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PLASMA BUBBLE ZONAL DRIFT CHARACTERISTICS OBSERVED BY AIRGLOW IMAGES OVER BRAZILIAN TROPICAL REGION

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ABSTRACT. Using airglow images observed at São João do Cariri (7.4°S, 36.5°W; dip angle: –11°S) from September 2000 to April 2007, plasma bubble zonal drifts for ninety-seven geomagnetically quiet nights (Dst index higher than –30 nT) were calculated. The plasma bubble eastward averaged drifts presented an increase from 18:00 to 22:00 local time (LT), and followed by a deceleration. The plasma bubbles observed during high solar activity were faster after 22:00 LT. Eastward drifts observed during the summer, after 21:00 LT, were higher than drifts observed during the equinox months. Few nights had plasma bubble eastward drifts higher than 100 m/s and almost all bubbles disappeared after 02:00 LT. Averaged zonal drifts observed between –9.5 and –5.5°S were almost constant, primarily, around 23:00 LT.

Keywords: plasma bubble, airglow, ionosphere.

RESUMO. Usando imagens de aeroluminescência coletadas em São João do Cariri (7,4°S, 36,5°W; latitude de dipolo magnético: –11°S) no período de setembro de 2000 a abril de 2007, foi possível calcular a deriva zonal de bolhas de plasma em noventa e sete noites geomagneticamente calmas (índice Dst maior que –30 nT). As derivas zonais médias das bolhas de plasma aumentaram das 18:00 até as 22:00 horas locais (HL) e desaceleraram em seguida. As bolhas de plasma observadas durante a atividade solar alta foram mais rápidas após as 22:00 HL. As derivas zonais de bolhas de plasma no verão, depois das 21:00 HL, foram maiores que nos meses de equinócio. Poucas noites apresentaram bolhas de plasma com derivas superiores a 100 m/s e quase todas as bolhas desapareceram depois das 02:00 HL. As derivas médias zonais observadas entre –9,5 e –5,5°S foram praticamente constantes, principalmente, por volta das 23:00 HL.

Palavras-chave: bolhas de plasma, aeroluminescência, ionosfera.

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INTRODUCTION

Large-scale plasma bubbles or depletions are nocturnal tropical phenomena of the ionospheric F-region. Radar measurements reveled that the plasma bubbles can reach widths $\sim$ 400 km in the east-west direction (Clemesha, 1964), and altitudes 100s-1000s km (Woodman & LaHoz, 1976). Normally, these irregularities extend hundreds of kilometers along the geomagnetic field lines (e.g., Sobral et al., 1980a, 2009).

Airglow observations of the plasma bubbles were reported early by Van Zandt & Peterson (1968). Later, Weber et al. (1978) observed that the bubbles and geomagnetic lines were quasi-aligned. In Brazil, the first observations were reported by Sobral et al. (1980a,b). They observed that the plasma bubbles vary the intensity of the airglow emissions and these variations were associated with an abrupt decrease of plasma density. A considerable improvement in the plasma bubble measurements was done by Taylor et al. (1997) during the Guará Campaign that started to use CCD cameras in the observations.

The Rayleigh-Taylor instability process in the bottom side of the F-region is the most accepted mechanism to explain the generation of the plasma bubbles (Dungey, 1956), but the seeding mechanism is an important topic of research (Fritts et al., 2009). Several works have pointed out gravity waves as a possible seeding (e.g., Kelley et al., 1981; Rottger, 1982; Huang & Kelley, 1996; Abdu, 2001; Abdu et al., 2009; Kherani et al., 2009; Takahashi et al., 2009; Vadas & Fritts, 2009; Makela et al., 2010; Paulino et al., 2011). However, others studies have pointed out that the post sunset plasma flow vortex system is more effective in seeding plasma bubbles (Kudeki & Bhattacharyya, 1999; Kudeki et al., 2007).

In the last three decades, the plasma bubbles have been largely studied in Brazil. Some aspects are well known, like the seasonality of occurrence (e.g., Sahai et al., 1998; Pimenta et al., 2001b; Sahai et al., 1999, 2000; Sobral et al., 2002; Paulino et al., 2007) and the relationship with the pre-reversal enhancement (PRE) after sunset (e.g., Batista et al., 1996; Abdu, 2005). The dynamic has also been exhaustively studied (e.g., Fagundes et al., 1995a,b; Santana et al., 2001; Pimenta et al., 2003a,b; Abalde et al., 2004; Arruda et al., 2006; Sobral et al., 2009, 2011; Paulino et al., 2010), and it is known that, during the magnetic quiet time, the plasma bubble zonal drifts are strongly coupled to the thermospheric wind, and are dependent on the solar cycle (e.g., Sahai et al., 2004). Outside Brazil, some airglow observations have contributed significantly for the understanding of the plasma bubble morphology and dynamics (e.g., Mendillo & Baumgardner, 1982; Mendillo et al., 1997; Otsuka et al., 2002; Martinis et al., 2003; Makela et al., 2006; Yao & Makela, 2007; Makela & Miller, 2008).

Characteristics of the nighttime plasma bubble eastward averaged drifts and their latitudinal variations obtained from an all sky imager deployed at São João do Cariri (7.4°S; 36.5°W) are presented and discussed in this paper.

INSTRUMENTATION AND OBSERVATIONS

Airglow images have routinely been taken at São João do Cariri since September 2000 by an all sky imager. This imager is an optical instrument that takes high resolution images and it is designed with a fish eye lens, a CCD camera, an optical system, and an interference filter wheel. The whole system is controlled by a microcomputer. The CCD camera consists of a large area (6.45 cm^2), high resolution and 1024 $\times$ 1024 back-illuminated array with a pixel of 14 bits. The high quantum efficiency, low dark noise level (0.5 electrons/pixel/s), low readout noise (15 electrons rms) and high linearity (0.05%) of this device made it possible to achieve quantitative measurements of the airglow emission. The camera uses a fast $(f/4)$ all sky telecentric lens system that enables monochromatic images of the plasma bubble to be obtained with a time integration of typically 90 s for the OI 630 nm emission. The images were binned on-chip down to 512 $\times$ 512 resolution to enhance the signal-to-noise ratio (see Medeiros et al., 2004). The OI 630 nm airglow emission is produced in the bottom side of the ionospheric F-region, between $\sim$ 220 and 300 km height, and represents an important tracer for the ionospheric studies. The main production mechanism of this emission is the dissociative recombination process (e.g. Peterson & Van Zandt, 1969).

In this paper, we are presenting results of an almost seven years database, from September 2000 to April 2007. Ninety-seven magnetically quiet nights were chosen, i.e., nights which the Dst index is higher than –30 nT, and do not have any characteristics of magnetic storms. Plasma bubble zonal drifts were estimated using a methodology similar that was published by Pimenta et al. (2001a), however, we have used the entire depletion motion instead of the border motions.

Due to limitations of the local imager field of view, the images correspond to a view angle of approximately 168°. For a fixed altitude of $\sim$ 250 km, this field of view corresponds to a diameter of $\sim$ 2400 km. Figure 1 shows a projection of an airglow image area (dashed circle) and some plasma bubbles on an unwarped image (512 km $\times$ 512 km) centered at São João

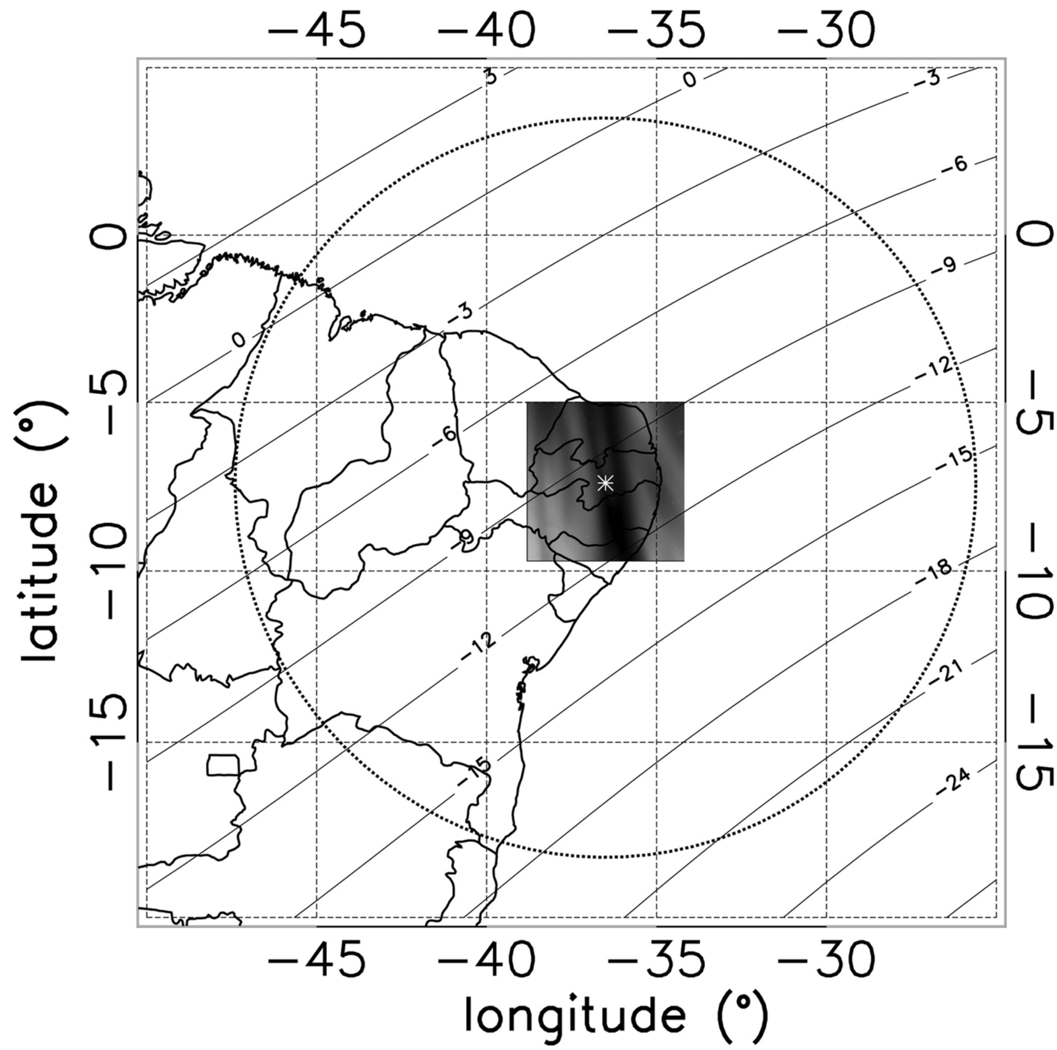

Figure 1 – Imager localization at São João do Cariri (white star) and its field of view (dashed circle) on Brazilian map. An OI 630 nm unwarped image (512 km × 512 km for 28 October 2003) is also shown.

do Cariri (white star), the solid lines represent dip latitudes at ∼ 250 km for October 2003 based on International Geomagnetic Reference Field (IGRF) model.

RESULTS AND DISCUSSIONS

Figure 2 shows the plasma bubble eastward averaged drifts during the nighttime. Open square curve represents the averaged drifts hourly binned over all observed period. The error bars are the standard deviation of the mean for each hour. Dashed star curve is the high solar activity (HSA) period (September 2000 to December 2002), and the dotted diamond curve is the low solar activity (LSA) period (January 2006 to April 2007). Solar activity has been delimited using the F10.7 cm solar flux index. All nights with F10.7 cm index lower than 80×10^{-22} $Wm^{-2}Hz^{-1}$ were classified as LSA. Whereas, the HSA nights were assumed as F10.7 cm index higher than 140×10^{-22} $Wm^{-2}Hz^{-1}$. The mean curve showed an increase from 18:00 LT (∼ 40 m/s) until 22:00 LT (∼ 65 m/s). After this time, the plasma bubbles decelerated until 05:00 LT (∼ 20 m/s). HSA and LSA curves showed a similar tendency, however, after 22:00 LT, the plasma bubble observed during the HSA were faster than LSA plasma bubbles.

The plasma bubble eastward averaged drifts were broken down according to the seasons, these results are shown in Figure 3. Dotted diamond curve is the averaged drifts for the equinox months (September, October, November, March, April, and May). Dashed star curve represents the summer months (December, January and February). Again, the error bars are the

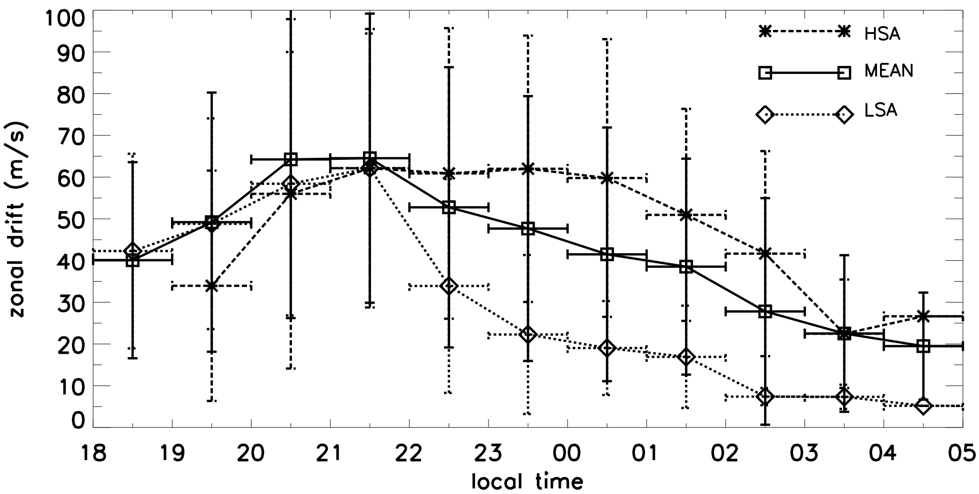

Figure 2 – Local time variation of the plasma bubble zonal mean drifts (squares). Dashed stars are the high solar activity (September 2000 to December 2002). Dotted diamonds represent the low solar activity (January 2006 to April 2007).

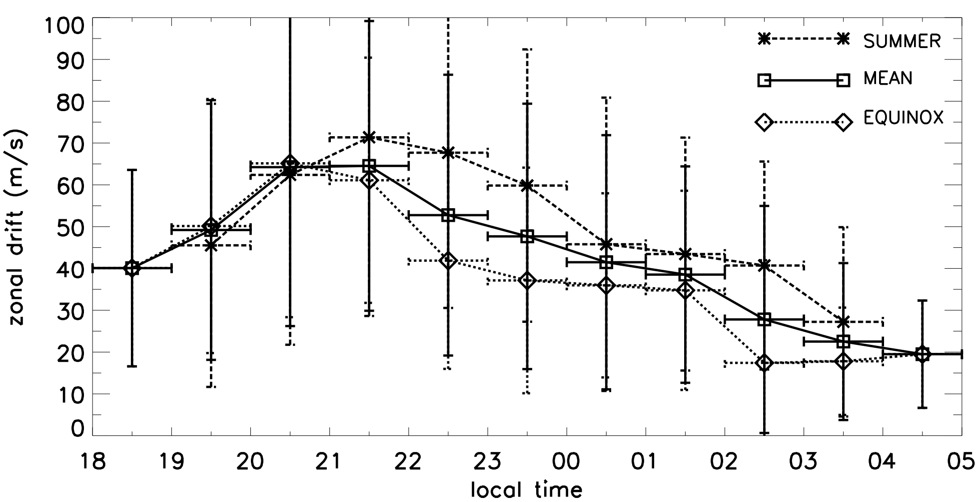

Figure 3 – Similar to Figure 2, but, in this case, the seasonal variation was broken down. Dashed stars represent the summer months (December, January, and February). Dotted diamonds are the equinox months (March, April, May, September, October, and November).

standard deviations of the hourly averaged drifts. The plasma bubbles observed during the summer were faster than the plasma bubbles observed during the equinox months after 21:00 LT.

Vertical electric fields generated by E- and F-region dynamos drive the ionospheric plasma drifts (e.g. Haerendel et al., 1992). During the nighttime, the E-region density is strongly reduced and, then, the F-region dynamo dominates the ionospheric plasma dynamics. Otherwise, the neutral thermospheric wind is the main driver of the F-region dynamo and the geomagnetic field develops an important role for the nocturnal plasma bubble dynamics, because they are flux tube integrated. Eccles (1998) simplified model can help in the understanding of this mechanism, that is,

$$V_\varphi = U_\varphi^P = \frac{\Sigma_P^F U_\varphi^{PF} + \Sigma_P^E U_\varphi^{PE}}{\Sigma_P}\,, \qquad (1)$$

where V_φ is the zonal plasma drift. U_φ is the neutral zonal wind integrated along of the magnetic field line. Σ is the integrated electric conductivity, the subscript P represents the Pedersen component, and the superscripts E and F indicate E- and F-region, respectively.

Looking to the Eq. (1), it is possible to see that the zonal plasma drift is proportional to neutral zonal wind and is weighted by Pedersen conductivity. If the E region Pedersen conductivity became negligible, the zonal plasma drift will be directly controlled by the variations of the neutral thermospheric zonal wind. Secondary variations can be expressive due to the E region ionization enhancements by the energetic particle precipitations, in South America, for instance. It has often been found near the South Atlantic Anomaly region (Abdu et al., 1998, 2003). The second weak hump showed in Figures 2 and 3 (solid line at 01:30 LT) was also predicted by Arruda et al. (2006) in their theoretical model, it can be associated with minor contributions due to vertical electric field variations. Therefore, the solar activity dependence and the seasonal variation of the plasma bubble eastward drifts could be related with modification in the thermospheric neutral wind system.

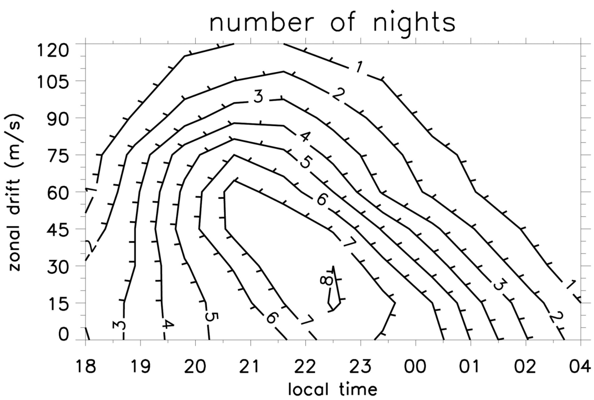

Figure 4 – Three dimensional histogram showing the number of observed night with regards to the local time (x-axis) and zonal drifts (y-axis). Contours show the same values of observed nights.

Figure 4 shows a three dimensional histogram of the numbers of observed night with a given velocity at a given time, the abscissa is the local time, the ordinate is the plasma bubble eastward drifts, and the contours are the number of observed nights. This plot is useful to identify simultaneous variations on the time and eastward drifts of the observed plasma bubbles. This plot is a more expansive visualization of Figures 2 and 3. A peak is clear around 22:00-23:00 LT with drifts of 15-60 m/s. Few nights had plasma bubbles faster than 100 m/s. Another interesting aspect was that most of the plasma bubbles disappeared after 02:00 LT. These results compare with the result by Arruda et al. (2006) over Cachoeira Paulista in the spring and summer for two years, however, the drifts in the present work were slower. The nocturnal variations of the zonal plasma bubble mean drifts are similar to those reported by Otsuka et al. (2002), Martinis et al. (2003), Pimenta et al. (2003a), Yao & Makela (2007), and Abalde et al. (2004). The seasonal and solar activity variations were shown theoretically by Arruda et al. (2006), while the geomagnetic activity influences on the plasma bubble drifts were discussed in more details by Sahai et al. (2004).

Figure 5 shows a contour plot of the plasma bubble zonal mean drifts with regards to local time and latitudes. This plot was made averaging the plasma bubble drifts for all latitudes covered between –9.5 and –5.5°S and for all observed nights. The nocturnal variation observed in Figures 2 and 3 were preserved in almost all latitudes. However, it is possible to see that the zonal drifts around the zenith were smaller after 20:00 LT until the end of the night. During the first two hours, does not had any defined pattern, and around 22:00-23:00 LT there were little latitudinal variations. The reduction of plasma bubble eastward drifts during the night can be a consequence of neutral thermospheric wind reduction as reveled by the Horizontal Wind Model (see Pimenta et al., 2003b, for instance). Similar results were also found by Pimenta et al. (2003a) over Brazilian tropical region. Martinis et al. (2003) showed also a latitudinal variation of the plasma bubble drifts as observed by two imagers separated of $\sim$ 10 degrees.

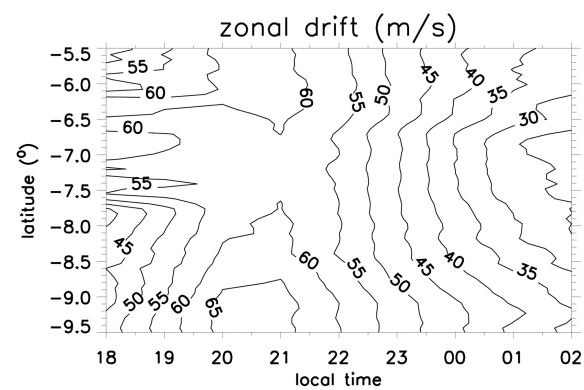

Figure 5 – Latitudinal and local time variations for the plasma bubble zonal mean drifts. Contours are the same drift lines.

It is important to note that, in the present work, the OI 630 nm emission peak was assumed to be located at 250 km height. However, the emission peak undergoes changes during the course of a night due to vertical variations of F-region. This vertical motion of the plasma may affect lightly the bubble drifts. For instance, if the OI 630 nm peak was assumed at 300 km, instead of 250 km, the plasma bubble drifts will increase by about 20%. Pimenta et al. (2003b) pointed out further details about the assumption of OI 630 nm peak be considered constant all the time. Furthermore, Abalde et al. (2004) presented a methodology of calculation of OI 630 nm peak based on variations of FpF2 observed by ionosonde. They obtained better results using OI 630 nm peak height based on simultaneous ionospheric observations.

CONCLUSIONS

Airglow images observed at São João do Cariri from September 2000 to April 2007 reveled several characteristics of the plasma bubble eastward drifts. It was obtained 97 quite nights with Dst index larger than –30 nT. The primary observed results are summarized as following:

1. The plasma bubble eastward averaged drifts at São João do Cariri increased from 18:00 to 22:00 LT, after this, the bubbles were decelerated until the end of the night;
2. After 22:00 LT, the plasma bubble eastward averaged drifts were faster during high solar activity;
3. The bubbles observed during the summer months were faster than bubbles observed during the equinox months;
4. Most of the observed nights presented plasma bubbles between 22:00-23:00 LT with drifts of 15-60 m/s;
5. Plasma bubble zonal drifts do not vary significantly between –9.5 and –5.5°S, primarily around 23:00 LT.

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