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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

A. A. Pimenta,[1] Y. Sahai,[2] J. A. Bittencourt,[1] and F. J. Rich[3]

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[1] 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 (ΣKp = 38 –/40+; $|\mathrm{Dst}|_{\mathrm{max}}$ = 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 Sao 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.

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1. Introduction

[2] 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 equatorial 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 April6; ΣKp = 38–/40+; $|\mathrm{Dst}|_{\mathrm{max}}$ = 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

[3] 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 O_2^+ 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:

$$O^+ + O_2 \rightarrow O_2^+ + \mathrm{O} \tag{1}$$

$$O_2^+ + e \rightarrow O + O^*\left({}^1D\right) \tag{2}$$

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[1] Instituto Nacional de Pesquisas Espaciais, San José dos Campos, Brazil.

[2] Instituto de Pesquisa e Desenvolvimento, Universidade do Vale do Paraíba, San José dos Campos, Brazil.

[3] Space Vehicles Directorate, Air Force Research Laboratory, Hanscom Air Force Base, Massachusetts, USA.

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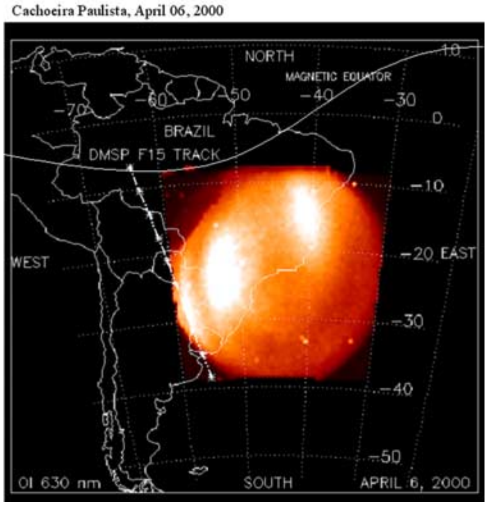

Figure 1. OI 630.0 nm emission all-sky image obtained at Cachoeira Paulista on April 06, 2000, at 21:36 LT, with its respective field of view (considering an emission height around 275 km). Three blobs (bright regions) are seen in the image, which are associated with intensity enhancements produced through 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.

$$O^*(^1D) \rightarrow O + h\nu(630nm) \tag{3}$$

It is considered that production of O(^{1}D) 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 [O$_2$] 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 [O$_2$] 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 OI630.0 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 cm^2), high resolution, 1024 × 1024 back-illuminated array with a pixel depth of 14 bits. The images were binned on-chip down to 512 × 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 ±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 São Luis (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 obtained 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 passing over one blob, indicating that the same blob is observed by the OI 630 nm image and detected by the orbiting DMSP satellite. This shows the enormous altitude extent (from about 275 km (OI 630.0 nm emission) to

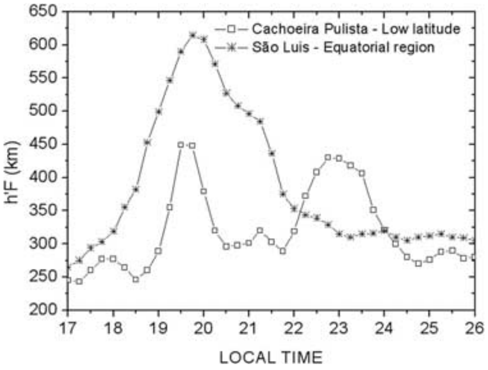

Figure 2. Behavior of the ionospheric parameter h'F, in Cachoeira Paulista and São Luis during the major geomagnetic storm of April 6–7, 2000 (ΣKp = 38−/40+; $|\mathrm{Dst}|_{\mathrm{max}}$ = 288 nT). From approximately 19.5 LT to 22:00 LT, at Cachoeira Paulista, the drift velocity changes from upward (eastward electric field) to downward (westward electric field) during the plasma bubble and blob occurrences.

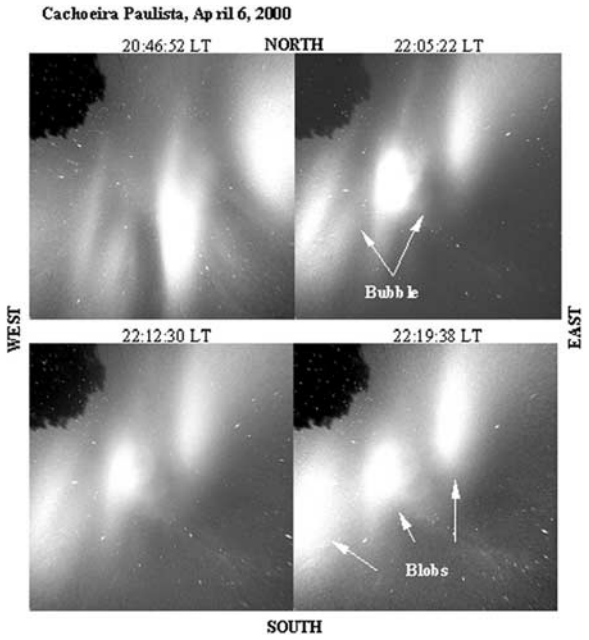

Figure 3. Sequence of OI 630 nm all-sky images obtained from 20:46:52 LT to 22:19:38 LT, on the night of April 6, 2000, showing airglow depletion bands and blobs during the post-sunset period. Unwarped images which correspond to a mapped area of the processed image of 1,742,400 km^2 in the OI 630 nm 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.

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 km^2 at the airglow layer, is mapped assuming an emission altitude of 275 km. Full details of the ground-based all-sky imaging system used in this study was presented earlier [*Pimenta et al.*, 2001]. 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).

3. Results and Discussion

[4] Figure 3 presents a sequence of OI 630 nm all-sky unwarped images obtained from 20:46:57 LT to 22:19:15 LT, showing depletion bands and the associated plasma blobs. In this image sequence, 3 blobs can be clearly seen near the density depletion bands, with one of them near the zenith of Cachoeira Paulista at 20:46:52 LT (also registered by the ionogram in Figure 4b). The nearly continuous sequence of images makes it possible to optically track the regions of plasma density enhancements and depletions. To obtain an estimate of zonal drift velocities from the imaging data, we first scan the optical images from west to east to obtain a cross-section of the brightness and depletion patterns for each plasma blob and plasma bubble. Then, these cross-sectional scans are subjected to a correlation analysis leading to the best fit spatial shifts required to match the time between images. A succession of such space and time shifts leads to a zonal velocity versus local time relation for the blobs and bubbles. The mean westward speeds of the plasma blobs and plasma bubble were, approximately, 30 m/s and 40 m/s, respectively. Furthermore, the blobs showed, typically, east-west and north-south extensions of 110–160 km and of 200–450 km,

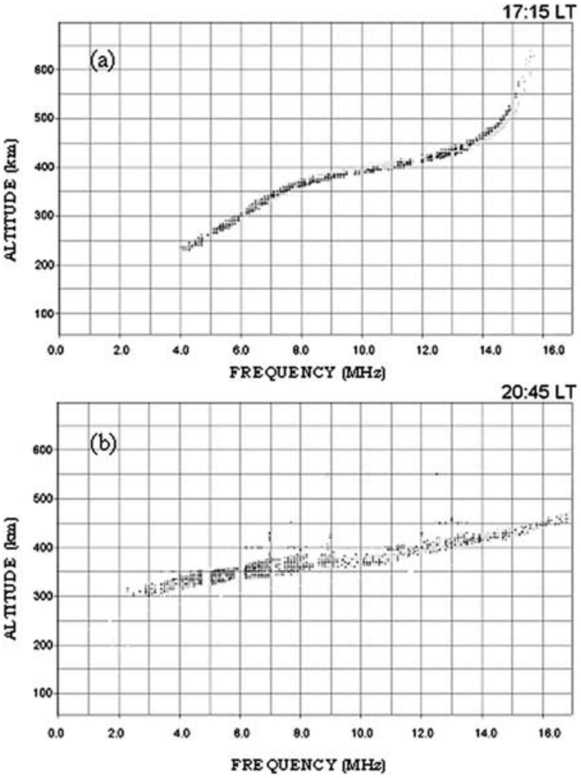

Figure 4. Ionograms obtained at Cachoeira Paulista on April 06, 2000. (a) Background ionosphere near sunset before the plasma blob event. (b) During the plasma blob occurrence. At this time, the F-layer critical frequency (foF2) and height (hmF2) could not be measured, as foF2 exceeded 17 MHz (upper limit of the ionosonde operating frequency).

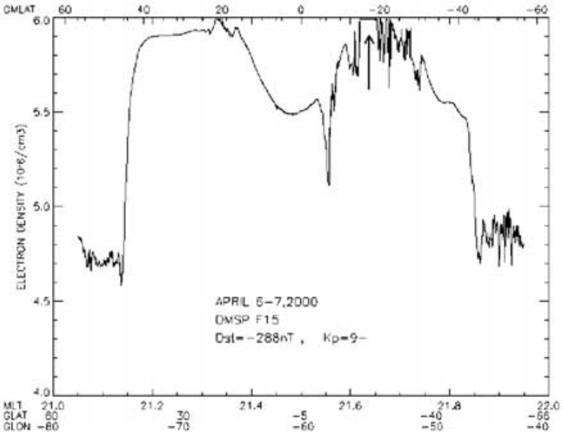

Figure 5. Electron density observed by the DMSP F15 satellite in the nightside ionosphere on April 06, 2000. The vertical black arrow corresponds to the latitude/longitude coordinates of the electron density enhancement or blob measured by the probes on the satellite.

respectively. The thermal plasma monitor on the DMSP F15 satellite made nearly simultaneous observations of the nightside tropical region at 850 km altitude during this night. Figure 5 shows the ion density observed by the total ion trap experiment (SSIES/SM) on the DMSP F15 satellite at time resolution of 1 sample per second. In Figure 5, one of the localized density enhancements is present at approximately 28°S geographic latitude (−17°S magnetic latitude) and 57°W geographic longitude, as indicated by a black arrow, which coincides with the ground-based airglow observation (see Figure 1). At this time, the ion density at 850 km altitude exceeded the upper limit of the range of the ion trap. Note that the density enhancements, observed on the DMSP (Figure 5) and those observed by the all-sky image (Figure 1) are seen at different altitudes (850 km and 275 km, respectively). *Watanabe and Oya* [1986] have presented a detailed study of plasma bubbles and blobs using observations obtained from the Hinotori satellite, orbiting at an altitude of about 650 km, during both geomagnetic quiet and disturbed periods. They have pointed out that occurrence of the plasma blobs has a complementary nature with that of the plasma bubbles. Therefore, it appears that the simultaneous observations of plasma blob at DMSP altitude (about 850 km; topside) and OI 630 nm imaging (about 275 km; bottomside) (Figure 1) are possibly associated with the same ionospheric process. In a previous work, *Le et al.* [2003] suggested that during the upward motion of the plasma bubble, the field-aligned plasma pressure gradient at the poleward edges of the depletions produces an equatorward force that drives the plasma particles towards the equator. Therefore, the density depletions cannot extend to higher latitudes, and remain limited to the region of the anomaly crests. The polarization electric field that is generated within the bubble can be mapped along the magnetic field lines to higher latitudes, beyond the limited density depletion structure. In this way, the polarization electric field within the flux tube moves the high-density plasma, near the anomaly crests, upward, so that density increments occur just above the flux tube. On the other hand, *Ossakow et al.* [1979] performed four different 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 $\mathbf{E} \times \mathbf{B}$ 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 $(-c/B)\nabla\ \phi_1\ x\ \vec{z}$, 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 354km, 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 (hpF2) 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 (hpF2) reached altitudes higher than 850 km (the ionosonde was not able to register the hpF2 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

[5] 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.

[6] 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.

[7] 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.

[8] 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.

[9] 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.

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J. A. Bittencourt and A. A. Pimenta, Instituto Nacional de Pesquisas Espaciais, CEP 12227-010, San José dos Campos, SP, Brazil. (pimenta@laser.inpe.br)

F. J. Rich, Space Vehicles Directorate, Air Force Research Laboratory, Hanscom Air Force Base, MA 01731-3010, USA.

Y. Sahai, Instituto de Pesquisa e Desenvolvimento, Universidade do Vale do Paraíba, Univap, CEP 12244-000, San José dos Campos, SP, Brazil.