Plasma bubbles in the top side ionosphere: from automatic detection to possible sources

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PLASMA BUBBLES

Plumes of low-density plasma that rise up from the botton side of the F layer towards the exosphere.

EPBs remain an important component of space weather since they may cause loss of signal and loss impairing the operation of satellite-based communication and navigation systems.

Generically appear at **local dusk** where they are observed at different spatial (~50 - 1000 km) and temporal scales and, during their ascending motion in the ionosphere, present a stretched, wedge-like structure in the north-south direction along the geomagnetic field lines.

Plasma depletions are also observed during **geomagnetic storm**

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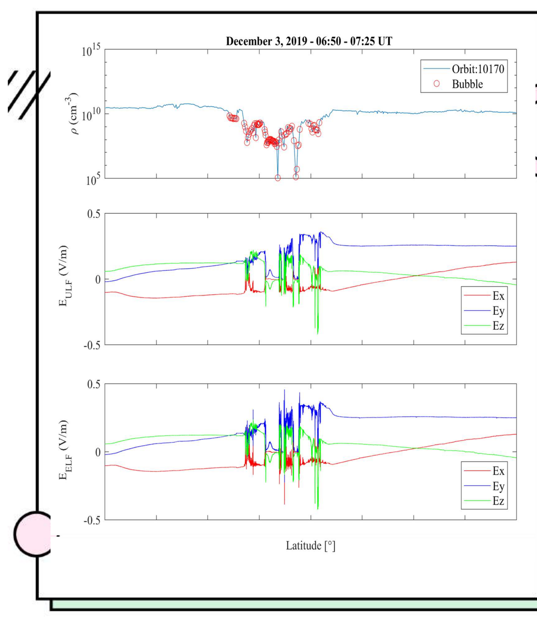
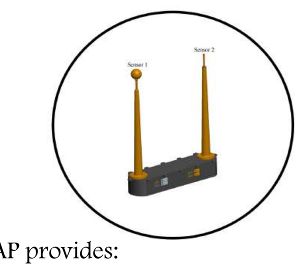
AUTOMATIC DETECTION OF PLASMA DEPLETIONS

LAP Algorithm: based on **five** different **thresholds** imposed on **LAP** measurements:

- The running mean of the electron density is computed over 57 points;
- The ratio between the density measured at each point along the orbit and the running mean of the density is **less than 1/2**;
- The condition in the previous point is satisfied for at least five points along the orbit;
- The time difference between two consecutive density measurements is greater than 40 s;
- The depletions searching is limited in a latitudinal range spanning from -30° to 30°



CHINESE SEISMO - ELECTROMAGNETIC SATELLITE - 01

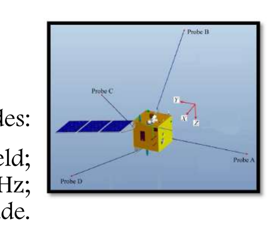


CSES-01 orbits sun-synchronously at an altitude of ~500 km:

- with an inclination of 97.4°
- with descending and ascending nodes at ~14:00 local time (LT) and ~02:00 LT, respectively, and a revisit period of 5 days;
- with an average speed of ~7.2 km/s;
- with an orbital period of ~94 minutes.

LAP provides:

continuous measurements of the electron density and temperature;
with a sampling frequency of 3s;
between roughly −65° and +65° of geographic latitude.



EFD-ELF provides:

continuous measurements of the vector electric field;
with a sampling frequency of 5 kHz;
between roughly −65° and +65° of geographic latitude.

AUTOMATIC DETECTION OF PLASMA DEPLETIONS

EFD Algorithm*: based on **five** different **steps**

1) Take $E_{[xyz]}(t)$ in the ELF band above/below ±40° lat
2) Perform a Fast Iterative Filtering (FIF) decomposition of its amplitude:

$$|E|(t) = \sum_{i=1}^{M} \hat{E}_i(t) + r(t)$$

3) Calculate the Median Weighted Moving Variance (MWLVM):

$$V_i(t, T_i) = \frac{1}{N}\sum_{\tau=t-T_i/2}^{t+T_i/2}(\hat{E}_i(\tau) - \mu_i(t, T_i))^2$$

$$V_i^{med}(t, T_i) = \frac{V_i(t, T_i)}{med[V_i(t, T_i)]_t}$$

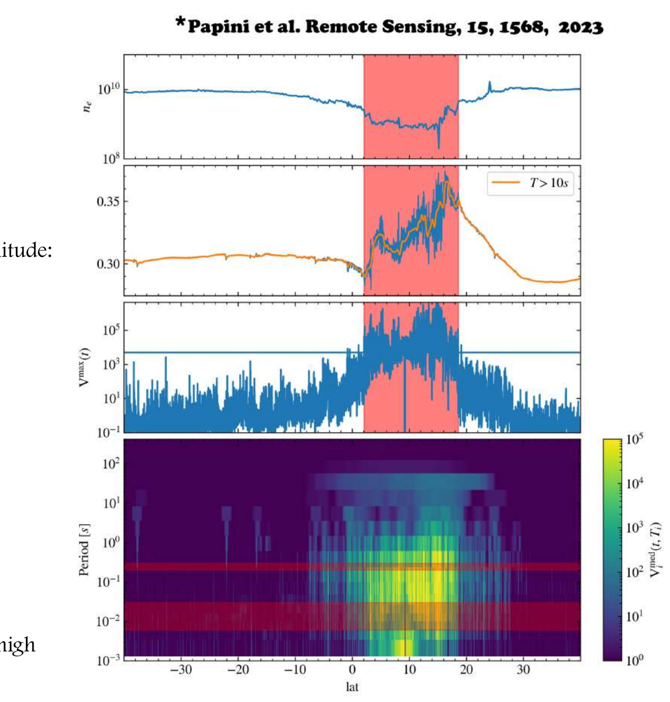
4) Calculate the MWLVM Proxy:

$$V^{max}(t) = \max_{T_i \in A}\{V_{i,[xyz]}^{med}(t, T_i)\}$$

with A=[0,006s, 0,03s]∪[0,2s, 0,3s]

5) Apply a thresholding clustering algorithm to find intervals with high levels of activity (if present).

*Papini et al. Remote Sensing, 15, 1568, 2023

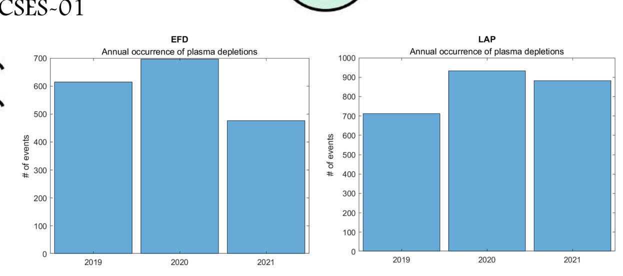


COMPARISON BETWEEN LAP AND EFD ALGORITHMS

preliminary results

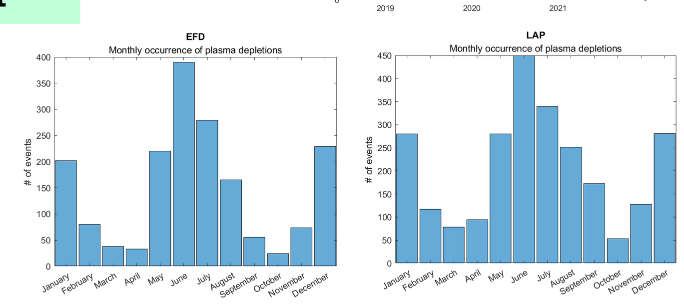
Depletions automatically detected from January 1st, 2019, to September 30th, 2021, by LAP and EFD on-board CSES-01

	# of detected bubbles
LAP	2525
EFD	1789
COMMON	1191



Differences due to:

- EFD saturation;
- No EFD data;
- EFD constrain on interval extension ≥1°
- LAP also ran on diurnal orbit



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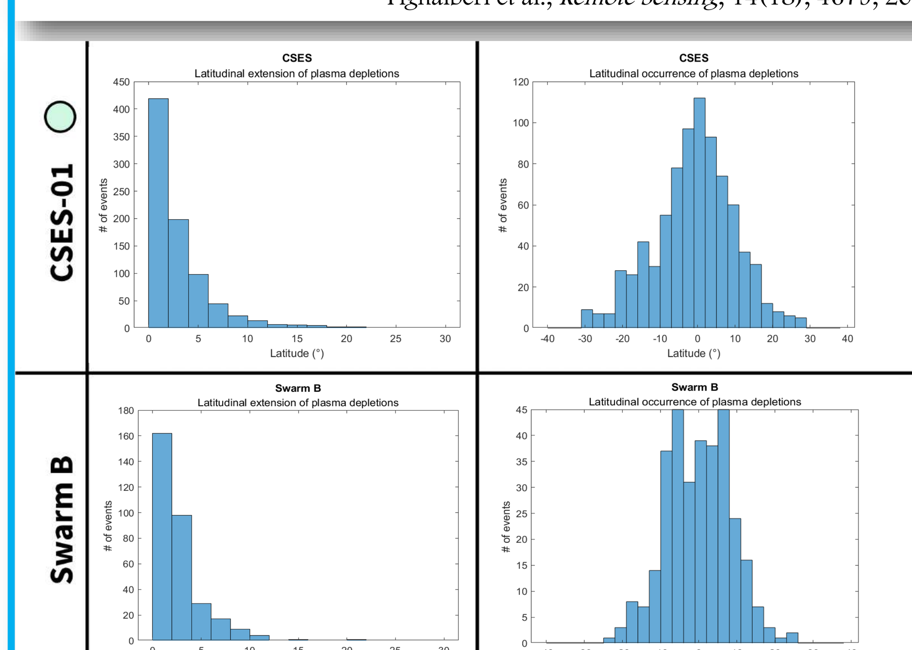
RESULTS: testing robustness of the LAP algorithm

According to what is reported by Pignalberi* et al., 2022, we selected Swarm B observations in the range 01:00 ≤ LT < 03:00 for the night-time sector and in the range 13:00 ≤ LT < 15:00 for the day-time sector.

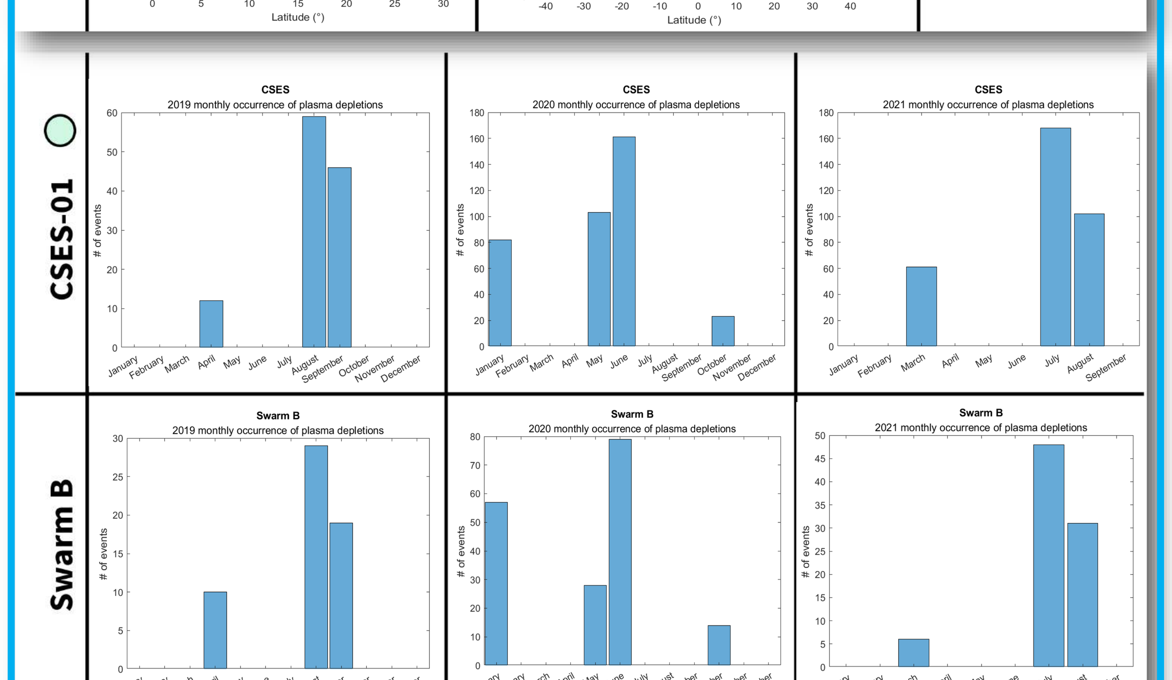
Comparison of plasma depletions detected, from January 1st, 2019, to September 30th, 2021, by LAPs on bord Swarm BRAVO and CSES-01

*Pignalberi et al., *Remote Sensing*, 14(18), 4679, 2022



Differences

Due to differences between the LPs, which inevitably affect the response to the conditions imposed on the algorithm



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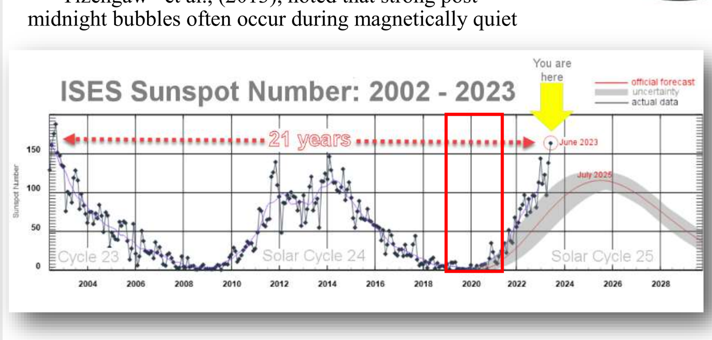
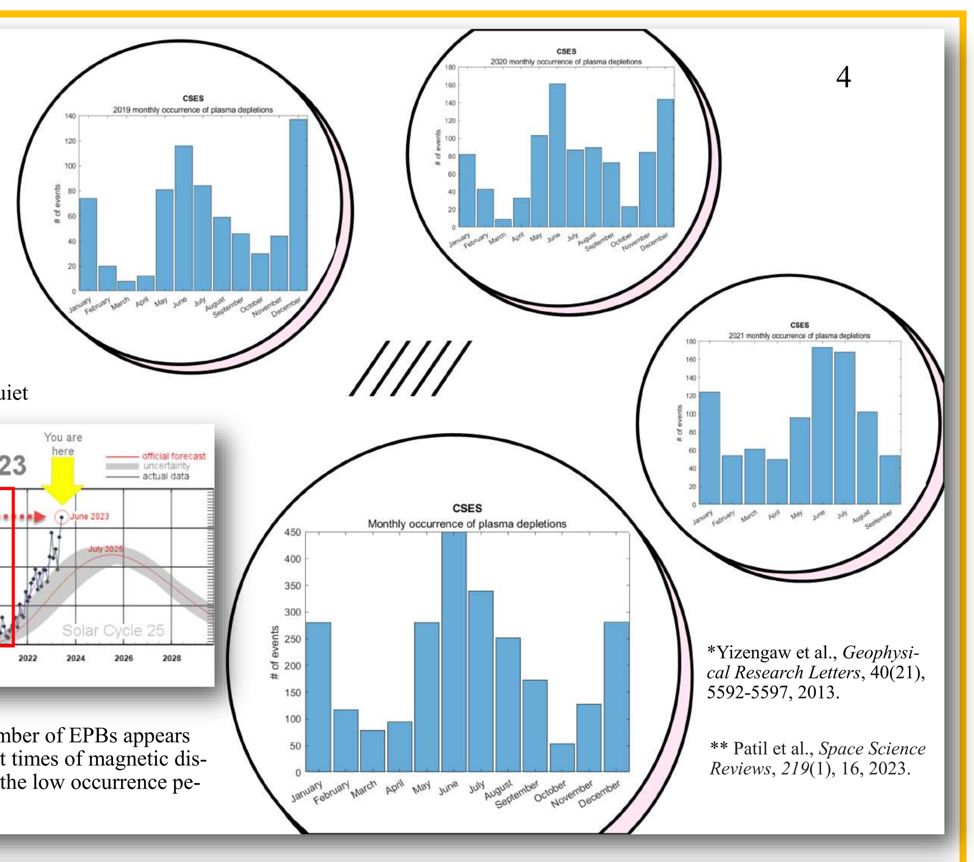
Monthly occurrence of plasma depletions detected by CSES-01

Major occurrence found in correspondence with solstice month

Yizengaw* et al., (2013), noted that strong post-midnight bubbles often occur during magnetically quiet



Patil** et al., (2023) reports that the maximum number of EPBs appears from October to March but on several occasions, at times of magnetic disturbances, the presence of EPBs was noted during the low occurrence period (May to August).



*Yizengaw et al., *Geophysical Research Letters*, 40(21), 5592-5597, 2013.

** Patil et al., *Space Science Reviews*, *219*(1), 16, 2023.

Investigation of the Swarm L2 IBI Product at the same LT as CSES-01

$$\Delta B \approx -\frac{\mu_0 k_B}{B}\Delta[N_e(T_e + T_i)]$$

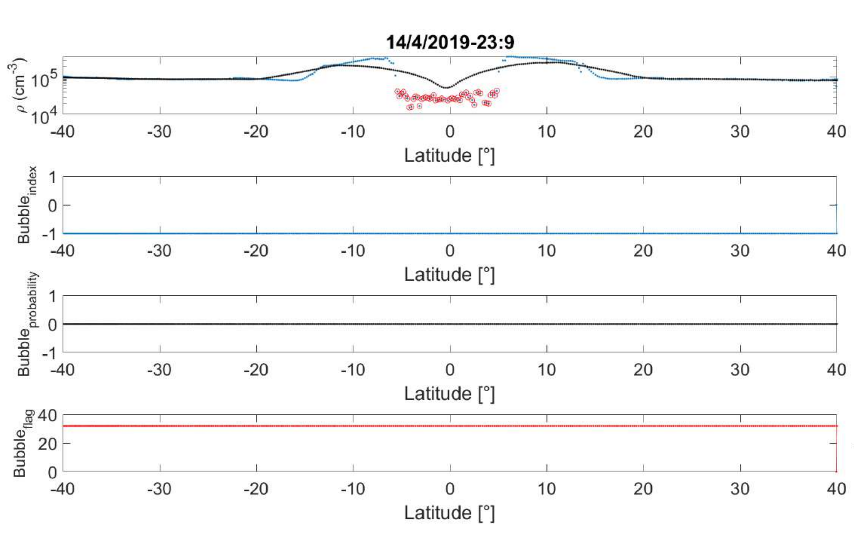
Assumption:
- Plasma is in a steady- state configuration;
- Gravity can be neglected;
- Field line geometry is linear;

Bubble Index	Description
0	Quiet data point
1	Data point affected by bubbles
-1	unanalyzable data point

Bubble Flag	Description
0	Quiet
1	Bubble confirmed by high-correlation between plasma density and magnetic field
2	Bubble unconfirmed by high-correlation between plasma density and magnetic field
4	Large jump in magnetic field
8	Data gap
16	Pulsations in magnetic field
32	Outside the night-time low-latitude region where bubbles can be found

Sometime IBI fails:

- because depletion occurs outside the night-time low-latitude region where bubbles can be found;
- because depletion occurs in a quite period from magnetic point of view;



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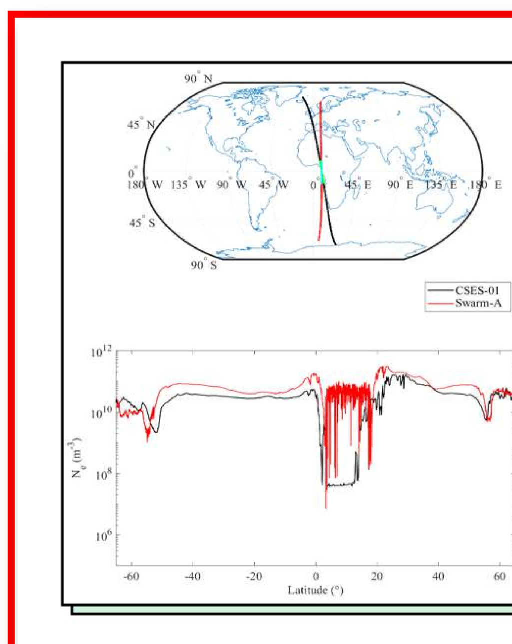
Plasma bubble detection by CSES-01 and Swarm A



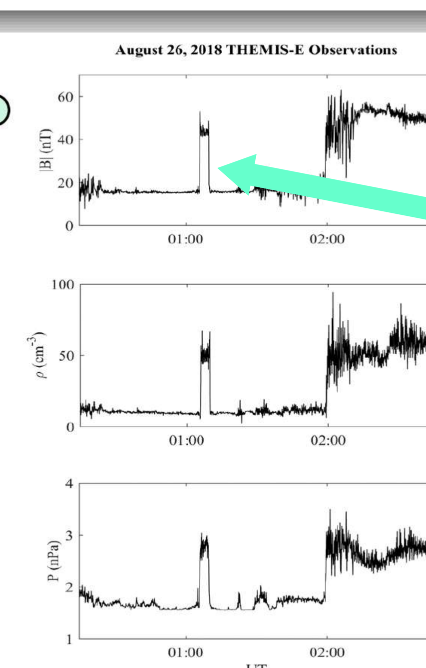
on August 26th, 2018, in the equatorial region of West Africa, a very large plasma bubble was observed by

CSES-01: between 01:27 UT and 01:31 UT
Swarm A: between 01:55 UT and 02:05 UT

- the EPB latitudinal extension (~15°–20°) is well defined by both satellites, even though Swarm A saturates for electron density values higher than those recorded by CSES-01 .
- slight difference should be ascribed to the evolution characterizing the bubble in the time interval differentiating the two orbits.
- considering that the Swarm A orbit is about 30 min later than the CSES-01 one, we can claim that this structure is rather stable both in space and time.

THEMIS-E observations

between 00:15 UT and 02:45 UT on August 26th, 2018



Impulsive variation (a sudden decrease followed by a quick recovery) of the solar wind dynamic pressure during the ICME passage

leading to an impulsive expansion and contraction of the magnetosphere, lasting approximately 5 min.

Comparison between bubble and solar wind structure occurring times

$$T_E \approx T_D$$

- **impulsive variation of the SW pressure at the passage of magnetic cloud**
- **triggered an eastward PPEF propagating from high to equatorial latitudes**
- **overlapped the local westward electric field causing either a sudden decrease of the nightside westward equatorial electrojet or a reversal of it**
- **Intensification of an upward disturbance dynamo drift**

significant uplift of the ionospheric plasma at the base of the detected EPB

consistent with the transmission time of the interplanetary electric field to the equatorial ionosphere

Delay time between CSES-01 and THEMIS-E observations

$$T_E = 21 \pm 1\, min$$

*DELAY TIME BETWEEN SATELLITE OBSERVATIONS IN THE INTERPLANETARY SPACE AND GROUND-BASED MEASUREMENTS

$$T_D = T_A + T_{B,M} + T_{Alf} + T_T + T_R + T_{Trans}$$

T_A	Advection time of solar wind to travel from satellite to Earth's bow shock
$T_{B,M}$	Propagation time from the bow shock to the magnetopause
T_{Alf}	Travel time along magnetic field lines from magnetopause to polar ionosphere
T_T	Time needed by interplanetary electric field to cross the magnetosphere
T_R	Reconfiguration time of the magnetosphere-ionosphere system
T_{Trans}	Propagation time from the high latitudes to the equatorial ionosphere

$$T_D = 20,2 \pm 2,0\ min$$

*Bhaskar and Vichare., *J. Geophys. Res*. 118, 4696–4709, 2013

CONCLUDING REMARKS

✓We developed new methods to automatically detect post-midnight plasma bubble directly from in-situ measurements of both ionospheric electron density and electric field.

✓Our results show a good agreement between the two algorithms suggesting their complementarity in detecting such kind of irregularities.

✓The comparison between CSES-01 and Swarm B confirms the robustness and the accuracy of our algorithm.

✓Results from CSES-01 are consistent with Swarm B observations once same LT orbits have been considered.

✓Investigations of both Swarm L2 IBI Product at the same LT as CSES-01 and multiple case studies suggests that plasma bubbles observed by CSES-01 seem to be mostly related to sudden variations of solar wind parameters triggering an eastward PPEF able to intensify of the upward disturbance dynamo drift, which is at the base of the detected EPBs.

Such results open the door to new systematic study of the statistical properties of post-midnight EPBs, with many potential applications in the framework of space weather.

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