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OBSERVATIONS OF IONOSPHERIC PLASMA DEPLETIONS USING OI 630.0 nm NIGHTGLOW IMAGING

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Ionospheric plasma irregularities associated with nighttime equatorial spread-F phenomena have been the subject of intensive experimental and theoretical investigations during recent years. Large scale plasma depletions, referred to as transequatorial bubbles or plumes, continue to attract considerable attention. The studies of ionosphere plasma irregularities assume great importance, because the irregularities degrade the radio wave signals passing through the region and, therefore, have considerable influence on the ionospheric/trans-ionospheric radio wave communications. The F-region nightglow emissions arising from ionospheric recombination processes can be used to remotely observe the dynamics of transequatorial ionospheric plasma bubbles and smaller scale plasma irregularities. In a collaborative project between the Center for Space Physics, Boston University, USA, and the National Institute for Space Research (INPE), Brazil, an all-sky imaging system was put in operation at Cachoeira Paulista (22.7° *S*, 45.0° *W*, dip latitude 15.8° *S*), in March 1987. This wide angle imaging technique provides an unique capability of permitting observations over regions covering several million square kilometers from a single observing station. Also, regular measurements of several nightglow emissions and ionospheric sounding are carried out at Cachoeira Paulista and Fortaleza (3.9° *S*, 38.4° *W*, dip latitude 3.7° *S*). A VHF electronic polarimeter was in operation at Cachoeira Paulista. This clustering of observational facilities in the Brazilian sector provided coincident and complementary observations of various upper atmospheric parameters. In this paper we present and discuss some features of the OI 630.0 *nm* emission all-sky imaging observations carried out during the period 1987-1989. The transequatorial ionospheric plasma bubbles manifest in all-sky optical imaging observations as nearly north-south aligned intensity-depleted regions. The observed seasonal variation of the airglow depletions shows a maximum during the summer months and virtually no airglow depletions during the winter months. The case studies presented show different forms of generation and development phases of airglow depletions during the course of a night. The all-sky images also permitted the determination of the altitude-latitude extent of the plasma depleted regions and some results are presented. It has been observed that the altitudes reached by the plasma depleted flux tubes over the magnetic equator in the Brazilian sector often exceed 2500 *km*.

Key words: Ionospheric plasma; Ionospheric bubbles; Atmospheric airglow; Optical imaging; OI 630.0 nm emission.

OBSERVAÇÕES DE DEPLEÇÕES NO PLASMA IONOSFÉRICO USANDO IMAGEAMENTO DA LUMINESCÊNCIA ATMOSFÉRICA EM OI 630,0 nm - *Irregularidades no plasma ionosférico associadas com o fenômeno noturno de espalhamento-F equatorial têm sido recentemente objeto de intensos estudos experimentais e teóricos. Depleções de plasma em grande escala, conhecidas como bolhas transequatoriais ou plumas, continuam a atrair atenção considerável. Os estudos destas irregularidades no plasma ionosférico são de grande importância pois elas degradam os sinais de ondas de rádio que atravessam a ionosfera e afetam consideravelmente as comunicações ionosféricas/transionosféricas. As emissões de luminescência atmosférica noturna da região F ionosférica, resultantes de processos de recombinação ionosférica, permitem um sensoriamento remoto da dinâmica destas bolhas transequatoriais de plasma e de irregularidades de pequena escala. Através de um projeto de colaboração entre o Centro de Física Espacial da Universidade de Boston e o Instituto Nacional de Pesquisas Espaciais (INPE), um sistema de imageamento celeste está sendo operado em Cachoeira Paulista (22,7°* S, *45,0°* W, *latitude* dip *15,8°* S*) desde março de 1987. Esta técnica de imageamento com amplo ângulo de visada permite observar regiões no céu cobrindo vários milhões de quilômetros quadrados. Medidas de várias outras emissões noturnas e rádiossondagens ionosféricas são também regularmente conduzidas em Cachoeira Paulista e Fortaleza (3,9°* S, *38,4°* W, *latitude* dip *3,7°* S*). Um polarímetro em VHF é também operado de Cachoeira Paulista. Este conjunto de equipamentos no setor brasileiro permitiu a observação simultânea de vários parâmetros ionosféricos. Neste artigo são apresentadas e discutidas algumas características das observações de imageamento da emissão OI 630,0 nm conduzidas no período 1987-1989. As bolhas transequatoriais de plasma manifestam-se nas observações de imageamento ótico como regiões de depleção em intensidade quase alinhadas na direção norte-sul magnética. As variações sazonais destas depleções apresentam um máximo nos meses de verão, com praticamente nenhuma depleção nos meses de inverno. Os casos apresentados aqui mostram diferentes formas de iniciação e fases de desenvolvimento das depleções na intensidade das emissões durante a noite. As imagens permitem ainda a determinação da extensão em altitude e latitude das bolhas de plasma e alguns resultados são apresentados. Tem sido observado que elas chegam a atingir altitudes excedendo 2500 km sobre o equador magnético no setor brasileiro.*

Palavras-chave: *Plasma ionosférico; Bolhas ionosféricas; Luminescência atmosférica; Imageamento ótico; Emissão OI 630,0 nm.*

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INTRODUCTION

Ionospheric plasma irregularities associated with nighttime equatorial spread-F phnomena (Booker & Wells, 1938) have been the subject of intensive experimental and theoretical investigations during recent years. These irregularities are of different scale sizes with wavelengths varying from several tens of kilometers to as small as a meter, or less, and have been observed using ionosondes (e.g., King, 1970; Rastogi, 1978, 1986; Abdu et al., 1981, 1983a; Huang et al., 1987), topside sounders (e.g., Dyson & Benson, 1978; Ben'kova et al., 1988), radar backscatter (e.g., Woodman and La Hoz, 1976; Tsunoda et al., 1979, Tsunoda, 1980), satellite beacon and radio star scintillations (e.g., Basu & Kelley, 1979; Aarons, 1977, 1982), and in situ rocket (e.g., Kelley et al., 1976, Morse et al., 1977; Szuszcewicz et al., 1980) and satellite (e.g., McClure et al., 1977; Hoegy et al., 1982; Oya et al., 1986) measurements. The irregularities characterized by large scale transequatorial plasma depletions, generally refered to as plasma bubbles and plumes, continues to attract much attention. Considerable interest in the studies related to the equatorial ionospheric plasma irregularities stems from the fact that the irregularities degrade radio wave signals passing through the ionospheric region and, therefore, influence ionospheric/trans-ionospheric radio wave communications.

Several investigators have carried out theoretical and computer simulations of equatorial irregularities associated with large scale plasma depletions (e.g., Ossakow et al., 1979; Chiu & Strauss, 1979; Anderson & Mendillo, 1983; Mendillo et al., 1985; Hanson et al., 1986). According to present theoretical interpretations, large scale plasma depletions or spread-F bubbles are initially generated at the F-region bottomside, through a fluid type gradient instability mechanism, such as the gravitational Rayleigh-Taylor instability (Dungey, 1956; Haerendel, 1973; Ossakow et al., 1979) in conjunction with **E x B** instability (Martyn, 1959).

The ionospheric plasma bubbles are aligned along the magnetic field lines, owing to the much greater conductivity in the magnetic field direction as compared with the perpendicular conductivity. As these bubbles move buoyantly upward with respect to the ambient plasma in the equatorial region, their bottomside feet migrate away from the equator, reaching dip latitudes of over ± 15° (Rohrbaugh et al., 1989), and break up into smaller scale size electron density irregularities, which are associated with spread-F, backscatter and scintillations. They usually drift toward the east in the equatorial ionosphere and are often tilted or curved to the west of the magnetic meridian because of the bubble upward motion.

Airglow observations provide a convenient technique for sensing remotely the dynamics of the upper atmosphere. During recent years rapid advances have been made in electro-optical devices and have offered considerable improvement in the capability of instruments used for optical studies of the upper atmosphere. It is now possible to obtain monochromatic all-sky (180° field of view) imaging observations for studying the morphology and dynamics of nightglow structures, over regions extending several million square kilometers.

The F-region nightglow emissions arising from ionospheric recombination processes can be used to remotely observe the dynamics of transequatorial ionospheric plasma bubbles and smaller scale size plasma irregularities. During recent years several investigators have carried out observations of the F-region OI 777.4 nm and/or OI 630.0 nm nightglow emissions using wide-angle airglow imaging techniques (e.g. airborne studies: Weber et al., 1978, 1980, 1982; Moore & Weber, 1981; ground-based studies: Mendillo & Baumgardner, 1982; Mendillo & Tyler, 1983; Rohrbaugh et al., 1989; Sahai et al., 1994a) and conventional photometer methods (e.g., Sobral et al., 1980, 1981, 1985; Sahai et al., 1981, 1983; Sipler et al., 1981; Bittencourt et al., 1983; Carman, 1983; Malcolm et al., 1984), to study equatorial and low latitude ionospheric irregularities and have provided valuable and important results related to the evolution, structures, movements and velocities of large scale plasma depleted regions. Rohrbaugh et al. (1989) have used a field-aligned observing geometry which has been discussed in detail by Tinsley (1982).

In order to carry out regular observations of the F-region OI 630.0 nm nightglow emission using wide-angle (180° field of view) imaging to map the nightglow emission structures and their movements, an all-sky imaging system was put in operation at Cachoeira Paulista (22,7° S, 45.0° W), Brazil, in March 1987, in a bilateral collaborative project between the Center for Space Physics, Boston University, USA, and the National Institute for Space Research (INPE), Brazil. Also, two multichannel zenith photometer, an ionosonde, a polarimeter and a magnetometer are in regular operation at Cachoeira Paulista (CP).

This clustering of observational facilities at CP provides coincident and complementary observations of various ionospheric and geomagnetic parameters. In this paper we present and discuss some results from the OI 630.0 nm emission all-sky imaging observations carried out during the period March 1987 to July 1989, related to the morphology and dynamics of transequatorial plasma depletions in the Brazilian sector.

INSTRUMENTATION

A low light level all-sky (180° field of view) airglow imaging system, very similar to that described in detail by Mendillo et al. (1982) and Mendillo & Baumgardner (1982), was put in routine operation at CP in March 1987 (Fig. 1). The magnetic dip latitude in 1987 for CP was 15.8° S. The imaging system records intensified monochromatic imagens on 35 mm films using a conventional single lens reflex camera and, in its present configuration, the system can be used only for one selected nightglow emission. A 4 in diameter interference filter with 1.35 nm bandwidth has been used for the OI 630.0 nm emission observations. Most of the images presented in this paper were obtained at 20 min intervals, using a 32 sec time exposure. As pointed out by Mendillo & Baumgardner (1982), a zenith angle of 75° encompasses approximately ± 8° of latitude/longitude, equivalent to a horizontal diameter of 1800 km at about 300 km. Zenith angles from 75° to 90° encompass an additional ± 8° latitude/longitude, but compression effects are large in this region. The observing geometry with the all-sky imaging system for the OI 630.0 nm emission at CP, is shown in Fig. 2.

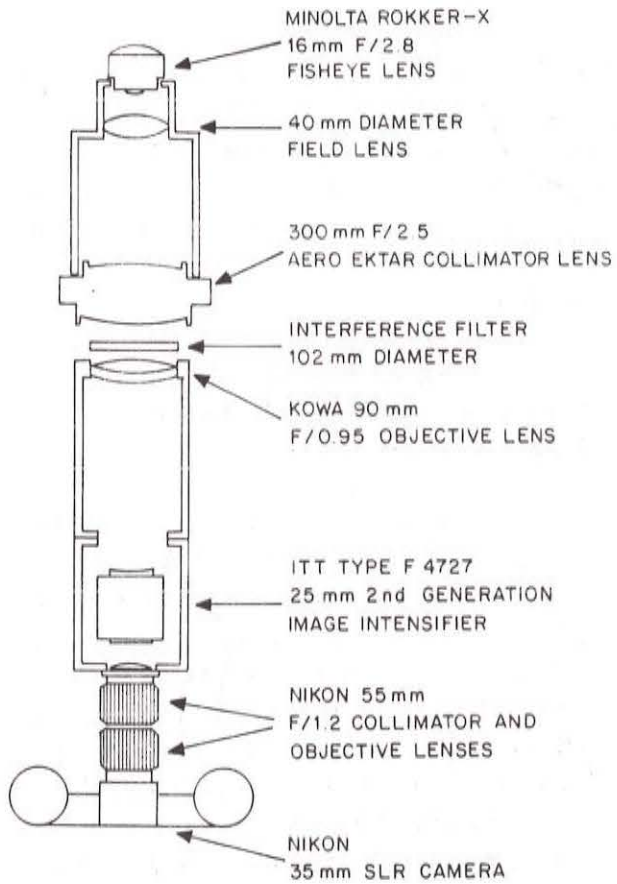

Figure 1 - Schematic diagram of the OI 630.0 nm all-sky imaging system.

***Figura 1** - Diagrama esquemático do sistema de imageamento do céu na linha OI 630,0 nm.*

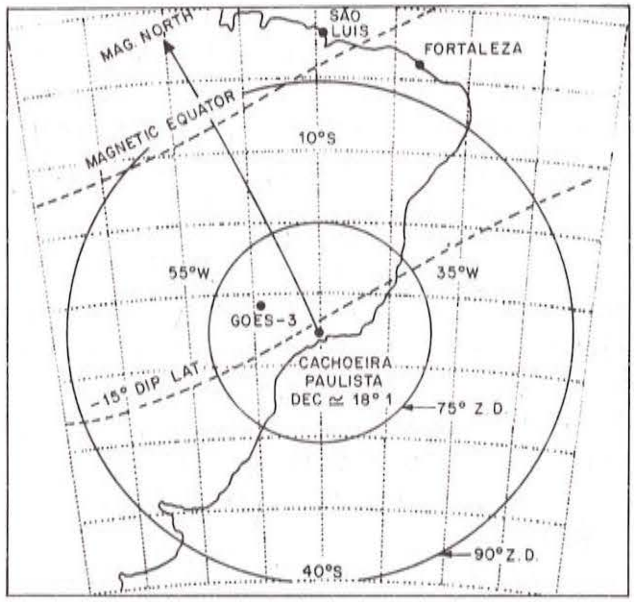

Figure 2 - The imaging system field of view at 75° and 90° zenith angles at 300 *km*. The magnetic north direction is also indicated.

***Figura 2** - Campo de visão do sistema de imageamento para ângulos zenitais de 75° e 90° a 300 km de altitude. A direção norte magnética está também indicada.*

The OI 630.0 *nm* nightglow emission intensities presented in this study were measured by a multi-channel tilting filter type zenith photometer, which has been in operation at CP since January 1987. The photometer provides measurements of the OI 777.4 *nm*, 630.0 *nm* and 557.7 *nm*, NaD 589.3 *nm*, OH(9-4) and O_2 - *atm.*(0-1) nightglow emissions at intervals of 3 *min*. The photometer operation and the data acquisition system were controlled by a Z80A microprocessor and the data were recorded on a digital cassette system. The photomultipler used is a cooled Hamamatsu R943-02 (GaAs photocathode). The photometer has a field of view of 2° full angle and the effective diameter of the interference filters used is 2 *in*. The effective bandwidths of the interference filters for the OI 630.0 *nm* and 777.4 *nm* emissions are 1.46 and 1.05 *nm*, respectively. A calibrated standard light source (Eppley ES-8315) was used for determination of absolute sensitivities of the photometer. A substandard light source (Tungsten filament pilot lamp) was used for field calibration. The OI 630.0 *nm* emission absolute intensities were calculated using tilting filter (Yano, 1966) and calibration (Kulkarni & Sanders, 1964) techniques. As narrow band filters are used, the OH(9-3) band contamination at 630.0 *nm* has been considered to be negligible. The estimated error in the absolute sensitivity for this emission is approximately ± 15%. The OI 777.4 *nm* absolute intensities are calculated using the technique described by Sahai et al. (1981). The absolute calibration is estimated as ± 20%.

The ionospheric data presented in this study were obtained from ionosondes in routine operation at CP and Fortaleza (3.9° *S*, 38.4° *W*), Brazil. Fortaleza (FTZ) is the closest ionospheric sounding station to the magnetic dip equator in this region. The magnetic dip latitude in 1987 for FTZ was 3.7° *S*. Abdu et al. (1983a) have pointed out that the longitude at which the magnetic meridional plane of CP intersects the magnetic equatorial plane, is about 12° westward of FTZ.

A VHF (136.379 *MHz*) electronic polarimeter monitoring the Faraday rotation angle and amplitude of geostationary satellite (GOES 3) beacon signals was in operation at CP during the imaging observations. The sub-ionospheric point corresponding to these measurements was -20.9° latitude and -49.4° longitude. Also, some results from the VHF polarimeter are presented in this study.

TROPICAL ATOMIC OXYGEN AIRGLOW EMISSION MECHANISMS

The OI 630.0 *nm* nightglow emission comes from a relatively narrow layer centered near 300 *km* altitude in the bottomside region of the F-layer and is an optical manifestation of several ionospheric processes (Serafimov et al., 1977). At equatorial and low latitude regions the OI 630.0 *nm* emission is mainly due to dissociative recombination of O^+ ions in the F-region (e.g. Peterson & Van Zandt, 1969), produced by the two-step process

$$O^+ + O_2 \rightarrow O + O_2^+ \quad (1)$$

$$O_2^+ + e \rightarrow O + O(^1D) \quad (2)$$

As discussed by Van Zandt & Peterson (1968), this emission is strongly dependent on the height changes associated with the bottom-side of the F-region, with smaller dependence to changes in the F-region electron density. The spatial distribution is mostly governed by the **E** x **B** vertical plasma drifts and thermospheric neutral winds.

The OI 777.4 *nm* emission is produced mainly by the radiative recombination process,

$$O^+ + e \rightarrow O^* + h\nu \quad (3)$$

as discussed by Tinsley et al. (1973), and provides an indirect measurement of the F-region peak electron density n_m(e). The OI 777.4 *nm* emission intensities observed at CP, during the course of the present study, have been, in general, very low and nearly at the threshold level of detection. Therefore, they have not been included in some of the case studies presented here.

OPTICAL AND RADIO DIAGNOSTICS OF LARGE-SCALE F-REGION PLASMA DEPLETIONS

The F-region ionospheric irregularities associated with large-scale plasma depletions or bubbles cause intense range-type spread-F and VHF/UHF scintillations at equatorial and low latitude regions (see e.g., Maruyama, 1990; Rastogi et al., 1990). The pioneering work of Weber et al. (1978), using all-sky OI 630.0 *nm* airglow imaging, showed that the north-south aligned equatorial airglow depletions (see e.g. Weber et al., 1978, Fig. 1) are the optical signatures of large-scale plasma depletions or bubbles associated with F-region ionospheric irregularities. Sahai et al. (1981), using a conventional photometric method (5° field of view), observed simultaneous short-time large intensity drop-outs or depletions in the OI 630.0 *nm* and 777.4 *nm* emissions at CP during range-type spread-F conditions. The F-region airgow intensity depletions are associated with the passage of F-region holes or bubbles drifting across the sky. As pointed out by Mendillo and Baumgardner (1982), in the study of equatorial plasma depletions, radio (ionosonde and scintillation) and optical methods are complementary. Whereas all-sky optical methods offer broad, instantaneous coverage of general features, radio and photometric diagnostics offer possibilities for very detailed *line of sight* studies.

Both range/and or frequency spreading are observed in ionograms at equatorial and low latitude regions. King (1970) has pointed out that range type spread-F echoes are due to partial reflection from large tilted surfaces of ionization, possibly similar in nature to the walls of plasma bubbles, and much of the frequency spreading is simply the decay product of the range spreading (see also Rastogi, 1980). However, frequency spreading has been observed immediately after sunset, independent of range spreading (see e.g. Abdu et al., 1981; Valladares et al., 1983). An analysis of VHF electronic polarimeter data obtained at CP by Abdu et al. (1985) shows Faraday rotation angle fluctuations correlated with range-type spread-F events in the local ionograms and amplitude scintillations in satellite beacon signals, indicating that those variations are associated with large scale plasma depletions in the equatorial region (see also Basu et al., 1987).

RESULTS AND DISCUSSION

During the period March 1987 / July 1989, a good series of simultaneous measurements of the OI 630.0 *nm* emission zenith intensities and all-sky images was obtained at CP. Also, complementary data from ionosondes (CP and FTZ) and VHF electronic polarimeter (CP) measurements were available during this period. This was a period of ascending solar cycle. The monthly average 10.7 *cm* flux varied from a minimum value of 73.3 (March 1987) to a maximum value of 247.2 (June 1989). The average 10.7 *cm* flux during the period under study was 139.3 ($\sigma = 50.1$).

Seasonal occurrence pattern

Several investigations have recently studied the seasonal and longitudinal variations in the occurrence characteristics of equatorial scintillations and spread-F using radio diagnostic techniques (e.g. Maruyama & Matuura, 1984; Tsunoda, 1985; Ben'kova et al., 1988). Abdu et al. (1983a) have studied the seasonal variation of the spread-F (both range and frequency-type) in the Brazilian sector from simultaneous ionosonde measurements at CP and FTZ.

In Fig. 3 we present the observed seasonal occurrence pattern of large scale plasma depletions as evidenced by quasi north-south aligned valleys of intensity depletions in the OI 630.0 *nm* all-sky images (hereafter referred to as airglow depletions). The occurrence frequency is very low during the period April to September and shows a maximum during the summer season. This is very similar to the seasonal pattern observed for range type spread-F (Abdu et al., 1983b) and from scintillation measurements (Tsunoda, 1985) in this region. It appears, therefore, that the airglow depletions or large scale plasma depletions generally do not develop in this region during winter months and have high occurrence probabilities during summer, with equinox months occupying an intermediary position. This is in accordance with the result obtained by Tsunoda (1985, see also Abdu et al., 1983a; Batista et al., 1986), that the seasonal maximum in the occurrence of equatorial scintillation and spread-F coincides with the time of year when the solar terminator is most nearly aligned with the geomagnetic meridian.

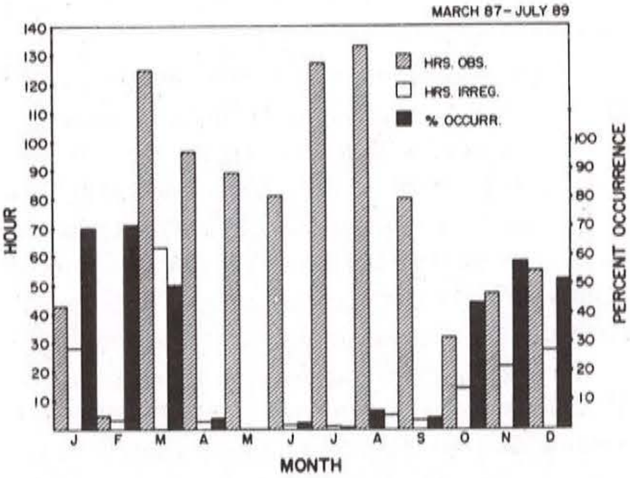

Figure 3 - Seasonal variation of north-south aligned OI 630.0 *nm* nightglow emission depletion occurrences observed at Cachoeira Paulista.

Figura 3 - *Variação sazonal das ocorrências de depleções da emissão de luminescência noturna OI 630,0 nm alinhadas norte-sul, observadas em Cachoeira Paulista.*

An analysis of the airglow depletions observed on a few nights during winter months (May, June, July and August), a period when these depletions are almost absent, revealed that, unlike summer months, the few depletions that were observed occurred on nights which were magnetically disturbed. These observations have been discussed in detail by Sahai et al. (1994b).

During the month of August 1988, an intensive campaign of the OI 630.0 *nm* imaging observations was carried out a CP in conjunction with the Equatorial Dynamics campaign in the Pacific sector. While fully developed equatorial spread-F signatures were observed in the Pacific sector on several nights in August 1988 (Mendillo, private communication), no airglow depletions were observed in the Brazilian sector. Also, weather conditions permitted a good series of airglow observations during the months of August, September and October, 1988. The frequency of occurrence of airglow depletions was observed to increase from zero in August (nights of observations: 11; nights with depletions: 0) to a situation where most nights showed strong depletions in October (nights of observations: 4; nights with depletions: 4), with September (nights of observations: 9; nights with depletions: 3) showing depletions on a few nights. It appears there is a *transition period* from no equatorial irregularities to strong generation as we move from August to October in this region.

In Fig. 4 we show complementary ionospheric data for the night of August 15-16, 1988, an example of a night in which no airglow depletions were observed. Also, no spread-F or scintillations were observed on this night. It may be noted that the afternoon f_0F2 at FTZ is generally higher than that at CP and there is virtually no post-sunset uplifting of the F-layer, as evidenced by the $h'F$ variations at both CP and FTZ on this night. In order to investigate the relative changes in the ionospheric parameters, during the period August to October, we show, in Fig. 5, average monthly values of f_0F2 and h_pF2 (virtual height at 0.834 x f_0F2, a good approximation for the F-layer peak height, h_mF2) observed at FTZ and CP during these months in 1978. The reduced ionospheric data (f_0F2 and h_pF2) for both the stations CP and FTZ were available for these three months and the average 10.7 *cm* fluxes for these months in 1988 (144.5, = 19.1) and 1978 (160.2, σ = 6.1) are comparable.

Rastogi (1989) has pointed out, that spread-F at equatorial stations is preceded by a marked rise of $h'F$ during the post-sunset hours, and the post-sunset rise of $h'F$ is accompanied by a similar rise of the F-region peak height, h_mF2. It is observed, from Fig. 5, that in addition to amplification in post-sunset uplifting of the F-layer at FTZ, there is a considerable increase in afternoon f_0F2 at CP compared with FTZ, indicating intensification of the equatorial ionospheric anomaly as we move from August to October. Recent investigations by Raghavarao et al. (1988), Alex et al. (1989) and Rastogi (1989) also show the significant role of the intensification of the equatorial ionospheric anomaly in the initiation of spread-F. The present *transition-period* observations of airglow depletions are in agreement with the results of spread-F reported by these investigators.

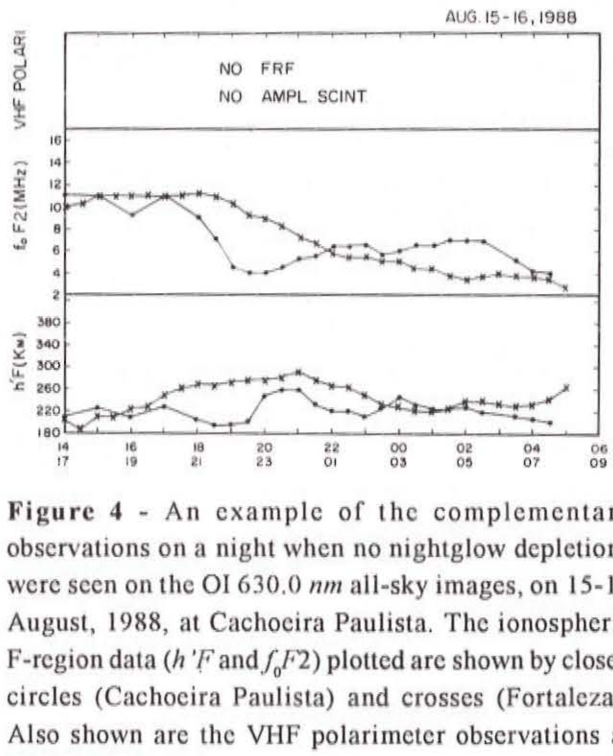

Figure 4 - An example of the complementary observations on a night when no nightglow depletions were seen on the OI 630.0 *nm* all-sky images, on 15-16 August, 1988, at Cachoeira Paulista. The ionospheric F-region data ($h'F$ and f_0F2) plotted are shown by closed circles (Cachoeira Paulista) and crosses (Fortaleza). Also shown are the VHF polarimeter observations at Cachoeira Paulista.

Figura 4 *- Um exemplo de observações complementares numa noite quando não ocorreram depleções na emissão OI 630,0 nm observadas pelo sistema de imageamento, durante 15-16 de agosto de 1988, em Cachoeira Paulista. Os dados da região-F ionosférica (h'F e f_0F2) estão apresentados por circulos cheios (Cachoeira Paulista) e por cruzes (Fortaleza). Estão também apresentadas as observações com polarímetro VHF em Cachoeira Paulista.*

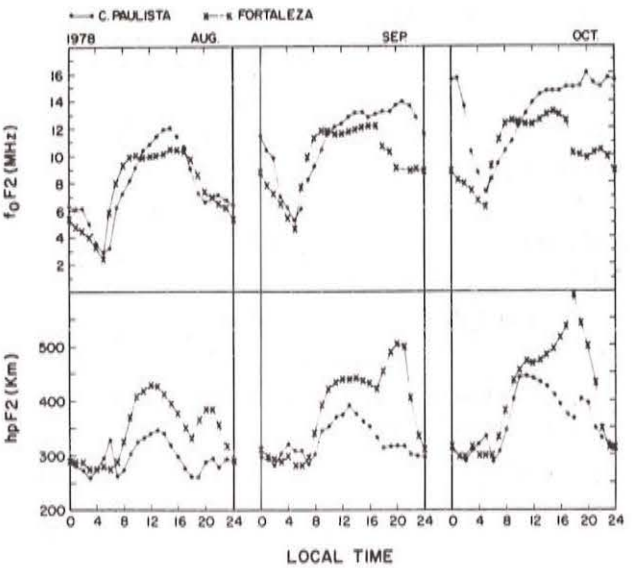

Figure 5 - Mean F-region peak heights (h_pF2) and peak electron densities (f_0F2) variations observed at Cachoeira Paulista (closed circles) and Fortaleza (crosses) for the months of August, September and October, 1978.

Figura 5 - *Médias das altitudes do pico da região-F (h_pF2) e das densidades do pico ionosférico (f_0F2) observadas em Cachoeira Paulista (círculos cheios) e em Fortaleza (cruzes) para os meses de agosto, setembro e outubro de 1978.*

Post-sunset onset and development of equatorial ionospheric plasma depletions

In this section we present two case studies of the post-sunset onset and development of the equatorial ionospheric depletions as evidenced by a series of the OI 630.0 *nm* all-sky images. Both the nights 19-20 January, 1988 (summer) and 22-23 March, 1988 (equinox) are magnetically quiet.

i) March 22-23, 1988

In Fig. 6a we present a sequence of the OI 630.0 *nm* all-sky images obtained on 22-23 March, 1988. This night shows the formation phase of airglow depletions or ionospheric plasma bubble structures and the west to east movement of a plasma bubble structure, possibly formed well beyond the western horizon (fossil depletion). In Fig. 6b we present complementary photometric and ionospheric data for this night. A comparison of ionospheric data at CP and FTZ shows large post-sunset uplifting of the F-region in the equatorial region and a well developed equatorial ionospheric anomaly. The range-type spread-F at CP occurred later than at FTZ and only during two short intervals, when the airglow depletions passed overhead, as discussed later. The Faraday rotation fluctuations and amplitude scintillations obtained by the VHF polarimeter were observed over a longer period than the range-type spread-F on the ionograms at CP.

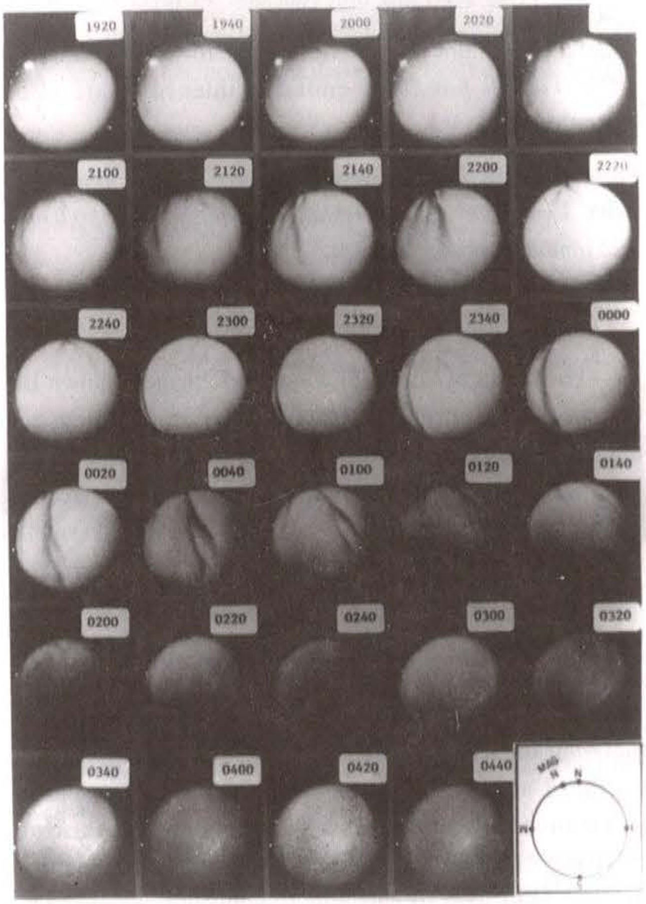

Figure 6a - Sequence of OI 630.0 *nm* all-sky images obtained on 22-23 March, 1988.

Figura 6a - *Seqüência de imagens do céu em OI 630,0 nm obtidas durante 22-23 de março de 1988.*

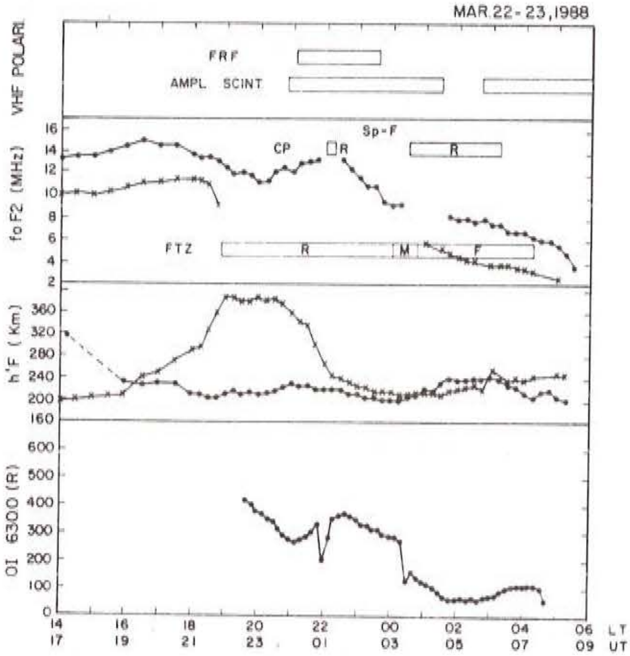

Figure 6b - Same as in Fig. 4., but for 22-23 March, 1988. The OI 630,0 *nm* emission intensities are also presented.

Figura 6b - *Análogo à Fig. 4, mas para 22-23 de março de 1988. A variação das intensidades da emissão OI 630,0 nm está também apresentada.*

The series of OI 630.0 *nm* all-sky images, shown in Fig. 6a, shows considerably lower emission intensities in the northern region, indicating an uplifted F-region, when the observations started at 1920 LT (local time referred to 45° *W* longitude). At 2000 LT we start seeing several small north-south protruding airglow depletions (multiple plasma bubbles) from the low intensity region on the northern side. The subsequent images show evolution of the airglow depleted regions. At 2100 LT we observe one of the airglow depleted regions growing in the west of the magnetic meridian and a part of this well-developed structure passes overhead at about 2200 LT. The OI 630.0 *nm* zenith observation (Fig. 6b) shows a sharp intensity decrease at this time. At 2300 LT we observe a single airglow depletion moving from west to east and subsequently acquiring a wishbone structure (Mendillo & Baumgardner, 1982) by 0040 LT. This is one of the good examples of the isolated formation and evolution of a bifurcated depletion (Mendillo & Tyler, 1983).

ii) January 19-20, 1988

In Figs. 7a and 7b, respectively, we present a series of OI 630.0 *nm* images and complementary photometric and ionospheric data, from the summer night of January 19-20, 1988. The post-sunset *h'F* variation at FTZ and the f_0F2 variations at CP and FTZ are similar to those observed on the earlier equinox night discussed here. However, the h'F variation at CP shows similar uplifting of the layer as observed at FTZ, thus the uplifting of the F-region covered a large latitudinal region. The occurrence of spread-F at FTZ and CP and Faraday rotation fluctuations and amplitude scintillations are very similar to the those on the night discussed earlier.

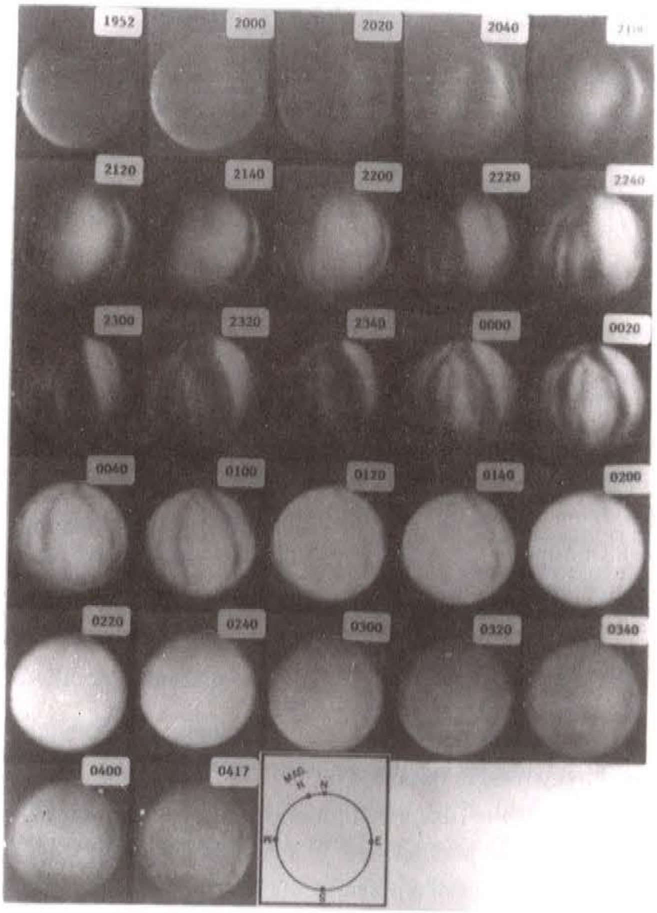

Figure 7a - Same as in Fig. 6a, but for 19-20 January, 1988.

Figura 7a - *Análogo à Fig. 6a, mas para 19-20 de janeiro de 1988.*

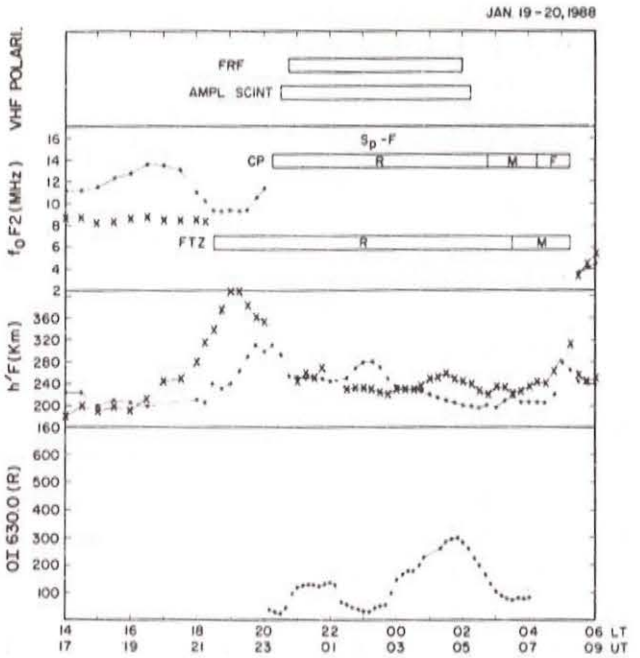

Figure 7b - Same as Fig. 6b but for 19-20 January, 1988.

Figura 7b - *Análogo à Fig. 6b, mas para 19-20 de janeiro de 1988.*

It is observed, from Fig. 7a, that when the observations started at 1952 LT, the western horizon was still under twilight conditions. However, a generally low intensity level all-round indicates extended uplifting of the F-region in the entire low latitude region. At 2020 LT we start seeing well-formed airglow depletion regions extending fully from north to south. Similar results were seen on a few other nights during this month. Possibly an extended latitudinal uplifting of the F-region results in rapid formation of elongated airglow depleted regions. This initiation mechanism is different from that discussed for the earlier night. Strong airglow depletions continue till about 0020 LT and then gradually disappear. At about 2300 LT a broad airglow depleted region passes overhead CP and Fig. 7b shows a broad intensity depletion in the OI 630.0 *nm* emission and an increase in h'F around this time. Weber et al. (1978) have also reported that regions of airglow depletions are characterized by an increase in the virtual height of the F-layer.

In this section we presented two nights (one equinox and one summer) of coincident optical and radio diagnostic observations of equatorial ionospheric irregularities. It is observed that although the post-sunset ionospheric condition (marked uplifting of the F-layer and well-developed equatorial ionospheric anomaly) are somewhat similar on these nights, the initiation and development of airglow depleted regions are very different. Large day to day differences have been observed during the course of this long series of airglow imaging observations. These results will be important for present efforts in modelling equatorial ionospheric irregularities.

Altitude-latitude extent of equatorial ionospheric plasma depletions

Mendillo & Tyler (1983) have discussed the geometry of depleted plasma regions in the equatorial ionosphere, using the OI 630.0 *nm* all-sky images. The OI 630.0 *nm* images exhibit nearly north-south aligned intensity depleted regions, which are the bottomside signatures of plasma-depleted flux tubes.

Fig. 8 shows the geometry of the low-latitude magnetic field lines, the height of the OI 630.0 *nm* emission layer (~ 300 *km*) and the field of view of the all-sky imaging system for the zenith angles 75° and 90° as seen from Cachoeira Paulista. The latitudinal extension

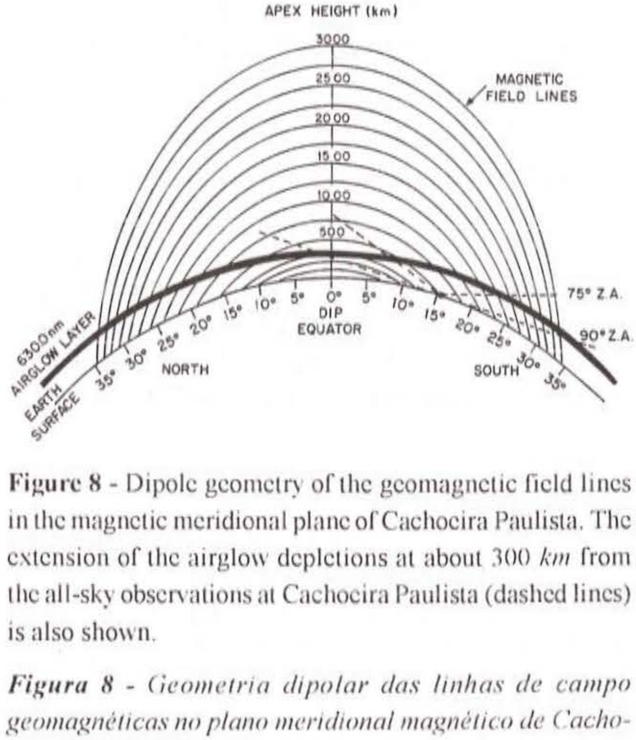

Figure 8 - Dipole geometry of the geomagnetic field lines in the magnetic meridional plane of Cachoeira Paulista. The extension of the airglow depletions at about 300 *km* from the all-sky observations at Cachoeira Paulista (dashed lines) is also shown.

Figura 8 - *Geometria dipolar das linhas de campo geomagnéticas no plano meridional magnético de Cachoeira Paulista. A extensão das depleções na luminescência atmosférica, em torno de 300 km, observadas pelo sistema imageador do céu, em Cachoeira Paulista, está também apresentada.*

of the intensity depleted regions are mapped along the magnetic field lines to equatorial crossing altitudes as shown in Fig. 9. For example, the single bubble at 0000 LT in Fig. 6a, which is occupying the full field of view, has a latitudinal extension as far as about 30° *S* dip latitude, and the corresponding plasma depleted flux tube crosses the magnetic equatorial plane at an altitude above 2500 *km*.

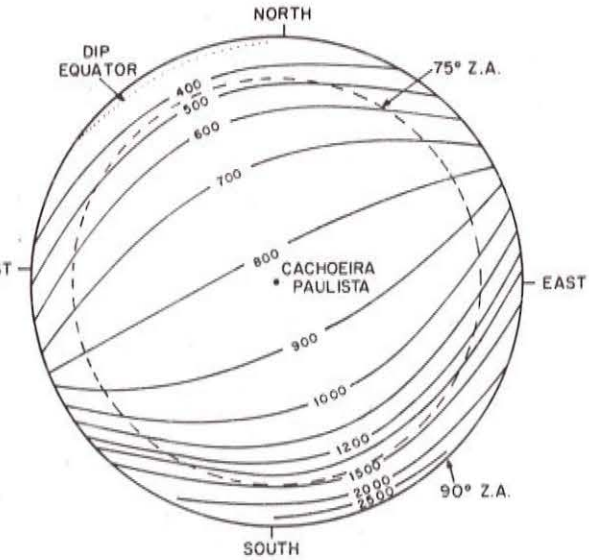

Figure 9 - An image overlay pattern as seen from Cachoeira Paulista. The near north-south aligned airglow depletions can be used to estimate the field-aligned plasma bubble altitudes above the magnetic equator, considering that the OI 630.0 *nm* emission layer is located near 300 *km*. A depleted region extending well up to the southern edge of the image will correspond to an altitude greater than 2500 *km* above the magnetic equator.

***Figura 9** - Projeção das altitudes equatoriais das linhas de campo sobre a imagem celeste vista de Cachoeira Paulista. As depleções de luminescência quase alinhadas norte-sul podem ser usadas para estimar as altitudes das bolhas de plasma alinhadas ao longo das linhas do campo geomagnético sobre o equador, considerando que a camada de emissão em OI 630,0 nm está localizada próxima de 300 km. Uma região de depleção que se estende até a borda sul da imagem mapear-se-á para altitudes maiores que 2500 km sobre o equador magnético.*

Several plasma depleted regions, shown in Fig. 7a, also present similar latitude-altitude extent. The altitude-latitude extent of the equatorial plasma depletions reported here are not readily observed by other ionospheric diagnostic techniques. The observed apex altitudes of the plasma-depleted flux tubes in the present series of observations in the Brazilian sector are much higher compared with those reported by Mendillo & Tyler (1983) at Ascension island (8° *S*, 14° *W*), about 1200 *km*, and by Rohrbaugh et al. (1989) at Hawaii (21° *N*, 157° *W*), about 900 *km*.

CONCLUSIONS

In this paper we have presented some results from a long series (1987-1989, a period of ascending solar cycle) of OI 630.0 *nm* all-sky imaging observations carried out at a low latitude station in the Brazilian sector. Complementary photometric and radio propagation measurements were used to study the formation and evolution of large-scale ionospheric plasma depletions. The principal features are summarized below.

1) The observed seasonal variation of the airglow depletions shows a maximum during the summer months and virtually no airglow depletions during the winter months.

2) A good series of observations during the period August-October, 1988, indicated the existence of a *transition period*, that is from virtually no airglow depletions in the month of August, to frequent occurrence in October. Also, an analysis of the mean diurnal variation of the ionospheric parameters f_0F2 and h_pF2 at CP and FTZ, during these months, showed an increase in the post-sunset rise of the layer height (h_pF2) at FTZ and strong intensification in the F-region peak electron densities at CP, as we move from August to October. It appears that in addition to marked uplifting of the layer, a well-developed equatorial ionospheric anomaly is important for the occurrence of large-scale ionospheric plasma irregularities.

3) Two case studies presented showed different types of development of the plasma depletions during the course of a night. These studies, one equinox night and one summer night, involved 630.0 *nm* all-sky images, zenith photometer and ionospheric radio sounding data. A large day-to-day variability was observed in the geometry of the airglow depletions. On about 40% of the nights studied in the present investigations, on which depletions occurred, both the initial formation of irregularities and the later eastward motion of airglow depletions were observed. On the remaining 60% of nights showing depletions only the latter phase was seen. The formation phase was characterized by an initial lowering of intensity in the northern sky followed by north-south depletions protruding into the field of view of the imaging system.

4) By mapping the airglow depleted regions, along geomagnetic field lines to the magnetic equatorial plane, the latitude-altitude extent of the large-scale equatorial plasma depletions have been studied. Plumes with heights exceeding 2500 *km* above the geomagnetic equator have been observed. The unusually very high apex altitudes observed, warrants further investigations and simulations for the instability conditions required to cause such pronounced effects.

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