

1 Unique Combinations of Differently Shaped Equatorial Plasma Bubbles 2 Occurring Within a Small Longitude Range

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13 14 **Key Points:**

- 15 • Differently shaped EPBs are observed simultaneously within a small longitude of $\sim 10^\circ$
- 16 • Observations indicate longitudinal variations in EPBs' zonal drift velocities at the
17 magnetic equator and EIA crests
- 18 • Indication of the effect of small spatial scale E-region density, electric field, neutral wind
19 variations, or a combination of them

20
21 **Key Words:** NASA GOLD mission, Equatorial Plasma Bubbles, EPB Morphology, Plasma
22 Irregularities, Nighttime ionosphere, OI 135.6 nm nightglow

23 24 **Abstract:**

25 On 12 October 2020 and 26 December 2021, NASA's Global-scale Observations of the Limb and
26 Disk (GOLD) mission observed differently shaped EPBs simultaneously within $\sim 10^\circ$ longitude,
27 near the subsatellite point and over the Atlantic, respectively which is unusual. On 12 October
28 2020, three EPBs with differing curvatures were observed in a $\sim 12^\circ$ longitude sector. The westside
29 EPB was curved towards the east, in a C-shape. The middle was straight. The eastside EPB was
30 curved westward, in a reversed C-shape. In the second case, 26 December 2021, in a smaller
31 longitude range of $\sim 6^\circ$ adjacent C-shaped and reversed C-shaped EPBs were observed. EPBs'

32 zonal drift velocities at the magnetic equator and both EIA crests were compared. These
33 occurrences of oppositely shaped EPBs simultaneously in a narrow longitude may indicate that
34 small-scale longitudinal variations in the E-region density, electric field, neutral wind variations,
35 or a combination of them were present.

36

37 **Plain Language Summary:**

38 The post-sunset ionosphere becomes conducive to the formation of plasma irregularities associated
39 with depleted plasma densities. In the images obtained from space or ground, these plasma
40 depleted regions appear as latitudinally elongated dark bands, which are known as “equatorial
41 plasma bubbles (EPBs)”. Satellite communication and navigation systems are adversely affected
42 when the trans-ionospheric radio signals travel through the EPBs. Thus, investigations of EPBs’
43 formation and development are important. In 2-D airglow images, the EPBs appear to be straight
44 (aligned along the magnetic field lines). However, sometimes the poleward extensions of the EPBs
45 can be tilted eastward or westward from the magnetic field line resembling either a C-shape or
46 reversed C-shape, respectively. These differently shaped EPBs have been observed before. But,
47 NASA’s Global-scale Observations of the Limb and Disk (GOLD) mission observed them
48 simultaneously within $\sim 12^\circ$ and 6° longitudes on 12 October 2020 and 26 December 2021 which
49 is unusual. Such occurrence of opposite-shaped EPBs within a small longitude range indicates
50 small-scale longitudinal variations in the E-region density, neutral winds, electric fields, or a
51 combination of them. We present detailed observations of these two unique events with possible
52 explanations.

53

54 **Introduction:**

55 Equatorial plasma bubbles (EPBs) are manifestations of post-sunset plasma irregularities
56 associated with depleted plasma densities that occur over the equatorial and low-latitude
57 ionosphere. Trans-ionospheric radio wave propagation for communication, navigation, and timing
58 is adversely affected when passing through these plasma irregularities. Thus, the investigation of
59 plasma irregularities is an important priority for researchers, with societal implications. The
60 formation and development of plasma irregularities depend on several factors such as vertical and
61 horizontal ionospheric density gradient (both neutral and plasma), background neutral winds, zonal
62 electric fields, chemical recombination, and atmospheric waves (Sultan, 1996; Taori et al., 2011;

63 Liu et al., 2017; Bhattacharyya, 2022). EPBs are expected to be aligned to the magnetic field lines,
64 and when they are, they are straight in rectified airglow images. However, in some cases, the
65 poleward extensions of the EPBs are tilted eastward or westward from the magnetic field line
66 resembling a C-shape or reversed C-shape, respectively.

67 Using a ground-based all-sky airglow imaging system, the westward tilt of the airglow
68 depletions to the magnetic field lines was reported (Mendillo and Baumgardner, 1982; Mendillo
69 and Tyler, 1983). A decrease of the eastward plasma drift velocity with increasing altitude
70 (latitude) could be produced if the eastward neutral wind velocity also decreases with altitude
71 (latitude) (Rishbeth, 1972; Anderson and Mendillo, 1983). This could form reversed C-shape EPB.
72 Such a decrease in zonal neutral wind speed at the EIA crests due to larger ion drag has been
73 observed by Dynamics Explorer-2 (DE-2) satellite (Raghavarao et al., 1991) and ground-based
74 Fabry-Perot interferometer (Martinis et al., 2001, 2003). Reversed C-shape EPBs were observed
75 in the OI 135.6-nm emission images by the Global Ultraviolet Imager (GUVI) on board the
76 Thermosphere, Ionosphere, Mesosphere Energetics and Dynamics (TIMED) satellite (Kelley et
77 al., 2003). Kil et al. (2009) explained the reversed C-shape structure by (a) the reduction of the
78 eastward plasma flow inside the EPB due to the development of a polarization electric field that
79 retarded at higher apex height (indicated by Woodman and La Hoz, 1976) and (b) the latitudinal
80 variation of the eastward drift of the background ionosphere, as explained by Anderson and
81 Mendillo (1983) and Martinis et al. (2003). Huba et al. (2009) have investigated the model
82 (HWM93) zonal winds' effect on the EPBs' morphology through SAMI3, a three-dimensional
83 modeling simulation. They found that stronger neutral zonal winds at lower altitudes and a
84 decrease of velocity at latitudes away from the equator cause the reversed C-shape EPBs which
85 agreed with the observations reported by Kelley et al. (2003) and Kil et al. (2009).

86 C-shape EPBs were reported for the first time using the Jicamarca radar backscatter maps
87 (Woodman and La Hoz, 1976); where no explanation for the formation mechanism was given.
88 During the early night, zonal plasma drifts over the off-equatorial latitudes were observed to be
89 stronger than the equatorial latitudes using electric field measurements from DE-2 (Aggson et al.,
90 1987) and ground-based airglow measurements (Martinis et al., 2003). These latitudinal variations
91 in the zonal plasma drifts can be related to their altitudinal variations at the magnetic equator. Even
92 if the zonal neutral wind is constant with altitude, plasma drifts can vary with altitude due to the
93 variations in the Pedersen conductivity. Zalesak et al. (1982) incorporated an eastward neutral

94 wind in the equatorial F region and E region Pedersen conductivity effects in their two-dimensional
95 numerical simulation and found that the rising EPBs were caught up in the vertical shears of the
96 plasma motion, resulting in the ‘C’ shape. Thus, the actual EPB shape depends strongly on both
97 the zonal neutral wind profile and the Pedersen conductivity. SAMI3 produced a C-shape EPB
98 when HWM07 neutral wind was taken as input (Huba et al., 2009). In this case, the HWM07 zonal
99 winds produced a strong westward drift at low altitudes which caused an eastward tilt of EPB (C-
100 shape EPB) at higher altitudes. Further, maximum eastward zonal neutral winds over low latitudes
101 could favor the C-shape EPB.

102 On October 12, 2020, the NASA Global-scale Observations of the Limb and Disk (GOLD)
103 mission observed three consecutive EPBs; a C-shape, a straight, and a reversed C-shape EPBs,
104 within $\sim 12^\circ$ longitudes at magnetic equatorial latitudes. The observed longitude is close to the
105 GOLD’s subsatellite point ($\sim 47^\circ$ W). In another case on 26 December 2021, a reversed C-shape
106 and C-shape EPB were observed sidewise within $\sim 6^\circ$ longitude. While there are numerous images
107 with EPBs having different shapes, these two examples of consecutive EPBs with reversing shapes
108 within a small longitude range are unusual. This points to small longitudinal variations in the E-
109 region density, electric field, neutral wind variations, or a combination of them. We report detailed
110 observations of these two unique and rare events and discuss their possible formation mechanisms.

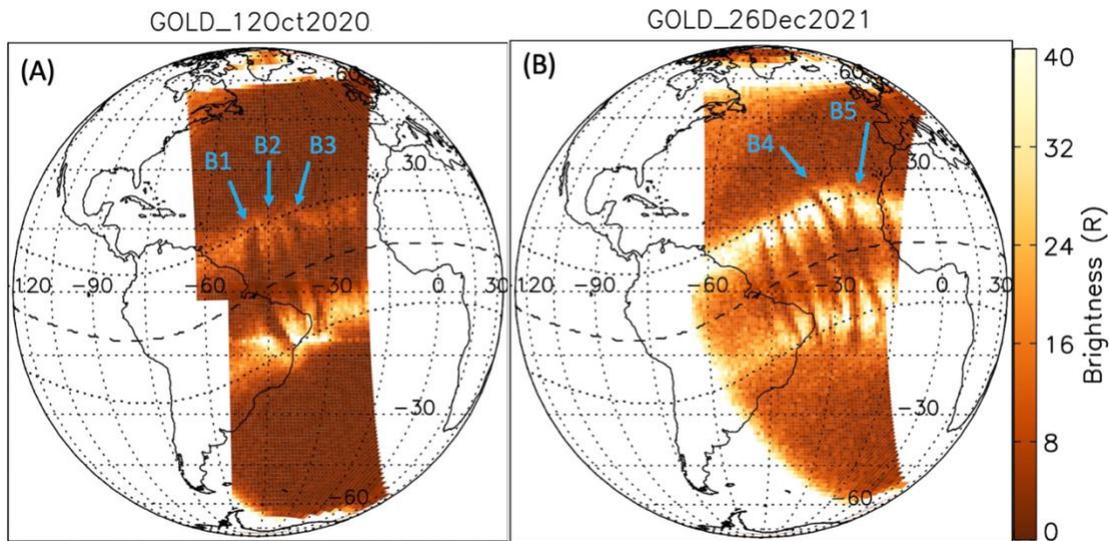
111

112 **Data:**

113 Nighttime OI 135.6 nm partial disk scans made by the GOLD imager are the data used in this
114 study. The GOLD imager was launched on a commercial communications satellite on 25 January
115 2018 and it is in geostationary orbit at 47.5° W. Nominal operations and observations started on 9
116 October 2018. It has two identical spectrographs that obtain the Earth images in the far-ultraviolet
117 (FUV) range, at ~ 134 - 162 nm wavelength. It measures the column-integrated emission rate along
118 the line of sight. When geolocating the observations, an emission altitude of 300 km is assumed.
119 GOLD can observe the American, Atlantic, and Western African longitudes, which provides a
120 unique opportunity to unambiguously observe the spatial-temporal evolution of various
121 ionospheric-thermospheric features in this active region of the Equatorial Ionization Anomaly
122 (EIA). The nighttime LIC disk images are obtained at a cadence of 15 minutes and binned to
123 90×80 km at the nadir. Detailed information about the GOLD instrument and observation modes
124 are discussed in Eastes et al., (2017, 2020) and McClintock et al., (2020, 2023).

125 **Results and Discussion:**

126 GOLD takes nighttime disk observations using both channels A and B (CHA and CHB hereafter).
127 Most individual scans cover $\sim 45^\circ$ in longitude, ~ 3 hours in local time, just to the east of the sunset
128 terminator. Starting from 20:10 UT, CHB takes nighttime partial disk images, alternating between
129 the Northern and Southern hemispheres until 23:10 UT. From 23:10 to 00:09 UT (the next day)
130 simultaneous observations of the Northern and Southern hemispheres are made using CHA and
131 CHB. The observation sequence is described in detail by Karan, et al. (2020).



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Figure 1. (A) The nighttime images obtained by GOLD in OI 135.6 nm simultaneously by CHA and CHB at 23:10 UT on 12 October 2020 are combined. The white dashed line shows the geomagnetic equator. The two bright emission patches seen at all longitudes on either side of the magnetic equator are the EIA crests. EPBs are the depletions in brightness across the EIA crests. The C-shape, straight, and reversed C-shape EPBs are marked as B1, B2, and B3, respectively. (B) Similar to Figure A but the CHB images obtained on 26 December 2021 at 22:40 UT and 22:55 UT are combined. The reversed C-shape and C-shape EPBs are marked as B4 and B5.

133 Figure 1A shows simultaneous images obtained by CHA and CHB from the northern and southern
134 hemispheres, respectively on 12 October 2020 at 23:10 UT. The white dashed line marks the
135 geomagnetic equator. The emissions peaking on either side of the geomagnetic equator are the
136 EIA crests. At 10°S GLat there is a faint data artifact. At that latitude, there appears to be a
137 longitudinally extended region of slightly brighter emission, but EPBs are still apparent as
138 depletions in the brightness across the EIA crests. This artifact is due to the high voltage being too
139 low during the flat field measurements, which is explained in Section 3.1.18 of the GOLD data
140 release note Rev 4.6 (<https://gold.cs.ucf.edu/wp->

141 content/documentation/GOLD_Release_Notes_Rev4.6.pdf). Over the Eastern side of South
142 America ($\sim 50^\circ$ - 35° W longitudes) there are three distinct and differently shaped EPBs. This
143 longitude range is close to the crossing of the geographic and geomagnetic equators and near the
144 subsatellite location. The EPB on the left side (marked as B1) has a C-shape, the one in the middle
145 (B2) is straight, whereas the right EPB (B3) has a reversed C-shape. B3 appears to be bifurcated
146 at the south (S) EIA crests. Each of these EPB shapes has been observed previously by others and
147 by GOLD, but in the observations on October 12, 2020, the three distinct EPB shapes occurred
148 consecutively over a narrow longitude range ($\sim 12^\circ$). Contrary to this case, the C- and reversed C-
149 shape EPBs were observed in an opposite order within $\sim 30^\circ$ and 20° W longitudes on 26 December
150 2021. Consecutive images taken by CHB at 22:40 UT and 22:55 UT on 26 December 2021 are
151 combined and shown in Figure 1B. The EPBs at the west side of 30° W longitude appear to be
152 straight. But the EPBs (B4 and B5) observed within $\sim 30^\circ$ and 20° W longitudes are of opposite
153 shapes and are the focus in this image. The reversed C-shape EPB (B4) is observed to the west of
154 the C-shape EPB (B5) and the two are separated by $\sim 6^\circ$ at their magnetic equators (Figure 1B). In
155 both cases (Figure 1A, B) the EPBs are observed multiple times between $\sim 19:30$ to 22.00 LT
156 (Local Time) with initial observations around ~ 2 hrs after the local sunset. To investigate the
157 different EPBs' shapes (B1 to B5) observed at similar local times but within a small longitude

158 range, we derived their zonal drift velocities at the magnetic equator and EIA crest latitudes. The
 159 EPB drift velocity derivation method is explained below for 12 October 2020 and is also used for
 160 26 December 2021.

161 For the investigation, images are first transferred into magnetic coordinates (Laundal and
 162 Richmond, 2017; Thébault et al., 2015). Figures 2 (A), (B), (C), and (D) show the images at 23:10,
 163 23:25, 23:40, and 23:55 UT on 12 October 2020, respectively. At 23:10 UT (Figure 2A) the
 164 locations of B1, B2, and B3 at the magnetic equator are ($\sim 47^\circ$ W Glon, 0.5° N Glat, 26.5° Mlon),
 165 ($\sim 40^\circ$ W Glon, 2.5° N Glat, 33.2° Mlon), and ($\sim 35.5^\circ$ W Glon, 5.7° N Glat, 38.5° Mlon),
 166 respectively. Next, we obtain the EPBs' longitudes at three different magnetic latitude ranges; (10°
 167 to 15°), (-6° to 6°), and (-15° to -10°), shown by green, blue, and magenta boxes, respectively, in
 168 Figure 2. These latitude ranges distinguish the EIA crests from the magnetic equatorial region.
 169 Since B2 reaches lower latitudes than B1 and B3, the EIA crest latitude ranges for B2 are
 170 considered to be (6° to 12°) and (-12° to -6°). The brightness along the latitudes in each box is
 171 summed at each longitude. From the longitudinal variations of the summed brightness, the EPBs'
 172 longitudes in an image were obtained. This method is explained in detail by Karan et al., 2020.
 173 B1, B2, and B3 longitudes are obtained from all the nighttime partial disk images on October 12,

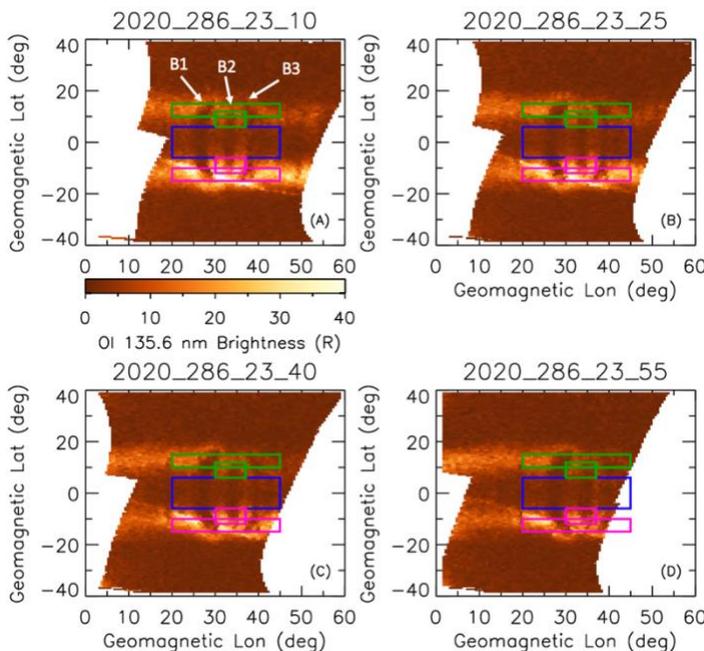
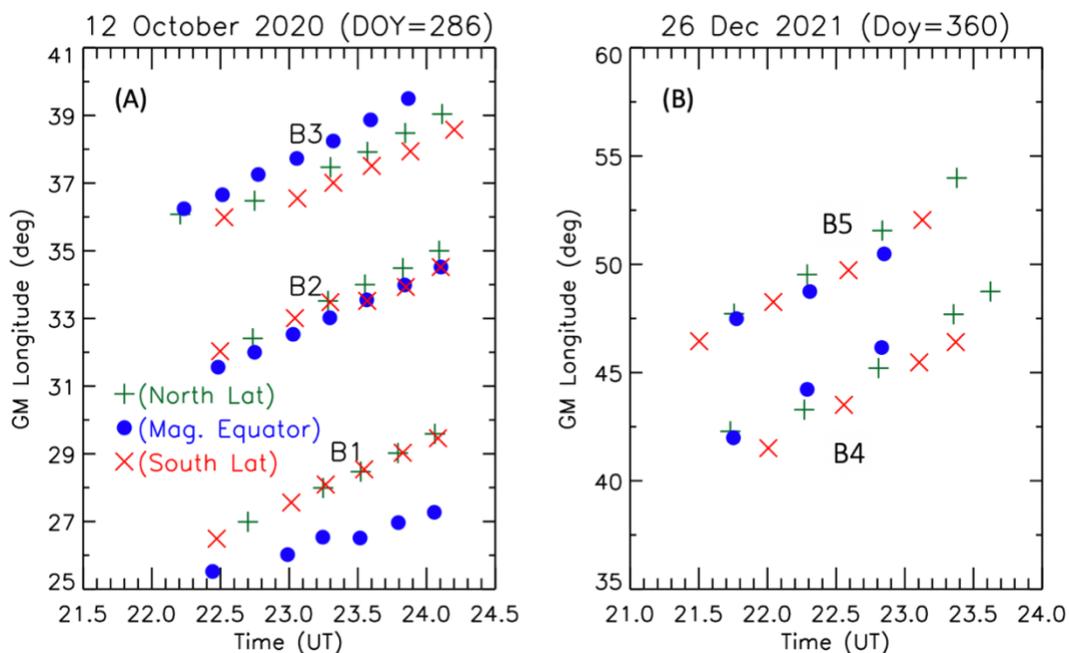


Figure 2. (A, B, C, and D) show the nighttime images observed by GOLD at 23:10, 23:25, 23:40, and 23:55 UT on 12 October 2020, respectively in geomagnetic coordinates. The green, blue, and magenta boxes mark the N- crest, magnetic equator, and S- crest of EIA latitudes (common on each panel).

174 2020, which are shown in Figure 3A. Following the same method, B4 and B5 longitudes on 26
 175 December 2021 are obtained and are shown in Figure 3B.

176 EPB longitudes obtained at the magnetic equator, N and S EIA crests latitudes are shown
 177 by blue dots, green plus, and red cross symbols, respectively in Figure 3. One of the advantages of
 178 the GOLD observations is that EPB locations are obtained multiple times. Earlier detection of B3
 179 at 22:10 UT is due to the GOLD imager's observation sequence from east to west following the
 180 sunset terminator. EPBs are developed at the geomagnetic equator and grow to higher altitudes
 181 and latitudes. Thus, EPBs are detected first closer to equatorial latitudes. All EPBs shift eastward
 182 with time at each latitude range. From the changes in the longitudes, EPB drift velocities are
 183 derived at the three latitude ranges and are listed in the table-1.

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Figure 3 shows EPB longitudes at different times of observations on (A) 12 October 2020 and (B) 26 December 2021. Blue dot, green plus, and red cross symbols indicate to longitudes as obtained at the magnetic equator, N and S EIA crests latitudes, respectively.

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Table 1. EPBs' zonal drift velocities (m/s) at the magnetic equator, N and S EIA crest latitudes on 12 October 2020 and 26 December 2021. Positive drift velocities are eastward.

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Magnetic Latitude Zone	12 October 2020			26 December 2021	
	B1	B2	B3	B4	B5
N-EIA crest	65 ± 2	62 ± 4	57 ± 9	115 ± 20	123 ± 16
Equator	48 ± 6	62 ± 2	68 ± 4	125 ± 7	88 ± 14
S-EIA crest	62 ± 3	61 ± 5	52 ± 5	108 ± 3	104 ± 14

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193 From the EPB zonal drift velocities, it can be seen that for B1 and B5, the zonal drift
 194 velocities at the EIA crests are higher than at the magnetic equator which is consistent with their
 195 C-shape. Bubbles B3 and B4 show opposite behavior and higher drift velocities at the magnetic
 196 equator. On 12 October 2020, the drift velocities at both EIA crest latitudes decreased from west
 197 to east (B1 to B3), whereas increased at the magnetic equatorial latitudes. So, we calculated the
 198 inter-bubble separations at different observation times to better understand the connection between
 199 the drift velocities and EPBs shapes. Due to the lower zonal velocity of B1 (C-shape) at the
 200 magnetic equator and its location, west of B3, the separation of B1 from B3 increased from $\sim 11.1^\circ$
 201 to 12.8° during ~ 22.5 - 24.0 UT. On the other hand, B5 (C-shape) is east of B4. So, the separation
 202 between B4 and B5 decreased from $\sim 5.5^\circ$ to $\sim 4.3^\circ$ during ~ 21.8 - 22.8 UT. Therefore, if an EPB
 203 with higher zonal drift velocity at the magnetic equator is located near a C-shape EPB (moving
 204 slower at the equator), then it separates more or gets closer to the C-shape EPB depending on its
 205 location (whether to the east or west of the C-shape EPB).

206 At the EIA crests, where the electron densities are largest, we would expect larger ion drag
 207 forces and lower zonal wind speeds than at the magnetic equator. As a result, EPB zonal drift
 208 velocity would be lowered at these EIA crests than at the equator (Raghavarao et al., 1991; Martinis
 209 et al., 2001, 2003; Valladares et al., 2002) producing a reversed C-shape EPB (Huba et al., 2009).
 210 This is the case with B3 and B4. Since B2 did not reach the peak of the EIA crests, ion drag effects
 211 might not be too different at the three latitude ranges and hence, no latitudinal variation in the
 212 shape of B2 is observed. The ion drag force mechanism does not explain the formation of the C-

213 shape EPBs (B1 and B5), where the drift velocities at the EIA crests are higher than at the equator.
214 A possible mechanism for this could be due to the contribution of plasma flux tube integrated
215 neutral zonal wind and F region Pedersen conductivity (Aggson et al., 1987; Martinis et al., 2003;
216 Huba et al., 2009). A strong westward zonal wind in the lower F region producing an eastward tilt
217 at higher altitudes as reported by Huba et al., (2009) is another possibility for the C-shape EPBs
218 like B1 and B5. This is particularly important during post-sunset conditions when any potential
219 contribution from E-region could be important. Martinis et al. (2003) compared zonal drifts
220 measured near the magnetic equator and away from it. The results showed that early in the night
221 (~20:00 to 22:30 LT) when E-region contribution can be important, drifts near the equator were
222 slower than later when no significant E-region contribution exists. In the present case, the GOLD
223 imager scanned the C-shape B1 apex at about 23:15 UT (~20:00 LT) which was about 2 hrs past
224 the E-layer sunset. The C-shape EPB (B5) on 26 December 2021 was scanned at about 22:53 UT
225 (~21:15 LT) which was 2.5 hrs past the E-layer sunset. So, during these early nights the slower
226 zonal plasma drifts at the equatorial latitudes as suggested by Martinis et al., (2003) could have
227 caused the C-shape of B1 and B5.

228 While the above-mentioned observations and mechanisms may explain the C and reversed
229 C-shape EPBs, the occurrence of both shape EPBs within a small (~12° and ~6°) longitude range
230 is significant here. This indicates the existence of small spatial scale E-region density, electric
231 field, neutral wind variations, or a combination of them affecting the EPB shapes. Lower
232 atmospheric gravity waves or in-situ generated secondary gravity waves can cause small-scale
233 longitudinal variations in the E-region density (Mandal et al., 2019; Manju et al., 2023; Pallamraju
234 et al., 2016; Yoshimura et al., 2003). The other potential factor is the longitudinal variation of the
235 electric field. Before about 22 LT, the presence of a perturbation electric field associated with the
236 R-T instability contributes to the vertical as well as zonal movement of an EPB (Huba and Joyce,
237 2010). The upward movement of an EPB causes an increase in its latitudinal extent, as it maps
238 along geomagnetic field lines which can be seen for B1 and B2. The shorter latitudinal extent of
239 B2 indicates that the EPB did not rise to the heights above the dip equator as reached by B1 and
240 B3. This could be due to the prevalent ambient ionospheric-thermospheric conditions at the
241 longitude where B2 was generated. Small spatial scale variations (~3° longitude) in the daytime
242 equatorial electric fields have been reported (Karan and Pallamraju (2017). B1 and B3 are
243 separated by ~11.5° longitudes at 23:10 UT. Between the ~46 minutes LT, the ambient zonal and

244 vertical plasma drifts also change considerably (Fejer, 2011) which could affect the different EPBs
245 shapes. But, B4 and B5 are separated by $\sim 5.5^\circ$ longitudes (which is ~ 22 minutes). So, the
246 difference in the ambient zonal and vertical plasma drifts may not be significant. Contributions
247 from the longitudinal variations of the zonal neutral winds cannot be ruled out. We observed that
248 over the magnetic equatorial latitudes, the zonal plasma drifts are slower at the longitudes of B1
249 and B5 as compared to the longitudes of other EPBs (see Table-1). Further, the zonal plasma drifts
250 depend on both E and F region conductivities and neutral zonal wind shears; both vary in altitude
251 and latitude. The post-sunset prereversal enhancement (PRE) strength (Haerendel et al., 1992)
252 changes the shear altitude which affects the EPBs shape. So, longitudinal variations in PRE-
253 strength could also have contributed to forming the observed EPB shapes. Overall the dynamics
254 of the EPBs are quite complex, particularly in the initial phase after their development. So, the
255 different shapes at such a small longitude range could be due to the combined effect of the factors
256 mentioned above.

257 On 12 October 2020, the EPBs were observed close to the South Atlantic Anomaly (SAA)
258 regions. Because of particle radiation in the SAA, uncertainties in the ICON (Ionospheric
259 Connection Explorer) measurements are too large for them to be useful. On 26 December 2021,
260 ICON concurrent measurements were not available in the same spatial area of B4 and B5. One
261 potential effect that may be excluded is geomagnetic activity, since in both cases, the geomagnetic
262 conditions were quiet. Unfortunately, it is not possible to conclusively identify the mechanisms
263 responsible for the occurrence of different EPB shapes within a small longitude range. However,
264 observations reported in this study provide a challenge for numerical simulations and an
265 opportunity for advancing our understanding of the I-T system. Numerical simulation efforts are
266 required to understand such events. Considering the adverse impact of ionospheric plasma
267 irregularities on trans-ionospheric satellite communication and navigation, the present observation
268 needs immediate attention in the space science research community for further investigations.

269

270 **Conclusions:**

271 The C-shape and reversed C-shape EPBs have been observed previously. However, in this paper,
272 we report two cases when NASA's GOLD imager observed these differently shaped EPBs within
273 $\sim 10^\circ$ longitudes which have not been reported before. Three consecutive EPBs with C-shape,
274 straight, and reversed C-shape were observed within the $\sim 12^\circ$ longitude range over the eastern side

275 of South America on October 12, 2020. In another case on 26 December 2021, a reversed C-shape
276 and C-shape EPB were observed within the $\sim 6^\circ$ longitudes over the Atlantic sector. These are
277 observed close to the crossing of geographic and geomagnetic equators and, close to the
278 subsatellite point of the GOLD imager. The calculated EPB drift velocities at the magnetic equator
279 and EIA crest latitudes are different which could be due to the latitudinal variations of the zonal
280 wind speeds that drive their motions. Also, the inter-bubble separations corroborated these
281 findings. Further, different EPBs' shapes in such small longitude ranges indicate small-scale
282 longitudinal differences in the E-region density, electric field, neutral wind variations, or a
283 combination of them. These rare and unique observations are crucial for a better understanding of
284 plasma irregularities and provide a challenge for numerical simulations to advance our
285 understanding of the I-T system.

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290

291 **Open Research:**

292 The GOLD LIC nighttime partial disk data presented in this paper (Level 1C – N11) can be
293 accessed at the GOLD Science Data Center (<http://gold.cs.ucf.edu/search/>). Please be sure to read
294 the GOLD data release note Rev 4.6 ([https://gold.cs.ucf.edu/wp-](https://gold.cs.ucf.edu/wp-content/documentation/GOLD_Release_Notes_Rev4.6.pdf)
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