Assessment of the plasma and magnetic pressure balance across equatorial plasma depletions

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Abstract

Equatorial plasma depletions **(EPDs)** are a post-sunset phenomenon well-known for their steep plasma density gradients and adverse effect on radio wave propagation. In this study, we use continuous measurements of the magnetic field and electron density from the ESA's *Swarm* mission to assess the balance between plasma and magnetic pressures across large-scale EPDs. The study of the pressure balance sheds light on the evolution of EPDs and its spatiotemporal characteristics.

The results show that most of the EPDs detected by *Swarm* present a decrease of the plasma pressure relative to the ambient plasma. However, EPDs with high plasma pressure are also identified mainly in the vicinity of the South Atlantic magnetic anomaly. It is inferred that such an increase in plasma pressure within EPDs might be possible by temperatures as high as twice the temperature of the ambient plasma. This finding corresponds to the first observational evidence of plasma pressure enhancements in regions of depleted plasma density in the ionosphere.

Background

There is a drift exclusively related to magnetized plasmas with pressure gradients. It is commonly referred to as diamagnetic drift $\mathbf{V_d}$ and has an associated current $\mathbf{j_d}$.

The $\mathbf{j_d}$-related magnetic field $\delta\mathbf{B}_{||}$ opposes the ambient magnetic field $\mathbf{B}$ in the region where the plasma pressure p enhances.

$$\mathbf{V}_{\mathbf{d},j} = -\frac{\nabla p_j \times \mathbf{B}}{q_j n_j B^2} \qquad p_j = n_j k T_j$$

$$\mathbf{j_d} = q_e(n_i \mathbf{V}_{\mathbf{d},i} - n_e \mathbf{V}_{\mathbf{d},e}) = -\frac{\nabla p \times \mathbf{B}}{B^2}; \quad p = p_i + p_e$$

EPDs-related diamagnetic current:

By assuming plasma and magnetic pressure are balanced under isothermal conditions ($T_{in} = T_{out}$) and positive isotropic plasma pressure gradient (∇p, pointing outside the EPD),

$$\delta\mathbf{B}_{||} = -\delta n_e k(T_e + T_i)\frac{\mu_0}{B}$$

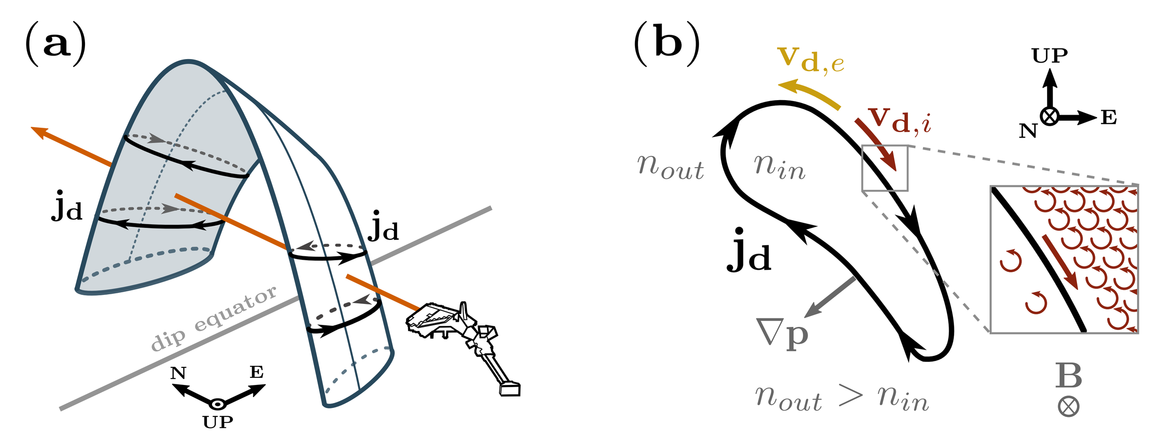

Figure 1. **(a)** Description of a wedge-like EPD, its associated diamagnetic current $\mathbf{j_d}$ and a *Swarm* satellite crossing the EPD. **(b)** A zonal-cross section at the dip equator of the EPD in **(a)**. It shows both the diamagnetic drifts of ions and electrons $\mathbf{V}_{\mathbf{d},i}$, $\mathbf{V}_{\mathbf{d},e}$, the plasma pressure gradient $\nabla\mathbf{p}$ and the diamagnetic current $\mathbf{j_d}$. The box to the right is a zoom in to the ions gyrating in the magnetic field at the edge of the EPD.

Motivation and method:

The balance between magnetic and plasma pressure across EPDs gives valuable information about the effect of both the ambient plasma and magnetic field on the evolution of EPDs.

To assess the balance, we use simultaneous measurements of the magnetic field and electron density gathered by *Swarm* from December 2013 to April 2018. The criterion to determine low- or high-plasma pressure within EPDs stands on the orientation of the diamagnetic current at the edges of EPDs.

Observations

1. EPDs detected by *Swarm*

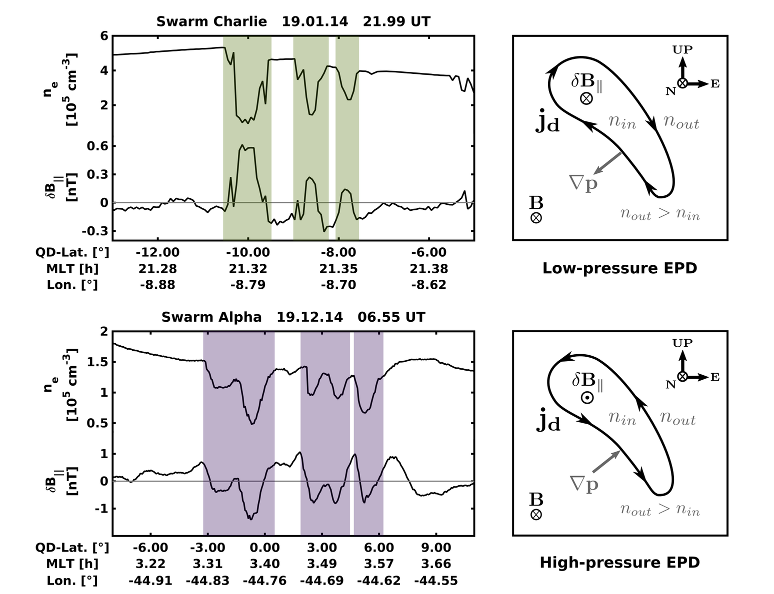

Figure 2. (Left) Passes of *Swarm* Charlie (top) and Alpha (bottom) showing n_e and $\delta\mathbf{B}_{||}$ as a function of quasi-dipole latitude, magnetic local time and longitude. (Right) Description of the current and pressure configuration.

2. Spatial distribution

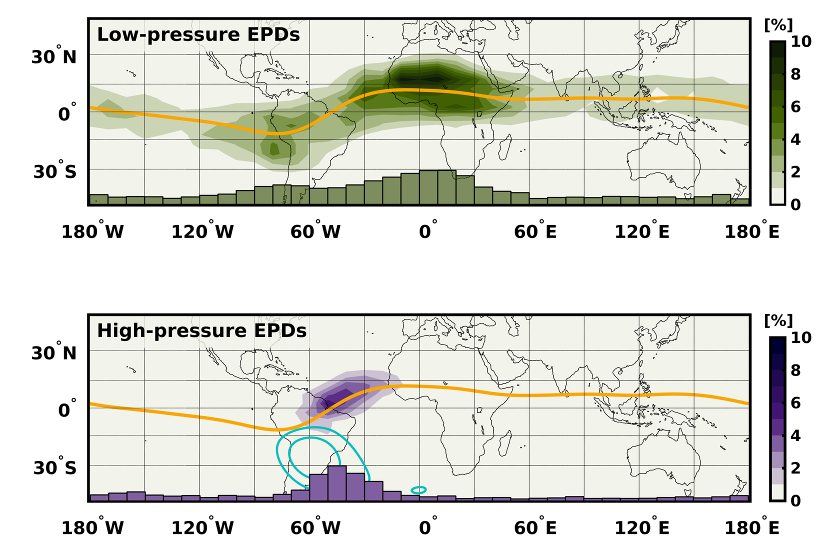

Figure 3. Occurrence rate of low-pressure EPDs (top) and high-pressure EPDs (bottom) in a grid of 10° × 5° in longitude and latitude, respectively. The highest number of events in each histogram is 665 (top) and 305 (bottom). Blue lines indicate the SAA.

3. Seasonal, longitudinal and MLT variability

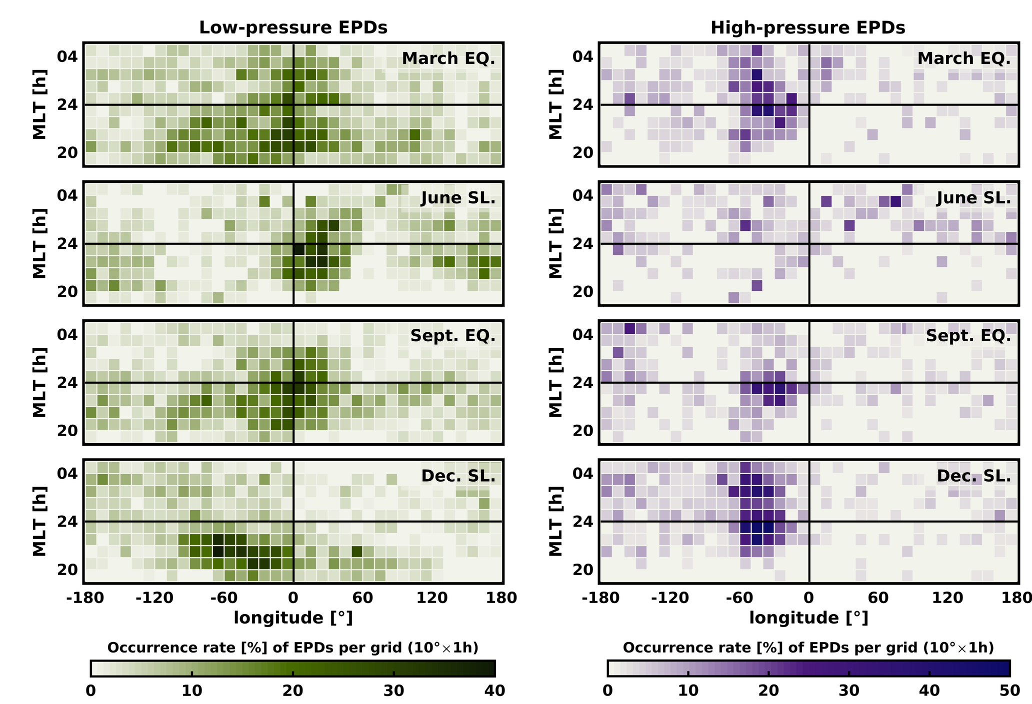

Figure 4. Occurrence rate of low-pressure EPDs (left column) and high-pressure EPDs (right column) as a function of magnetic local time and longitude.

4. Magnetic pressure and plasma density relationship

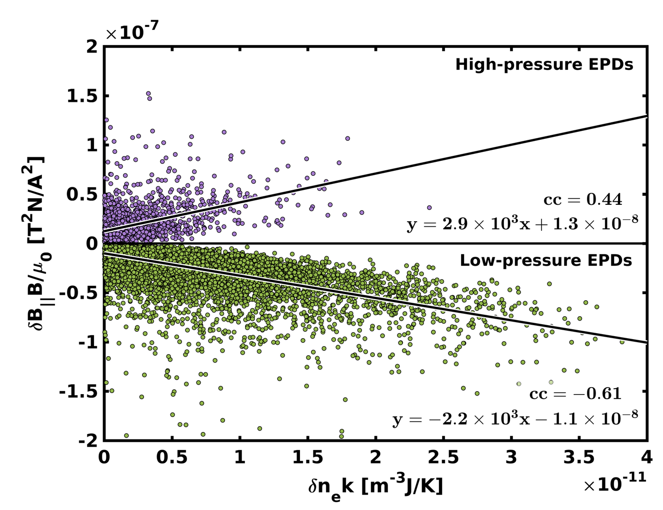

Figure 5. Linear regression between the magnetic pressure and electron density variations for all the EPDs detected. Green dots represent low-pressure EPDs and purple dots high-pressure EPDs. In black, regression lines and related equations. The slope of the regression line indicates the mean temperature. Low-pressure EPDs show that the pressure balance occurs mostly through variations of the plasma density.

5. Ambient magnetic field features at the dip equator

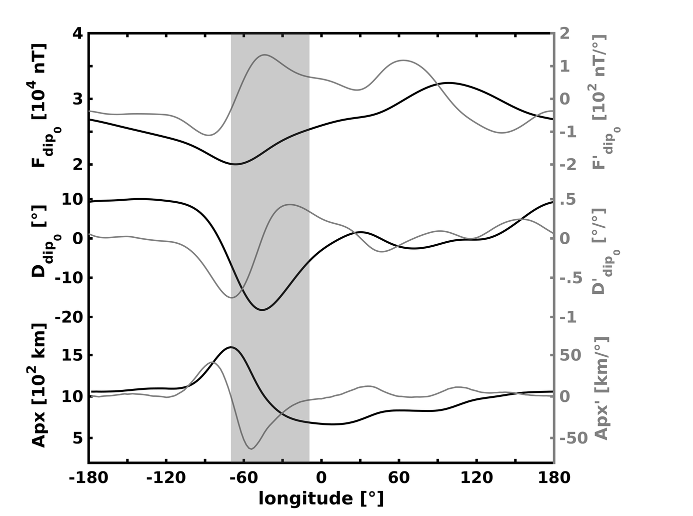

Figure 6. From top to bottom, magnetic field intensity (F) and declination (D) at the dip equator, and magnetic field apex height (Apx) for field-lines between ±40° of magnetic inclination as a function of longitude. Gray lines show the first derivative of each parameter. The highlighted longitude in gray corresponds to the region with the highest occurrence rate of high-pressure EPDs.

Analysis

By defining the plasma pressure gradient,

$$\nabla p = \nabla(nkT) = k\,(T\nabla n + n\nabla T)$$

we can deduce that,

low-pressure EPDs ($\nabla p > 0$, pointing outside the EPD) can present temperature values

- equal to the ambient plasma ($T_{in} = T_{out}$, isothermal).
- lower than the ambient plasma ($T_{in} < T_{out}$).
- higher than the ambient plasma ($T_{in} > T_{out}$) and $|T\nabla n| > |n\nabla T|$.

high-pressure EPDs ($\nabla p < 0$, pointing inside the EPD) present temperature values

- higher than the ambient plasma ($T_{in} > T_{out}$) and $|T\nabla n| < |n\nabla T|$.

In the case of high-pressure EPDs,

$$T_{in} > \frac{n_{out}}{n_{in}} T_{out}.$$

From the *Swarm* measurements, the ratio n_{out}/n_{in} presents a median of 1.96 among all the high-pressure EPDs (95% bootstrap confidence interval of 1.92–2.00).

Summary and conclusions

1. For low-pressure EPDs, the plasma pressure gradient is dominated by plasma density variations. Changes in the plasma temperature are not expected to play a significant role. On the contrary, variations of the plasma temperature are significant for high-pressure EPDs.
2. Among all the EPDs detected, 18.3% correspond to high-pressure EPDs and 81.7% to low-pressure EPDs.
3. High-pressure EPDs occur at the American/Atlantic sector mainly, between about 70°W and 10°W, corresponding to 54% of the total number of high-pressure EPDs detected. A preference in magnetic local time is found around midnight and post-midnight hours.
4. High-pressure EPDs are characterized by temperatures as high as twice the ambient plasma temperature.
5. Based on the location of the highest occurrence rate of high-pressure EPDs (i.e., near the South Atlantic magnetic anomaly), we suggest the primary heating mechanism to be due to particle precipitation from the radiation belts.

References:

Rodríguez-Zuluaga, J., Stolle, C., Yamazaki, Y., Lühr, H., Park, J., Scherliess, L., and Chau, J.L. (2019), On the balance between plasma and magnetic pressure across equatorial plasma depletions, *J. Geophys. Res. Space Phys.*

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