Mutual Evolution of Plasma Density and Temperature within Super EPBs

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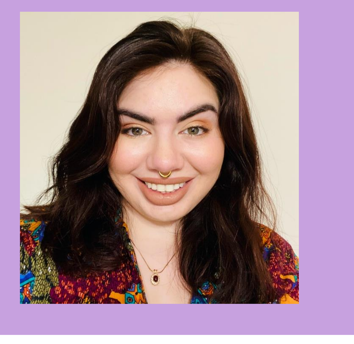

1) Introduction

Equatorial Plasma Bubbles (EPBs) are one of the most severe ionospheric phenomena regarding the creation of amplitude and phase scintillations of radio signals. Generally, EPBs remain close to the magnetic equator, not usually varying more than 15 to 20 degrees from it. **When EPBs extend into midlatitudes (greater than ± 25° Mlat), they are called Super Equatorial Plasma Bubbles (Super EPBs).** However, it is not known how often this phenomenon occurs or under what solar and geomagnetic activity conditions cause such an expansion and the scintillations they induce. In this analysis, we discuss our detection algorithm using Swarm and show a super EPB event that is analyzed using the Swarm satellite constellation, VISTA TEC, GOLD, and OMNI solar wind data to better understand the nature of Super EPBs.

2) Background

EPBs are regions usually in the low latitudes/equator where there is a depleted segment of plasma density in the ionosphere. They occur most often during the post-sunset (18-24 LT) and post-midnight (0-6 LT) hours, when the E-Region ionosphere is not present (Aa et al., 2020). Gravity waves, enhanced zonal eastward electric fields, neutral wind shear, and nighttime medium-scale traveling ionospheric disturbances (MSTIDs) have been suggested as seeding mechanisms for triggering plasma bubbles, which are thought to be **a result of the generalized Rayleigh-Taylor (R-T) instability** (Sultan 1996). The EPB is shown growing over time in Figure 1 (Yokoyama et al., 2014). The blue shows the low density, and the yellow shows the high density. A small perturbation can grow significantly because of an unstable equilibrium where lighter fluid tends to rise to the top of the heavier fluid. **The bubble then bifurcates into smaller structures called Equatorial Plasma Irregularities.**

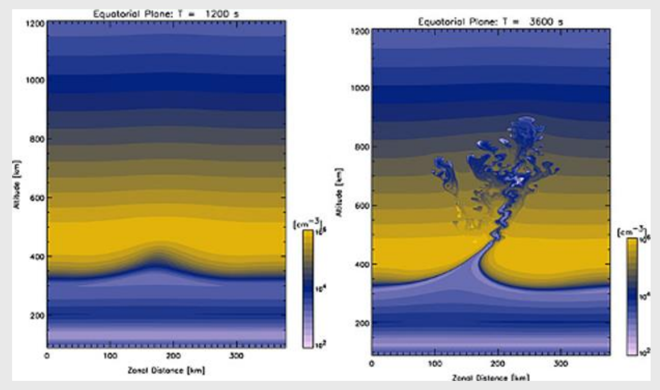

Figure 1. Simulation of the growth of an Equatorial Plasma Bubble (Yokoyama et al., 2014)

3) EPB Detection Algorithm

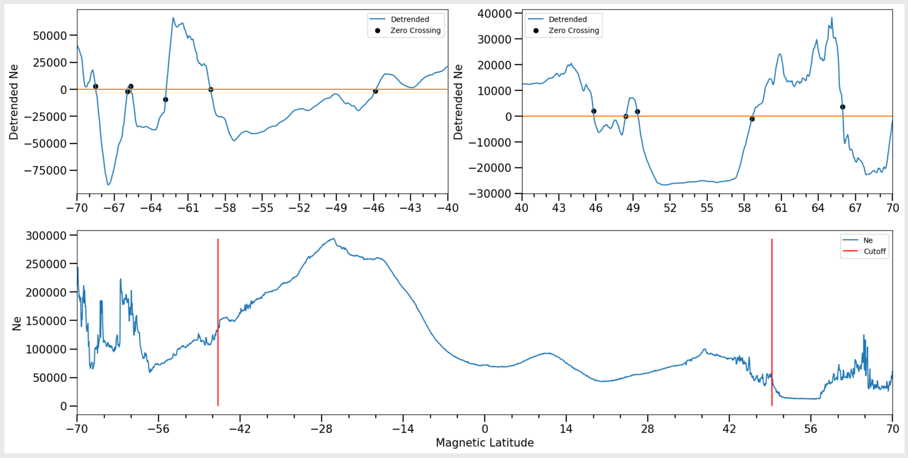

Figure 2: Example of midlatitude trough detection. Top panels show detection between ±70 and ±40 Mlat. Bottom panel shows full electron density span with trough cutoff (red lines)

i) Finding Midlatitude Trough Location

- Algorithm adapted from Liu and Xiong (2020)
- Trough search ranges from ± 70° to ±40° Magnetic Latitude (MLat)
- Use two moving averages to obtain the large-scale trend (320s) and remove the small-scale fluctuations (10s) and subtract the two
- "Zero crossings" are trough candidate locations
- Calculate depth of each zero point
- Look for a minimum depth of 40% on either side of a negative region
- **Using this method, we are looking to see if the trough extends below 50 MLat to limit our EPB search location shown in Figure 2**
- Next, we calculate the percentage of "bad" N_e values based on the provided flags and continue with passes that have < 5% "bad" data points

ii) Barrel Roll as a Detrending Method

- Detrend N_e using the methods described by Pradipta et al. (2015) and Wan et al (2024)
- Data treated as terrain for a barrel to roll over
- Barrel finds contact points using minimum angular distance within set radius
- 10 barrel sizes from largest to smallest 80 seconds (560 km to 640 km) to 8 seconds (56 km to 64 km) in a bidirectional rolling pattern
- Contact points are used to create an envelope
- Savitzy-Golay filter applied to data inside envelope
- **Final panel in Figure 3 shows the flipped detrended data so that the depletions are peaks**
- **We apply a 5 second moving average filter and use a peak finding algorithm to detect the EPBs**

iii) Detection Criteria

- For a peak to be considered a bubble, it's halfwidth must be at least 3 seconds and the prominence must exceed 10^4
- The 95th minus 5th percentile of Delta N_e during the halfwidth of the peak must exceed 5000 cm^{-3} to distinguish between depletions and artifacts of the barrel roll
- A bubble inside of another bubble is not considered
- The bubble width is limited to < 4° latitude
- Conservatively, any bubble within ± 1 minute of a "bad" N_e value is removed

iv) Traveling Ionospheric Disturbances (TIDs)

- Final check is to distinguish between TIDs and EPBs using the 50 Hz magnetic field data provided by Swarm
- Algorithm developed by Yin et al (2019)
- TID should have a fluctuation in the high pass filtered B field zonal direction of at least ± 0.2 nT fluctuation and should not have any fluctuations greater than 0.15 nT in the parallel direction (Yin et al. 2019) (Figure 3)
- They adapted a magnetic pulse check from Park et al (2013)
- **Once we have a confirmed list of TIDs, we can use that to remove any detections that may be TIDs instead of EPBs**

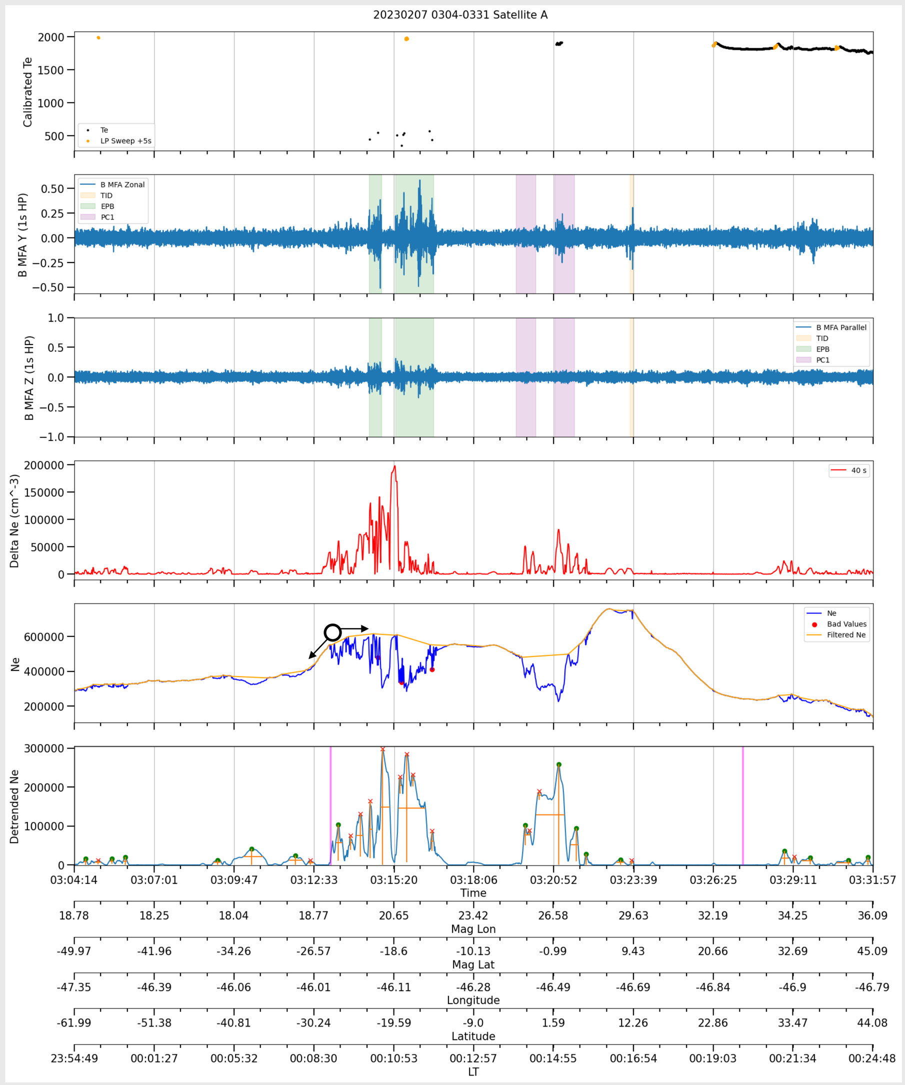

Figure 3: Example of detection algorithm on 07 February 2023 Swarm Satellite A. Panels (top to bottom): Calibrated electron temperature, magnetic field zonal direction, magnetic field parallel direction, change in electron density, electron density, and detrended/flipped electron density

If a detection meets all criteria, it is considered a bubble. Figure 3 shows confirmed detections (green circles). A few bubbles were removed (red exes) because of bad data, others because they were inside another detection, and one was removed as a TID. Based on Figure 3, it can be noted that we are removing some bubble events; however, being more selective ensures we are almost exclusively detecting bubbles.

4) 25 September 2023 EPB Event

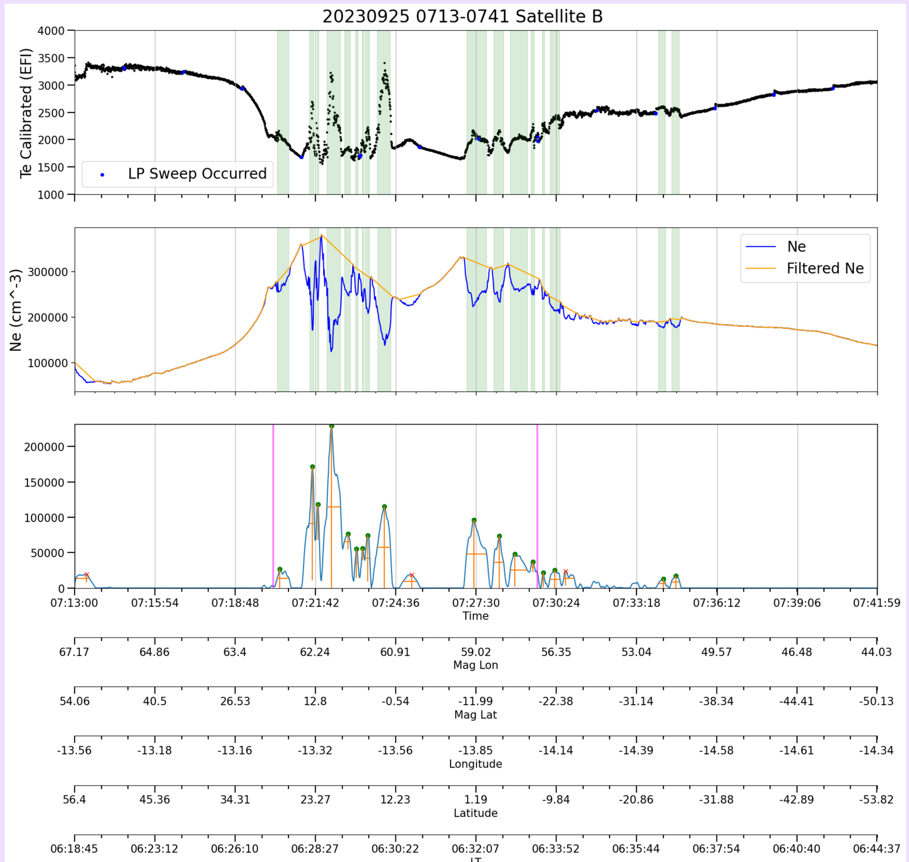

Figure 4: Swarm B EPBs for 25 September 2023: electron temperature, density, detrended density. Confirmed bubbles shaded in green

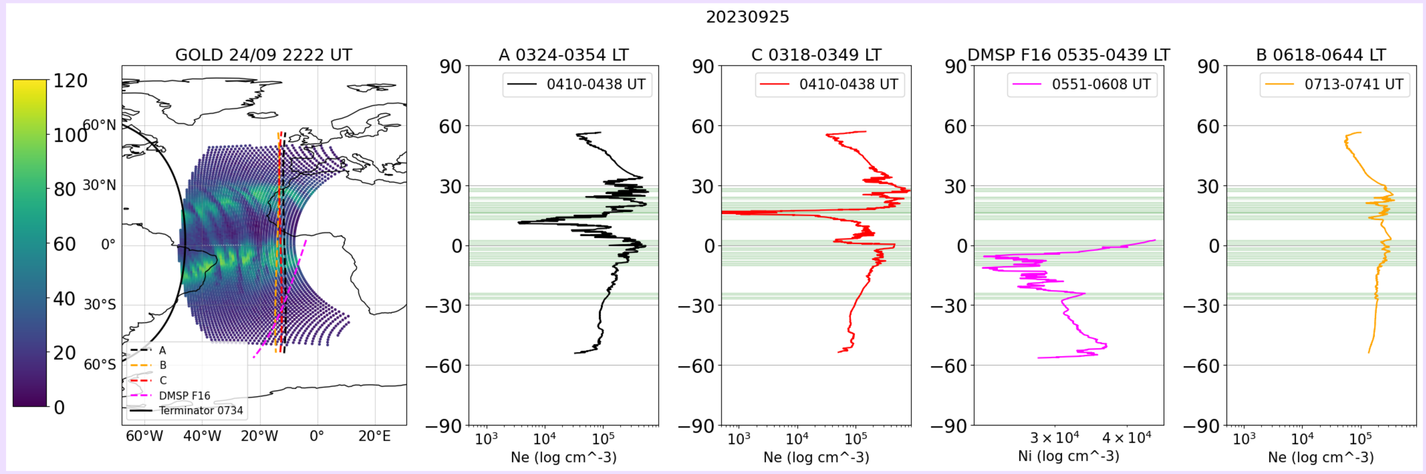

Figure 5: Maps showing GOLD electron density with trajectories for Swarm A, B, and C, and electron densities for Swarm A, C, DMSP F16, and Swarm B at different local times. Green shaded regions are confirmed bubbles in Swarm B

i) Bubble Detection

- Swarm B (511 km) passed over Dawn EPBs on 25 September 2023 (Figure 4)
- Super EPBs can be seen ~0636 LT and ~0735 UT Extending to -34° magnetic latitude at about -14° longitude
- **There is a distinct increase in the electron temperature within the density depletions**
- The presence of the EPBs seen in Swarm B is also seen by DMSP F16 at 830km altitude around 05 LT (Figure 5)
- **Swarm A/C also shows the presence of EPBs at the same longitudinal region but at earlier local times (around 3 LT)**
- GOLD emission shows multiple EPBs formed in this region around 22 UT, about 6 hours before Swarm B detection

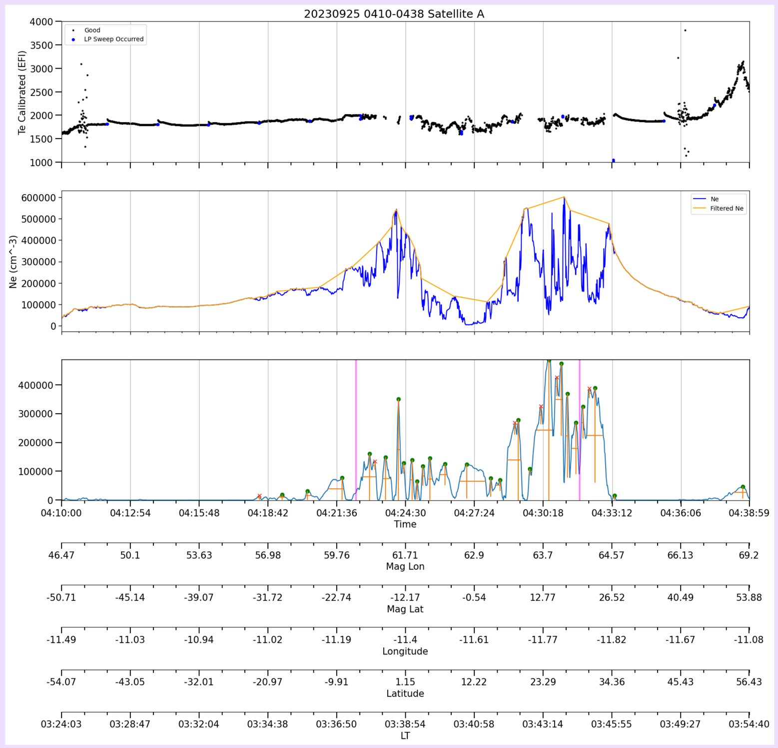

Figure 6: Swarm A EPBs for 25 September 2023: electron temperature, density, detrended density

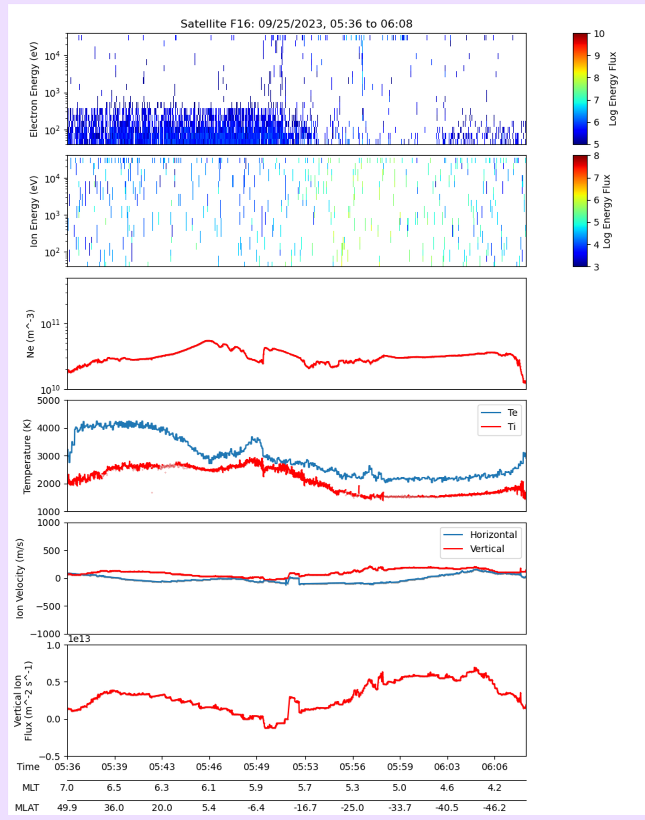

Figure 7: DMSP F16 electron energy, ion energy, N_e, T_e, ion velocity, and vertical ion flux

ii) Swarm A and DMSP F16 Measurements

- Swarm A passed about -11° longitude at 03:30 LT about 3 hours before B
- Evidence of super EPBs close to -30° magnetic latitude
- **First panel in Figure 6 shows no temperature increase for these EPBs**
- Figure 7 shows a hemispheric asymmetry in low energy electron precipitation
- No clear ion precipitation
- Bubbles shown in the dawn hours around the same location as Swarm B
- Hemispheric asymmetry in electron temperature seen similar to the electron precipitation
- **Increase in electron temperature within EPBs**
- Low ion velocity and vertical flux, minimal increases during EPBs

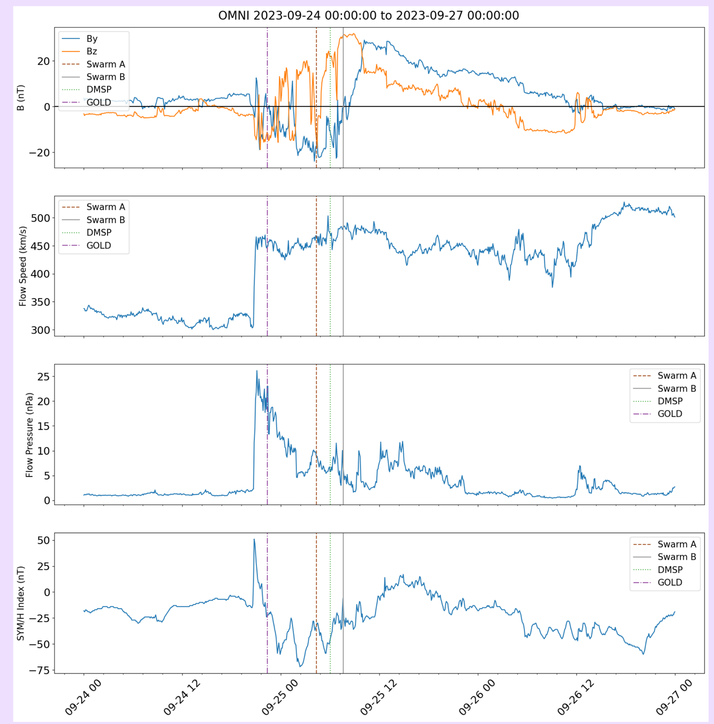

Figure 8: NASA OMNI solar wind data magnetic field, flow speed, flow pressure, and SYM-H

iii) Solar Wind Measurements

- GOLD EPB detection occurred after shock arrival of the ICME and during strong southward IMF pre-midnight allowing PPEF to uplift ionosphere (Figure 8)
- Large IMF fluctuations and sudden southward turning before Swarm A detection; possibly resulting in overshielding post-midnight
- **Strong northward B_z before DMSP and Swarm B detection; likely resulting in continued overshielding of Prompt Penetration Electric Field (PPEF)**
- Disturbance Dynamo Electric Field (DDEF) could have also played a role in uplifting the ionosphere post-midnight
- Moderate geomagnetic storm with SYM-H minimum of about -75nT

5) Electron Temperature and EPBs

- Figure 9 shows the temperature difference (T_e at depletion minimum - mean T_e at the halfwidth) and bubble prominence (based on detrended N_e)
- February 2023 (00,01,02 LT) and September 2023 (06,07,08 LT) for Swarm B
- Strongest negative correlation between T_e difference and bubble prominence at 01 LT and strongest positive correlation at 06 LT
- **May indicate that during postmidnight hours, the deeper bubbles experience a lower T_e compared to background T_e During post sunrise hours, deeper depletions may experience higher T_e compared to the background**
- The positive correlation was also seen in Oyama et al (1988)

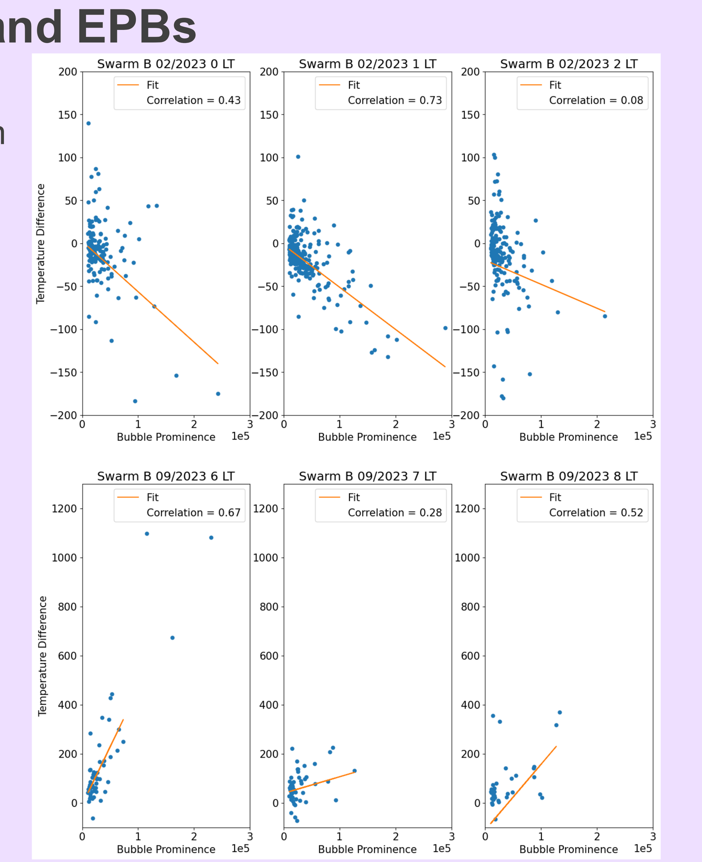

Figure 9: Te Difference vs Bubble Prominence at different local times for Swarm B February and September 2023

6) Discussion and Conclusion

- **We developed an algorithm for detecting EPBs using in situ Swarm electron density data**
  - The algorithm uses a midlatitude trough detection, a rolling barrel detrending method, and a peak finding function to detect potential EPBs as outlined in the chart to the right
  - Swarm has 3 satellites and a data span of over 10 years
  - **Allowing us to perform a detailed and extensive statistical analysis once the algorithm has been used on all data**
- **We showed evidence of a Super EPB event with increasing electron temperatures during dawn local time**
  - This was also seen in Oyama et al. 1988, their explanation includes:
    - Particle precipitation heating the electron gas
    - Photoelectrons from (1) upper ionosphere travelling down B field lines or (2) conjugate points
  - Due to the evolution of the electron temperature and terminator location, the Super EPBs shown may have been heated by photoelectrons
  - Hemispheric asymmetries of low energy electron and electron temperature are observed by DMSP F16 The source of the low energy electron needs further analysis
  - The event occurred during disturbed geomagnetic conditions.
  - Overshielding and the DDEF may have played a role in the formation and maintaining of the EPBs

Detection Method Flowchart

1. Midlatitude Trough Detection
2. Skip passes containing >5% "bad" data
3. Barrel Detrending
4. Flip/Smooth Detrended Data
5. Peak Detection
6. Delta Ne Check | Latitudinal Width Check | Bubble in Bubble Check | Bad Data Check
7. TID Check
8. Confirmed Bubble

7) References and Acknowledgements:

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