Diamagnetic and paramagnetic signatures related to equatorial plasma depletions: observations from the *Swarm* mission

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Key points

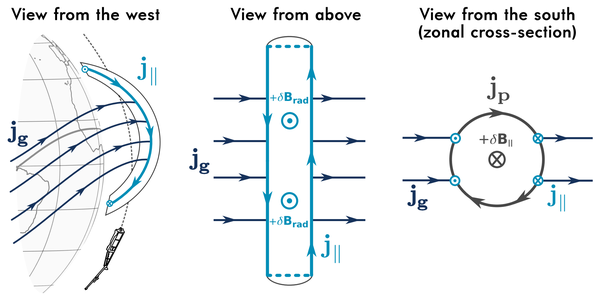
First observational evidence of paramagnetic signatures related to large-scale equatorial plasma depletions **(EPDs)**.

EPDs with paramagnetic signatures occur where the ambient magnetic declination is the highest (i.e., 60°W-30°W), different to the ones with diamagnetic signatures which occur at all longitudes.

Between 60°W and 30°W, the magnetic effect depends on local time, such that diamagnetism is observed right after sunset and paramagnetism after midnight.

Introduction

The common understanding of the EPDs-related electric current system has been carried out by theoretical studies mainly.
The most prominent magnetic signatures related to EPDs come from field-aligned ($\mathbf{j}_{\parallel}$) and pressure-driven currents ($\mathbf{j}_\mathrm{p}$).



$$\mathbf{j}_\mathrm{g} = nM\left(\frac{\mathbf{g}\times\mathbf{B}}{B^2}\right) \qquad \mathbf{j}_{\parallel} = \frac{1}{\mu_0}\left(\frac{\partial \mathbf{B}_\mathrm{zon}}{\partial \mathrm{rad}} - \frac{\partial \mathbf{B}_\mathrm{rad}}{\partial \mathrm{zon}}\right) \qquad \mathbf{j}_\mathrm{p} = -\frac{k_b}{B^2}\{\nabla[n(T_i+T_e)]\}\times\mathbf{B}$$

$\mathbf{j}_{\parallel}$ are interhemispheric **[Rodriguez-Zuluaga and Stolle, 2018; under review]** and produce transverse magnetic fluctuations. $\mathbf{j}_\mathrm{p}$ flow perpendicular to the pressure gradient and generate magnetic fluctuations parallel to the ambient magnetic field ($\delta B_{\parallel}$).

A comprehensive description of the EPDs-related electric current system is essential for understanding EPDs evolution and day-to-day variability. Here we show that contrary to expectations, EPDs sometimes present paramagnetic signatures likely due to a reverse of $\mathbf{j}_\mathrm{p}$. The observations exhibit an apparent spatial and temporal dependence of the phenomenon. Our results emphasize the importance of analyzing the electromagnetic characteristics of EPDs from observations to advance in the current knowledge and to improve their forecasting.

Swarm data and method

The Swarm constellation mission consists of three identical satellites launched into a near-polar, circular orbit on 22 November 2013. One of them (Bravo) flies at 510 km of altitude and the other two (Alpha and Charlie) at 450 km separated by 1.4° in longitude at the equator.

Here we use continuous measurements of electron density and magnetic field spanning from 1 Dec. 2013 until 31 Dec. 2017. The EPDs detection follows the method by **Rodriguez-Zuluaga et al. [2017]**.

The magnetic effect is defined to be diamagnetic or paramagnetic based on the correlation cœfficient (R) between δN_e and $\delta B_{\parallel}$ (for |R|>=0.6). Thus, negative R values refer to diamagnetism and positive ones to paramagnetism.

Pressure-driven currents-related magnetic fluctuations

Based on the assumption of a stationary momentum equation every decrease in plasma pressure must be counter-balanced by an increase in the magnetic pressure through $\mathbf{j}_\mathrm{p}$. The variations in the magnetic field due to such balance are referred to as diamagnetic effect (b) and is described by **Lühr et al., [2003]**, as

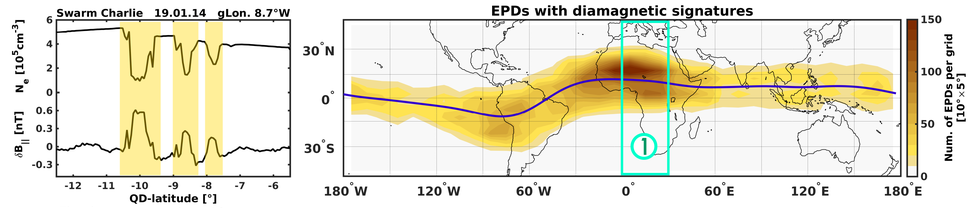
$$b = nk_b(T_i + T_e)\frac{\mu_0}{B} \qquad \textbf{(1)}$$

Here we show the first observational evidence of "paramagnetism" on EPDs.

I. Spatial distribution and single event samples:

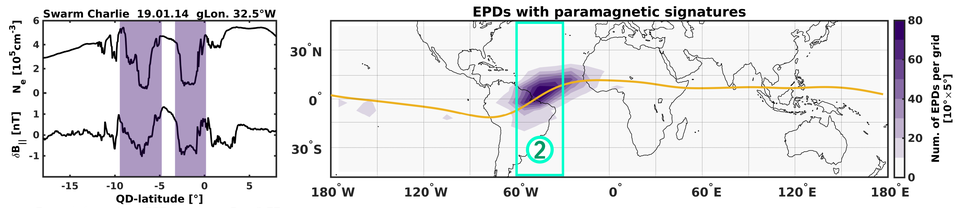
For each magnetic signature, the figures below present from left to right individual samples and global distribution of EPDs. Among all the EPDs detected, **82.4%** correspond to diamagnetic EPDs and **17.6%** to paramagnetic ones.

Diamagnetic signatures:



The three consecutive EPDs present R=-0.86 between $\delta B_{\parallel}$ and δN_e.

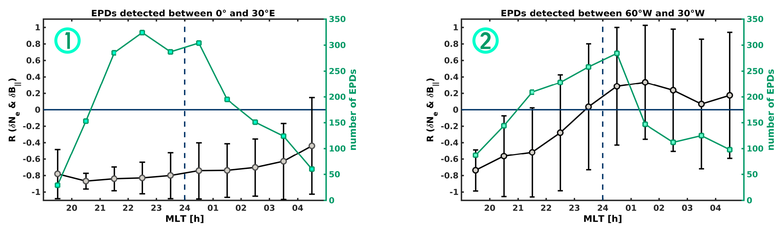
Paramagnetic signatures:



From left to rigth EPDs present R=+0.77 and +0.87 between $\delta B_{\parallel}$ and δN_e.

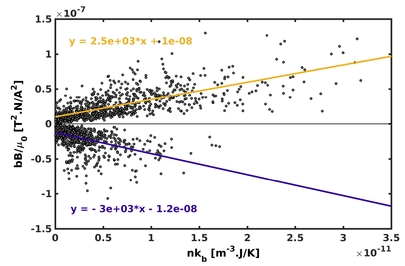
II. Temporal distribution at specific sectors:

We evaluate the temporal evolution of the magnetic signatures at two sectors of interest (i.e., 60°W-30°W and 0°-30°E) where only diamagnetism ① and both diamagnetism and paramagnetism ② occur.
Below: Correlation cœfficients (R) as a function of magnetic local time (MLT) for each region.



In ② a transition from diamagnetism to paramagnetism occurs as a function of magnetic local time. Paramagnetism dominates after midnight.

III. Mean plasma temperature:

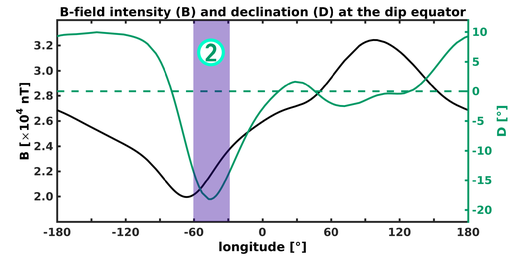


The mean plasma temperature $(T_i + T_e)$ is deduced as the ratio of the change of bB/μ_0 to nk_b.

A temperature of 2500K related to diamagnetic effects agrees with previous studies **[e.g., Lühr et al., 2003]**. Mean temperature of 3000K is deduced for EPDs with paramagnetic signatures. Negative temperatures are unreal so **Eq. (1) is not generally valid**.

Geomagnetic characteristics of region ②:

The transit phenomenon between diamagnetism and paramagnetism appears in the region with the highest magnetic field declination and low magnetic field intensity.



Which ionospheric parameters can be affected by the configuration of the Earth's magnetic field in region ②?

Conclusions

a. Magnetic field fluctuations related to pressure-driven currents on EPDs:

* First observational evidence of paramagnetism related to EPDs.
* The significance of the EPDs with paramagnetic signatures suggest that Eq. (1) (balance of the magnetic and plasma pressures between inside and outside EPDs) is no longer valid.

b. Spatial and temporal variability:

* Diamagnetism is observed on EPDs at all longitudes throughout the night.
* Paramagnetism occurs on EPDs detected in region ②, mainly, with a preference for postmidnight hours.
* In region ② the magnetic signatures present a transit process from diamagnetism to paramagnetism, suggesting a continuous mechanism along the night.

c. Deduced plasma temperature:

* EPDs with diamagnetic signatures present mean temperatures of 2500K in agreement with previous studies.

Outlook:

* Analysis of electron temperature measurements gathered by *Swarm* over region ②.
* Assess missing terms in the "diamagnetic equation" to fit the new findings.

References

* EPDs-related interhemispheric field-aligned currents: **Rodriguez-Zuluaga and Stolle, 2018. Under Review. *Sci. Reports.***
* EPDs detection method: **Rodriguez-Zuluaga et al., 2017. *GRL.***
* Diamagnetic effect: **Lühr et al., 2003. *GRL.***

Acknowledgements

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https://earth.esa.int/web/swarm