A multi-disciplinary approach to investigate particle dynamics in the South Atlantic Magnetic Anomaly

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Abstract

The South Atlantic Anomaly (SAA) represents the minimum magnetic field intensity on Earth, influencing the energetic particle motion within the radiation belts, drawing them closer to our planet. The anomaly region serves as a key location for understanding the dynamics of the radiation belts affected by the magnetospheric response to solar activity. Our investigation relied mainly on our recent numerical simulation results of the inner radiation belt during two magnetic storm events: May 15, 2005, and February 3-4, 2022. We developed a test particle simulation code to compute the 70-180 MeV proton trajectories in the inner magnetosphere. The IGRF and Tsyganenko models provided the background time-dependent electromagnetic field in response to the input solar conditions. The AP8 model and SAC-C satellite observation confirmed the numerical results. We summarize that protons tend to concentrate more in the SAA's southern region, while further research found that electrons exhibit a higher tendency to populate the SAA's northern region due to wave-particle interaction. In light of this conclusion, we identified prolonged Pc5 waves in the ground magnetic field data acquired from stations near the SAA's northern region provided by MAGDAS/CPMN network. Examining the particle dynamics inside the SAA is crucial for predicting the radiation environment of LEO missions, forecasting the thermosphere's response to intense space weather, and anticipating the possible long-term climate changes.

Introduction

The South Atlantic Anomaly (SAA) refers to a significant decrease in the strength of the Earth's geomagnetic field, resulting from an inverse magnetic flux within the outer core of the planet (Fig. 1).

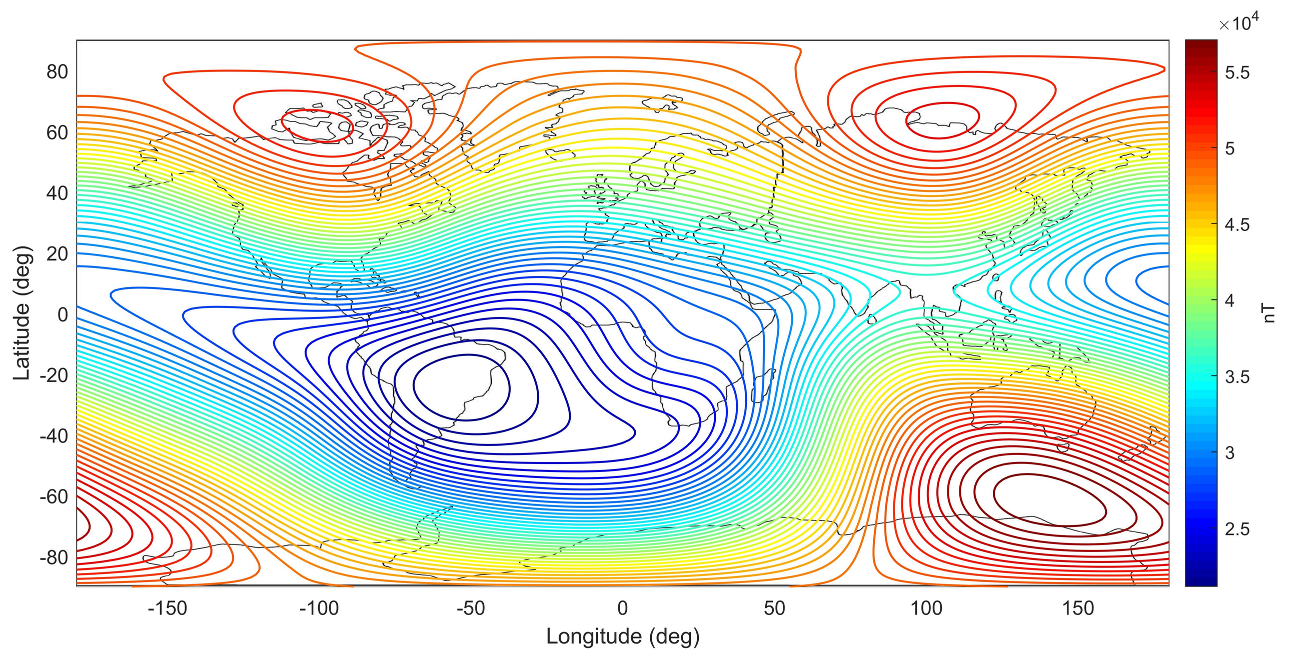

Figure 1. Earth's magnetic field strength @800 km computed by IGRF model **[Girgis et al., EGU (2020)]**

The effects of SAA extend to the particle and plasma environment surrounding the Earth, potentially altering conditions in the ionosphere, atmosphere, and impacting astronauts and space technology within the Low-Earth Orbit (LEO).

Methodology

In order to comprehend and forecast the particle dynamics within the geospace environment, researchers have extensively relied on prior findings from spacecraft observations, semi-empirical models, and numerical simulations. In this study, we present Pc5 wave observations obtained from magnetic ground stations within the MAGDAS/CPMN international network (Fig. 2), located in various countries. Specifically, we focus on stations SMA and EUS in Brazil, and ANC and HUA in Peru. These stations are positioned at both the center and north of the magnetic anomaly, respectively.

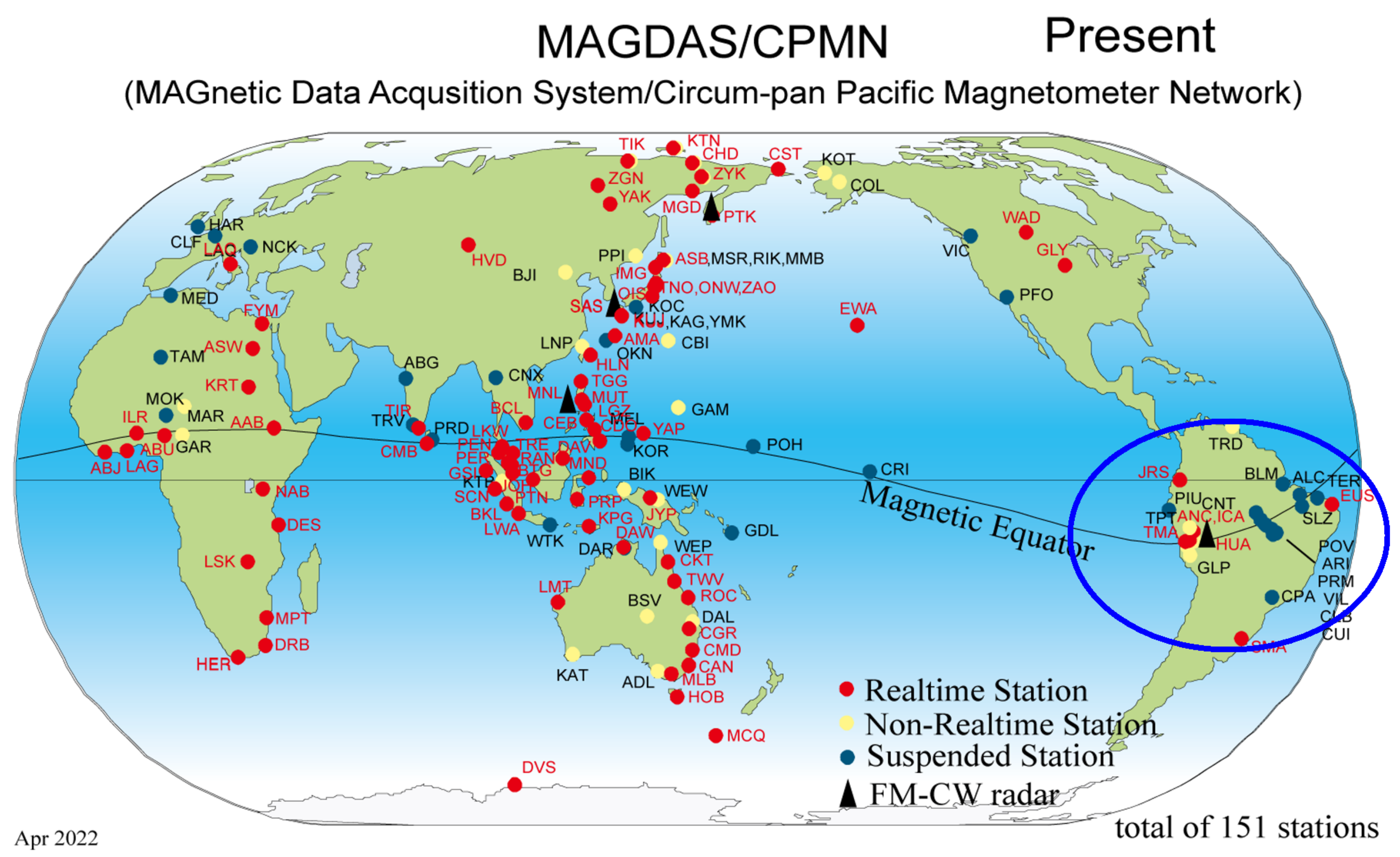

Figure 2. MAGDAS/CPMN worldwide network: The region of interest is outlined in blue.

Previous Results

[Sauvaud et al., JGR (2013)] demonstrated that geomagnetic storms often coincided with the emergence of multiple bands of energetic electrons within the inner radiation belt, occurring at L = 1.1–1.9, and with prominent energy structures of protons within the slot region at L = 2.2–3.5. These structures, typically ranging from 100 keV up to the MeV range, are the result of coherent interactions between energetic particles and quasi-monochromatic ultra-low frequency (ULF) Pc5 and Pc4 waves (Fig. 3).

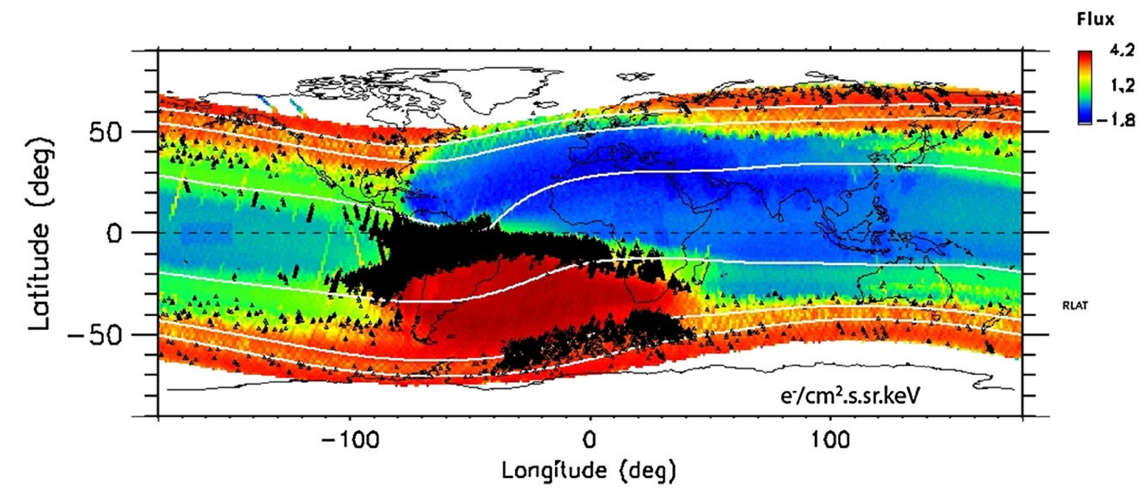

Figure 3. Geographical distribution of energetic particle flux observed by Demeter spacecraft during the year 2005: maximum electron and proton fluxes, depicted by black symbols, are located north and south of SAA respectively **[Sauvaud et al., JGR (2013)]**

For protons with higher energy levels of 10 MeV, SAC-C spacecraft observations and the AP8 semi-empirical trapped models have shown an increase in proton flux during intense space weather conditions, particularly in the southern region of the magnetic anomaly (Fig. 4).

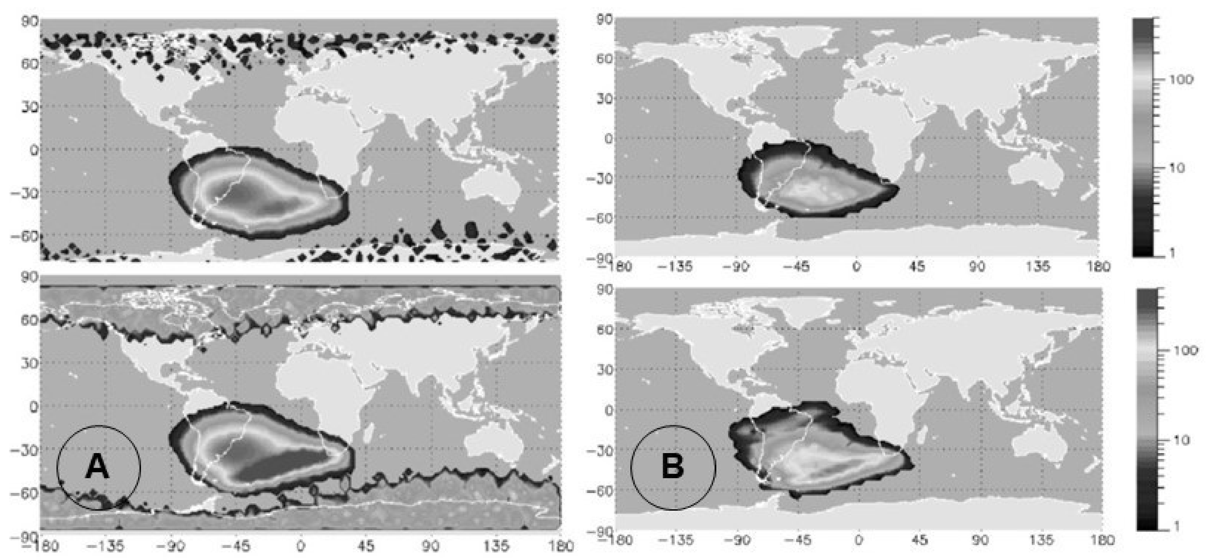

Figure 4. Comparison between the spacecraft observations (Panel A) and semi-empirical model AP8 (Panel B) revealing the enhancement of the proton flux south the SAA **[Falguere et al., TNS (2002)]**

To model and predict the dynamics of the inner radiation belt during solar and magnetic storms, we developed a relativistic three-dimensional test particle simulation code to compute the trajectories of 70-180 MeV protons in a time-varying electromagnetic field background generated from IGRF and Tsyganenko models (Fig. 5). 10^5 protons were initially distributed within the combined geomagnetic field (TS05+IGRF). Each proton was assigned random values for energy ranging from 70 to 180 MeV and pitch angle from 10° to 170°. The simulation domain took the shape of a cube whose volume was $(6Re)^3$ where each dimension was $-3Re < Rx, Ry, Rz < 3Re$, and a grid size of 128^3, with the Earth positioned at its center. (Re = Earth's radius)

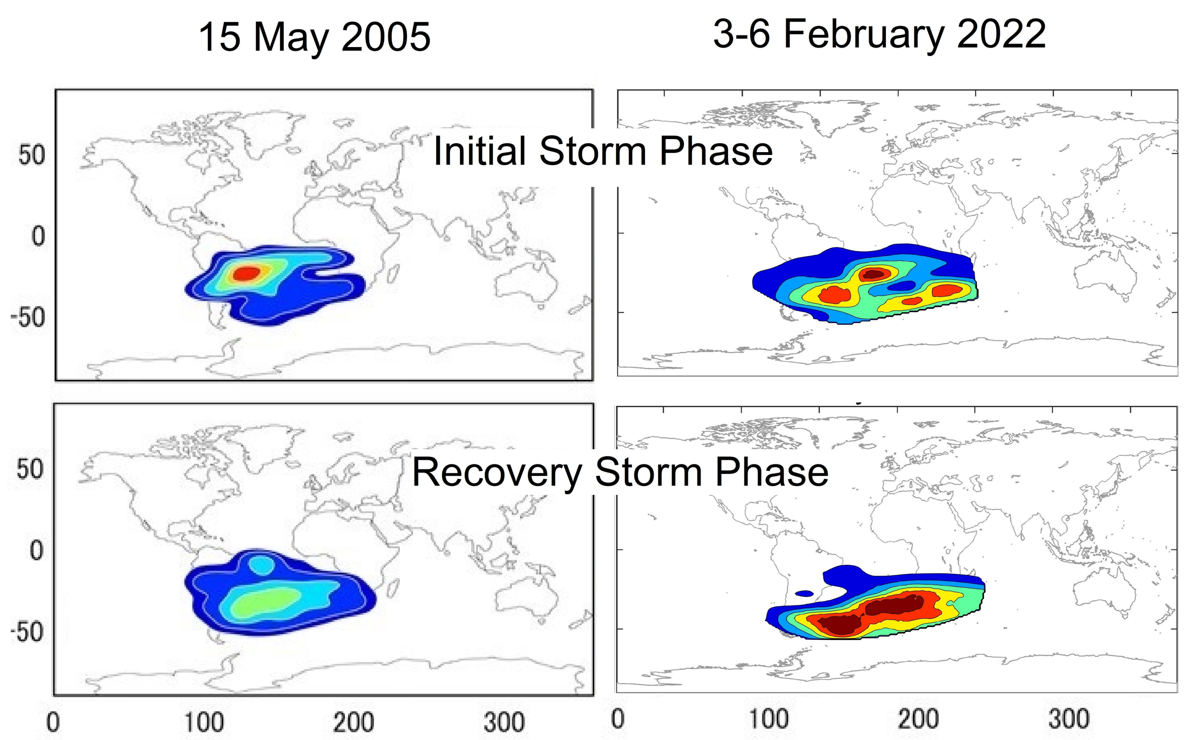

Figure 5. Numerical simulations of the inner radiation belt for 70-200 MeV protons in two magnetic storm events **[Girgis et al., JSWSC (2021)]** & **[Girgis et al., SW (2024, accepted with minor revision)]**. The contour plots display the normalized proton flux levels at 800 km (left) and 1000 km (right).

Numerical results of both events showed an enhancement in the proton flux in the southern region of the SAA during the recovery phases of both magnetic storms.

New Results

By using MAGDAS/CPMN network, we analyzed the wave activities in three magnetic storm events in 2005: 21 January, 15 May, and 24 August. We used wavelet analysis to filter and decompose the geomagnetic data into different time series of specific frequency bands of interest for geomagnetic pulsation studies. The wavelet package used in this analysis was the "Signal Multiresolution Analyzer" toolbox embedded in MatLab. We divided the continuous fluctuations to the five frequency ranges of ULF waves, denoting the Pc1 →Pc5 **[Xu et al., U.S. Geological Survey (2013)]**. For instance, we selected the 24 August 2005's magnetic storm event (Fig. 6) to demonstrate the Pc5 wave activity (Fig. 7).

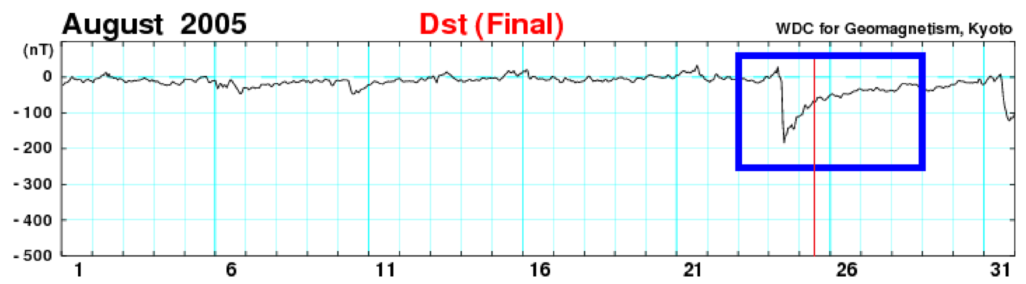

Figure 6. Dst index profile in August 2005 from WDC, Kyoto University.

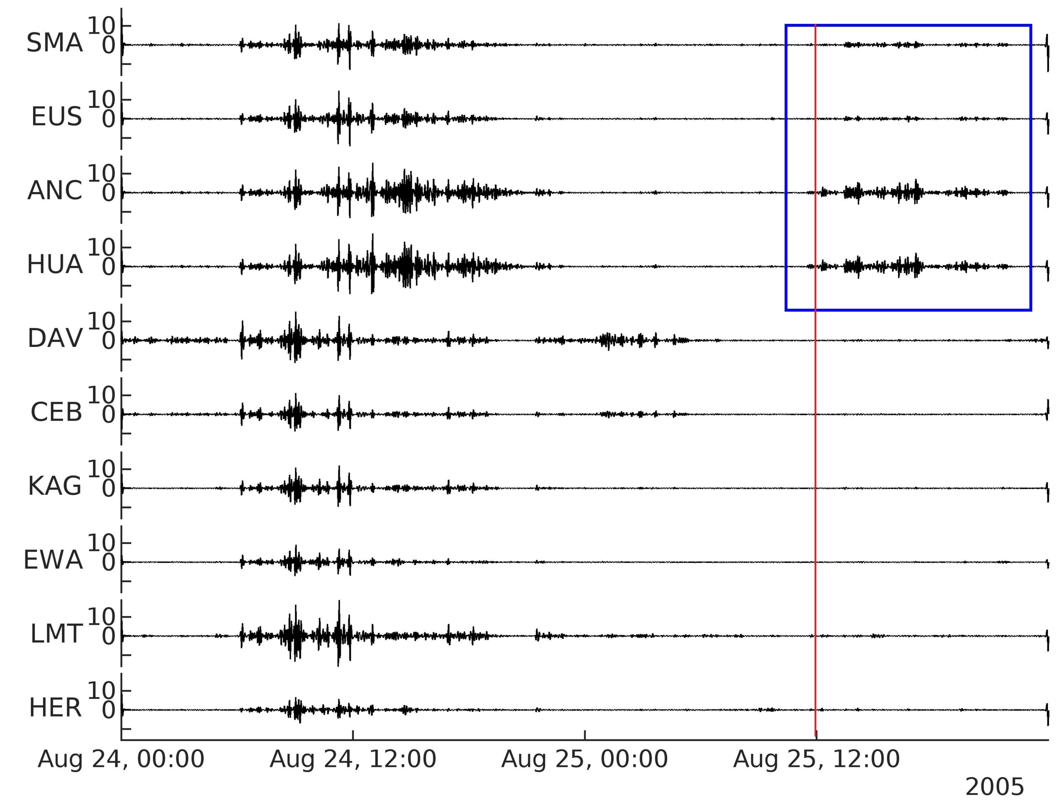

Figure 7. Corresponding Pc5 waves from selected MAGDAS/CPMN stations.

Based on the previous findings, we deduced the presence of significant Pc5 waves detected by stations near the SAA, especially in its northern part (ANC & HUA) during the recovery storm phase. This phenomenon was similarly observed in the two other events. The intense wave activity suggests a potential particle acceleration and precipitation in the ionosphere and atmosphere above the magnetic anomaly region.

Conclusions

1. Recent findings confirmed the increase of the electron and proton fluxes in the north and the south of the SAA, respectively.
2. Previous research using different methodologies proved the prominence of energetic protons in the southern part of the SAA during disturbed magnetic conditions
3. New results from magnetic ground stations revealed that Pc5 waves were generated during the recovery phases of three geomagnetic storms north the SAA
4. The generated Pc5 waves induce particle acceleration and precipitation in the ionosphere and atmosphere.
5. In future work, we plan to incorporate wave-particle interactions into our inner electron radiation belt model, and integrate it with ionosphere/atmosphere models to assess the corresponding ionization rate.

Selected References

1. Kirolosse M. Girgis, Tohru Hada, Shuichi Matsukiyo, Akimasa Yoshikawa, "Inner radiation belt simulations of the proton flux response in the South Atlantic Anomaly during the Geomagnetic Storm of 15 May 2005", J. Space Weather Space Clim. 11 48 (2021), DOI: 10.1051/swsc/2021031
2. Kirolosse M. Girgis, Tohru Hada, Shuichi Matsukiyo, Akimasa Yoshikawa, Abraham Chian, Ezequiel Echer, "Inner Radiation Belt Simulations during the Successive Geomagnetic Storm Event of February 2022", Space Weather, accepted with minor revision, March 2024.

Acknowledgement

This work was supported by JSPS KAKENHI Grant Numbers: JP20H01961, JP22K03707, JP21H04518, JP22K21345.

*This poster has been designed by Inwon Kang and published by Overleaf.

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