IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received April 17, 2021, accepted May 4, 2021, date of publication May 11, 2021, date of current version May 20, 2021.

Digital Object Identifier 10.1109/ACCESS.2021.3079144

A Study of the Topside Plasma Blob and Adjacent Bubble Near Sunrise in Low-Latitude Ionosphere During the Main Phase of August 2003 Storm

YING XIONG AND LINGSEN GENG
College of Electronic and Information Engineering, South-Central University for Nationalities, Wuhan 430074, China
Corresponding author: Ying Xiong (yxiong@mail.scuec.edu.cn)

This work was supported in part by the Fundamental Research Funds for the Central Universities under Grant CZY18004, and in part by the China Scholarship Council.

ABSTRACT In this paper, a plasma blob and an adjacent plasma bubble in low-latitude region at 245°E region near sunrise recorded by the Defense Meteorological Satellite Program (DMSP) F13 satellite around 840 km on 18 August 2003 were presented. On the previous local night, the blob and adjacent bubble at 265°E region were also detected by the first satellite of the Republic of China (ROCSAT-1) at about 600 km. Total Electron Content (TEC) derived from ground-global positioning system (GPS) measurements also showed both the evident enhancements and the decreases adjacent to the enhancements, at one low-latitude station near 265°E region. Based on the characteristics of the blob, we conclude that the blob and adjacent bubble near sunrise recorded by DMSP were the remnant of the blob and bubble formed on the previous night, which were detected by ROCSAT-1 satellite and ground-based TEC variations. The long duration of the blob and bubble during storm main phase may be related to the prompt penetration electric field.

INDEX TERMS Plasma blob, plasma bubble, low-latitude ionosphere, daytime, storm.

I. INTRODUCTION

There are the occurrences of F-region irregularities at the nighttime in the equatorial and low-latitude ionosphere, manifesting as plasma density depletions and plasma density enhancements which also referred as plasma bubbles and plasma blobs, respectively [1], [2]. These irregularities can cause the ionospheric scintillation, affecting the trans-ionospheric radio waves from various navigation and communication systems.

It is well known that the equatorial plasma bubbles mainly develop after sunset and persist into nighttime, and decay before sunrise, sometimes occur during the daytime under both geomagnetically disturbed and quiet conditions [3], [4]. During geomagnetic disturbed periods, many case studies of dayside plasma bubble have been studied. For instance, Chau and Woodman presented the occurrence of plasma bubbles during the storm recovery phase at Jicamarca [5]. Li *et al.* [6] reported the existence of ionospheric irregularities in late morning sector at low to mid-latitudes during magnetically disturbed periods. Huang *et al.* [7] reported the detections of dayside plasma bubbles after 0900 LT from Communication/Navigation Outage Forecasting System (C/NOFS) satellite under moderate magnetic condition. Zakharenkova *et al.* [8] presented observations of topside plasma bubbles around local sunrise (0500-0800 LT) in the Pacific sector during the storm recovery phase, from the measurements between global positioning system (GPS) and low-Earth-orbit satellites. Tulasi Ram *et al.* [9] reported the occurrence of field-aligned irregularities (FAIs) near sunrise during a geomagnetic storm, which were thought as the freshly generated irregularities near local sunrise, and the FAIs persisted into the local morning, with a duration of more than 90 minutes. Recently, Jiang *et al.* [10] and Luo *et al.* [11] presented a case of daytime F-region irregularity near local sunrise during a moderate geomagnetic storm, respectively.

Fewer case studies about the daytime plasma bubbles under geomagnetic quiet conditions have also been reported. For instance, Woodman *et al.* reported the occurrence of post-noon (1400-1600 LT) plasma bubbles at Jicamarca based on digisonde observations during geomagnetically quiet periods [12]. Shume *et al.* presented day-time (around 1300 LT) equatorial density depletions from radar, ground-based GPS and ionosonde observations [13]. Park *et al.* reported a

The associate editor coordinating the review of this manuscript and approving it for publication was Venkata Ratnam Devanaboyina.

detection of mid-latitude plasma depletion during daytime (magnetic latitudes: 25° ∼ 30°) from the Swarm and Gravity Recovery and Climate Experiment (GRACE) satellites [14], which later has been confirmed to be related to the rocket exhaust [15]. Chen *et al.* presented the detections of two noon FAIs from coherent scatter phased array radar in Hainan [16].

Compared to the investigations of dayside plasma bubbles or depletions, the occurrence of dayside plasma blobs was rarely seen in the previous reports. Based on statistical studies, Watanabe and Oya [4] indicated that the blob occurrence rate may be not zero at some daytimes (see their Fig. 6), without discussing the possible mechanism. In this paper, we present a case study of a plasma blob and adjacent plasma bubble near sunrise at 245°E region detected by Defense Meteorological Satellite Program (DMSP) F13 satellite. The observations near 265°E sector from the first satellite of the Republic of China (ROCSAT-1), GRACE and Challenging Mini-satellite Payload (CHAMP), and Total Electron Content (TEC) derived from one ground-based GPS station at Puerto Ayora, Ecuador (−0.743°N, 269.69°E; Magnetic latitude: 9.71°N) are also presented during the previous nighttime, to investigate the possible mechanism leading to the occurrence of the plasma blob and bubble near sunrise.

II. INSTRUMENTS AND DATA

The DMSP satellites fly in a near-circular orbit, which at about 840 km, with the inclination of about 98.8°-98.9° and the period of ∼102 min (http://dmsp.ngdc.noaa.gov). The data from DMSP satellites F13 is used in this study.

The ROCSAT-1 was placed in a circular orbit, with an altitude of about 600 km (inclination: 35°). The Ionospheric and Plasma Electrodynamics Instrument (IPEI) onboard ROCSAT-1 was used to continuously record ion composition, density and drifts in the low- and mid-latitude ionosphere [17]. To study the density irregularity, the linearly fitted density was chosen as the background density [18].

The Planar Langmuir Probe (PLP) on board the CHAMP satellite, which flied at an altitude of about 400 km and an inclination of 87.3°, measure the in-situ electron density and temperature per 15 seconds [19]. The GRACE mission, comprising two spacecraft on the same orbital track, in a near-circular, polar-orbit (inclination:89°), with an initial altitude of about 490 km [20]. From the K-band ranging (KBR) system between the GRACE two spacecraft, the electron density at the orbital altitude can be derived [21], which has been validated by comparing with radars of European Incoherent Scatter radar (EISCAT), Millstone hill and Arecibo [22], and the more details of the electron density retrieval is recommended to Xiong *et al.* [21].

III. GEOPHYSICAL CONDITIONS

Figure 1 presents the variations of *Dst* index, solar wind speed (*Vsw*), the south-northern component of Interplanetary Magnetic Field (IMF) B_Z, and the Interplanetary Electric Field (IEF) E_y during 16-20 August, 2003.

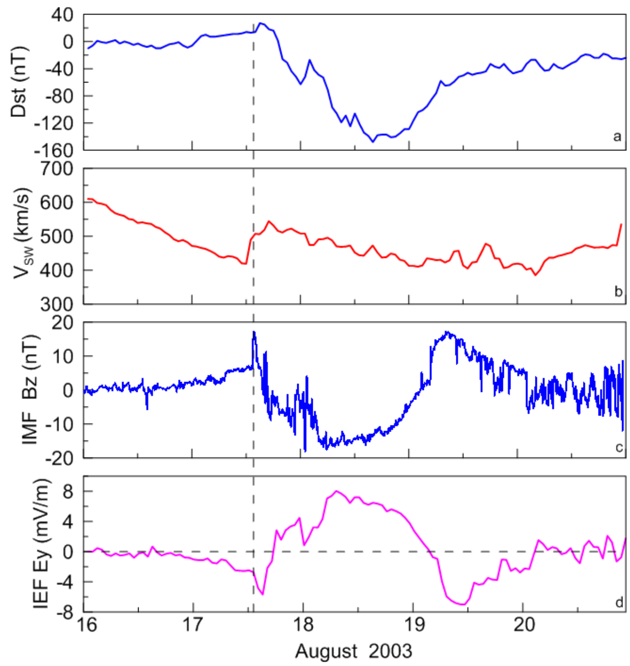

FIGURE 1. Variations of the Dst index (a), solar wind speed VSW (b), Interplanetary Magnetic Field (IMF) Bz component (c), and Interplanetary Electric Field Ey (d) during 16-20 August, 2003.

The 17-20 August 2003 storm started at 1421 UT on 17 August, the *Dst* index dropped to a minimum (−148nT) at about 1600 UT on 18 August. The B_Z component was mainly southward from the main phase until about 0200 UT on 19 August. *Bz* had sharp variations at 1636 UT of 17 August and 0130 UT of 18 August. After the storm occurred, E_y was westward, and it became eastward around 1800 UT on 17 August, and reached a maximum, with a value of about 8 mV/m, at 0800 UT of 18 August.

From Figure 1, it can be noted that the blob was recorded by the satellites during the storm main phase. During 0500-2000 UT of 18 August, E_y was eastward and reached a maximum at 0800 UT. The IEF could partially penetrate into the ionosphere as prompt penetration electric field (PPEF), and the efficiency of penetration is about ∼5 to 10% [23]. The ionospheric electric field responds to the IEF immediately.

IV. OBSERVATIONS

A. ION DENSITY OBSERVED BY DMSP

Figure 2 shows the ion density, velocities, composition, and temperature from DMSP F13 satellite in 245°E longitude region during 1351-1355 Universal Time (UT) on 18 August 2003, respectively. V_x is the component parallelled with the field line, V_y and V_z are the components perpendicular to the field line, which positive directions are northward, upward and eastward, respectively. At the bottom of figure, magnetic latitude (MLAT), geographic longitude (GLON), UT, LT are also displayed.

As shown in Figure 2, the density enhancement (region b) was about 56.3% (maximum density was about

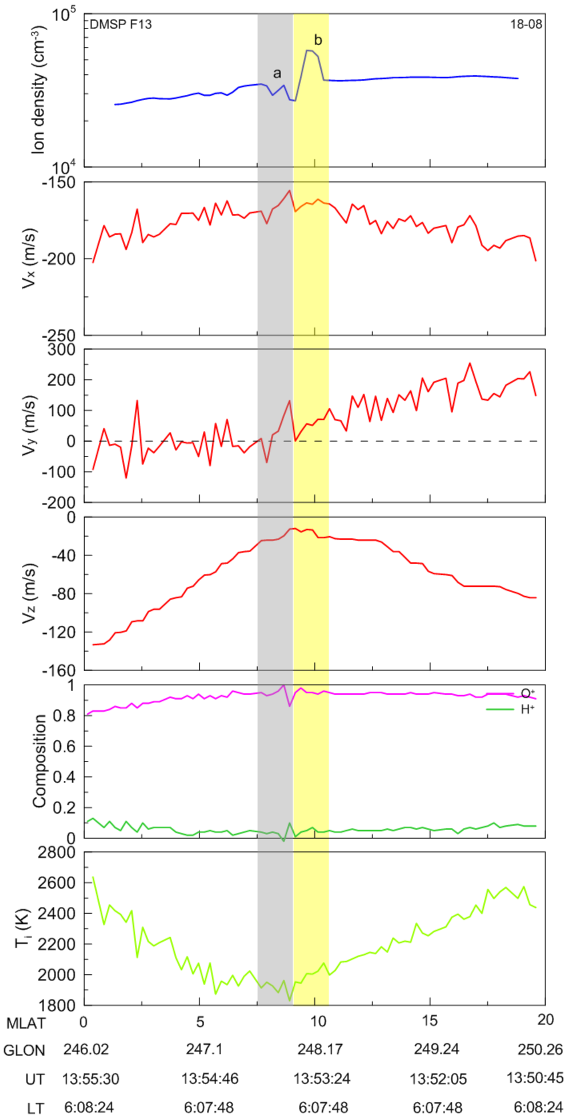

FIGURE 2. Variations of the ion density, drift, composition and temperature along the DMSP F13 trajectories at 245°E longitude region during 1351-1355 UT on 18 August 2003. V_X, V_Y and V_Z are parallel, vertical and zonal, respectively. Satellite altitude was about 840.8 km.

5.76×10^4 cm^{-3}) at 9.65°N in 248°E longitude around 1353 UT (0607 LT) according to the background plasma density, which was about 3.68×10^4 cm^{-3}.

The blob located at lower latitude than it usually stays, around ±20° off the dip equator [2]. The blob moved southward to the equator, with a velocity of about −170 m/s. The westward velocity was small, with the absolute value of less than 20 m/s, and the vertical velocity was around 50 m/s.

In addition, plasma depletion adjacent to the plasma enhancement was also detected, noted as region a by grey rectangle (region a). The density was about 2.94×10^4 cm^{-3} at 8.17°N, while the background density was about 3.4×10^4 cm^{-3}. The depletion was about 13.5%.

It should be noticed that the ion drifts inside the plasma blob and bubble did not show fluctuations, which means that the blob and bubble can be taken as dead plasma irregularities [23].

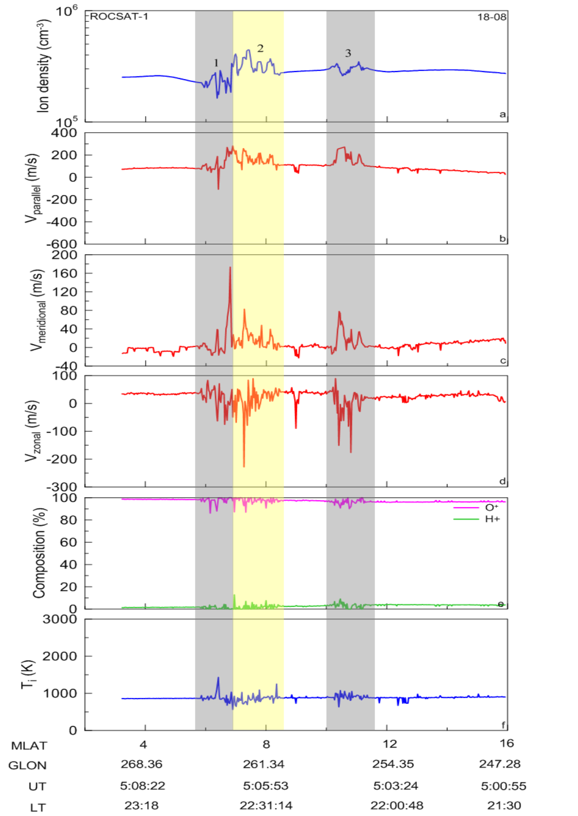

FIGURE 3. Variations of the ion density, drift, composition and temperature along the ROCSAT-1 trajectories at 265°E longitude region during 0500-0508 UT on 18 August 2003. $V_{parallel}$, $V_{meridional}$ and V_{zonal} are parallel, vertical, and zonal, respectively. Satellite altitude was about 590 km.

B. ION DENSITY OBSERVED BY ROCSAT-1

Figure 3 presents the variations of ion density, velocities, composition, and temperature along the ROCSAT-1 trajectories in 265°E longitude region during 0500-0508 UT on 18 August 2003. $V_{parallel}$ is the component parallelled with the field lines, $V_{meridional}$ and V_{zonal} are the two perpendicular components, which positive directions are northward, upward and eastward, respectively. Magnetic latitude, geographic longitude, UT, LT are also displayed in the figure.

From Figure 3, it can be seen that a plasma bubble (region 1) and plasma blobs (region 2), which were adjacent, were detected, respectively. In region 2, the ion density in 263.1°E around 6.98°N at 0506 UT (2239 LT of the previous day) was about 4.08×10^5 cm^{-3}. The density in 262.4°E around 7.41°N at 0506 UT (2236 LT) was about 4.45×10^5 cm^{-3}. The density in 261.1°E around 8.13°N at 0505 UT (2230 LT) was about 3.7×10^5 cm^{-3}. The background density was about 2.7×10^5 cm^{-3}. The enhancements were about 51.1%, 64.8% and 37%, respectively.

In region 1, the density in 264.2°E around 6.37°N at 0507 UT (2242 LT) was about 1.64×10^5 cm^{-3}.

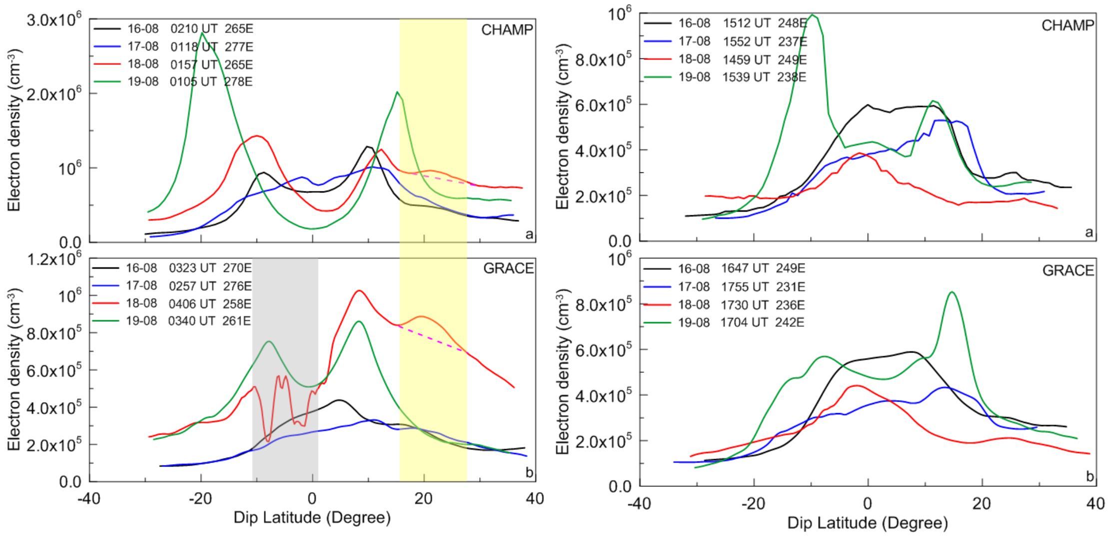

FIGURE 4. Electron density from CHAMP (a) and GRACE (b) in 265°E longitude sector (left panel) and in 245°E longitude region (right panel) at different times during August 16-19, 2003, respectively.

The background density was about 2.49×10^5 cm^{-3}. The depletion was about 34.1%. The magnitude of depletion was larger than the bubble observed by DMSP shown in Figure 2.

In region 3, the density in 256.9°E around 10.52°N at 0504 UT (2212 LT) was about 2.6×10^5 cm^{-3}. The background density was about 2.97×10^5 cm^{-3}. The depletion was about 12.5%.

The blobs shown in Figure 3 moved westward, upward, and poleward along the field line. The background particles moved eastward. The velocity of westward motion was usually about 40-50 m/s, some could exceed 80 m/s, and upward velocity was about 80-160 m/s. The parallel velocity was about 200 m/s. The bubble also moved westward, with an average velocity of about −36 m/s, which was smaller than that of the blob.

C. ELECTRON DENSITIES FROM CHAMP AND GRACE

The variations of electron density in 265°E longitude sector (left panel) around 0200-0400 UT and 240°E longitude sector (right panel) around 1500-1800 UT along the CHAMP and GRACE trajectories were represented in Figure 4, respectively.

It can be seen from Figure 3 that the density enhancements were also recorded in 260°E longitude region around 20°N by CHAMP and GRACE on 18 August, respectively.

At GRACE altitude, the background density was about 8.4×10^5cm^{-3} around 0406 UT (2112 LT) at 15.17°N, and the density was about 8.86×10^5cm^{-3} at 19.4°N. The enhancement was about 5.6%.

At CHAMP altitude, the background density was about 9.29×10^5 cm^{-3} around 0157 UT (1940 LT) at 18.15°N, and the density was about 9.65×10^5cm^{-3} at 21.07°N. The enhancement was about 3.9%.

It should be noticed that the magnitude of density enhancements recorded by CHAMP and GRACE were remarkable smaller than that by ROCSAT-1. It may because the observations from CHAMP and GRACE were at earlier time and lower altitudes.

Moreover, plasma bubbles were detected at GRACE altitude in equatorial region, which were also observed by ROCSAT-1 shown in Figure 3. The density was about 2.15×10^5 cm^{-3} at −7.88°N, while the background density was about 5.09×10^5cm^{-3}. The density was about 2.15×10^5 cm^{-3} at −1.42°N, while the background density was about 5.67×10^5cm^{-3}. The depletions were about 57.8% and 47.4%, respectively.

D. TEC OBSERVATIONS AT A LOW-LATITUDE STATION

Figure 5 displays the UT variations of TEC derived from ground-GPS observations at Puerto Ayora, Ecuador during 16-19 August, 2003. The green lines represent the vertical TEC derived from different GPS pseudo random noise (PRN) satellites (the elevations larger than 20° were chosen), the solid red lines represent the fitting TEC values.

From Figure 5, it can be seen that TEC enhancements were detected during 0300-0800 UT on 18 August, 2003. Furthermore, Figure 6 shows the variations of vertical TEC with UT for satellite PRN 8 (left panel) and PRN 27 (right panel) during 0100-0800 UT on 18 August 2003, respectively. The satellite elevation, geographic longitude and latitude of the ionospheric pierce point (IPP), assuming a thin ionospheric shell at 350 km height, are also showed in the figure.

For PRN 8, it can be seen that a TEC decrease (region a) was adjacent to a TEC enhancement (region b), which was similar with the observations from ROCSAT-1 shown in Figure 2. During 0500-0700 UT, TEC also showed a slight increase(region c).

The geographic latitude of IPP at 0353 UT (region a) was about 0.59°N (Magnetic latitude: 11°N), and at 0414 UT (region b) was about −0.04°N (Magnetic latitude: 10.4°N), respectively.

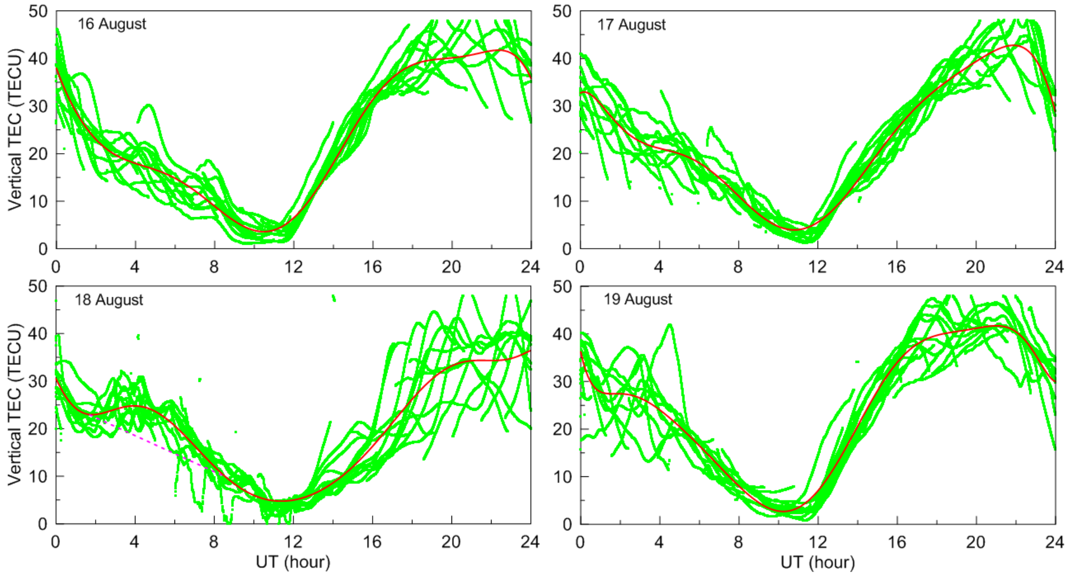

FIGURE 5. UT variations of vertical TEC derived from GPS at Puerto Ayora, Ecuador during 16-19 August, 2003. The green lines represent vertical TEC derived from different GPS satellites (the elevations larger than 20° were chosen), the solid red line represents the fitting TEC values.

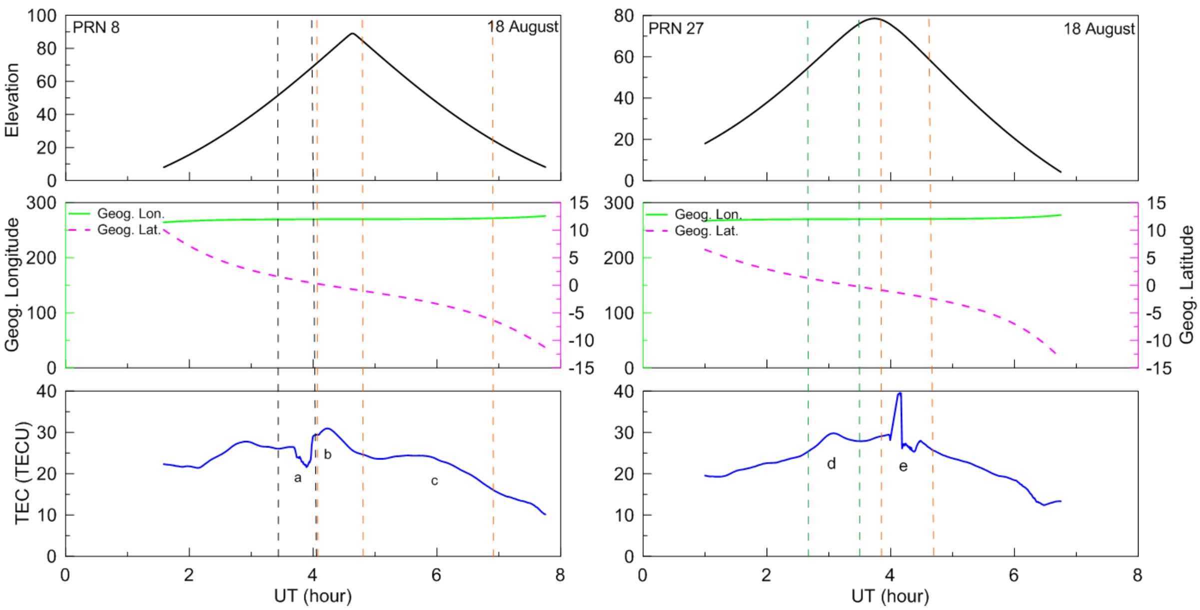

FIGURE 6. Variations of the satellite elevation (top), geographic longitude and latitude of the IPP (middle), and vertical TEC (bottom) for satellite PRN 8 (left panel) and PRN 27 (right panel) during 0100-0800 UT on 18 August 2003, respectively.

For PRN 27, remarkable TEC enhancements were detected. Especially in region e, TEC increased to about 39.5 TECU, which means that the enhancement was about 36.2%. The geographic latitudes of IPP at 0304 UT (region d) and at 0410 UT (region e) were about 0.52°N (Magnetic latitude: 10.9°N) and −1.43°N (Magnetic latitude: 9°N), respectively.

V. DISCUSSION

To study the origin of plasma blob near sunrise recorded by DMSP, Figure 7 displays a low-latitude regional map at 230-280°E longitude sector, including the trajectories of DMSP, ROCSAT-1, GRACE, CHAMP satellites, the location of ground-based GPS station at Puerto Ayora, Ecuador, and the IPP tracks of the GPS PRN 8 and PRN 27, respectively. The red short lines and green short lines besides the satellite tracks represent the density enhancements and density depletions encountered by the satellites, respectively. The grey solid line represents the magnetic equator, the dashed grey arrows represent the motion of plasma blob. The times of the event recorded by the satellites are also marked in the figure.

TEC enhancement in equatorial anomaly region may be linked with the plasma density enhancements, and TEC decrease was related to plasma depletions in low-latitude

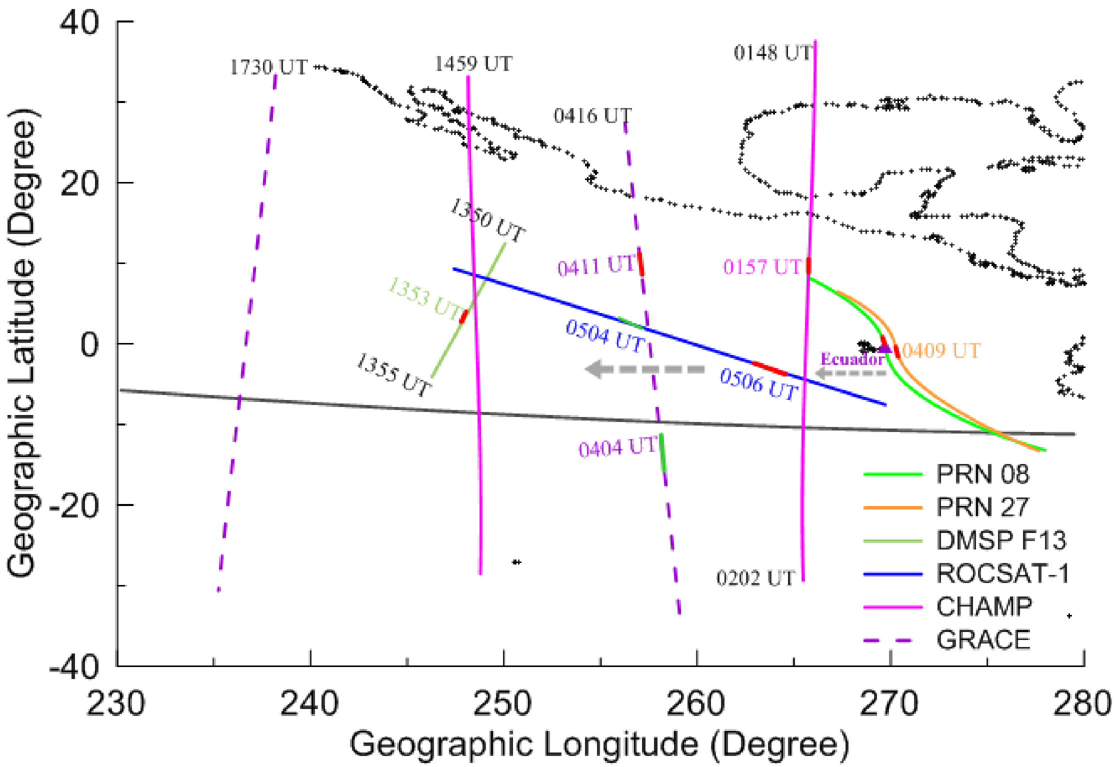

FIGURE 7. The regional map at 230-280°E longitude sector including the trajectories of DMSP, ROCSAT-1, GRACE, CHAMP satellites, the location of ground-based GPS station at Puerto Ayora, Ecuador, and also the IPP tracks of GPS PRN8 and PRN 27. The red short lines represent the density enhancements encountered by the satellites, the green short lines represent the density depletions recorded by the satellites. The dashed arrows represent the motion of plasma blob.

ionosphere [24]. In Figure 5 and Figure 6, the TEC variations on 18 August showed remarkable enhancements and a decrease adjacent to the enhancement during 0300-0800 UT, which were consistent with the observations from ROCSAT-1, the results indicated that plasma blob and an adjacent plasma bubble occurred on 18 August (local night of 17 August), causing the TEC fluctuations.

From Figure 7, it can be seen that the TEC fluctuations occurred about 1 hour earlier than the observations from ROCSAT-1 and located in eastward direction of satellite measurements. Assuming the plasma blob recorded by ROCSAT-1 originated from the TEC enhancement detected by ground-based GPS receiver, the blob moved westward about 6° in longitude during 1 hour, which means that the westward velocity of the blob was about 167 m/s. The drift velocity is reasonable, and with the evolution of the bubbles, the bubble velocity would increase at the early stage and decrease at the late stage [25]. Thus, it means that the observations detected by ROCSAT-1 can be correlated with the TEC fluctuations by ground-based receiver, and the blob and bubble occurred before 0400 UT, and moved westward.

Moreover, it should be noted that the plasma density enhancements recorded by GRACE and CHAMP, shown in Figure 4, may be different from the density enhancements detected by ROCSAT-1 and TEC fluctuations by ground-based receiver. These density fluctuations detected by GRACE and CHAMP around 20°N were similar to the third ionization peak [26], [27], but they have some different features. The characteristics of the density fluctuations are out of the scope of this study, which need to be further studied.

As shown in Figure 3, the blob detected by ROCSAT-1 on local pre-midnight of 17 August moved westward, upward, and poleward along the field line. The westward particle velocities inside the blob were about 40-50 m/s, some could exceed about 80 m/s, with the average particle velocity inside the blob of about 52.5 m/s, which was smaller than that at earlier time, and upward velocity was about 80-160 m/s.

Assuming the westward motion of the blob with the average velocity of about 52 m/s, after about 8 hours later, the blob moved about 1500 km in zonal direction (westward), referring as about 15° in longitudes. It means that the blob moved from 263°E to about 248°E region, where was detected by DMSP. The upward motion of the blob would be different from that in zonal direction. During the periods of motion, the blob moved about 250 km from ROCSAT-1 altitude to DMSP altitude in vertical direction, which means that the upward velocity of particles inside the blob would decrease eventually with the motion of blob. As shown in Figure 2 and Figure 3, the upward velocity of blob detected by DMSP was lower than that by ROCSAT-1. The blobs observed by ROCSAT-1 were located at 6.98°N-7.41°N regions, with the poleward movements. After several hours, the blob moved

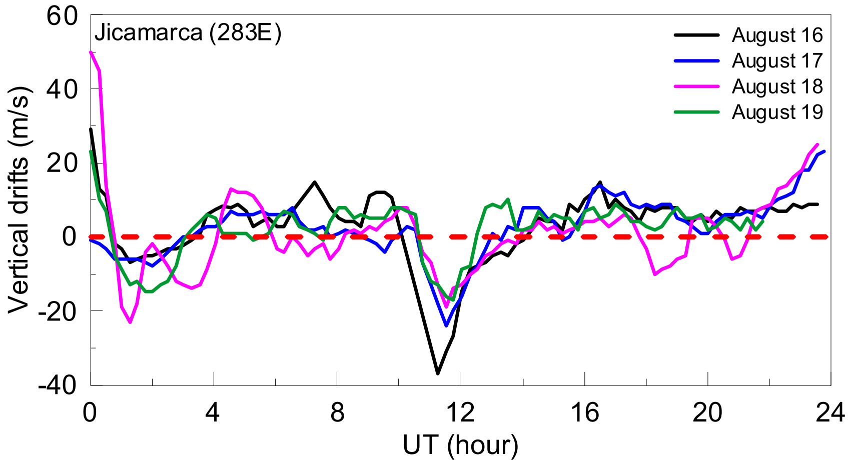

FIGURE 8. Vertical plasma drift derived from ionosonde at Jicamarca(−12°N, 283.2°E) during 16-19 August, 2003.

along the field lines to higher latitude staying at about 9.65°N. The magnitude of density enhancement and depletion near sunrise recorded by DMSP were less than that observed on the previous night by ROCSAT-1, respectively.

Thus, the blob detected by DMSP may be related to the blob recorded by ROCSAT-1, which also caused the TEC enhancements at earlier time.

There is still one question remained. Why could the blob and the adjacent bubble exist for a long duration? To study the reason of long duration of the blob and bubble, Figure 8 displays the vertical drift derived from ionosonde observations at Jicamarca (Geographic coordinate: −12°N, 283.2°E).

On 18 August, the plasma vertical drifts were downward (westward electric field) during 0100-0400 UT, and turned to upward (eastward electric field) during 0400-0600 UT. The downward drifts were smaller on 18 August than that on 16-17 August, and the upward drifts were larger than that on other days. The variations of vertical drift on 18 August may be related to the PPEF. As displayed in Figure 1, IEF E_y was eastward and reached a maximum at 0800 UT, the amplitude was 8 mV/m.

From 2200 UT of 17 August to 0100 UT of 18 August, it can be seen that the upward plasma drifts were larger than that on 16 August. The enhancements of vertical drift may be related to the PPEF and promote the generation of the plasma bubbles, detected by GRACE and ROCSAT-1 shown in Figure 3 and Figure 4, respectively. During 0600-1400 UT of 18 August, when the zonal electric field usually is westward, the absolute values of downward drifts were smaller than that on 16-17 August.

Moreover, on 18 August, as shown in Figure 4, the Equatorial Ionization Anomaly (EIA) was not well developed at both CHAMP altitude and GRACE altitude around 1500 UT and 1730 UT in 245°E region. The densities at the equator were smaller than that on other days. It means that the background electric field on 18 August was small, which would uplift the density from the bottom to the topside ionosphere.

Thus, the background westward electric field during 0600-1400 UT of 18 August was affected by the PPEF, and the smaller background westward electric field was benefit for the duration of the blobs and the adjacent bubble, which would cause the higher F-layer and lead the blob and bubble to move into higher ionosphere over 800 km.

As indicated by Park et al [14] and Luo *et al.* [11], favorable conditions for the existence of daytime plasma bubbles include: (a) at early time (e.g. local morning), (b) at lower-latitude region than nighttime bubbles, (c) at higher altitude, and (d) during geomagnetic disturbed periods. Li *et al.* [6] also indicated that the eastward disturbance dynamo electric field may support the formation/persistence of dayside bubbles during the storms. In addition, as pointed out by Huang *et al.* [7], the high altitude of plasma irregularities is an important factor for their long-duration and existence at daytime.

As described above, the occurrence of plasma blob and adjacent plasma bubble near sunrise satisfied the conditions for the occurrence of dayside bubbles, occurring at a high altitude and during the disturbed periods. Similar to the existence of dayside plasma bubbles, the plasma blob formed on the night may also have a long duration and occur at the early morning, becoming a remnant of the nightside blob, under the effects of small zonal electric field in background ionosphere.

It can be concluded that the blob and the adjacent bubble near sunrise observed by DMSP F13 would be the remnant of the blob and bubble occurred on the previous night, which were detected by ROCSAT-1 on local pre-midnight of 17 August. The long duration of the blob and bubble during main phase of the storm may be related to the prompt penetration electric field, which affects the westward electric field in background ionosphere and drives the blob and bubble to move upward to a high altitude of >800 km, where can be protected from active photo-ionization process [7].

Furthermore, the factors leading to the development and occurrence of plasma blob in low-latitude ionosphere have not been well understood. Previous investigations proposed that the occurrence of blob may be associated with the polarized electric field [29], Travelling Ionospheric Disturbances [30], neutral wind [31] and so on. Unfortunately, in 240-280°E longitudinal (America) regions, we cannot find more ground-based observational evidences to study the factors leading to the occurrence of plasma blob. As presented before, the blobs detected by multi-instruments were close to the bubbles during nighttime, and the blob was adjacent to the bubble near sunrise, which were consistent with the mechanism proposed by Huang *et al.* [29]. Thus, we can conclude the occurrence of blob was related to the evolution of plasma bubbles due to the polarization electric field.

There is another question should be noted. When and why do the blobs stop the upward movement and disappear. Krall *et al.* indicated that the bubbles would stop moving upward when the upward E $\times$ B drifts of the particles at the upper edge of bubble become 0 and inside the upper edge of bubble, the flux-tube-integrated ion mass density is identical with the adjacent background density [32]. Do the blobs stop moving and disappear under similar conditions with that of bubbles? It needs to be further studied by more observations and simulations.

VI. CONCLUSION

In this paper, a plasma blob and an adjacent plasma bubble in low-latitude region near sunrise detected by DMSP F13 during the main phase of 17-18 August 2003 storm were reported, and the source of the occurrence of the daytime blob and bubble was investigated from observations by CHAMP, GRACE, ROCSAT-1, and GPS TEC. At early morning of 18 August (around 1353 UT, 0607 LT), a blob at 245°E longitude region was recorded at about 840 km around 9.65°N, locating at a lower magnetic latitude than the blobs usually stay, around ±20° off the dip equator [2], [4]. A plasma bubble adjacent to the blob was also recorded around 8.17°N by DMSP. On the previous local pre-midnight, plasma blob and plasma bubble adjacent to the blob at 265°E longitude region were also observed by ROCSAT-1 at 0506 UT (2231 LT). At 265°E longitude region, remarkable TEC enhancement and TEC decrease adjacent to the enhancement were also detected around 0409 UT.

Based on the characteristic of the blob from multi-satellites, the blob and the adjacent bubble near sunrise recorded by DMSP can be thought as the remnant of the blob and bubble formed on the previous night, which were recorded by in situ measurements from ROCSAT-1 and ground-based TEC observations. The results provided the evidence for the mechanism proposed by Huang *et al.* [29], which indicated that the generation of blob is related to the occurrence of bubble, and the blob would be close to the bubbles.

The occurrence of blob and adjacent bubble near sunrise can be associated with the PPEF, affecting the zonal electric field in the background ionosphere and driving the blob and bubble to high altitude for long duration. Both the physical mechanisms or factors leading to the occurrence of the plasma blob and also the duration of the plasma blob need to be further studied in more details.

ACKNOWLEDGMENT

The Dst data are downloaded from the World Data Center at Kyoto (http://swdcdb.kugi.kyoto-u.ac.jp/dstdir/index.html). The authors would like to thank UCAR, NCU, UT at Dallas, and the ACE Science Centre for providing the satellites data, respectively. The ROCSAT-1 data can be downloaded from the website (https://cdaweb.gsfc.nasa.gov/index.html/). The DMSP data are downloaded from the Center for Space Science at the University of Texas at Dallas (http://cindispace.utdallas.edu/DMSP/dmsp_data_at_utdallas.html). The CHAMP and GRACE data can be downloaded from CDAAC (http://cdaac- www.cosmic.ucar.edu/cdaac/products.html). The Interplanetary Magnetic Field and Solar wind speed are downloaded from the ACE center (http://www.srl.caltech.edu/ACE/ASC/). The vertical drift data are downloaded from the GIRO DRIFTBASE (http://ulcar.uml.edu/DriftBase/). The GPS RINEX data can be downloaded from the IGS FTP site (ftp://igs.gnsswhu.cn/pub/).

They would also like to thank the reviewers for their constructive comments on the manuscript.

REFERENCES

[1] M. C. Kelley, "The Earth's ionosphere: Plasma physics and electrodynamics," in *International Geophysics Series*, 2nd ed. San Diego, CA, USA: Academic, 2012.

[2] V. P. Kim and V. V. Hegai, "Low latitude plasma blobs: A review," *J. Astron. Space Sci.*, vol. 33, no. 1, pp. 13–19, Mar. 2016.

[3] H. Oya, T. Takahashi, and S. Watanabe, "Observation of low latitude ionosphere by the impedance probe on board the Hinotori satellite," *J. Geomagn. Geoelectr.*, vol. 38, no. 2, pp. 111–123, 1986.

[4] S. Watanabe and H. Oya, "Occurrence characteristics of low latitude ionosphere irregularities observed by impedance probe on board the Hinotori satellite," *J. Geomagn. Geoelectr.*, vol. 38, no. 2, pp. 125–149, 1986.

[5] J. L. Chau and R. F. Woodman, "Interferometric and dual beam observations of daytime spread-F-like irregularities over jicamarca," *Geophys. Res. Lett.*, vol. 28, no. 18, pp. 3581–3584, Sep. 2001.

[6] J. Li, G. Ma, T. Maruyama, and Z. Li, "Mid-latitude ionospheric irregularities persisting into late morning during the magnetic storm on 19 March 2001," *J. Geophys. Res.: Space Phys.*, vol. 117, no. 8, 2012, Art. no. A08304, doi: 10.1029/2012JA017626.

[7] C.-S. Huang, O. de La Beaujardiere, P. A. Roddy, D. E. Hunton, J. O. Ballenthin, and M. R. Hairston, "Long-lasting daytime equatorial plasma bubbles observed by the C/NOFS satellite," *J. Geophys. Res.: Space Phys.*, vol. 118, no. 5, pp. 2398–2408, May 2013, doi: 10.1002/jgra.50252.

[8] I. Zakharenkova, E. Astafyeva, and I. Cherniak, "Early morning irregularities detected with spaceborne GPS measurements in the topside ionosphere: A multisatellite case study," *J. Geophys. Res.: Space Phys.*, vol. 120, no. 10, pp. 8817–8834, Oct. 2015, doi: 10.1002/2015JA021447.

[9] S. Tulasi Ram, K. K. Ajith, M. Yamamoto, Y. Otsuka, T. Yokoyama, K. Niranjan, and S. Gurubaran, "Fresh and evolutionary-type field-aligned irregularities generated near sunrise terminator due to overshielding electric fields," *J. Geophys. Res.: Space Phys.*, vol. 120, no. 7, pp. 5922–5930, Jul. 2015, doi: 10.1002/2015JA021427.

[10] C. Jiang, G. Yang, J. Liu, T. Yokoyama, T. Komolmis, H. Song, T. Lan, C. Zhou, Y. Zhang, and Z. Zhao, "Ionosonde observations of daytime spread F at low latitudes," *J. Geophys. Res.: Space Phys.*, vol. 121, pp. 12093–12103, 2016, doi: 10.1002/2016JA023123.

[11] W. J. Z. Luo Xiong Chao; Xu Zhu and S. Chang, "The low-latitude plasma irregularities after sunrise from multiple observations in both hemispheres during the recovery phase of a storm," *Remote Sens.*, vol. 12, no. 18, p. 2897, 2020, doi: 10.3390/rs12182897.

[12] R. F. Woodman, J. E. Pingree, and W. E. Swartz, "Spread-F-like irregularities observed by the Jicamarca radar during the day-time," *J. Atmos. Terr. Phys.*, vol. 47, nos. 8–10, pp. 867–874, 1985.
[13] E. B. Shume, F. S. Rodrigues, E. R. de Paula, I. S. Batista, M. D. Butala, and D. A. Galvan, "Day-time F region echoes observed by the Sao Luis radar," *J. Atmos. Sol.-Terr. Phys.*, vol. 103, no. 2, pp. 48–55, 2013.
[14] J. Park, C. Stolle, C. Xiong, H. Lühr R. F. Pfaff, S. Buchert, and C. R. Martinis, "A dayside plasma depletion observed at midlatitudes during quiet geomagnetic conditions," *Geophys. Res. Lett.*, vol. 42, no. 4, pp. 967–974, 2015, doi: 10.1002/2014GL062655.
[15] J. Park, H. Kil, C. Stolle, H. Lühr, W. R. Coley, A. Coster, and Y.-S. Kwak, "Daytime midlatitude plasma depletions observed by swarm: Topside signatures of the rocket exhaust," *Geophys. Res. Lett.*, vol. 43, no. 5, pp. 1802–1809, Mar. 2016, doi: 10.1002/2016GL067810.
[16] G. Chen, H. Jin, J. Yan, S. Zhang, G. Li, T. Yokoyama, G. Yang, C. Yan, C. Wu, J. Wang, D. Zhong, Y. Li, and Z. Wang, "Low-latitude daytime F region irregularities observed in two geomagnetically quiet days by the Hainan coherent scatter phased array radar (HCOPAR)," *J. Geophys. Res.: Space Phys.*, vol. 122, no. 2, pp. 2645–2654, 2017, doi: 10.1002/2016JA023628.
[17] H. C. Yeh, S. Y. Su, Y. C. Yeh, J. M. Wu, R. A. Heelis, and B. J. Holt, "Scientific mission of the IPEI payload onboard ROCSAT-1," *Terr., Atmos. Ocean. Sci.*, vol. 10, no. 1, pp. 19–42, 1999, doi: 10.3319/TAO.1999.10.S.19(ROCSAT).
[18] S. Y. Su, C. H. Liu, H. H. Ho, and C. K. Chao, "Distribution characteristics of topside ionospheric density irregularities: Equatorial versus midlatitude regions," *J. Geophys. Res.: Space Phys.*, vol. 111, Jun. 2006, Art. no. A06305.
[19] C. Reigber, H. Lühr, and P. Schwintzer, "CHAMP mission status," *Adv. Space Res.*, vol. 30, no. 2, pp. 129–134, 2002.
[20] B. D. Tapley, S. Bettadpur, M. Watkins, and C. Reigber, "The gravity recovery and climate experiment: Mission overview and early results," *Geophys. Res. Lett.*, vol. 31, no. 9, May 2004, Art. no. L09607, doi: 10.1029/2004GL019920.
[21] C. Xiong, J. Park, H. Lühr, C. Stolle, and S. Y. Ma, "Comparing plasma bubble occurrence rates at CHAMP and GRACE altitudes during high and low solar activity," *Annales Geophysicae*, vol. 28, no. 9, pp. 1647–1658, Sep. 2010.
[22] C. Xiong, H. Lühr, S. Ma, and K. Schlegel, "Validation of GRACE electron densities by incoherent scatter radar data and estimation of plasma scale height in the topside ionosphere," *Adv. Space Res.*, vol. 55, no. 8, pp. 2048–2057, Apr. 2015, doi: 10.1016/j.asr.2014.07.022.
[23] O. P. Verkhoglyadova, B. T. Tsurutani, A. J. Mannucci, A. Saito, T. Araki, D. Anderson, M. Abdu, and J. H. A. Sobral, "Simulation of PPEF effects in dayside low-latitude ionosphere for the October 30, 2003, superstorm," vol. 181, pp. 169–177, Mar. 2008.
[24] C. S. Huang, O. de La Beaujardiere, R. F. Pfaff, J. M. Retterer, P. A. Roddy, D. E. Hunton, Y.-J. Su, and F. J. Rich, "Zonal drift of plasma particles inside equatorial plasma bubbles and its relation to the zonal drift of the bubble structure," *J. Geophys. Research: Space Phys.*, vol. 115, no. 7, 2010, Art. no. A07316, doi: 10.1002/2010JA015324.
[25] N. Dashora and R. Pandey, "Observations in equatorial anomaly region of total electron content enhancements and depletions," *Annales Geophysicae*, vol. 23, no. 7, pp. 2449–2456, Oct. 2005.
[26] D. C. S. Arruda, J. H. A. Sobral, M. A. Abdu, V. M. Castilho, H. Takahashi, A. F. Medeiros, and R. A. Buriti, "Theoretical and experimental zonal drift velocities of the ionospheric plasma bubbles over the Brazilian region," *Adv. Space Res.*, vol. 38, no. 11, pp. 2610–2614, Jan. 2006.
[27] E. Astafyeva and I. Zakharenkova, "First detection of the supersonic upward plasma flow structures in the early morning sector," *Geophys. Res. Lett.*, vol. 42, no. 22, pp. 9642–9649, Nov. 2015, doi: 10.1002/2015GL066369.
[28] E. Astafyeva, I. Zakharenkova, and Y. Pineau, "Occurrence of the dayside three-peak density structure in the F_2 and the topside ionosphere," *J. Geophys. Res.: Space Phys.*, vol. 121, pp. 6936–6949, 2016, doi: 10.1002/2016JA022641.
[29] C. S. Huang, G. Le, O. de La Beaujardiere, P. A. Roddy, D. E. Hunton, R. F. Pfaff, and M. R. Hairston, "Relationship between plasma bubbles and density enhancements: Observations and interpretation," *J. Geophys. Res.: Space Phys.*, vol. 119, pp. 1325–1336, Art. no. 2014, doi: 10.1002/2013JA019579.
[30] H. Kil, L. J. Paxton, G. Jee, and R. Nikoukar, "Plasma blobs associated with medium-scale traveling ionospheric disturbances," *Geophys. Res. Lett.*, vol. 46, pp. 3575–3581, Apr. 2019, doi: 10.1029/2019GL082026.
[31] W. Luo, C. Xiong, Z. Zhu, and X. Mei, "Onset condition of plasma density enhancements: A case study for the effects of meridional wind during 17–18 August 2003," *J. Geophys. Res.: Space Phys.*, vol. 123, n o. 8, pp. 6714–6726, 2018, doi: 10.1029/2018JA025191.
[32] J. Krall, J. D. Huba, S. L. Ossakow, and G. Joyce, "Why do equatorial ionospheric bubbles stop rising?" *Geophys. Res. Lett.*, vol. 37, no. 9, Art. no. L09105, 2010, doi: 10.1029/2010GL043128.

YING XIONG was born in Wuhan, Hubei, China, in 1978. He received the bachelor's degree in communication engineering and the master's degree in software engineering from the Huazhong University of Science and Technology, in 2001 and 2005, respectively, and the Ph.D. degree from the China Ship Research and Design Center, in 2011. His research interests include ionospheric irregularities and scintillation in equatorial and low-latitude ionosphere.

LINGSEN GENG is currently pursuing the master's degree with the South-Central University for Nationalities, Wuhan, China. His research interests include communication and the variations in equatorial and low-latitude ionosphere, and ionospheric scintillation.