Ionospheric plasma blobs observed by OI 630 nm all-sky imaging in the Brazilian tropical sector during the major geomagnetic storm of April 6–7, 2000

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Received 20 October 2006; revised 28 November 2006; accepted 27 December 2006; published 27 January 2007.

This paper presents first observations of plasma blobs (localized plasma density enhancements) associated with large-scale plasma density depletions (plasma bubbles) in the nighttime low-latitude F-region during a major geomagnetic disturbance. Ground-based observations of the OI 630 nm all-sky images obtained at Cachoeira Paulista (22.7°S, 45.0°W), Brazil, in the Appleton anomaly region, showed the presence of plasma blobs during the major geomagnetic storm of April 6–7, 2000 (∑Kp = 38 –/40+; |Dst|max = 288 nT). The OI 630 nm emission images were used to map the spatial and temporal locations of plasma blobs and bubbles in the bottomside of the F-region. The F-region parameters, presented in this work, were obtained from ionosondes operating near the same site and also at São Luis (2.6°S, 44.4°W), Brazil. Ionospheric plasma blobs and bubbles zonal drift velocities, measured by the all-sky imaging system, showed that both the plasma blobs and the bubbles moved westward (normally the plasma drift is eastward during nighttime) on this magnetically disturbed night. Furthermore, the plasma blobs showed typically east-west and north-south extensions in the range of 110–160 km and 200–450 km, respectively. It appears that the DMSP-15 satellite, orbiting at about 850 km altitude, passed through one of the blobs detected by the ground-based observations on this night while crossing the Brazilian sector. This indicates the enormous altitude extent [from about 275 km (OI 630.0 nm emission) to 850 km (DMSP satellite altitude)] of the localized plasma density enhanced regions. In this work, we present and discuss several features related to the dynamics of the localized plasma density enhancements and large-scale plasma density depletions during this major geomagnetic disturbance.


1. Introduction

Localized F-region electron density enhancements, or plasma blobs, with densities increased by a factor of two, or more, above the background density, have been measured “in situ” by satellites orbiting at different altitudes (Hinotori (about 600 km); DMSP (about 850 km); ROCSAT-1 (about 600 km); and KOMPSAT-1 (about 685 km)) in the tropical F-region [e.g., Watanabe and Oya, 1986; Le et al., 2003; Park et al., 2003]. Using data from the Hinotori satellite, Watanabe and Oya [1986] reported the first observations of localized regions of plasma density enhancements in addition to plasma depletions in the nighttime tropical F-region. Their statistical study showed that the occurrence probabilities of plasma depletions and plasma blobs appear to be complementary to each other, and the occurrence region of the plasma blobs is limited to the adjacent parts of the plasma bubble occurrence region. Also, their study indicated that the occurrence of plasma blobs decreases with increasing magnetic activity, while there is a strong anti-correlation of the occurrence of plasma blobs to the solar radiation flux (F10.7). Pimenta et al. [2004], using all-sky images in the OI 630 nm emission, were the first to report ground-based observations of blobs in the tropical region and their association with equatorward spread-F plasma depletions. The OI 630 nm emission comes from an altitude region of about 220–300 km (F-region bottomside). In this paper we present and discuss the first ground-based observations of plasma blobs associated with plasma bubbles in the Brazilian tropical sector during the major geomagnetic storm of April 6–7, 2000 (SSC at 16:40 UT on April 6; ∑Kp = 38 –/40+; |Dst|max = 288 nT at 01:00 UT on April 7; AE index showing rapid increase in the index starting at about 16:40 UT and attaining a maximum value > 2500 nT at about 17:50 UT), a period of high solar activity (monthly average F10.7 = 185.5 SFU).

2. Measurement Technique and Observations

Observations of the morphology and time evolution of large-scale airglow depletions using an all-sky imager in the OI 630.0 nm emission is very useful for studying the mechanisms related to the development and dynamics of F-region plasma irregularities. At tropical latitudes the dissociative recombination of O₂⁺ in the F-region is the dominant process for producing the excited oxygen atoms that give rise to the OI630.0 nm nightglow. The major chemical reactions that generate the OI630.0 nm airglow emission in the F-region are as follows:

\[
O^+ + O_2 \rightarrow O_2^+ + O \tag{1}
\]

\[
O_2^+ + e \rightarrow O + O^* \left(^1D\right) \tag{2}
\]
Odissociative recombination

OI 630.0 nm emission all-sky image obtained at Cachoeira Paulista (2.6°S, 44.4°W), Brazil. Figure 1 shows a sample of a plasma blob image recorded by the OI 630.0 nm imager on April 06, 2000, at 21:36 LT. The center of the image corresponds to the location of the observing site. It should be mentioned that, on the previous night (April 5–6), the ionograms obtained at the two stations show only moderate equatorial spread-F (ESF) with no plasma blobs and plasma bubbles. Figure 2 shows the local time variations in h′F attained on the night of 6–7 April, where it is seen that the F-region bottomside attains high altitudes at about 19:45 LT, with onset of strong ESF on this night. Also, Figure 2 shows another uplifting of the F-layer at Cachoeira Paulista with maximum height (h′F) attained at about 23:00 LT. This is possibly associated with disturbance winds because no such uplifting was observed at Sao Luis. As pointed out by Sastri et al. [2002], at and close to the magnetic equator, vertical plasma drift is essentially due to zonal electric fields and meridional winds are usually ineffective in producing vertical plasma drifts close to the magnetic equator but gain importance with increasing dip angle (I), with maximum effect for I = 45°.

On April 6, during the period 19–23 UT, the Dst was decreasing rapidly at about −54 nT/hour in the main phase of the storm. As pointed out by Wygant et al. [1998] and Basu et al. [2001], when rapid changes of the Dst index occurs in the main phase of a storm, electric fields of magnetospheric origin penetrate to tropical regions. The F-region observations from the ionosondes indicate prompt penetration of electric fields resulting in intensification of ESF and presence of both plasma depletions (bubbles) and plasma enhancements (blobs). Part of the tropical region in the Brazilian sector is adequately covered by the all-sky imaging system, as seen from Figure 1. Three blobs are observed in the OI 630 nm emission image, associated with enhancements in the volume emission rate produced through the O2+ dissociative recombination process. The dashed trace shows the trajectory of the DMSP F15 satellite. The dark region in the upper left corner is due to trees in the view range.

\[
O^+(1^D) \rightarrow O + h\nu(630nm)
\]

It is considered that production of O(1D) by dissociative recombination of NO+ is unimportant [Dalgarno and Walker, 1964]. Therefore, the production of the OI 630.0 nm emission depends on the molecular oxygen density [O2] and the oxygen ion density [O+]'. The oxygen ion density [O+] is approximately equal to the electron density in the F-region. The height of the F-layer peak electron density occurs around 350–400 km, while the molecular oxygen density [O2] increases with decreasing height. Thus, the 630.0 nm emission peak occurs in the bottomside of the F-region around 220–300 km. When the F-layer moves downward, the OI 630.0 nm emission is enhanced, so that the 630 nm emission intensity is a sensitive indicator of F-region vertical motions and plasma density variations. Observations of the OI 630.0 nm nightglow emission intensity using a wide-angle imager with CCD camera (180° field of view) have been carried out at Cachoeira Paulista (22.7°S, 45°W), Brazil, since 1998. The CCD imager consists of a large area (6.45 cm2), high resolution, 1024 \times 1024 back-illuminated array with a pixel depth of 14 bits. The images were binned on-chip down to 512 \times 512 resolution to enhance the signal-to-noise ratio and are recorded at intervals of 7 minutes with 90 seconds exposure time rate. An important characteristic of the imager is the relationship between zenith angle and image size. A zenith angle of approximately 90° encompasses \pm 16° latitude/longitude from the zenith, which is equivalent to a horizontal diameter of approximately 3600 km at 275 km altitude. The F-region parameters presented in this work were obtained from ionosondes operating near the same site at Cachoeira Paulista and also at Sao Luis (2.6°S, 44.4°W),
850 km (DMSP satellite) of the localized plasma density enhanced regions. One of the problems associated with the use of all-sky optics for airglow studies is that the image appears curved and compressed at low elevation angles. This occurs because the lens projects an image onto the CCD such that each pixel subtends an equal angle of the sky. Therefore, in order to calculate the plasma blob and bubble zonal drift velocities as a function of local time and the spatial extent of these structures, we must first transform the images using the unwarped method described by Garcia et al. [1997]. Figure 3 shows an example of 4 unwarped all-sky images obtained by using the technique given by Garcia et al. [1997]. In Figure 3, an area of the processed image, corresponding to 1,742,400 km² at the airglow layer, assuming an emission altitude around 275 km. The dark region in the upper left corner is due to trees in the view range.

3. Results and Discussion

Figure 3 presents a sequence of OI 630 nm all-sky unwarped images obtained from 20:46:52 LT to 22:19:38 LT, on the night of April 6, 2000, showing airglow depletion bands and blobs during the post-sunset period. Unwarped images which correspond to a mapped area of the processed image of 1,742,400 km² in the OI 630 nm airglow layer, assuming an emission altitude around 275 km. The dark region in the upper left corner is due to trees in the view range.

Ionosonde measurements at Cachoeira Paulista also registered a strong increase of plasma density within the blob boundary, as illustrated in Figure 4. Unfortunately, during these observations the ionosonde was set to cover a frequency range of 1–17 MHz, so that the ionosonde was not able to register the enhanced critical frequency of the F-layer (foF2). Figure 4a shows the ionograms obtained at 17:15 LT with the critical frequency of the F-layer close to 15.5 MHz, before the occurrence of the plasma blob. The ionogram in Figure 4b shows an abrupt enhancement of the electron density (and foF2) that characterizes the plasma blob, when foF2 exceeded 17 MHz. Also, the DMSP F15 satellite made nearly simultaneous observations at approximately 850 km altitude (see satellite track in Figure 1).
two-dimensional plasma fluid-type numerical simulations, based on the nonlinear evolution of the collisional Rayleigh-Taylor instability in the nighttime equatorial F-region. These simulations show that, under appropriate condition, the collisional Rayleigh-Taylor instability shows linear growth on the bottomside of the F-region. This causes the formation of plasma density depletions that rise to the topside F-region by polarization $E \times B$ motion. High altitude of the F-peak, small bottomside electron density gradient scale lengths, and large percentage depletions yield large vertical bubble rise velocities. In addition, Ossakow et al. [1979] also showed that the growth of the collisional Rayleigh-Taylor instability exhibited plasma density depletions moving upward, as well as plasma density enhancement regions in the F-region bottomside. Their calculations of the electric potential distribution indicates that the upper part of the bubble is acted on by an induced eastward electric field, causing the bubble to rise with a velocity $(-c/B) \nabla \phi_1 \times \hat{z}$, where $c$ is the speed of light, $\nabla \phi_1$ is the induced or polarization electric field, and $B$ is the ambient geomagnetic field in the $z$ direction. However, the lower portion of the bubble (F-region bottomside) is acted on by an induced westward electric field, causing the localized plasma density enhancements to move downward along with the lower altitude depletions. This type of height variation in the induced electric field results from the solution of the equation for the electric potential [Ossakow et al., 1979, equation (24)], which reflects the dependence on the vertical plasma density gradient that changes from positive to negative around the F-peak. In their simulations, the localized plasma density enhancements are confined to a height region between 275–315 km, when the F-peak height is around 354 km, which is consistent with our observations. However, when the F-peak height was changed to 434 km, the localized plasma density enhancements were confined between 340–380 km altitude. During quiet geomagnetic periods, it is well known that, after sunset, the equatorial F-region rises to high altitudes, attaining sometimes F-layer peak heights (hfP2) and base heights (h'F) around 650 km and 450 km, respectively. However, during the major geomagnetic storm of April 6–7, 2000, it seems that the peak height (hfP2) reached altitudes higher than 850 km (the ionosonde was not able to register the hfP2 due to equatorial spread F events) while h'F reached 650 km (see Figure 2). It must be noticed that during strong uplifting of the F layer that precedes spread-F formation the shape of the vertical plasma density profile becomes very elongated and then quite irregular, so that there is not a well-defined F-peak, which may imply in a quite irregular vertical variation of the induced electric potential. It appears that the lower part of the bubble might have been around 650 km when it started to develop in the equatorial region. One of the manifestations of these depleted magnetic flux tubes is a reduction in the OI 630 nm emission airglow intensity as compared with the surrounding regions. As these depleted flux tubes rise through the F layer in the equatorial region, their bottomside feet migrates poleward, sometimes reaching dip latitudes of over ±20°, and can reach well over 1500 km apex height at the magnetic equator. So, during this major geomagnetic storm, the growth of the collisional Rayleigh-Taylor instability generated plasma density depletions associated with plasma...
density enhancements around 700 km to 900 km, that were detected by the DMSP satellite. The density enhancements can be further reinforced if the background ionosphere moves downward into the region near the equatorial anomaly crests. Our observations from ground-based and satellite measurements have shown the occurrence of localized ionospheric plasma density enhancements, associated with plasma bubbles, similar to the satellite observations reported by Le et al. [2003] and Park et al. [2003]. From the vertical ionospheric plasma drift velocity variations (see h’F variation in Figure 2), it is seen that the blobs appear just after the reversal of the electric field (compare with blobs occurrence in Figure 3), when the drift velocity changes from upward (eastward electric field) to downward (westward electric field) and, consequently, they can be observed through the OI 630.0 nm volume emission rate variations in the F-region bottomside.

4. Conclusions

[1] Ground-based and satellite measurements have shown the occurrence of localized ionospheric plasma density enhancements associated with plasma bubble development during the major geomagnetic storm of April 6–7, 2000.

[2] During this disturbed period, the mean westward speeds calculated from the plasma blob and plasma bubble images, obtained from the OI 630.0 nm all-sky imager, were approximately 30 m/s and 40 m/s, respectively. Normally the plasma drift is eastward during the nighttime.

[3] All-sky imaging showed that the blobs have, typically, east-west and north-south extensions of 110–160 km and 200–460 km, respectively.

[4] The DMSP-15 satellite orbiting at about 850 km altitude detected a blob on this night around 28°S geographic latitude (−17°S magnetic latitude) and 57°W geographic longitude, when crossing the all-sky imager field of view in the Brazilian sector.

[5] It seems that the blobs develop just after the reversal of the electric field, when the drift velocity changes from upward (eastward electric field) to downward (westward electric field). A combination of plasma dynamic processes associated with bubble formation and with the equatorial anomaly fountain effect, near the anomaly crest, may provide the conditions for the formation of plasma blobs in regions adjacent to plasma bubbles.

[10] Acknowledgments. We would like to thank the Ionosphere Group of INPE for kindly providing the ionospheric parameters obtained at Cachoeira Paulista and M. J. Taylor for the use of the OI 630 nm images presented in this work. This work was partially supported by grant 02/12755-1 from the financing agency FAPESP, São Paulo. Analysis of the DMSP data was funded by the U.S. Air Force Office of Scientific Research under Task 2311DSA3.

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