

1 **Equatorial broad plasma depletions associated with the enhanced fountain effect**

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10

11 **Abstract**

12 Broad plasma depletions (BPDs), plasma depletions whose longitudinal width is over several hundred
13 kilometers, have been detected in the equatorial F region by low-earth-orbit satellites during both
14 magnetically quiet and magnetically disturbed periods. A few hypotheses were suggested to explain the
15 creation of BPDs, but the underlying mechanism of this phenomenon is still under debate. We
16 investigate the origin of BPDs by analyzing the simultaneous in situ and optical observations of the
17 ionosphere on 30 May 2003 ($K_p = 8^+$), 24 April 2012 ($K_p = 7^-$), and 31 October 2012 ($K_p = 0^+$). A BPD
18 on 30 May 2003 was detected by the Republic of China Satellite-1 at an altitude of 600 km, and BPDs
19 on the other days were detected by the Communication/Navigation Outage Forecasting System satellite
20 near an altitude of 400 km. Our results show that the detection of BPDs is closely associated with
21 background ionospheric morphology; BPDs are detected on the days when the equatorial ionization
22 anomaly (EIA) is intense and the crests of the EIA have moved poleward. Measurements of upward
23 plasma motion further support the existence of ionospheric uplift at BPD locations. **On 29–30 May**
24 **2003, the uplift of the F peak height above an altitude of 700 km in the region where BPDs were**
25 **detected is evidenced by an ionosonde observation.** These observations and the detection of BPDs
26 near the magnetic equator lead to the interpretation that the satellite detection of BPDs during those
27 three days is likely related to the uplift of the F peak height above the satellite orbits. Coincident
28 observations of small-scale plasma depletions near the BPDs can be explained by enhanced likelihood of
29 plasma instability caused by the ionospheric uplift.

30

31 **1. Introduction**

32 Plasma bubbles indicate plasma depletions relative to the background plasma density in the equatorial F
33 region. Bubbles are a nighttime phenomenon and occur during both magnetically quiet and magnetically
34 disturbed periods. The longitudinal width of bubbles is typically ~ 100 km [Hei *et al.*, 2005]. The
35 latitudinal and altitudinal extents of bubbles vary depending on the bubbles' growth. Because plasma
36 instability occurs in a whole magnetic flux tube, bubbles appear as elongated structures along the
37 magnetic field lines. Steep plasma density gradients form on the bottomside of the F region after sunset,
38 which leads to the growth of the Rayleigh-Taylor (R-T) instability [Kelley, 2009; Sultan, 1996].
39 Although bubbles are the dominant irregularity feature in the equatorial F region, sometimes abnormally
40 large plasma depletions whose longitudinal width is over several hundred kilometers appear. We call
41 those depletions broad plasma depletions (BPDs) to distinguish them from regular bubbles. BPDs may
42 be considered a different type of bubble, but no study showed the creation of such broad bubbles by the
43 R-T instability.

44

45 BPDs have been detected by various satellites during large geomagnetic storms [Basu *et al.*, 2001;
46 Burke *et al.*, 2000, 2009; Greenspan *et al.*, 1991; Kil and Paxton, 2006; Kil *et al.*, 2006; Lee *et al.*, 2002;
47 Su *et al.*, 2002]. For this reason, BPDs were considered to be a storm-time phenomenon. A rigorous
48 investigation of the BPD phenomenon began from the report of BPDs detected by the Defense
49 Meteorological Satellite Program F9 [Greenspan *et al.*, 1991]. The observation of large upward plasma
50 drifts in the region where the BPD was detected led the authors to the conclusion that an extreme
51 equatorial fountain process, caused by either the penetration electric fields or the disturbance dynamo
52 electric fields, is responsible for the BPD. From the investigation of BPDs detected by the Republic of

53 China Satellite-1 (ROCSAT-1) at an altitude of 600 km, *Su et al.* [2002] reached a similar conclusion.
54 However, *Kil and Paxton* [2006] noticed the coincidence of BPDs with bubbles and suggested that the
55 consolidation of small-scale bubbles might form BPDs. *Burke et al.* [2000] understood the formation of
56 BPDs in terms of the bubbles whose growth was accelerated by storm-induced electric fields.

57

58 Recent observations of Communication/Navigation Outage Forecasting System (C/NOFS) satellite show
59 that BPDs occur during magnetically quiet as well as magnetically disturbed periods. *Huang et al.*
60 [2011] proposed that bubbles grow as time progresses and form BPDs by a merging process. This idea is
61 similar to the explanation of storm-time BPDs by *Kil and Paxton* [2006]. To explain the creation of
62 BPDs by a merger, bubbles are supposed to exist prior to the detection of BPDs. However, we noticed
63 many BPDs that developed in regions where bubbles were absent prior to the detection of BPDs. **Using**
64 **the coincident C/NOFS and radar observations over Jicamarca in Peru, *Kil and Lee* [2013]**
65 **reported a BPD event that did not show an association with bubbles.** The C/NOFS satellite detected
66 BPDs mostly near the magnetic equator and at low altitudes. In many cases, regular-size bubbles appear
67 in the longitude regions where BPDs are detected when the satellite orbit moves slightly to higher
68 latitudes or altitudes. These observations pose a question: Why is the merging process effective only
69 near the magnetic equator and at low altitudes?

70

71 Frequent detection of BPDs near the magnetic equator when the C/NOFS is near perigee provides a clue
72 to the origin of BPDs. Satellites have a greater chance of passing through the bottomside of the F region
73 when their heights are low and when they cross the magnetic equator. As suggested by *Su et al.* [2002],
74 detection of BPDs under those conditions can be understood in terms of the relationship between the
75 satellite orbit and F region height. We extend the study of *Su et al.* [2002] by providing further

76 supporting evidence for this view. To investigate the background ionospheric conditions when BPDs are
77 detected, we have chosen BPD events on the days when simultaneous optical observations of the
78 ionosphere were available. These conditions occurred on 30 May 2003 and 24 April 2012 (magnetically
79 disturbed periods) as well as on 31 October 2012 (magnetically quiet period). A BPD on 30 May 2003
80 was detected by ROCSAT-1, and BPDs on the other days were detected by the Coupled Ion-Neutral
81 dynamics Investigation (CINDI) instrument onboard the C/NOFS satellite. The measurements of the
82 atomic oxygen (OI) 135.6 nm intensity from the Global Ultraviolet Imager (GUVI) onboard
83 Thermosphere–Ionosphere–Mesosphere Energetics and Dynamics (TIMED) satellite are available on 30
84 May 2003, and the observations from the Special Sensor Ultraviolet Spectrographic Imager (SSUSI)
85 onboard Defense Meteorological Satellite Program (DMSP) F18 are available on the other two days.
86 GUVI and SSUSI observations are used for the investigation of the severity of the fountain process (or
87 uplift of the ionosphere) and for the identification of the existence of bubbles at the locations of BPDs.
88 **The measurements of the ion density by the CHALLENGING Minisatellite Payload (CHAMP) satellite**
89 **and the ionosonde observations at São Luis (2.5°S, 44.3°W) in Brazil are also used to support the**
90 **GUVI observations on 30 May 2003.**

91

92 **2. Data**

93 ROCSAT-1 was launched in March 1999 at an altitude of 600 km, and its orbital inclination was 35°.
94 The ROCSAT-1 mission was ended in June 2004. The C/NOFS satellite, launched in 2008, has an orbit
95 inclination of 13°, and its orbit altitude varies from 400 km (perigee) to 850 km (apogee). The CHAMP
96 satellite was initially launched into near polar orbit with an altitude of 454 km and an inclination of 87°.
97 Its mission was over in September 2010. The altitude of CHAMP in 2003 was near 400 km. This study
98 uses the measurements of the ion density and vertical velocity by the Ionospheric Plasma and

99 Electrodynamic Instrument (IPEI) onboard ROCSAT-1 and C/NOFS/CINDI and the measurements of
100 the ion density by the Planar Langmuir Probe (PLP) onboard CHAMP.

101

102 TIMED satellite has a circular orbit at an altitude of 630 km with an inclination of 74°. The GUVI
103 instrument onboard the TIMED satellite observes spectral images of far ultraviolet (FUV) airglow with
104 five colors (HI 121.6 nm, OI 130.4 nm, OI 135.6 nm, N₂ Lyman-Birge-Hopfield (LBH) from 140.0 to
105 150.0 nm (LBHS) and from 165.0 nm to 180 nm (LBHL)) [*Christensen et al.*, 2003; *Paxton et al.*, 1999;
106 2004]. SSUSI is the previous generation spectrometer observing FUV airglow carried by sun-
107 synchronous DMSP satellites at an altitude of 830 km [*Paxton et al.*, 1992a, 1992b, 2002]. The GUVI
108 and SSUSI instruments use a cross-track scanning mirror to produce horizon-to-horizon and limb
109 images of the ionosphere and thermosphere. This study uses the disk-scan images of OI 135.6 nm
110 intensity at night.

111

112 **3. Results and discussion**

113 **3.1 Observations on 29–30 May 2003**

114 Intense geomagnetic disturbances were recorded on 29–30 May 2003. The Dst index reached -144 nT at
115 2300 UT on the 29th, and it stayed below -100 nT until 0400 UT on the 30th. The peak Kp value was 8⁺
116 at 1800–2400 UT on the 29th. The CHAMP satellite detected plasma depletions about 30° wide in
117 latitude on four consecutive orbits in the African, Atlantic, and American sectors during the storm
118 period. Figure 1 presents the CHAMP observations at 0200 LT. The ground tracks of the CHAMP
119 satellite and the UTs of the satellite pass at the geographic equator are shown in Figure 1a. The electron
120 densities along the CHAMP orbits are shown in Figure 1b. The colors of the density and orbits are
121 arranged to match. Broad plasma depletions are detected in the equatorial region on the orbits between

122 1.8 and 6.4 UT. **Those depletions are indicated with thick lines in the orbit and density plots.**
123 Although BPDs are defined on the basis of the longitudinal width of the depletions, latitudinally broad
124 depletions may also be categorized as BPDs because those depletions are abnormally wide compared
125 with typical bubbles. The densities at 0.3 UT (black dotted curve) are shown as a reference for the
126 latitudinal density profile in the region where BPDs are not detected. Along the orbit at 0.3 UT, the
127 density peak occurs near the magnetic equator, and the equatorial ionization anomaly (EIA) feature does
128 not appear. On the following orbits, BPDs are detected in the equatorial region, and the densities in low-
129 middle latitudes are much greater than those at 0.3 UT. The formation of deep plasma depletions at the
130 magnetic equator simultaneously with the intensification of the EIA can be explained by the occurrence
131 of a severe fountain process or uplift of the ionosphere. On the density plot at 1.8 UT (red curve in
132 Figure 1b), the latitudinal density variation is quite smooth with no irregularities. Thus bubbles do not
133 seem to be involved in the formation of the depletion. Excluding bubbles as the source, the enhanced
134 fountain process is the most likely mechanism for the formation of deep plasma depletion near the
135 magnetic equator. However, bubbles are still the candidate cause of the BPDs on other orbits because
136 small-scale irregularities accompany the BPDs. The role of bubbles in the creation of BPDs is further
137 discussed in the following sections.

138

139 The CHAMP observations in Figure 1 show the increase of the latitudinal width of BPDs as time
140 progresses or as the satellite orbit moves westward; the BPD detected at 6.4 UT over South America is
141 the widest (blue thick curve) and the BPD detected at 1.8 UT over Africa is the narrowest (red thick
142 curve). If the formation of the BPDs detected by CHAMP is associated with the enhanced fountain
143 process, the EIA morphology would show a similar longitudinal variation. The GUVI OI 135.6 nm
144 intensity map provides a tool for testing the severity of the fountain process and its longitudinal variation.

145 Figure 2 presents GUVI OI 135.6 nm intensity maps on the nights of (a) the 28th through 29th (before the
146 storm) and (b) the 29th through 30th (during the storm) May 2003. Time progresses from right to left, and
147 UTs at the time of the satellite passes at the geographic equator are given on the top of each map. The
148 GUVI observation LT is around 2200. The OI 135.6 nm intensity maps represent the square of the
149 height-integrated electron density up to the satellite altitude. To provide a longitudinally continuous
150 view of the ionospheric morphology, the intensity is projected onto an altitude of 150 km instead of onto
151 a more realistic *F* peak altitude. The intensity map projected onto an altitude of 350 km is shown in
152 Figure 3. The distinctive behavior of the ionosphere during the storm period is observed in the auroral
153 and EIA regions. The intensification and equatorward expansion of the aurora (bright arcs in high
154 latitudes) during the storm period is clearly visible. At low latitudes, the EIA intensity is strengthened
155 and the northern and southern EIAs are farther separated during the storm period. These low latitude
156 changes are most severe in the American sector. The EIA morphology observed by GUVI demonstrates
157 the existence of an enhanced fountain process in the African–American sectors, especially in the
158 American sector during the storm period. **The thick white lines in Figure 2b indicate the BPD**
159 **locations shown in Figure 1.** The detection of wider BPDs closer to the American sector is consistent
160 with the observation of farther separations of the northern and southern EIAs closer to the American
161 sector. In Figure 2b, one may notice overall enhancements of the OI 135.6 nm intensity from the auroral
162 region to the equatorial region between 2000 and 0340 UT. This time period corresponds to the period
163 of main phase and large negative Dst index. This brightening of the nightglow is explained by the effect
164 of the precipitation of energetic neutral atoms originating from the ring current [Zhang *et al.*, 2006].

165

166 During the 29–30 May 2003 storm, BPDs are detected even at an altitude of 600 km over South
167 America. The measurements of the ion density and vertical velocity by ROCSAT-1 provide further

168 insight into the ionospheric conditions during the storm. Figure 3a shows the GUVI OI 135.6 nm map
169 and ROCSAT-1 passes. The OI 135.6 nm intensity map is the same as Figure 2b except for the
170 projection onto an altitude of 350 km. The ion densities and vertical ion velocities along the ROCSAT-1
171 orbits are shown in Figures 3b and 3c, respectively. Bubbles are detected over South America on orbit 2.
172 Those depletions are detected at the magnetic latitude of 20°S. Bubble signatures are also seen on the OI
173 135.6 nm intensity map at the northern anomaly region (near 20°N geographic latitudes on the second
174 swath from the left). They are considered to be the conjugate images of the bubbles detected on the
175 ROCSAT-1 orbit 2. As the satellite orbit moves closer to the magnetic equator, wider depletions appear.
176 The locations of those BPDs (red shaded regions) on orbits 3 and 4 are marked with thick lines in Figure
177 3a. The detection of wider depletions may be understood as a consequence of the temporal evolution of
178 bubbles (for example, a merging process), but this phenomenon can also be understood in terms of the
179 relationship between the F region height and satellite altitude. The latter idea is supported by the
180 ROCSAT-1 detection of BPDs in the longitude region (South America) where the strongest fountain
181 process, and therefore, the strongest uplift of the equatorial ionosphere occurred.

182

183 The measurements of the vertical ion velocity (upward is positive) on orbit 1 show the upward drift of
184 the ionosphere between the longitudes of 300° and 340°E. On orbit 2, the vertical velocity is near zero in
185 that region, and the vertical drift is downward in other longitude regions. Typically, the equatorial
186 ionosphere moves downward at premidnight longitudes during magnetically quiet periods [e.g., *Fejer et*
187 *al.*, 1991]. Thus the vertical ion drift between the longitudes of 300° and 340°E is unusual. The
188 enhancement of the upward drift that started before 0000 UT on the 30th is seen to be responsible for the
189 intensification of the EIA in that longitude region. The spike-like increases in the upward velocity on
190 orbit 2 indicate the occurrence of bubble activity in the longitude region where BPDs are detected. In the

191 longitudinal range of 340°E–0°, the upward drift occurs at a later UT than it does west of 340°E. The
192 uplift of the ionosphere at a later time is considered to be responsible for the bubble features detected
193 after midnight on orbits 3 and 4. Combining the CHAMP and ROCSAT-1 observations, the F peak
194 height is seen to be lifted between the CHAMP and ROCSAT-1 altitudes in the African-Atlantic sectors
195 and above the ROCSAT-1 altitude in the American sector. The longitudinal difference of the vertical
196 drift during storm-time is supported by the longitudinal difference in the EIA morphology observed by
197 GUVI. The occurrence of bubbles near BPDs is explained by the enhancement of bubble activity caused
198 by the uplift of the ionosphere. This interpretation implies that the mechanism responsible for BPDs is
199 the cause and the nearby bubbles are the effect. *Kil and Paxton* [2006] hold the opposite view and
200 interpret bubbles as the cause of BPDs.

201

202 **Direct evidence for the uplift of the F peak height above the ROCSAT-1 altitude over South**
203 **America is provided by the ionosonde observations at São Luis (2.5°S, 44.3°W) in Brazil. The**
204 **location of São Luis is indicated with a diamond symbol in Figure 3a. The F peak height (hmF_2)**
205 **and F peak electron density (NmF_2) are shown with red and blue dots, respectively. hmF_2 begins**
206 **to increase at 2100 UT and reaches above 700 km at around 2300 UT. The rapid hmF_2 increase**
207 **accompanies the rapid NmF_2 decrease. These observations indicate the occurrence of severe**
208 **fountain process between 2100 and 2300 UT and are consistent with the GUVI observation of a**
209 **wide EIA separation over South America. The data gap between 0000 and 0800 UT is attributed**
210 **to the plasma density drop below the ionosonde detection limit ($\sim 2 \times 10^4 \text{ cm}^{-3}$).**

211

212 **The observations of severe fountain process and ionospheric uplift in the region where BPDs were**
213 **detected lead us to interpret the BPD phenomenon in association with the ionospheric uplift.**

214 Penetration or disturbance dynamo electric field may be responsible for the uplift during the
215 storm period. If storm-induced electric fields were responsible for the ionospheric uplift (or
216 creation of BPDs), one may question how storm-induced electric fields act at a narrow longitude
217 range confined within the BPD location. The ROCSAT-1 observation along orbit 1 in Figure 3c
218 shows a gradual longitudinal variation of the upward plasma velocity rather than a step-like
219 longitudinal variation. The idea of the creation of BPDs by a merger of bubbles [*Kil and Paxton,*
220 *2006; Kil et al., 2006*] arose from the observation of steep walls on BPDs against the observation of
221 a gradual longitudinal variation of the upward plasma velocity. We seek an answer to this
222 question from the coincident occurrence of BPDs and bubbles.

223

224 The schematic diagram in Figure 5 illustrates our interpretation of the BPD morphology observed
225 by ROCSAT-1. The ROCSAT-1 data along orbits 3 and 4 are shown as a function of magnetic
226 longitude. The diagram indicates the existence of wave-like small-scale modulations of the F
227 region height in addition to a large-scale modulation of it. The region below the F peak height is
228 shown gray. The gray dotted lines indicate the composition of large- and small-scale modulations.
229 Storm-induced electric fields may induce the large-scale modulation and cause a gradual
230 longitudinal variation of the F region height. The small-scale wave-like modulations can be
231 produced by gravity waves. Both the uplift of the ionosphere and gravity wave seeding promote
232 the creation of bubbles. Orbit 3 passes through the wave-like modulations and depletions broader
233 than regular bubbles are detected. Orbit 4 is below the wave-like modulations and a single broad
234 depletion is detected. On the single broad depletion in orbit 4, a steep density gradient is formed
235 on the west wall and a gradual variation of the density appears on the east wall. The steep density
236 gradient on the west wall of the depletion in orbit 4 coincides with the location of a sharp depletion

237 **in orbit 3. This observation may explain why a steep density gradient is formed on the west wall.**
238 **Ignoring the walls between the three broad depletions in orbit 3, the morphology of the depletion**
239 **is similar to the morphology of a single broad depletion in orbit 4. The gradual variation of the**
240 **density on the east wall may represent the trough morphology in the absence of bubbles. On the**
241 **other hand, the coincidence of the uplift with bubbles creates a steep density gradient on the west**
242 **wall.**

243

244 **3.2 Observations on 24 April 2012**

245 **In the following two sections, we provide additional support for the occurrence of BPDs under the**
246 **uplifted condition of the ionosphere using the coincident observations of CINDI and SSUSI.**

247 CINDI detected BPDs around 2.4 UT between the 240° and 270°E longitudes during the storm of 24
248 April 2012. The Dst index started to decrease at 1900 UT on the 23rd and reached its minimum value (-
249 104 nT) at 0500 UT on the 24th. The maximum Kp index was 7 at 0000–0300 UT on the 24th. Figure 6a
250 shows the SSUSI OI 135.6 nm intensity maps on 23–25 April. The maps are the projection onto an
251 altitude of 350 km and the observation LT is 2000. The maps on the 23rd and 25th are presented as a
252 reference picture of what the ionosphere looked like before and after the storm, respectively. On the map
253 on the 24th, the C/NOFS orbit (orbit 1 in Figure 6b) on which the BPDs are detected is shown with a
254 white solid curve. Emission depletion bands (or bubbles) appear at the location of BPDs marked with a
255 thick white line. One difference between 24 April and the other days is that bubbles appear on the 24th
256 but not on other days. Intensification of the EIA is another difference of the ionosphere on the 24th from
257 that on other days.

258

259 The measurements of plasma density and vertical velocity by CINDI on the 24th are shown in Figures 6c
260 and 6d. The latitude, LT, and altitude of the C/NOFS orbits are shown in Figure 6b. BPDs (marked in
261 red) are detected along orbit 1 around 2000 LT and at a 400-km altitude. The plasma depletion detected
262 near 270°E on orbit 2 may also be categorized as a BPD, although the depletion depth is much shallower
263 than the depletions on orbit 1. In the longitude region where BPDs are detected on orbit 1, orbit 1 is
264 closer to the magnetic equator than orbit 2 and the altitude of orbit 1 is lower than that of orbit 2.
265 Because of the slight differences in magnetic latitude and altitude, the morphologies of plasma
266 depletions on the two orbits are largely different. Orbit 3 crosses the magnetic equator in the longitude
267 region where BPDs are detected on orbit 1, but the altitude of orbit 3 is about 100 km higher than that of
268 orbit 1. **On the 24th, the EIA has already been intensified at 2.0 UT (see the GUVI swath at 2.0 UT**
269 **in Figure 6a). Although we cannot identify the vertical plasma drift prior to orbit 1 from CINDI**
270 **observations (data are missing), we can infer the existence of upward drift of the ionosphere**
271 **before 2.0 UT from the GUVI observation. The observation of the upward drift of the background**
272 **ionosphere along CINDI orbit 1 (Figure 6d) indicates that the fountain process persisted until or**
273 **after 2.6 UT in some regions. In orbit 1, the creation of deep depletions at the locations where the**
274 **plasma drift is downward is not explained by the instantaneous velocity. Presumably, upward**
275 **plasma motion at earlier hours is responsible for those depletions.** We do not know whether bubbles
276 existed before the detection of BPDs on orbit 1 because observations are missing. Even if observations
277 were available for an earlier orbit, bubbles may not be detected because the sampling time is earlier than
278 the development time of bubbles. **What we can identify from Figure 6 is the fact that the vertical**
279 **background ionospheric motion was abnormal and a fountain process existed prior to the**
280 **detection of BPDs.**

281

282 Figure 7 is a close-up of the observations on the 24th. The vertical white dashed lines indicate the nadir
283 view of SSUSI. The SSUSI image marked with UT 0203 was taken about 30 min earlier than the CINDI
284 observation on orbit 1. Three wide depletions on orbit 1 are marked with letters A, B, and C. The
285 longitude of the dark emission depletion band (A') in the magnetic north is seen to match the longitude
286 of depletion A. The signature of the wide density depletion B does not appear in west of the emission
287 depletion A' on the SSUSI image, although density depletion B is detected less than 2° west from
288 density depletion A. Many bubble signatures appear on the SSUSI image marked with UT 0334. Two
289 emission depletion bands are clearly visible in the magnetic south on the SSUSI image. Density
290 depletions corresponding to those emission depletion bands are not identifiable on orbits 1 and 2. At the
291 location of density depletion C, the matching emission depletion is not visible on the SSUSI image. The
292 absence of the signatures of wide and deep plasma depletions on the SSUSI image is difficult to explain
293 if the formation of those depletions is associated with bubbles. One-to-one matching of the SSUSI and
294 CINDI observations or between CINDI observations contains a certain level of uncertainty because the
295 mapping of the SSUSI images onto an altitude of 350 km is not perfect and because the ionosphere is
296 not stationary. **However, as the small-size density depletions between the longitudes of 290° and**
297 **295°E on two C/NOFS orbits show, bubbles are often persistent for a few hours and traceable on**
298 **consecutive orbits. Although the depletions between the longitudes of 250° and 280°E are much**
299 **wider and deeper compared with the depletions between the longitudes of 290° and 295°E, they**
300 **are not traceable on the two consecutive orbits. We interpret that the depletions on orbit 1 were**
301 **detected under the condition of orbit 3 in Figure 5. Under that condition (satellite altitude is near**
302 **the bottomside), the morphology and occurrence of depletions can vary significantly for a slight**
303 **difference in sampling altitude.**

304

305

306 **3.3 Observations on 31 October 2012**

307 The BPD event detected by CINDI on 31 October 2012 is distinguished from the BPD events reported
308 in early sections because it is observed during a magnetically quiet time ($K_p < 1^0$). Figure 8 is the same
309 format as Figure 6 for the observations on 31 October 2012. The SSUSI OI 135.6 nm maps at 2000 LT
310 on 30 October, 31 October, and 1 November are shown in Figure 8a. The images on 30 October and 1
311 November are presented as a reference for the ionospheric morphology on days with no BPDs. A BPD is
312 detected near the magnetic equator, at 2000 LT, and at a 420-km altitude on orbit 2 (Figure 8b). On orbit
313 1 in Figure 8c, no irregularity appears in the longitudes where the BPD is detected. The LT of orbit 1 is
314 too early to detect irregularities. The single large BPD is detected on orbit 2, and only small magnitude
315 density fluctuations are detected on orbit 3. Bubble features that can account for the BPD do not appear
316 in the CINDI observations. Grown bubbles are absent in the SSUSI images. The SSUSI image at 7.4 UT
317 was taken about an hour after orbit 2. If the BPD were associated with bubbles, bubble signatures would
318 remain in the SSUSI image. The measurements of the vertical velocity in Figure 8d show the existence
319 of an upward movement of the ionosphere prior to the detection of the BPD. Comparison of the SSUSI
320 images on the three days in Figure 8a, the OI 135.6 nm intensity at the EIA location is strongest on the
321 31st, but the intensity at the magnetic equator is weakest on the 31st. This observation indicates that the
322 fountain process or uplift of the ionosphere was most significant on the 31st, which is consistent with the
323 observation of large upward velocity prior to the detection of the BPD. **The observations on the 31st**
324 **again show the occurrence of a BPD when the equatorial ionosphere is uplifted.**

325

326 **4. Conclusions**

327 We have investigated the origin of abnormally broad plasma depletions (named BPDs) in the equatorial
328 region by using the coincident optical (TIMED/GUVI and DMSP F18/SSUSI) and in situ satellite
329 (ROCSAT-1/IPEI, C/NOFS/CINDI, and CHAMP/PLP) observations of the ionosphere on 30 May 2003,
330 24 April 2012, and 31 October 2012. BPDs on 30 May 2003 and 24 April 2012 are detected during
331 geomagnetic storm periods, and a BPD on 31 October 2012 is not related to a geomagnetic storm. All
332 the observations indicate that BPDs are a phenomenon near the magnetic equator. C/NOFS detected
333 BPDs when its orbit is below an altitude of 450 km. The ionospheric morphology seen from the OI
334 135.6 nm intensity maps indicates that BPDs occur on days when strong EIAs develop. In addition to
335 the morphology of the EIA, the observations of the upward plasma drift support the occurrence of an
336 enhanced fountain process or uplift of the ionosphere on the days when BPD are detected. **The**
337 **ionosonde observations on 29–30 May 2003 at São Luis in Brazil provide direct evidence for the**
338 **uplift of the F peak height above an altitude of 700 km.** On the basis of these observations, we
339 suggest that the BPD phenomena on those three days are likely caused by the uplift of the bottomside F
340 region up to or above the satellite altitudes. The occurrence of bubbles by BPDs is explained by the
341 enhancement of plasma instabilities by the uplift of the ionosphere.

342

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349

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428

429 **Figure Captions**

430 **Figure 1.** BPDs detected by the CHAMP satellite on 30 May 2003. (a) Ground tracks of CHAMP
431 satellite from 0.3 UT to 6.4 UT on nightside observation. The magnetic equator is indicated by the black
432 dotted line. (b) Latitudinal profiles of the plasma density along the orbits shown in Figure 1a. LT of the
433 CHAMP observation is around 0200. The BPD locations are indicated with thick lines.

434

435 **Figure 2.** Global maps of OI 135.6 nm emission observed from TIMED/GUVI during (a) quiet time
436 (28–29 May 2003) and (b) storm time (29–30 May 2003). The maps are the projection onto an altitude
437 of 150 km. The white dashed line represents magnetic equator. UTs given on the top of each figure are
438 the times when the satellite passes over the geogrphaic equator. LT of the GUVI observation is around
439 2200. The thick white lines are the BPD locations shown in Figure 1.

440

441 **Figure 3.** (a) TIMED/GUVI OI 135.6 nm intensity map between 270° and 360°E longitudes on 30 May
442 2003. The intensity map is projected onto an altitude of 350 km. The white dotted line indicates the
443 magnetic equator. The white solid lines indicate ground tracks of ROCSAT-1 satellite. The locations of
444 BPDs are marked with thick white lines. (b) Ion density measurements by ROCSAT-1 along the orbits
445 shown in Figure 3a. (c) Vertical ion velocity measurements by ROCSAT-1. The locations of BPDs are
446 indicated with red dots in the density and velocity plots.

447

448 **Figure 4.** The ionosonde observations of the F peak height ($h_m F_2$) and F peak electron density ($N_m F_2$)
449 on 29–30 May 2003 at São Luis (2.5°S, 44.3°W) in Brazil.

450

451 **Figure 5.** Schematic illustration of the BPD morphology. The gray dashed line indicates the
452 composition of large- and small-scale modulations.

453

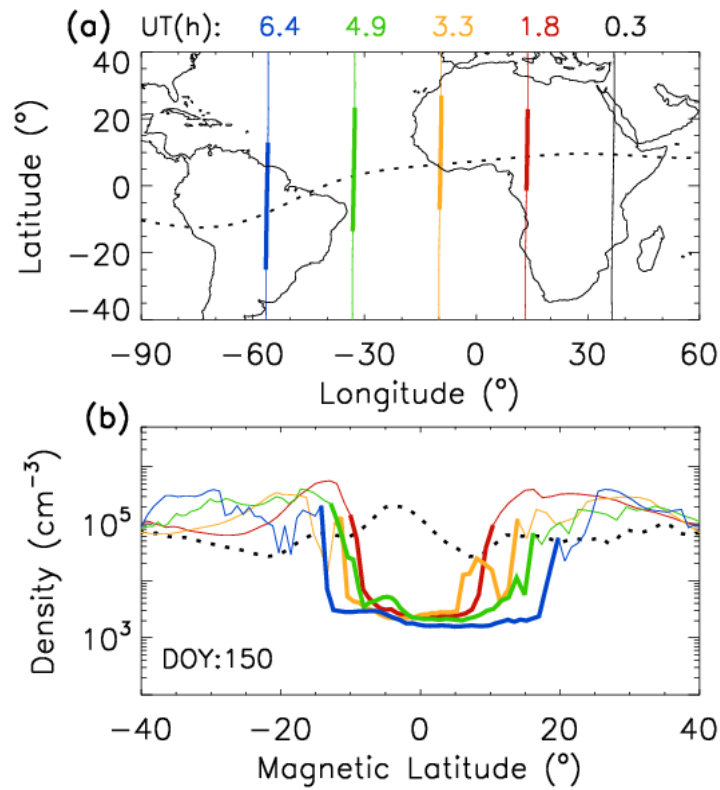
454 **Figure 6.** (a) DMSP/SSUSI OI 135.6 nm intensity maps on 23 April 2012 (left), 24 April 2012 (center),
455 and 25 April 2012 (right). The white dotted lines indicate the magnetic equator. (b) Latitude, LT, and
456 altitude of C/NOFS on April 24. (c and d) Measurements of the ion density and vertical ion velocity by
457 CNOFS/CINDI along the orbits shown in Figure 4b. The locations of BPDs are identified with red dots.

458

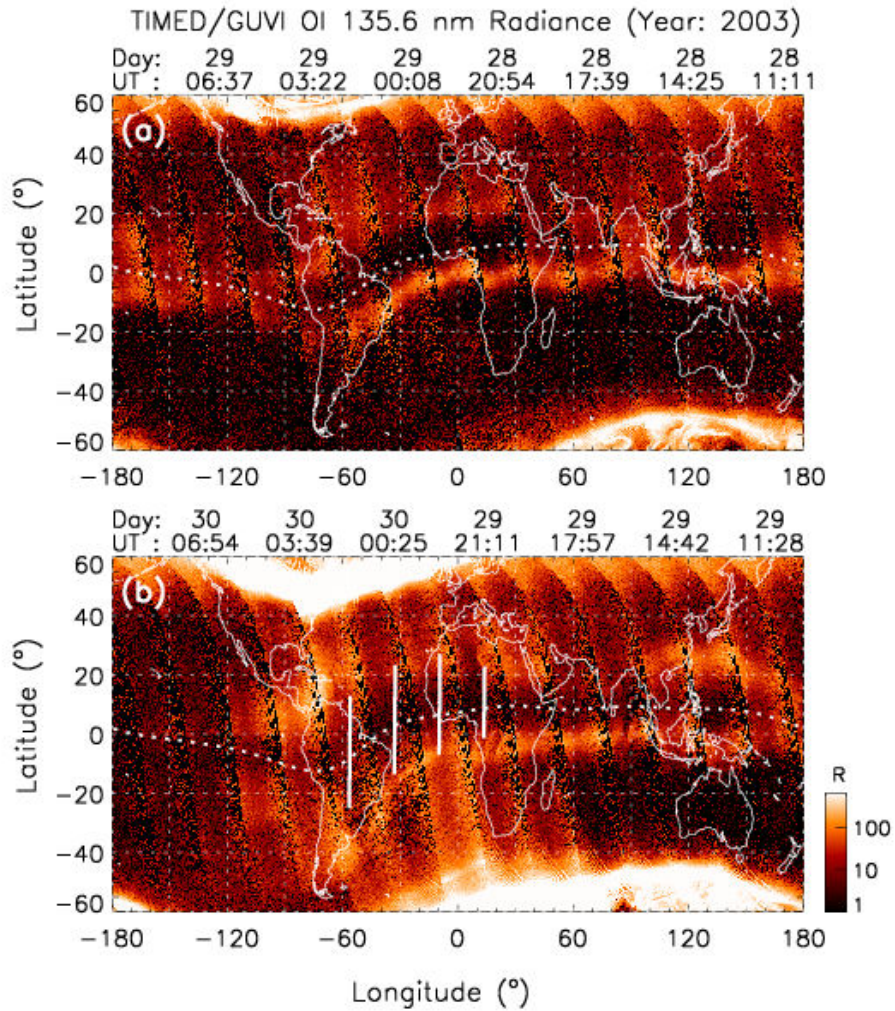
459 **Figure 7.** (top) Close-up of DMSP/SSUSI OI 135.6 nm map on 24 April 2012. The white dashed lines
460 indicate DMSP orbits. The white solid lines indicate ground tracks of C/NOFS. (bottom)
461 CNOFS/CINDI ion density measurements along the orbits indicated on the top image.

462

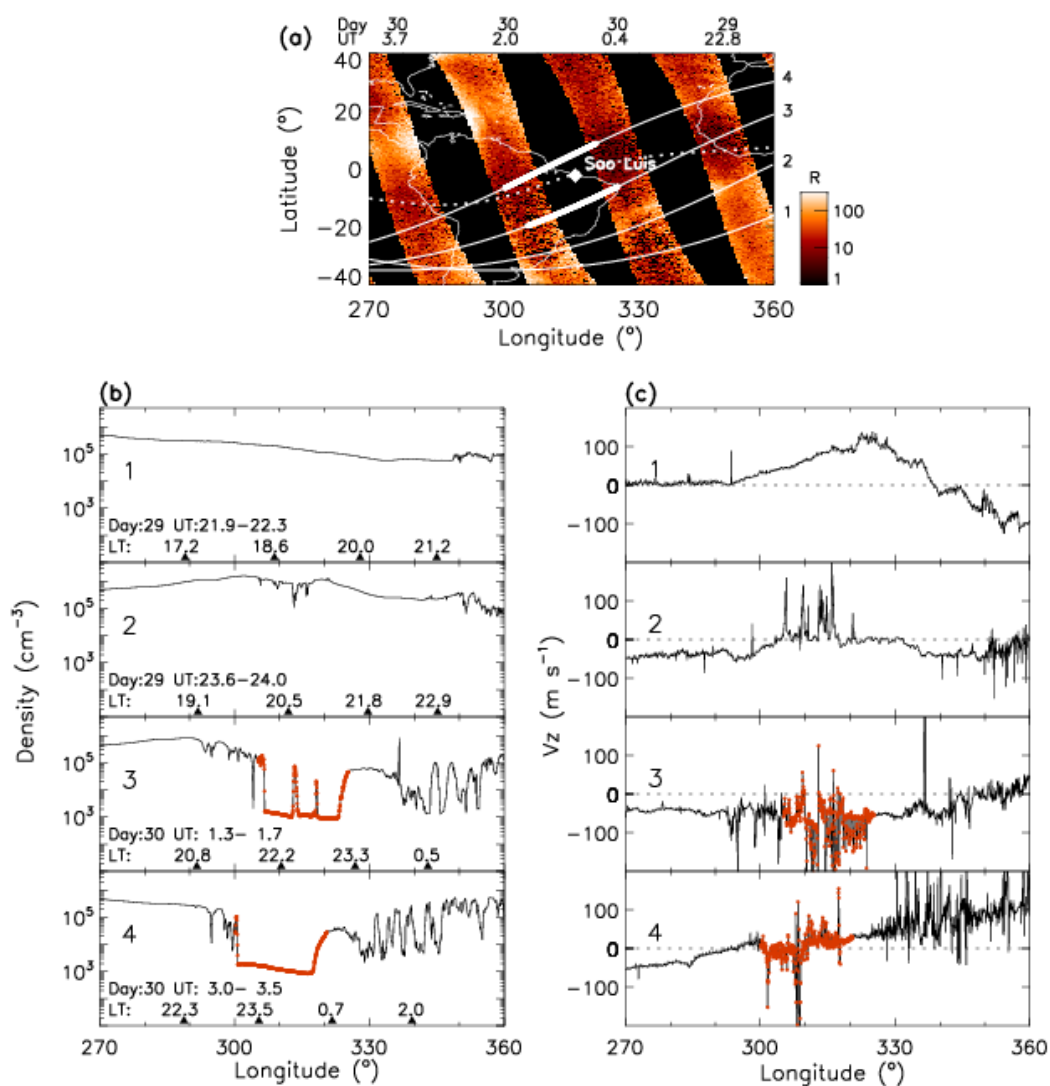
463 **Figure 8.** (a) DMSP/SSUSI OI 135.6 nm intensity maps on 30 October 2012 (left), 31 October 2012
464 (center), and 1 November 2012 (right). (b) Latitude, LT, and altitude of C/NOFS on 31 October. (c and
465 d) Measurements of the ion density and vertical ion velocity by CNOFS/CINDI along the orbits shown
466 in Figure 6b. The locations of BPDs are identified with red dots.



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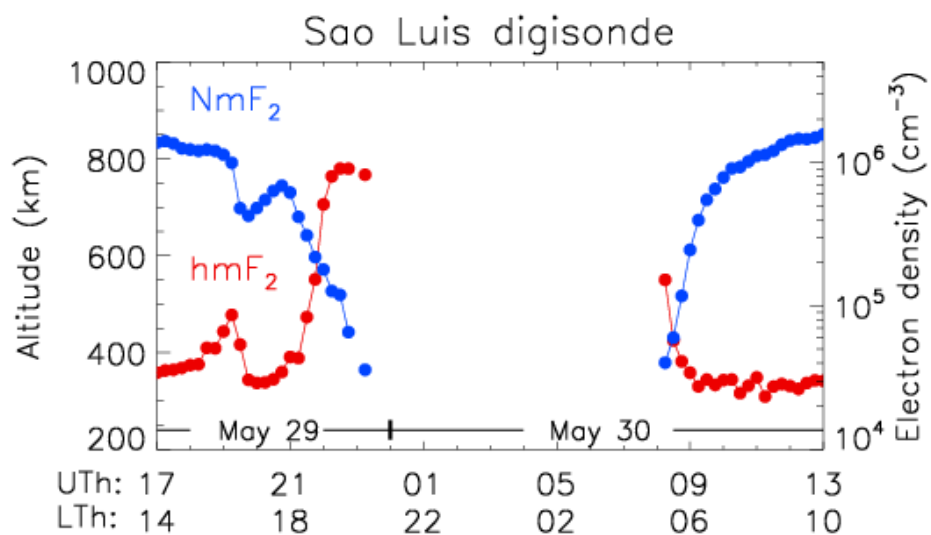


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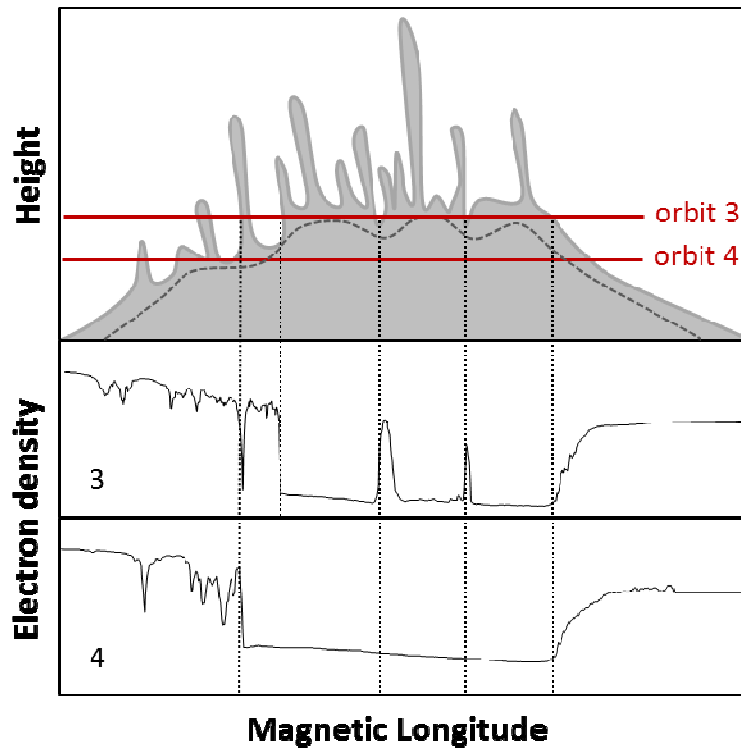


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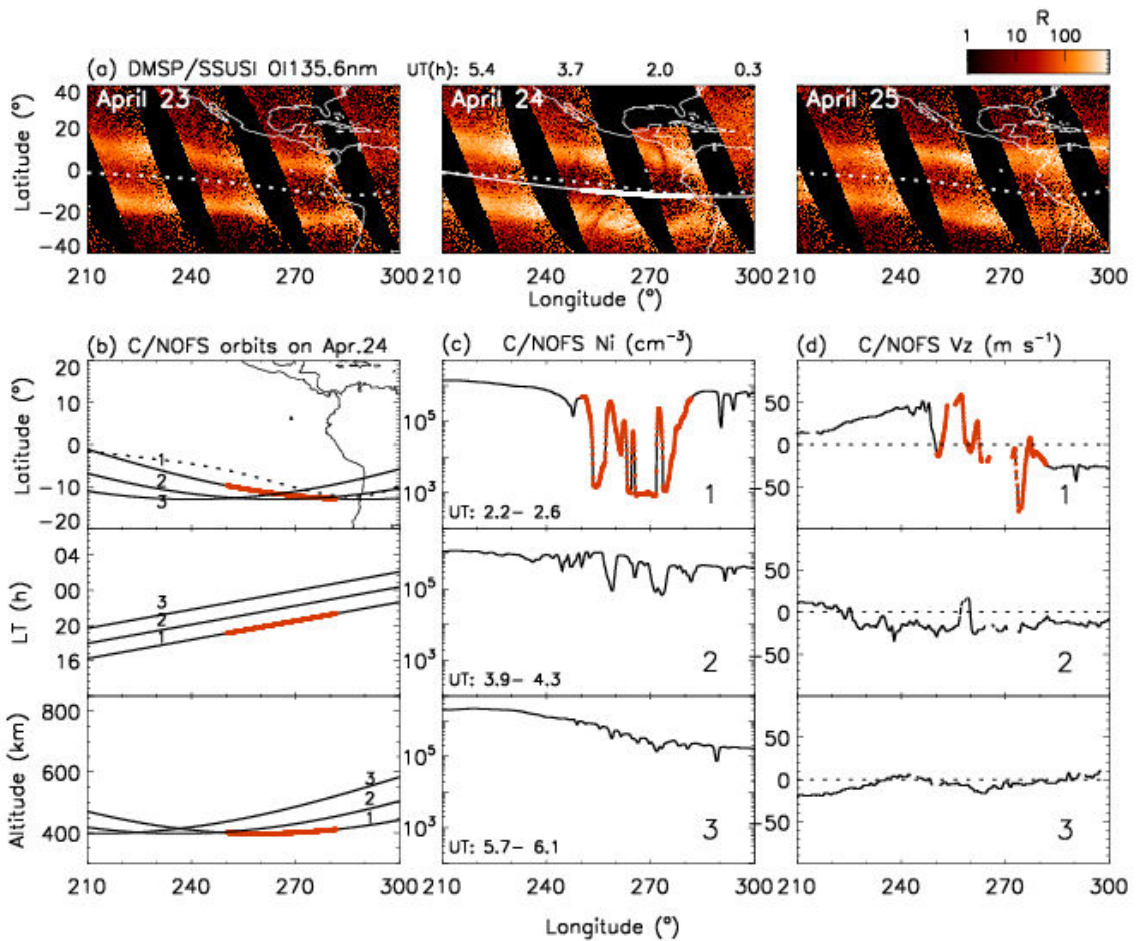
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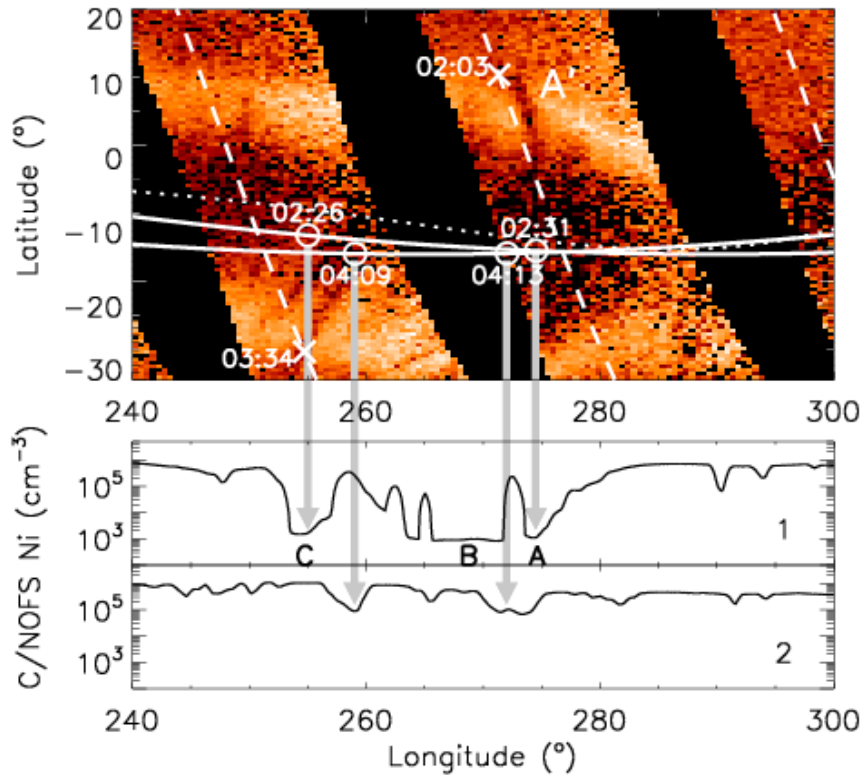
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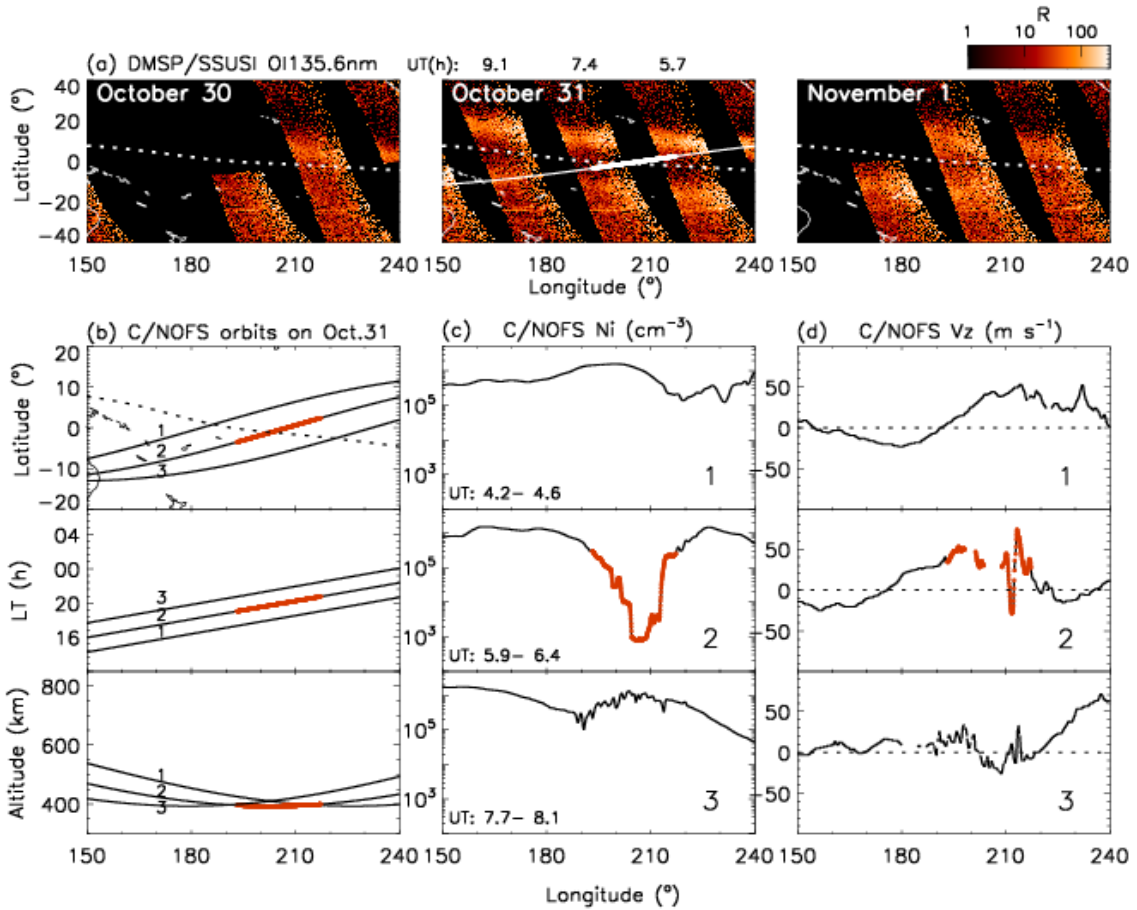


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