GOLD Observations of Equatorial Plasma Bubbles Reaching Mid-Latitudes During the 23 April 2023 Geomagnetic Storm

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Key Points:

- Maximum poleward shift (~11°) of EIA crests was observed between ~15°W-5°W Glon coinciding with a penetration electric field
- Reversed C-shape Equatorial Plasma Bubbles (EPBs) extended to ~$\pm$36° Mlat (~40°N and ~30°S Glat) with apex altitudes reaching ~4000 km
- EPBs at midlatitudes showed large westward tilts and zonal drifts that were quantified as a function of apex heights

Key Words: NASA GOLD mission, Geomagnetic storm, Equatorial Ionization Anomaly, Equatorial Plasma Bubble, Nighttime ionosphere, Extreme EPB, Super Plasma Bubbles

Abstract

A coronal mass ejection (CME) erupted from the Sun on 21 April 2023 and created a G4 geomagnetic storm on 23 April. NASA's Global-scale Observations of the Limb and Disk (GOLD) imager observed bright Equatorial Ionization Anomaly (EIA) crests at ~25° Mlat, ~11° poleward from their average locations between ~15°W-5°W Glon. Reversed C-shape Equatorial Plasma Bubbles (EPBs) were observed reaching ~±36° Mlat (~40°N and ~30°S Glat) with apex altitudes ~4000 km and large westward tilts of ~52°. A latitude shear in the EPBs zonal motion was observed, with eastward motion near the equator and westward at mid-latitudes. Prompt penetration electric fields affected the postsunset pre-reversal enhancement at equatorial latitudes while disturbance dynamo-induced westward neutral winds and perturbed westward ion drifts over mid-latitudes contributed to the observed latitudinal shear in zonal drifts.

Plain Language Summary

A severe geomagnetic storm occurred on 23 April 2023. The effects of the storm on the nighttime equatorial and mid-latitude ionosphere are investigated using NASA's Global-scale Observations of the Limb and Disk (GOLD) measurements. GOLD observed bright, widely separated Equatorial Ionization Anomaly (EIA) crests between ~15°W-5°W Glon. Extreme Equatorial Plasma Bubbles (EPBs) reaching mid latitudes at ~40°N and ~30°S Glat with apex altitudes of ~4000 km at the magnetic equator were observed over these longitudes. The EPBs velocities were eastward at low latitudes, between the EIA crests, and reversed to westward near mid-latitudes. At mid-latitudes EPBs showed westward tilts that were larger than previous observations during similar geomagnetic conditions.

1 Introduction

The characteristics and variations of the Equatorial Ionization Anomaly (EIA) depend on several factors, including neutral winds, tides, electric fields, magnetic declination, pre-reversal enhancement (PRE), ion production and loss rates, and the subsolar point location (Eastes et al., 2023 and references therein). Other features observed in the same region are Equatorial Plasma Bubbles (EPBs), which are linked to factors like neutral winds, electric fields, conductivities, and plasma density, as noted in Karan et al., (2020, 2023b).

During quiet geomagnetic conditions, zonal drifts at the magnetic equator are eastward near the peak F region and slower at higher and lower altitudes. This causes the EPBs to shift westward at higher apex altitude and the EPB appear to be a reversed C-shape structure (Karan et al., 2020; 2023a; Kil et al., 2009; Martinis et al., 2003; Zalesak et al., 1982). Using data form an all-sky imager at Ascension Island (~14^{o}W Glon, ~8^{o}S Glat, ~18^{o}S Mlat), Mendillo and Tyler (1983) formulated a relationship between the EPBs westward tilt and the local time, showing that the tilt increased as the night progressed.

Geomagnetic storms alter winds and electric fields through prompt penetration electric field (PPEF) (Kelley et al., 2003) and disturbance dynamo electric fields (DDEF) (Blanc and Richmond, 1980; Fejer et al., 1979), thereby changing the EIA morphology (Abdu et al., 1991, 1995; Balan et al., 2018). Sometimes the electron density at night in the EIA crests latitudes increases due to the penetration of an eastward disturbance electric field (Takahashi et al., 1987; Balan et al., 2018). Furthermore, storm-generated equatorward winds can move up ionospheric layers to higher altitudes, where recombination occurs more slowly, resulting in larger EIA peak densities that decay more slowly (Lin et al., 2005). During storms, the EIA may expand polewards, displacing the crests to mid-latitudes. Karan et al., (2023a) observed an 8^{o}-10^{o} poleward shift of post-sunset EIA crests during a storm, attributed to an enhanced PRE driven by an increase in eastward PPEF, corroborated by ionosonde measurements that showed an increase in the height of the peak electron density, hmF2.

Geomagnetic storms can either promote or hinder the formation of EPBs (Aarons et al., 1991; Abdu et al., 1995; Cherniak & Zakharenkova, 2022; Martinis et al., 2005; Kil et al., 2016; Patra et al., 2016;). During some storms, the PRE is intensified, causing EPBs to ascend to higher apex altitudes with field lines reaching latitudes around ~30-40^{o} Mlat (Aa et al., 2018, 2019; Martinis et al., 2015; Rajesh et al., 2022; Huba et al., 2023; Sousasantos et al., 2023). Zonal drifts at low and mid latitudes can become westward due to the disturbance dynamo westward neutral winds (Sutton et al., 2005), equatorward expansion of subauroral ion drifts (Ferdousi et al., 2019), or the influence of traveling ionospheric disturbances (TIDs) (Aa et al., 2019). These westward drifts can increase the EPBs' westward tilt but this has not been quantified under perturbed geomagnetic conditions.

In this work, we investigated the poleward expansion of EIA and reversed C-shape EPBs extending to mid-latitudes between ~15°W-5°W Glon during the 23 April 2023 geomagnetic storm, using NASA's Global-scale Observations of the Limb and Disk (GOLD) images. Relationships between the EPB's westward tilt and zonal drifts with apex altitude are established.

2 Data

This study utilizes nighttime partial disk images from the GOLD imager, situated in a geostationary orbit at 47.5°W, featuring two identical and independent channels (A and B, CHA and CHB hereafter), capturing FUV wavelengths (~132-162 nm). The instrument and its observations are detailed in Eastes et al., (2017, 2019, 2020) and McClintock et al., (2020). The nighttime OI 135.6 nm emission is produced by recombination of atomic oxygen ions and electrons in the Earth's ionosphere. Since the emission rate varies approximately as the square of the electron density, it maximizes at the peak F layer which is assumed to be 300 km. GOLD takes images across the American, Atlantic, and West African longitudinal sectors between 19 and 22 LT.

Solar wind parameters, geomagnetic indices, and modeled ionospheric PPEF (Manoj and Maus, 2012) are used to provide context for the GOLD observations. Zonal ion drifts from a Defense Meteorological Satellite Program (DMSP) satellite are compared with GOLD-inferred EPB zonal drifts.

3 Results

Figure 1 presents GOLD observations of the EIA and EPBs on the storm night, 23-24 April 2023. Images are selected to cover all the longitudes and to avoid repetition at similar longitudes. All the images during 23 April 20:10 UT to 24 April 00:25 UT are available as Movie-M1 in the supporting information. The images in the top row (panels A-D) illustrate that the EIA crests are brighter, and EPBs, represented by dark bands extending through the EIA crests, are observed at longitudes to the east of ~ 30° W, while no EPBs are seen to the west of ~30° W (panels E-H). All the EPBs exhibit significant westward tilts on both hemispheres.

The geomagnetic conditions on 22-23 April 2023 are shown in Figure 2. Solar wind parameters are in panels A (magnetic field IMF Bz and electric field IEF Ey) and B (solar wind

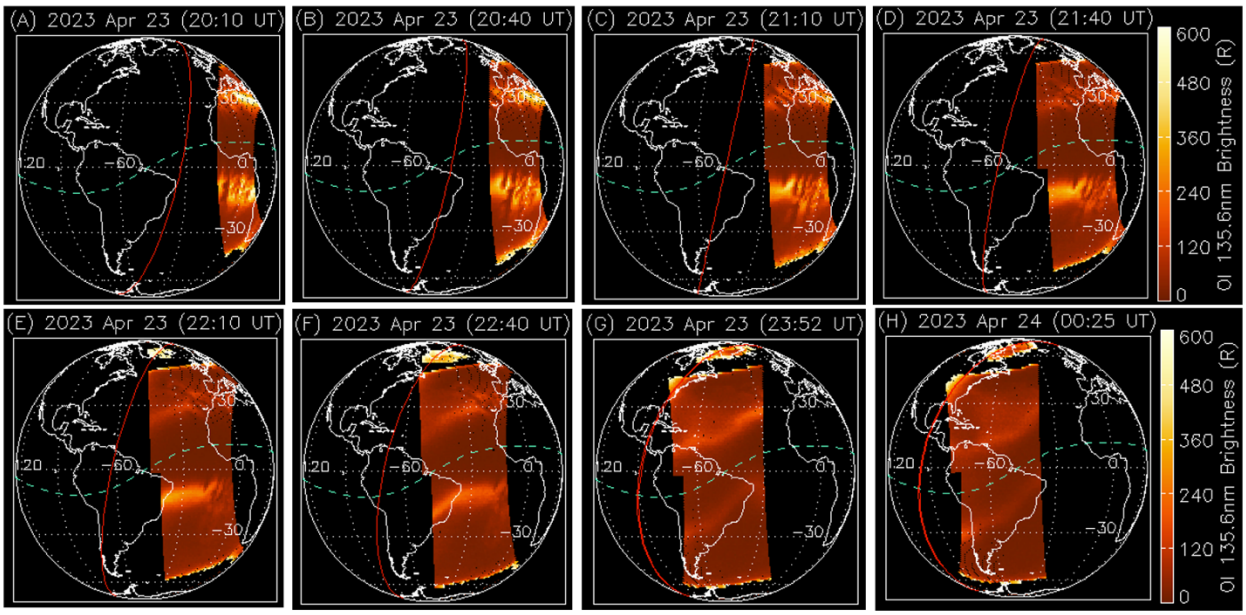

Figure 1. Nighttime 135.6 nm images captured by the GOLD imager on April 23-24, 2023. Highlighted are selective images covering all longitudes monitored by GOLD. The dashed green line and solid red line represent the geomagnetic equator and the sunset terminator, respectively.

proton density and speed). Panel C displays the equatorial geomagnetic index (SYM-H). The thick red line at the bottom of panel C indicates the times of GOLD's observations. The main phase of the storm commenced around 09:00 UT on 23 April and persisted until ~05:00 UT, when SYM-H reached a minimum value of ~ -220 nT. About 11 hrs after the initiation of the main phase, GOLD nighttime observations started as the SYM-H reached a minimum value of ~175 nT. At about 18 UT, Bz changed suddenly (density and speed also changed), reaching ~22 nT and maintaining this level for ~2 hrs. The 18-20 UT time range corresponds to post-sunset times in the longitudes ~15°W-5°E. These conditions led to the penetration of an E-field into equatorial latitudes.

To investigate the geomagnetic storm's effect on the EIA crests latitude values, we obtained the crests latitudes on the storm night (23-24 April). Panel A in Figure 3 displays the average and standard deviation of EIA crests latitudes (N in red and S in blue) obtained from all the images, following the method described in Eastes et al., (2023). Larger standard deviations, particularly near ~15°W, are a result of increased uncertainties during the calculation of EIA crests locations in the presence of EPBs. The red and blue solid lines indicate the average EIA crests latitudes during the previous geomagnetic quiet days (18 to 22 April). On the storm night, the EIA crests extended furthest between ~15°W-5°W Glon, with the N and S crests at ~27° and ~25° Mlat,

respectively. Panel B illustrates the differences between the storm night EIA crest latitudes and the quiet time average values. Maximum poleward shifts of ~11° and 9° in the N and S EIA crests

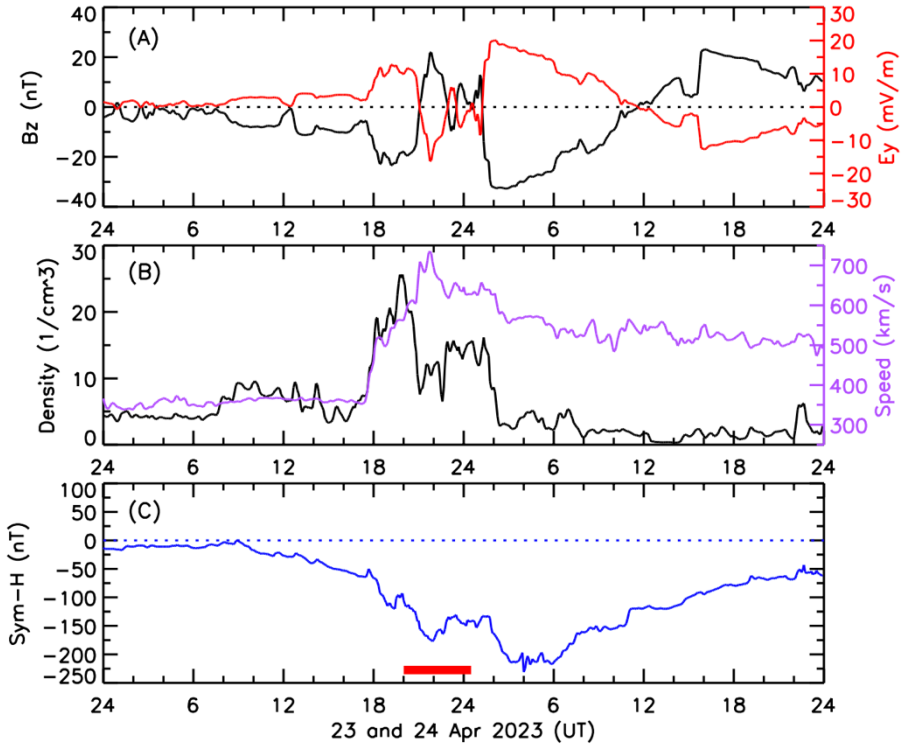

Figure 2. Solar wind parameters and geomagnetic indices on 23-24 April 2023. (A) IMF Bz and IEF Ey; (B) proton density and plasma flow speed, and (C) Sym-H. The thick horizontal red line indicates the timing of GOLD observations.

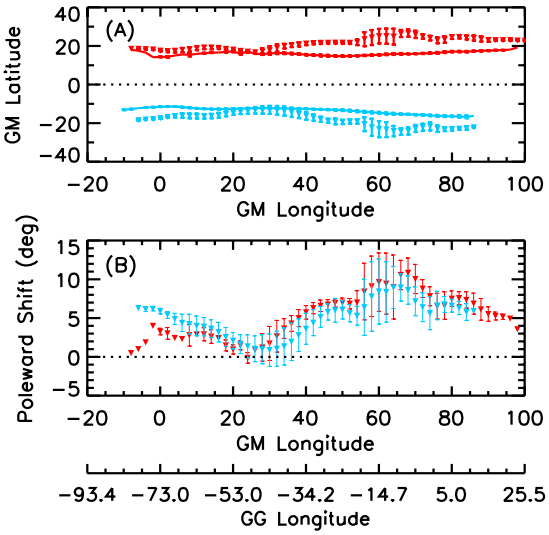

Figure 3. (A) EIA crests latitudes, North (red) and South (blue). 23 April shown as dashed lines and quiet time average as solid lines; (B) Relative shifts in EIA crests latitudes on 23 April 2023 compared to quiet time average with uncertainties.

were observed between ~15°W-5°W Glon.

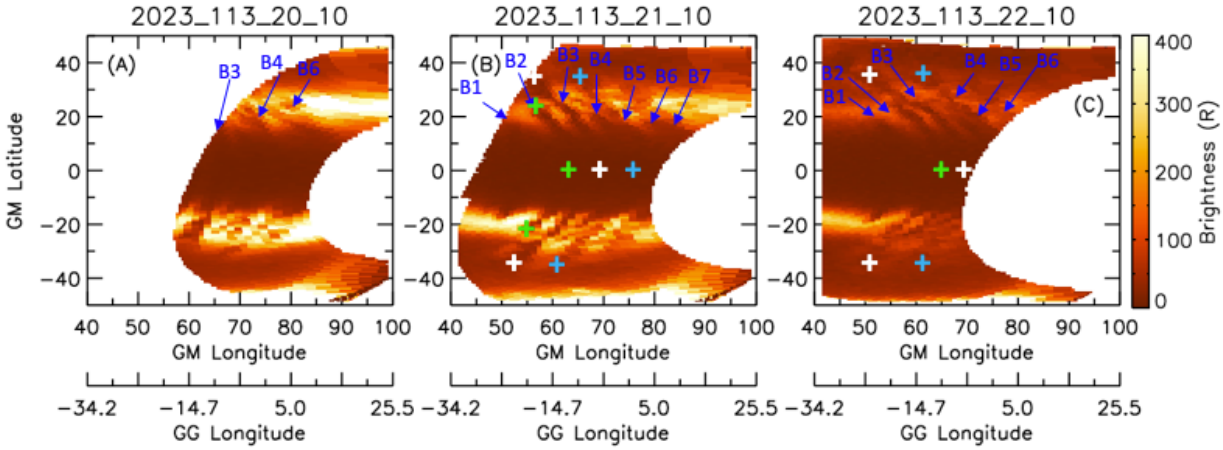

Figure 4. (A), (B), (C) combined CHA (N-hemisphere) and CHB (S-hemisphere) images at 20:10, 21:10, and 22:10 UT, respectively.

Panels A, B, and C in Figure 4 show the combined CHA and CHB images in quasi-dipole (QD) coordinates (Laundal and Richmond, 2017) at 20:10, 21:10, and 22:10 UT, respectively, encompassing seven EPBs (marked as B1 to B7) observed during this night. These EPBs exhibit a westward tilt relative to the magnetic meridian and extend poleward through and beyond the EIA crests. The foot points of B3 and B4 (indicated by white and cyan '+' symbols, respectively) extended beyond ~±36° Mlat (~40°N and ~30°S Glat) (panels 4B and 4C), implying structures with apex altitudes exceeding ~4000 km. Magnetic field lines were traced using the IGRF-13 model (Alken et al., 2021). EPB B2 appeared to merge with B3 at latitudes beyond the EIA crest (panel 4C). The time sequence of the behavior of EPBs is shown as a movie Movie-M2 in the supporting information. All seven EPBs were situated within ~15°W-0° Glon (~60° to 75° Mlon). For a clear view of EPB locations near the magnetic equator, where the brightnesses were lower compared to the EIA crests, panels 4A-C were replotted with a lower brightness scale in Figure S1 in the supporting information. The bubbles separation at the equator was ~5°, which increased to ~8° at the EIA crests latitudes.

The westward tilt angles of B2 and B3 at 22:10 UT are ~42° at ~16° Mlat, and ~52° at ~30° Mlat. These tilts can be related to altitudinal/latitudinal shears in the zonal plasma drifts. Thus, we tracked the EPBs drifts at several latitudes. The method for deriving EPBs' drift velocity is detailed in Karan et al., (2020). EPBs were moving eastward near equatorial and low latitude regions and

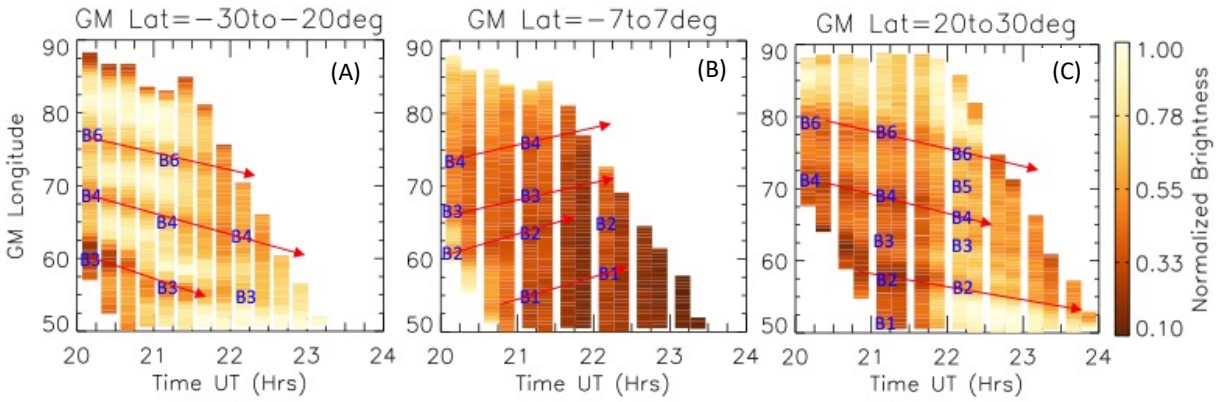

Figure 5. (A), (B), (C) longitudinal variations of normalized brightness obtained at different times as keograms for 30°-20°S, 7°S to 7°N and 20°-30°N latitude ranges, respectively.

westward at latitudes higher than ~±20° Mlat. Keograms in Figure 5 illustrate this behavior. Three magnetic latitude ranges, 30°-20°S, 7°S-7°N, and 20°-30°N were selected. In an image (at a fixed UT), within 30°-20°S latitude range, the brightness at each longitude is averaged to obtain the longitudinal variations of the brightnesses at that UT. To enhance visibility of the EPBs against the varying background brightness, the brightness array was normalized to a maximum of 1. This process was repeated for all the images, and the results were coplotted as a keogram in panel 5A. Same method is followed to obtain keograms for 7°S-7°N and 20°-30°N, shown in panels 5B and 5C, respectively. Different time gaps between the longitudinal stamps in the keograms are due to varying latitudinal coverage of the images. EPBs longitudinal shifts are shown by red arrows. The average zonal drifts of all EPBs during the observation periods is 120±15 m/s eastward within the 7°S-7°N latitudes (panel 5B), whereas within the latitude range of 20°-30°N and 30°-20°S, they reversed and are 70±3 and 85±4 m/s westward, respectively.

4 Discussion

On 23 April 2023, we observed maximum poleward shifts of ~11° in the northern and ~9° in the southern hemisphere EIA crests in between ~15°-5°W Glon. In the same longitude sector, reversed C-shape EPBs extending poleward beyond ±36° Mlat (~40°N and ~30°S Glat) were detected. The poleward shifts of the EIA crests are similar to the ones reported by Karan et al., (2023a) at a larger longitude range of ~65°-35°W Glon, during a geomagnetic storm weaker than the one on 23 April 2023. The ionospheric response in that study showed that the peak altitude of the ionospheric hmF2 layer increasing over those longitudes. The number of EPBs also increased, as on 23 April 2023, but now the morphology shows extreme characteristics.

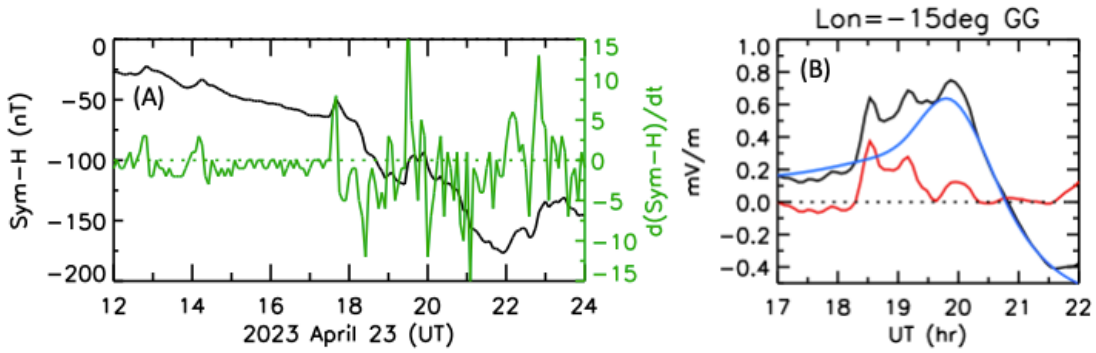

Figure 6. (A) Sym-H index in black and d(Sym-H)/dt in green during 12 to 24 UT on 23 April; (B) modeled total zonal electric field (black), PPEF (red), and quiet time electric field (blue) at 15°W Glon on 23 April.

The maximum poleward shifts of the EIA crests latitudes in between ~15°-5°W Glon (Figure 3) is likely due to an enhanced PRE (Abdu et al., 1991; Balan et al., 2018), This enhancement could be due to a penetration electric field. Sym-H and its rate of change, d(Sym-H)/dt, are shown in panel A of Figure 6. The rate of change of Sym-H showed a large negative excursion at ~18:30 UT with a maximum value of ~ -12 nT/5 min (~ -144 nT/hr). The sudden change in IMF Bz at ~18UT (panel 2A) and the sharp decrease in Sym-H at ~18-19 UT suggest a prompt penetration of an eastward electric field into the equatorial and low latitudes at this dusk sector (~15°W Glon) due to under-shielding conditions (Fejer et al., 1979). In the absence of electric field measurements over this longitude sector, the electric field model developed at Geomagnetism, CIRES (Cooperative Institute for Research in Environmental Sciences) (Manoj and Maus, 2012) was used. This model has been applied in other studies (Aa et al., 2019; Karan et al., 2023a; Spogli et al., 2021). Panel B shows the quiet time, prompt penetration (PPEF), and total electric fields in blue, red, and black lines, respectively. PPEF between ~18:15-20:15 UT contributed to ~2 hr extended PRE (peak value ~0.7 mV/m at ~20 UT). The maximum poleward shift in the EIA crests latitudes observed an hour after the peak PRE could be due to the transport time of plasma from equator to EIA crests (Karan et al., 2016, Karan and Pallamraju, 2020). A zonal electric field of ~0.7 mV/m produces an upward drift of ~32 m/s at this longitude. The PRE duration was ~1hr in the previous quiet days. For the mid latitude EPBs reported by Aa et al. (2019), the model total electric field was 0.9 mV/m with a duration of ~1hr. The longer duration

PRE in the present case (~2 hrs) could have enhanced plasma drift shifting the EIA crests further poleward.

The long-duration PRE is also an important factor for the generation and maximum altitude of the EPBs. At 20:10UT, just one hour after the sunset, GOLD detected a well-developed EPB B3 already reaching an apex altitude of ~2000 km (Panel A in Figure 4). This implies that the EPBs had upward drifts of ~500 m/s, an unusually large value that, has rarely been reported in the past. For example, upward drifts ~1200 m/s were measured by Abdu et al. (2008), between 100-1000 m/s by Aggson et al., (1992), and ~1200 m/s by Hysell (1994). While we have no means to effectively measure the upward drift, some inferences can be made from the poleward motion of EPBs as observed by GOLD. By measuring the poleward motion of B1, B2, B3, and B4 between 18^{o}-24^{o} Mlat an average speed of ~130 m/s is obtained, which is similar to ~110 m/s reported in Martinis et al., (2015) who investigated EPBs reaching midlatitudes. This poleward drift can be interpreted as a vertical drift near the magnetic equator with an eastward electric field of ~3.3 mV/m. In the present case, the long-duration PRE could have moved the F layer to high altitudes and caused the generation of EPBs with deep density depletion.

Along with the expansion of the EPBs to higher altitudes/latitudes, their drift directions changed from eastward (near the magnetic equator) to westward (at latitudes higher than ~$\pm 20^{o}$ Mlat) (Figure 5). The latitude where the EPB drifts reversed can be investigated by plotting the keograms in 5^{o} latitude ranges, shown in Figure 7. Panels 7A (10^{o}-15^{o}N) and 7G (10^{o}-15^{o}S) show that, at ~ 22 UT EPB's longitude shift with time becomes flat when compared to the variation within 7^{o}S to 7^{o}N latitude range (panel 5B). This indicates that the EPBs drifts slowed down from equatorial to low latitude regions. The reverse in EPBs' longitude shift direction with time around

±20º Mlat indicates that EPBs motion changed from eastward to westward close or below this latitude.

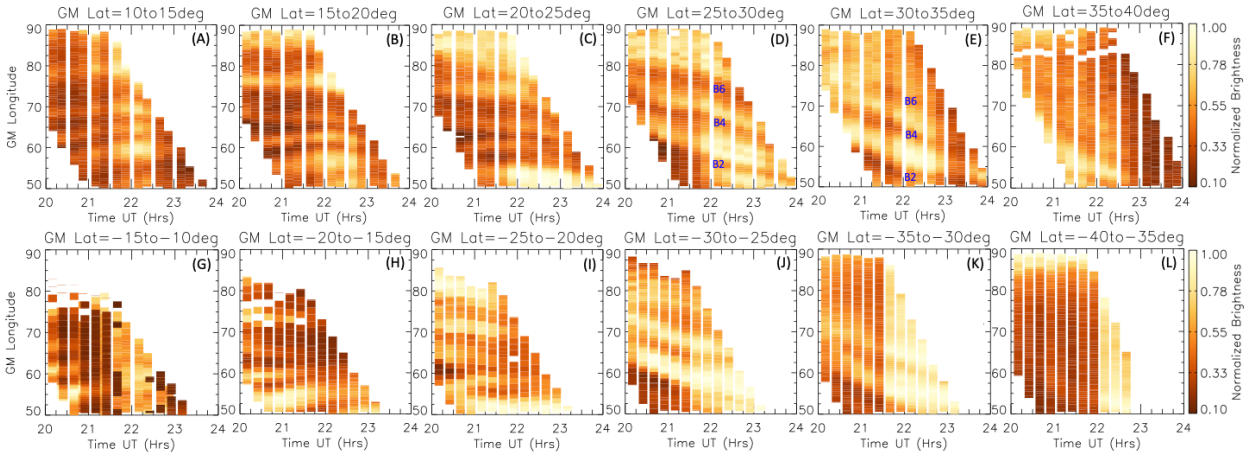

Figure 7. Same as Figure 5 (Panels A-C but at 5º latitude ranges. The transition in the EPBs eastward motion at equatorial and low latitudes to westward at mid latitudes can be seen close to ±20º Mlat, between panels B-C and H-I.

The reduction and reversal of eastward drifts from low to midlatitudes has usually been related to disturbance dynamo effects on zonal winds (Blanc and Richmond, 1980; Fejer et al., 1979; Sutton et al., 2005). Recently, Huang et al., (2021) show subauroral polarization streams (SAPS) effects reaching low latitudes. Figure 8 displays the net change (or difference) in zonal ion drifts between the storm and a quiet day (22 April), used as reference, as measured by DMSP F17. Panel 8a shows the difference in zonal ion drifts between 23 and 22 April. DMSP F17 observations at 18:30 LT at certain longitudes is interpolated for other UTs. Panel 8b shows the values at 18 and 19UT, which correspond to longitudes ~7.5ºE and ~7.5ºW on Apr 23, where westward tilted EPBs were observed. Reductions of ~30 m/s, ~60 m/s, and ~100 m/s at ~0º, ~15º, and ~30º Mlat, respectively, were observed. The westward drifts of ~800 m/s and ~500 m/s at subauroral latitudes of ~55º N and ~55º S indicate SAPS effects, potentially penetrating to middle and low latitudes, contributing to the westward drifts measured. Utilizing GOLD observations, we calculated the difference in EPBs' zonal drifts between 23 and 22 April. A reduction of ~90 m/s in EPBs' zonal drifts was identified at ~15º Mlat and ~7ºW Glon (location of B3) around 19 UT, result that is similar with the DMSP reduction observed at ~15º Mlat (60 m/s). Thus, the reversal of EPBs' zonal drifts, transitioning from eastward at low latitudes to westward at middle latitudes, as

observed by GOLD, agrees with the latitude profile of the difference in zonal plasma drifts measured by DMSP.

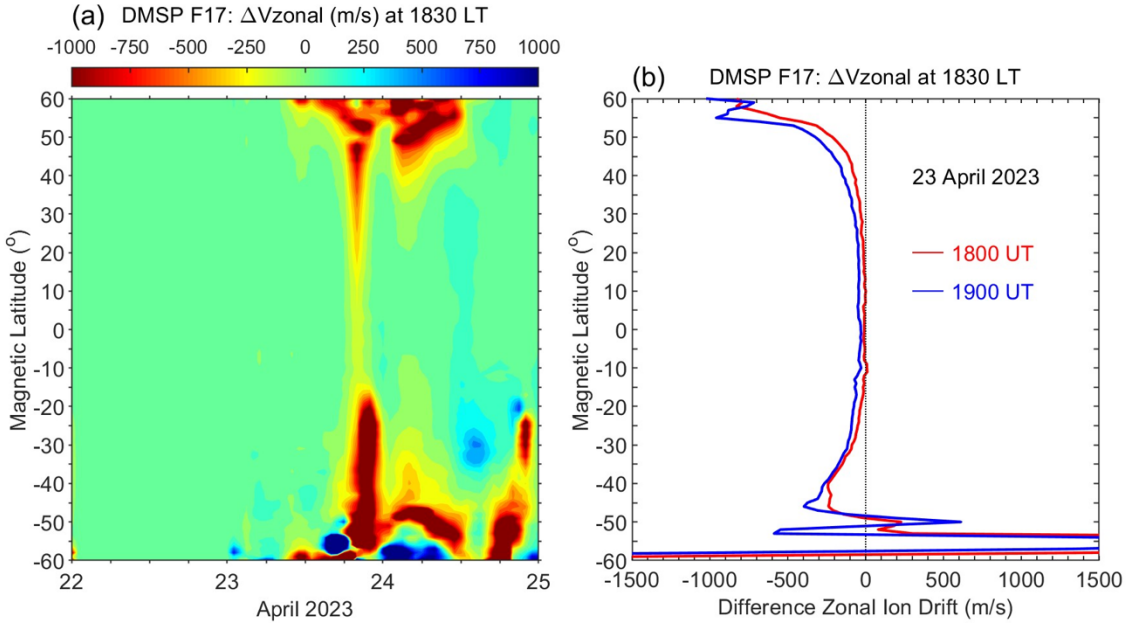

Figure 8. (a) Difference zonal ion drifts measured by the DMSP F17 satellite at ~18:30 LT considering April 22 as a reference and (b) Latitudinal profile of the difference zonal ion drifts at 18 and 19 UT.

As mentioned earlier, the EPBs appeared as reversed C-shape structures, related to their westward tilts. GOLD measures EPBs in a latitude and longitude plane, off the magnetic equator, at a fixed height of 300 km. Focusing on bubble B3 the tilt seems to change with latitude. At 22:10 UT around 35ºN Glat (~30º Mlat) and 25ºN Glat (~16º Mlat) the tilts are ~52º and ~42º westward. Considering that the magnetic declination at these locations are ~5º and 1.5º, then B3 is tilted ~47º and ~40.5º with respect to (w.r.t.) the magnetic meridian. Bubble B2 shows a tilt of 40º, or ~37º w.r.t. the magnetic meridian. In comparison, the westward tilt w.r.t. magnetic meridian from Aa et al., (2019) were ~25º and ~11º at similar magnetic latitudes and from Martinis et al., (2015), it was ~22º at ~30º Mlat. Geomagnetic conditions were similar, with Sym-H reaching ~ -110 nT in these studies. Because EPBs exhibit a plasma flux-tube nature along the magnetic field lines, an alternative method for measuring tilt involves mapping them into the magnetic equatorial plane. This representation depicts an EPB in an altitude-magnetic longitude plane, where altitude corresponds to the field line's apex height, and is linked to the magnetic latitude at the field line's

footpoint. In this plane, B3 reaches ~36° Mlat with a break or kink in the shape of the bubble between ~24-25 ° Mlat. The westward tilt for the upper portion of B3 is ~25 ° and for the lower part ~32 °. B2 reaches ~25° Mlat with a westward tilt of ~34°.

Mendillo and Tyler (1983) (M&T) used this approach to quantify the EPBs westward tilt (W) as a function of local time as observed from Ascension Island using gound-based imaging. The apex altitudes they observed ranged from 400-1200 km. For the relatively geomagnetic quiet conditions prevalent during their observations, they found:

$$W = 0.15\ (LT-18.3) \qquad (1)$$

W is the westward shift in degrees of magnetic longitude per 100 km in apex altitude. Applying this formula to EPBs B2 and B3 of Figure 4, we obtain W = 0.43. Expressed as the angle between the orientation of the EPB and the magnetic meridian, this becomes 23°.

We next compare this result with the measured tilt values of B2 and B3. At 20° Mlat B3 has $W_{B3l} = 0.63$ (corresponding to a tilt angle of 32°), while at 30° Mlat B3 has $W_{B3u} = 0.47$ (corresponding to 25°). For B2, which does not extend much past 25° Mlat, $W_{B2} = 0.67$ (corresponding to 34°). Since the GOLD observations occurred during a geomagnetic storm, it is not surprising that the westward tilts exceed those observed by M&T. Both studies found EPBs with westward tilts. Under storm conditions, however, we observe nighttime zonal drifts at low and mid latitudes that display a reduction or even a reversal of the typical eastward motion to westward. Consequently, EPBs observed during storm conditions may exhibit a more 'compressed' reversed C-shape, which is precisely what GOLD is measuring.

If the westward tilt increases linearly following equation (1), M&T obtained an expression for the altitude dependence for an effective westward drift, or reduction in the overall eastward drift, V'(h) as

$$V'(h) = 0.0464(1+h/R_E) \qquad (2)$$

Where 0.0464, in (m/s)/km units, is the product of the slope, 0.15 (measured in degrees of magnetic longitude per 100 km vertical height) from (1), and a constant 0.31 (result of geometric factors used in the calculation). At 300 km V'(300) = 0.049 m/s/km. This value represents the shear in altitude of the zonal drifts from a height of 300 km. An eastward drift at 700 km apex height (12.5°

Mlat) would lag the drift at 300 km by 0.049*(700-300) ~ 20 m/s. Using an imager with a field of view of ~ 47° located in Maui, Hawaii, Makela and Kelley (2002) applied the M&T approach to EPBs and obtained an average shear value of 0.05 m/s/km. But when they calculated the shear by computing the velocities obtained at each height, a value of 0.1 m/s/km was obtained. This discrepancy was not explained.

Figure 9 shows the calculated EPBs' average zonal drift velocities for each of the latitude ranges (as shown in Figure 7) as a function of apex altitudes (or magnetic latitudes). Below ~1500 km apex height the larger slope (compared to heights above 1500 km) indicating a faster decrease (with latitudes) in the drift speeds. The average zonal drifts of the EPBs at apex altitudes close to 300 km (magnetic equator), 700 km, and 1000 km, are 120 m/s, 62 m/s, and 25 m/s, respectively. The transition from eastward to westward drift occurs around 1000 km (17.5° Mlat). According to (2) the transition height (where the lag is equal to ~120 m/s) should occur at ~2750 km, much higher than the height observed. Like the underestimation in the westward tilt W from (1), V' is also showing a weak altitude variation.

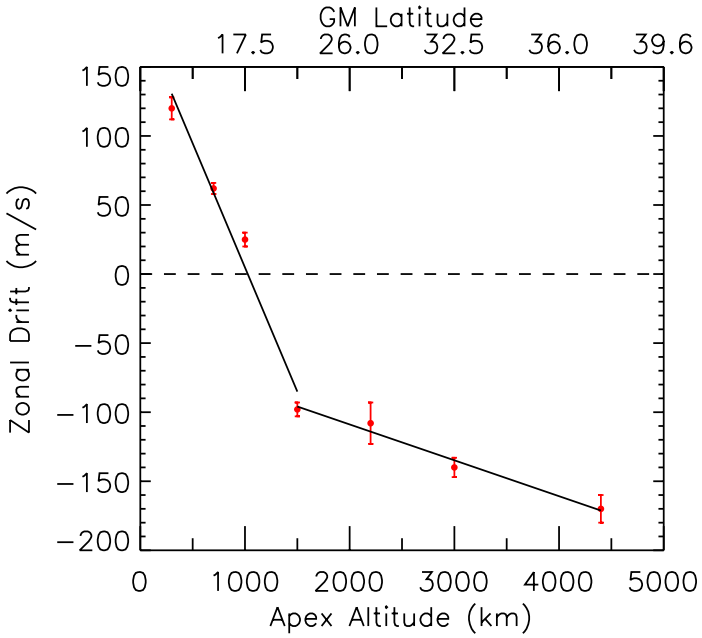

Figure 9. EPBs' average zonal drifts (m/s) for each latitude ranges (shown in Figure 7) with corresponding apex altitudes are shown. The transition from east to west occurred at ~1200 km (~20° Mlat).

The shear V'(300 km) for the GOLD data can be obtained from the slope of the fitted line to the data between 300 to 1500 km, shown in Figure 9. This slope is V'_{GOLDl} = 0.179 m/s/km. This shear can also be obtained by considering the average westward tilt of the EPBs measured in GOLD images. The westward tilt W_{GOLD} at 20^o Mlat can be calculated as the shift in magnetic longitude (5^o) divided by the extent of the bubble (920 km), equal to – 0.63. When this value is multiplied by 0.31, a shear of 0.195 m/s/km is obtained, close to the slope of the fitted curve in Figure 9. This result indicates a good agreement between the shears obtained by the two methods, something that was not observed in the Makela and Kelley (2003) study.

With these new shear values (0.179 and 0.195), drifts at 1000 and 1500 km will lag the drift at 300 km by 112 (136) m/s and 192 m/s (234), respectively. The drifts at these heights will be 8 (-12) m/s and -70 (-114) m/s. The transition from eastward to westward occur at the observed height range of ~1000-1100 km. The upper part of B3 shows a different shear V'_{GOLDu} = 0.026 m/s/km, so the height variation of the drifts is weaker, as seen in Figure 8. We can summarize the results that relate westward tilts and height variation of zonal drifts of B3 as:

W_{GOLDl} = 0.63
$Vel_{\_l}$ = 185 m/s - 0.179*h for h < 1500 km (3)

and

W_{GOLDu} = 0.47
$Vel_{\_u}$ = -57 -0.026*h for h > 1500 km (4)

Therefore, we obtained average expressions for the westward tilt and zonal drifts as a function of apex height. At lower altitudes, below ~1500 km, the height variation of zonal drifts is large, but above ~1500 km it proceeds at a smaller rate, but large westward drifts are measured. This indicates a different response of the ionosphere at low latitudes when compared to mid latitudes.

5 Summary

This paper investigated the EIA and EPB characteristics as observed by the NASA GOLD imager during the 23 April 2023 geomagnetic storm. The perturbed geomagnetic conditions prevailing on that night were responsible for the emergence of EPBs characterized by significant westward tilts and substantial latitudinal shears in the zonal drift velocities. The key findings are:

(i) Maximum (~11°) poleward shifts of both EIA crests latitudes and reversed C-shape EPBs were observed at ~15°-5°W Glon. A modeled eastward PPEF lasted for ~2hrs and extended the PRE, moving plasma to higher latitudes.

(ii) EPBs reached beyond ±36° Mlat (~40° N and ~30°S Glat), implying structures with apex altitudes exceeding ~4000 km. EPBs showed westward tilts of ~52° at ~30° Mlat and ~42° at ~16° Mlat, higher than previously reported cases under similar geomagnetic conditions.

(iii) EPBs zonal drifts showed a strong latitudinal shear, with eastward drifts of 120±15 m/s over equatorial latitudes and westward drifts of 70±3 m/s at N and 85±4 m/s at S EIA crests.

(iv) Inferred poleward drifts obtained by GOLD images were used to estimate an effective eastward electric field of ~3.3 mV/m near the magnetic equator.

(v) The reversal of EPBs' zonal drifts as observed by GOLD, agrees with the latitude profile of the difference in zonal plasma drifts measured by DMSP.

(vi) We obtained expressions for the westward tilt of EPBs and the apex height (or magnetic latitude) dependence of their zonal drifts. Results show a linear variation up to ~1500 km (~22.5° Mlat), with smaller shears observed at higher latitudes.

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Open Research

The GOLD data are available from the GOLD Science Data Center (https://gold.cs.ucf.edu/data/search/). The solar wind parameters and geomagnetic indices are taken from the NASA GSFC SPDF OMNI website

(https://omniweb.gsfc.nasa.gov/form/omni_min.html). Model ionospheric electric fields are obtained from (https://geomag.colorado.edu/real-time-model-of-the-ionospheric-electric-fields).

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