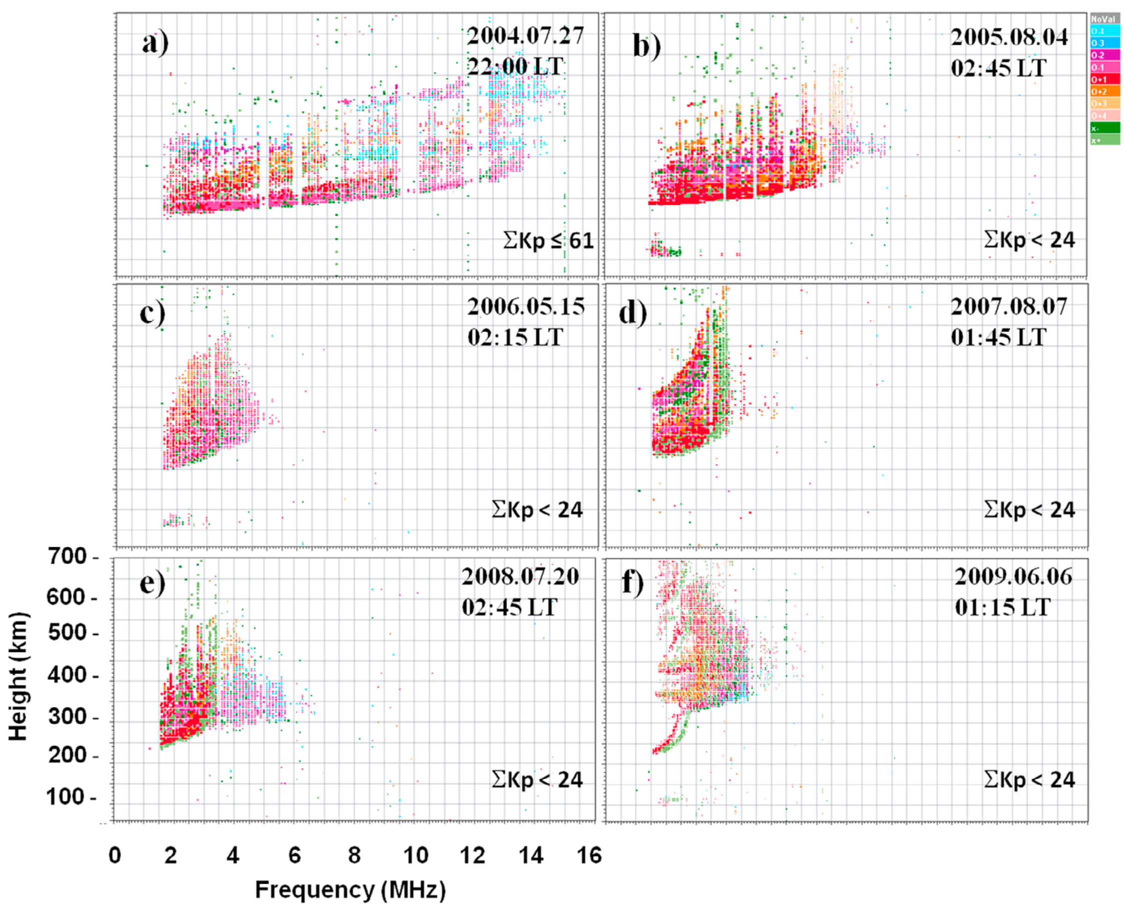

Figure 1. Examples of premidnight-postmidnight Spread F occurrence at Cachoeira Paulista during June solstice and their correspondent ΣKp. (a and b) Range Spread F due to EPBs, (c and d) mixed spread, and (e and f) mixed/spur Spread F.

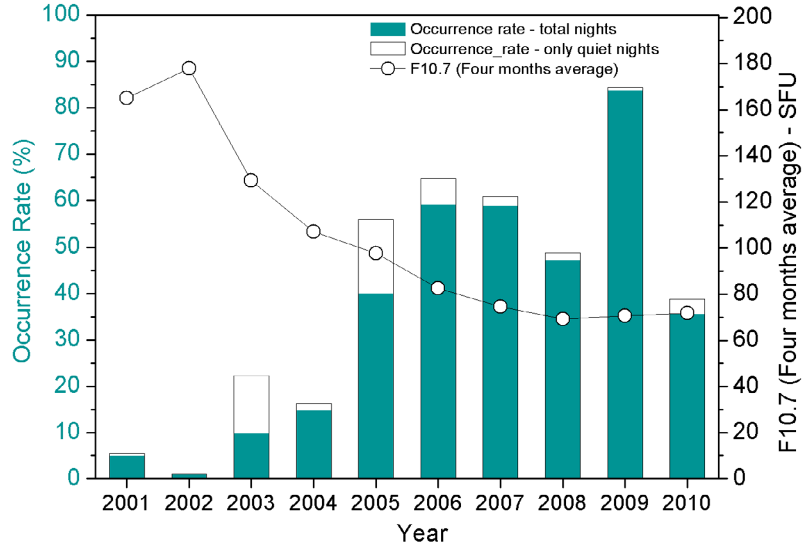

Figure 2. Spread F occurrence rate during quiet nights and F10.7 index (May–August average) at Cachoeira Paulista between 2001 and 2010. The full bars were obtained as the number of nights of Spread F occurrence under quiet conditions (∑Kp < 24) divided by the total number of nights of ionospheric data, and the unfilled bars were obtained as the number of nights of Spread F occurrence under quiet conditions (∑Kp < 24) divided by the total number of quiet nights with data from 1 May to 31 August.

Spread F, and the Spread F starting as "spur" trace evolving to mixed Spread F (Figures 1e and 1f).

[8] In order to verify the climatology of Spread F over CP we performed a statistical study using ionosonde data from 1 May to 31 August, for the period from 2001 to 2010. We analyzed hundreds of ionograms registered from 18:00 LT to 06:00 LT (21:00 to 09:00 UT), at 15 min cadence. The dependence of Spread F occurrence on the solar flux and on the geomagnetic activity was analyzed through the F10.7 and ΣKp indexes. For clarity we present some relevant information in Table 1: the F10.7 index (annual and four months average), the number of quiet and disturbed nights in each period of four months, the total number of nights of data in each period of 4 months and the number of Spread F events during each quiet period.

[9] Figure 2 shows the Spread F occurrence rate between May and August, from 2001 to 2010. During 2002 the F10.7 index was as high as 180 SFU while during 2008 it was as low as 68 SFU. We used the four months (May to August) F10.7 average to analyze the dependence of Spread F occurrence on the solar flux. We observe a low occurrence of Spread F during June solstice at high solar activity years and a progressive increase during moderate and low solar flux conditions. We should point out that during 2002 and 2005 the occurrence rate was based on less data than during the other years (108 and 105 nights, respectively). The inverse correlation between Spread F and solar flux is very clear from Figure 2. During the high solar flux period the Spread F rate was not higher than 25% while during low solar activity it reaches ~80%. A remarkable characteristic was that the Spread F presented a higher occurrence rate in the low solar activity years, between 2006 and 2009 (solar cycle 23/24). This minimum period has been pointed out as unexpected prolonged so the neutral and ionospheric features have been extensively studied under these unusual conditions [*Liu et al.*, 2011; *Huang et al.*, 2009; *Emmert et al.*, 2010].

[10] By inspection of the ionograms obtained in 2008 we observed that the plasma densities (critical frequencies foF2) were lower than in the other years. Despite this, the Spread F occurrence was higher during 2009, which suggest an inferior threshold in foF2 to Spread F occurrence. We believe that the occurrence peak in 2009, a transition year between the solar cycles 23/24, was due to optimum conditions for Spread F generation, but this point is merely speculative and needs confirmation.

[11] The dependence of Spread F occurrence during June solstice on geomagnetic activity is shown in Figure 3. In this analysis we excluded the Spread F events due to EPBs (25 cases, mostly occurring during disturbed conditions). Figure 3a shows the number of days for each level of ∑Kp divided in the following bins: 0–8, 8–16, 16–24, >24. It was observed that the number of disturbed nights (ΣKp ≥ 24) during June solstice was relatively low during the initial phase of solar cycle 23, presenting a peak at 2003 (72 cases) and finally presenting only few cases of disturbed nights during solar minimum years (2006–2009). The largest number of geomagnetic quiet days was observed in 2009 while in 2010 (initial phase of solar cycle 24) we can observe an increasing trend in ΣKp. Figure 3b shows the dependence of Spread F on Kp where the occurrence rate was calculated from the ratio between the number of events that occurred during each level of ΣKp and the number of nights of data within each ΣKp level. It is observed that the Spread F events occur mainly for low levels of geomagnetic activity, when ΣKp ≤ 8. For ΣKp ≥ 24 (white bars), the number of disturbed nights was very low and the occurrence rate have no statistical significance. The plot shown in Figure 3c represents the Spread F occurrence rate for each ΣKp level for the whole period of 10 years. As already

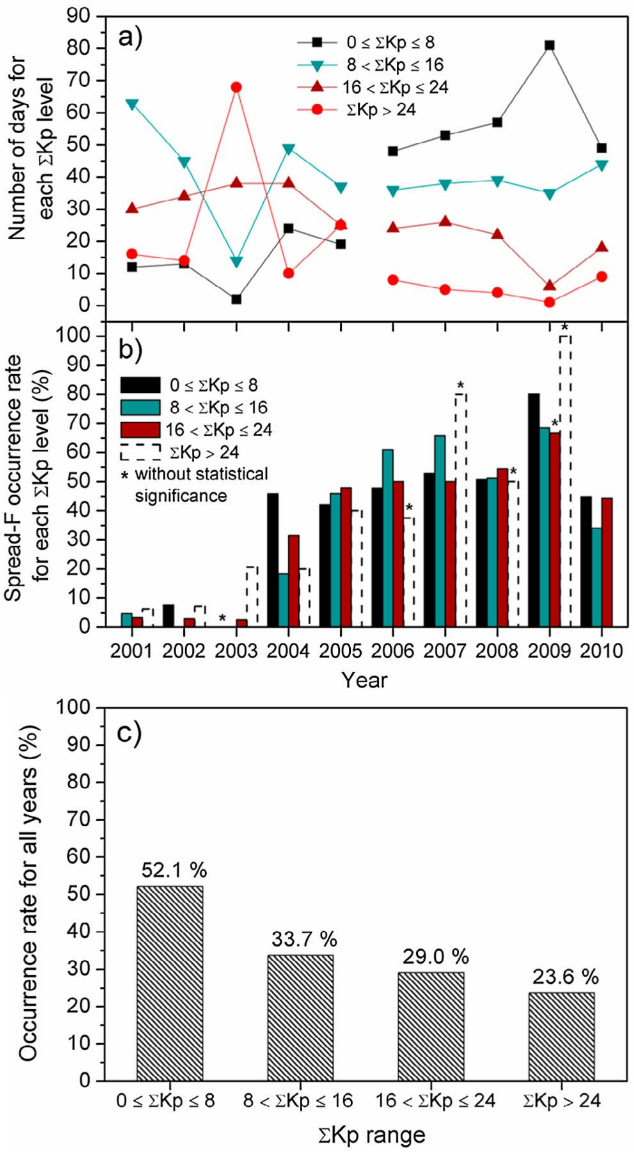

Figure 3. (a) Number of nights for each level of ΣKp during June solstice, (b) Spread F occurrence for each level of ΣKp, and (c) dependence of the Spread F occurrence rate on ΣKp for all studied years (2001–2010).

mentioned before, it is observed that the occurrence of Spread F during June solstice in low latitude is more frequent during quiet geomagnetic nights (∑Kp < 24).

[12] One of the most distinct features of this Spread F in relation to EPBs is the initiation time. In opposition to EPBs events related to the prereversal enhancement, that start around sunset times (around 19:30 LT in this longitudinal sector), this work shows that the Spread F onset times are distributed at later evening hours with the peak being at ~23 LT (02 UT). Other recent studies by *Chapagain et al.* [2009] compared the onset times of equatorial Spread F/plumes for different solar flux conditions and seasons at Jicamarca. They pointed out that during solar minimum period the Spread F onset time is around 19:30 LT during June solstice and around 22:30 LT for plumes. However, strong Spread F events and the plumes rarely can reach altitudes higher than 900 km; consequently they cannot reach higher latitudes (as CP for example). In order to verify the distribution of the onset time of the Spread F we have performed a statistical analysis of all initial time, defined as the first appearance of Spread F echoes, considering all the years from May to August for Kp < 24 (Figure 4a) We have observed that the events begin principally between about 22:00 and 01:00 LT, or (01:00 and 04:00 UT), although we can observe some Spread F starting as early at 20:00 LT, with few events starting around 03:00 and 05:00 LT. In order to confirm that the early Spread F was not associated with EPBs, we inspected equatorial ionosonde data or some available airglow data (not shown here). Also we present a plot of the duration of Spread F events in Figure 4b. We observed that the majority of the events have duration around 2 to 4 h, but some of the events can last for more than 5 h (those are obviously the events that started earlier).

4. Discussion

[13] Our observations revealed a frequent occurrence of Spread F at Cachoeira Paulista during June solstice, under geomagnetic quiet nights with a peak at low solar activity, when the occurrence rate reached about 80%. This result is really interesting since until now, most of the Spread F events studied over this low-latitude site were those associated with EPBs. This is so because a significant portion of ionospheric irregularities studies in the Brazilian region focused in these spectacular equatorial phenomena. *Abdu et al.* [1983] performed a comparative study of the occurrence of Spread F over Fortaleza and CP during maximum solar activity epoch. They observed very low probabilities of frequency type Spread F, and no range type Spread F occurrence during June solstice without the respective Spread F types at the equatorial site. In fact, we observed that at high solar activity years the most common type of Spread F in June solstice was the frequency Spread F. In this manner, this work complements a lack of analyses for southern winter and additionally includes also solar minimum years. Now, we will consider the ionospheric behavior over CP before discussing a possible explanation for the observed Spread F development. At Cachoeira Paulista, the EPBs are registered as range Spread F in ionograms or dark and highly structured depletions in airglow images, generally propagating eastward during evening/postsunset hours. It is well known that the EPBs are generated during postsunset in the equatorial region and can persist for several hours, mainly between October and March [*Abdu et al.*, 1983]. Although the EPBs occurrence is rare over CP during the June solstice their occurrence is not completely null, occasionally occurring under quiet or disturbed conditions, as shown in Figures 1a and 1b. Cases of EPBs occurrence during magnetic disturbances have been studied by *Sastri et al.* [1997]. The low occurrence rate of EPBs over CP during June solstices was verified by *Sobral et al.* [2002], who used an extended airglow database (~20 years) and found occurrence rate about 11% in May. It is important to point out that a necessary condition for EPBs to be observed over latitudes as at CP is that they should reach apex altitudes of around 1500 km over the equator, as studied by *Sahai et al.* [2000]. The low occurrence rate is attributed to the low intensity of vertical plasma drifts over equatorial

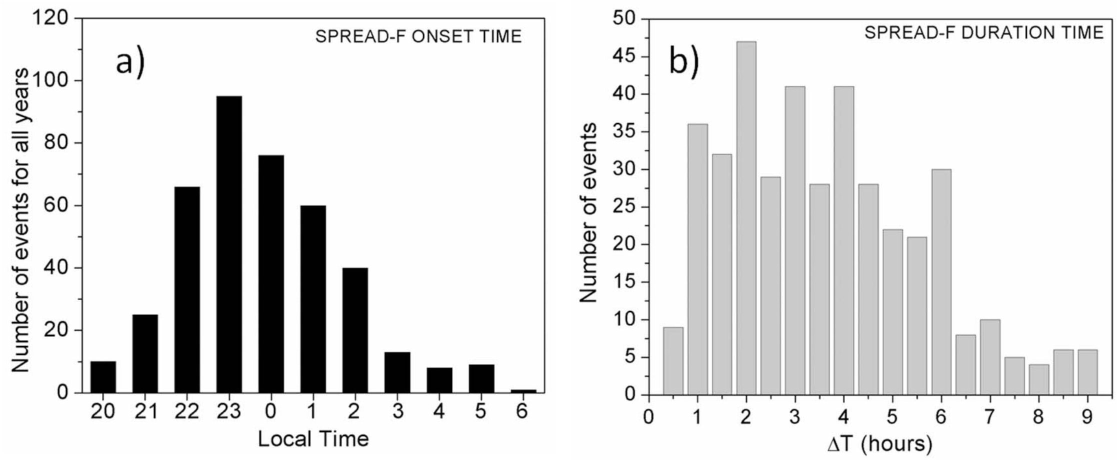

Figure 4. (a) Spread F onset time distribution and (b) Spread F duration time for all studied periods.

region during June solstice. It is well known that the intensity of the vertical drifts (Vz) at equatorial region is an important factor that determines the evolution of large-cale ionospheric irregularities to the topside ionosphere and it has been studied for several years using radar, ionosonde and satellite data [*Batista et al.*, 1996; *Fejer et al.*, 2008]. *Batista et al.* [1996] studied Vz for a Brazilian equatorial site using ionosonde data and verified a clear electric field prereversal enhancement (PRE) during June solstice of solar maximum activity but no evidence of PRE at solar minimum. *Abdu et al.* [2006] analyzed the equatorial F region vertical drift during winter months (June, July) at Brazilian equatorial region (São Luis) for high and low solar activity. They observed vertical drifts of about 50 m/s for high solar activity and the presence of very weak mean vertical drift peak during solar minimum period. Regarding the dependence of Spread F on geomagnetic activity in equatorial region, a study performed by *Whalen* [2002], for solar maximum revealed that the strength of Spread F (bottomside, strong bottomside Spread F, and plasma bubbles) during June solstice are lower than at other seasons and shows no dependence on Kp while it presents a linear dependence on the geomagnetic activity (Kp) for equinoxes and December solstice. Recently, *Tsunoda* [2010] has discussed the influence of seeding processes on the probability of occurrence of EPBs during the solstices and has found a correlation with the seasonal migration and latitudinal alignment of the inter-tropical convergence zone (ITCZ) with the magnetic dip equator. Finally, several studies using satellite data have improved the well known climatology of EPBs. *Su et al.* [2008] studied the global distribution of plasma irregularities occurrence using the ROCSAT-1 database obtained at high and moderate solar activity. Their study showed that the low occurrence of irregularities in Southern Hemisphere during June solstice was closely associated with the continuing and slow variation in the ionospheric conditions during this period, that are related to magnetic declination [*Abdu et al.*, 1981] together with the local seasonal effect at the dip equator. *Comberiate and Paxton* [2010] studied the occurrence of EPBs between 2002 and 2007 using data collected by Thermosphere Ionosphere Mesosphere Energetic and Dynamics (TIMED) satellite. Its orbit around 625 km provided important information about the topside ionosphere. Their report on the climatology of EPBs including the Brazilian sector showed a very low occurrence of EPBs over several longitudinal sectors from May to August, as earlier observed by others researchers. Finally, if the EPBs cannot be seen at the satellite orbit about 625 km over the dip equator, it is not possible that they can be observed at a low-latitude site.

[14] So, if most of the Spread F over CP during June solstice especially for the solar minimum years is unlikely to be caused by EPBs, an intriguing question arises as to what could cause these Spread F events under such quiet conditions? We believe that there are more than one possible answer to this question, mainly because of the variety of observed Spread F patterns and their duration times. In order to investigate one probable cause for the occurrence of Spread F during June solstice we selected an event observed on 21–22 June 2006 ($\sum Kp = 4$, $F10.7_{June} = 76, 68$ SFU), for which there were reliable ionosonde and airglow data.

[15] Figure 5a shows the sequence of ionograms with Spread F echoes starting about 23:00 LT (02:00 UT) and ending around 04:15 LT (only the ionograms until 03:30 LT are shown in Figure 5). That was a long-duration premidnight Spread F event (~5 h) of high intensity. Figure 5b shows the F layer behavior before and during the occurrence of Spread F, with the ionospheric parameters h′F, hmF2, foF2 and monthly averaged hmF2. It is observed a first rise of F layer after 22:30 LT and a tendency to rise immediately before the Spread F initiation (before 23:00 LT). The F layer critical frequency, foF2, present values not higher than 4 MHz (typical of the period), with a peak around 21:15 LT. It is important to point out that we have observed very low plasma critical frequencies during June solstice, principally after midnight. These results agree with the results reported by *Batista and Abdu* [2004] which showed that the lowest values of foF2 are observed during June solstice at solar minimum period.

[16] Additionally we analyze the h′I (minimum Spread F echoes height) and fxI (the highest frequency of F layer spread echoes). (Notice that the subtitle “x” does not mean

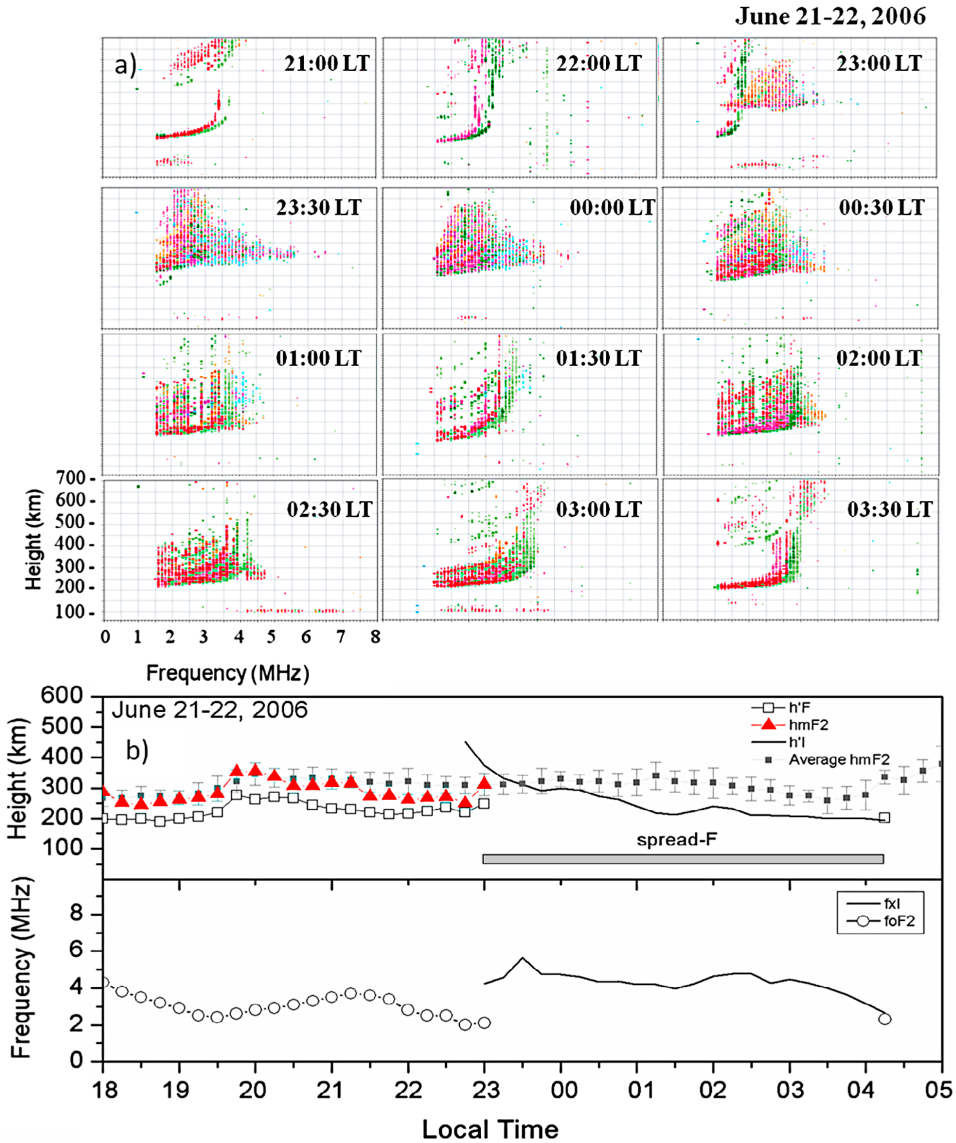

Figure 5. (a) Sequence of ionograms obtained at Cachoeira Paulista on 22 June 2006 and (b) ionospheric parameters: h′F, hmF2, h′I (km), monthly average hmF2, foF2, and fxI (MHz) on 22 June 2006 over Cachoeira Paulista, Brazil. (LT = UT, 3 h).

that the parameter is related to the extraordinary trace). The h′I starts at altitudes as high as 400 km (23:00 LT) and shows a descending trend with some oscillation during the Spread F occurrence. This apparent descending height is in fact the result of an irregularity approaching the zenith at an apparent velocity of 40 m/s (calculated from $\Delta h'I/\Delta t$). These additional parameters were extracted from F layer traces, commonly observed in this work as seen in Figures 1e and 1f and Figure 4a. According the U.R.S.I ionogram handbook [*Piggott and Rawer*, 1972] this F layer trace pattern is attributed to echoes coming from oblique reflections that can be associated with two main factors: high tilts in the F layer or ionization ridges above the F layer peak. Large tilts are expected to be generally imposed on ionospheric layer for the presence of TIDs [see *Abdu et al.*, 1982; *Bowman*, 2001; *Bowman and Mortimer*, 2002; and references therein]. So, their presence strongly suggests the occurrence of these disturbances over CP.

[17] Another important data source to understand what occurs over Cachoeira Paulista during the Spread F event is the airglow images of a thermospheric emission. The OI 630.0 nm emission, that peaks at 250 km has been very useful to trace ionospheric structures associated with plasma bubble irregularities or other disturbances as TIDs, brightness waves, etc. [*Weber et al.*, 1978; *Sobral et al.*, 1980; *Martinis et al.*, 2006; *Candido et al.*, 2008; *Pimenta et al.*, 2008; *Abalde et al.*, 2009]. Its intensity depends primarily on the vertical movements of F layer (and associated variations in the recombination rates) and on the electronic/neutral densities. At Cachoeira Paulista, EPBs are identified in the OI 630.0 nm emission images as dark and structured depletions in the airglow intensity quasi aligned along the

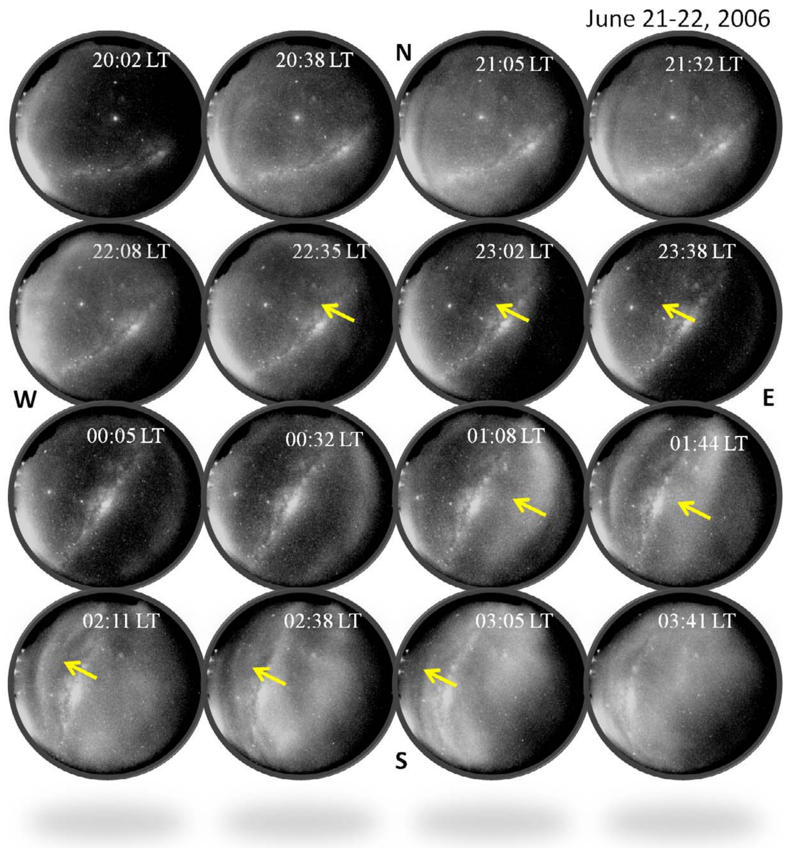

Figure 6. Sequence of raw images of OI 630.0 nm obtained with an all-sky imager on 21–22 June 2006 over Cachoeira Paulista. The arrows show the edge of the dark band and indicate the propagation direction.

magnetic field lines, usually propagating to eastward after sunset times or eventually to westward during quiet geomagnetic times at equatorial region as reported by *Sobral et al.* [2011]. TIDs are seen as dark bands oriented from northeast to southwest, propagating northwestward [*Pimenta et al.*, 2008]. It is important to point out that during solar minimum period the intensity of the airglow emission reached its lowest magnitudes. This dependence of airglow intensities on the solar flux were studied by *Sahai et al.* [2000], and the low intensities was attributed to the low availability of elements for the recombination processes. We selected an event observed with a sequence of raw images of OI 630.0 nm obtained at Cachoeira Paulista in the night of 21–22 June 2006, with simultaneous occurrence of Spread F (Figure 6). Around 22:35 LT we can observe a dark structure, oriented from northeast to southwest, entering at the east edge of image and propagating northwestward. Moreover, it is followed by a wide and diffuse region, which extends diagonally from the bottom left to the top right of the image at about 03:00 LT. Such wide and diffuse band should not be confused with the Milky Way signature on the images which is clearly characterized by a narrow bright band that also appears in the images. A remarkable feature is that the dark band is close to the image center around 23:00 LT, which matches with the first detected Spread F echoes in the ionogram (Spread F echoes coming from oblique direction and from height higher than h′F). This dark band seems to be associated with medium-scale traveling ionospheric disturbances (MSTIDs) reported to occur over Southern Hemisphere [*Martinis et al.*, 2006; *Pimenta et al.*, 2008; *Candido et al.*, 2008]. *Pimenta et al.* [2008] reported on the preferential northwestward propagation of these bands at low latitudes. They verified that these bands present larger lifetimes during solar minimum activity than during moderate solar activity. *Candido et al.* [2008] performed a statistical analysis of these disturbances and verified an occurrence peak during June solstice. Its signature and climatology features are very similar to midlatitude Spread F/TIDs, extensively studied for other longitudinal sectors [*Bowman*, 2001; *Bowman and Mortimer*, 2002]. These earlier reports about TIDs have pointed out as their signatures the rise of F layer accompanied by depletions in foF2. Also, they can produce Spread F. Additionally, an inverse relation between midlatitude MSTIDs and geomagnetic activity was recently studied by *Seker et al.* [2011]. They verified that MSTIDs occur principally under low values of geomagnetic parameters such as Kp, Ap, and Dst, agreeing with the results shown in Figure 3c. However, it is important to consider that regardless of being caused by TIDs or not, the Spread F depends on the magnitude of the wave-like perturbation as discussed by *Bowman* [2001]. Several of these previous studies pointed out the strong association between Spread F and medium-scale TIDs at midlatitude ionosphere. Large amplitude gravity waves produce isoionic surfaces at ionospheric heights which provide conditions for the Spread F occurrence. These large amplitude GWs can occur under very low neutral atmosphere densities conditions. Concerning these low neutral atmosphere densities, recent studies performed by *Emmert et al.* [2010], which analyzed a very extended database (40 years), have shown that the average neutral densities at 400 km during cycle 23/24 minimum was very low and reached values 29% lower than the corresponding average density during the cycle 22/23 minimum. We believe that the low plasma densities and the very low neutral atmosphere densities observed in the period studied in this work could be crucial to the development and propagation of wave-like structures (GWs) at ionospheric regions. Moreover, the observed characteristics showed a remarkable similarity in this inverse relation with solar activity with midlatitude Spread F [*Bowman*, 1992]. On the other hand, the high occurrence of Spread F over Brazilian low latitudes during June solstice is quite distinct of the Japanese sector. *Shiokawa et al.* [2003] analyzed the occurrence of Spread F associated with TIDs and verified that it is not higher than 10–15% in Japan. This significant difference between the two longitudinal sectors needs more investigation.

[18] Also, we should mention that other intriguing phenomena have been observed over South Atlantic Anomaly (SAA) during June solstice of solar minimum period. Recent observations by C/NOFS, an equatorial orbit satellite (altitude: 400–850 km) has revealed the occurrence of broad plasma depletions (BPDs), depletions trenches and irregularities over the equatorial region [*Huang et al.*, 2009; *Burke et al.*, 2009]. *Huang et al.* [2009] verified that the BPDs are frequently observed during June solstice of solar minimum activity, being the widest and deepest BPDs observed around the region of SAA (America-Africa). There is a notable similarity between the climatology of BPDs and the low-latitude Spread F reported in this work. However, as its latitudinal extension is not yet known, we cannot establish an association between them and more investigations are necessary. In addition, some authors have pointed out that the Spread F in low solar activity can be also associated with local irregularities whose causes are still unknown [*Cabrera et al.*, 2010].

5. Conclusions

[19] We presented new results about a frequent occurrence of Spread F over a Brazilian low-latitude site, Cachoeira Paulista, during June solstice. The Spread F events analyzed here present the following remarkable features: they occur around midnight-postmidnight hours, during June solstice and mainly under quiet geomagnetic conditions. Several events presented high intensities (>200 km) of range spreading and had long durations. The most important result is our finding of an inverse correlation between the Spread F occurrence rate and the solar activity during local winter (June solstice). The referred solar cycle 23 had a prolonged minimum that extended from 2006 to 2009. During this unusual minimum period, the number of disturbed days was the lowest since several decades. The typical plasma densities were observed around 0.49 to 1.98 × 10^6 el./cm^3 for midnight-postmidnight hours. Some airglow imaging of OI 630 nm showed the absence of EPBs and the presence of TIDs during the Spread F events. The dynamics of F layer heights and plasma densities suggest that these Spread F events are likely associated with ionospheric disturbances, possibly caused by TIDs originating from midlatitudes, especially during the very low plasma densities that characterized the background ionosphere preceding these events, whose causes are not yet established.

[20] The low neutral and plasma densities and, above all, the low occurrence rate of EPBs over CP during June Solstice of solar minimum (a well-known seasonal feature) enabled us to study Spread F over low latitude mainly associated with the enhancement of wave activity. This unique approach permit us to differentiate between the two most common ionospheric phenomena in low latitudes (EPBs and MSTIDs) using only ionogram data and without the aid of another instrument such as an all-sky imager. The same methodology for Spread F classification used in this work can help us to develop a confident analysis method to differentiate between the Spread F from EPBs and MSTIDs in other season/period as well.

[21] Finally, these new results show that the low-latitude ionosphere is not quiescent at solar minimum conditions and a variety of distinct disturbances associated with upper atmosphere/ionosphere coupling (as higher wave activity) can be separately studied without the direct influence of solar flux, geomagnetic activity and equatorial processes.

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M. A. Abdu, I. S. Batista, F. Becker-Guedes, C. M. N. Candido, J. H. A. Sobral, and H. Takahashi, Instituto Nacional de Pesquisas Espaciais, São José dos Campos, São Paulo 12227-010, Brazil. (claudia@laser.inpe.br)