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# Rotating Finger-Like Structures of Jovian Magnetodisc

Z. H. Yao[1], Y. Xu[2], Z. L. Zeng[1], B. Zhang[1], D. Grodent[3], B. Bonfond[3], Y. N. Chen[2], W. R. Dunn[4], J. W. Sun[5], R. W. Ebert[6,7], J. E. P. Connerney[8,9], and F. Allegrini[6,7]

[1]Department of Earth & Planetary Sciences, University of Hong Kong, Hong Kong, China, [2]Department of Earth and Space Sciences, Southern University of Science and Technology (SUSTech), Shenzhen, China, [3]Laboratory for Planetary and Atmospheric Physics, STAR Institute, Université de Liège, Liège, Belgium, [4]Department of Physics and Astronomy, University College London, London, UK, [5]School of Earth and Space Sciences, Peking University, Beijing, China, [6]Southwest Research Institute, San Antonio, TX, USA, [7]Department of Physics and Astronomy, University of Texas at San Antonio, San Antonio, TX, USA, [8]Space Research Corporation, Annapolis, MD, USA, [9]NASA/Goddard Space Flight Center, Greenbelt, MD, USA

**Key Points:**

- Magnetic curvature can be highly variable during quiet magnetospheric state
- We identify periodic ~30-min fluctuations in plasma measurements in the magnetodisc when Juno was in a specific location
- Observations support that Jupiter's magnetodisc has a Finger-like structure

**Supporting Information:**

Supporting Information may be found in the online version of this article.

**Correspondence to:**

Z. H. Yao,
yaozh@hku.hk

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**Author Contributions:**

**Conceptualization:** Z. H. Yao
**Formal analysis:** Y. Xu, Z. L. Zeng
**Funding acquisition:** Z. H. Yao
**Investigation:** Z. H. Yao, D. Grodent, B. Bonfond, Y. N. Chen, R. W. Ebert, J. E. P. Connerney, F. Allegrini
**Methodology:** Z. H. Yao
**Project administration:** Z. H. Yao
**Visualization:** Y. Xu
**Writing – original draft:** Z. H. Yao
**Writing – review & editing:** Z. H. Yao, B. Zhang, D. Grodent, W. R. Dunn, J. W. Sun, F. Allegrini



**Abstract** At Jupiter, the plasma is concentrated near the centrifugal equator, forming a magnetodisc. The planet's dipole tilt induces periodic disc flapping, generating magnetic oscillations observed by spacecraft. While centrifugal forces are theorized to drive interchange instability in this system, direct detection of such structures remains challenging due to flapping-induced variabilities. However, in situ and remote sensing data reveal ~tens-of-minute periodicities proposed to link to interchange dynamics. Using unique Juno observations, we analyze two events to: (a) resolve highly variable magnetic curvature changes during successive plasma sheet crossings and (b) identify periodic ~30-min fluctuations in plasma measurements in the magnetodisc while Juno occupied a magnetically favorable location. These findings provide the first direct examination of interchange-related magnetic curvature evolution and plasma signatures, to advance our understanding of the magnetodisc's 3D structure and instability-driven dynamics.

**Plain Language Summary** Jupiter's tilted magnetic field and rapid spin create a flapping motion in its magnetodisc, making it hard to directly study magnetic structures because measurements get blurred by motion over time and space. Using Juno spacecraft data from two events, we show: (a) The magnetic field's “bendiness” (curvature) changes dramatically, hinting at structures arranged around the planet. (b) Plasma near Jupiter's equator shows repeating ~30-min cycles in a specific region. These results give the first direct proof of “finger-like” structures in Jupiter's magnetodisc, helping us map how its magnetic environment behaves in 3D.

## 1. Introduction

The interactions between the solar wind and the Earth's magnetic field form a thin nightside plasma sheet, often called a current sheet (CS) due to the buildup of a cross-tail current (Baker et al., 1985; A. Lui et al., 1976; A. T. Y. Lui et al., 1990). Jupiter's magnetosphere is shaped not only by solar wind interactions but also by its rapid planetary rotation and the substantial plasma contribution from its volcanic moon, Io. These characteristics transform the thin plasma sheet near the magnetic equator into a more complex, disc-like structure, commonly called the magnetodisc (Barbosa et al., 1979; Nichols et al., 2015). The plasma from Io's volcanic activity continually replenishes the magnetodisc, while Jupiter's rapid rotation generates significant centrifugal forces that stretch and maintain the disc's shape, and due to the magnetic dipole tilt, strong oscillations are found in Jupiter's magnetic fields and particles (Bolton et al., 1997; Connerney et al., 2020; Khurana & Schwarzl, 2005; Kivelson et al., 1997; McNutt et al., 1981; Russell et al., 2005; Sands & McNutt, 1988; Thorne et al., 1997).

Despite decades of study, a comprehensive understanding of Jupiter's magnetodisc structure remains elusive (Achilleos et al., 2015; Russell et al., 2000). Observations of interchange structures in Jupiter's magnetodisc have occasionally been reported by missions such as Galileo and Juno (Daly et al., 2023; Thorne et al., 1997), suggesting that the magnetodisc is far from static. These unusual magnetospheric structures, which occur as dense plasma regions swap with less dense regions, could be the key to understanding complex dynamic processes in the Jovian magnetosphere. However, a coherent explanation for these instabilities has yet to be developed. The magnetodisc's variable properties and its interaction with the rapidly rotating Jovian magnetosphere create an environment that is ripe for deeper investigation.

Due to the strong centrifugal forces generated by Jupiter's rapid planetary rotation, the interchange instability frequently develops within the magnetosphere (Hill & Michel, 1976; Yang et al., 1994), which can modulate the periodic plasma density variation and radio emissions (Ansher et al., 1992). This instability occurs when flux tubes loaded with cold, dense plasma are driven radially outward, while hotter, less densely loaded flux tubes carrying hot plasma move inward to conserve magnetic flux. While the primary mode of this instability is interchange motion—where flux tubes swap positions with minimal change to the magnetic field's overall configuration—the process can become more dynamic. Under certain conditions, it can evolve into field-reconfiguring ballooning modes, where plasma pressure causes the magnetic field to bulge outward. This can lead to partial flux-tube instabilities, in which plasma "bubbles" break off from the outer portion of a flux tube (Kivelson & Southwood, 2005). As noted by Went et al. (2011), these instability processes are exacerbated in the outer magnetosphere, where centrifugal forces create a radially stretched magnetodisc, which in turn facilitates large-scale plasma injections. Recent observations from Juno further support this, showing multiple signatures of interchange events associated with plasma injections, which are accompanied by energetic particle flux enhancements and plasma waves, such as whistler-mode and Z-mode emissions (Daly et al., 2023). These plasma injections are closely tied to auroral emissions, as the injected energetic particles precipitate along magnetic field lines, contributing to the intense auroras observed in Jupiter's polar regions (Dumont et al., 2018; Mauk et al., 2002; Nichols et al., 2023). These processes play a critical role in the overall dynamics of the magnetosphere, directly linking interchange instability to both magnetospheric plasma transport and auroral phenomena.

The global distribution of ultralow frequency waves in the Jovian system is revealed by observations by Galileo (Manners & Masters, 2020) and Juno (Sun et al., 2024). It has been suggested that the interchange structure is related to the low frequency waves using Galileo data (Thorne et al., 1997). A recent investigation of Juno's magnetic field data obtained in Jupiter's magnetopause boundary layer reveals systematic periodic variations at 10s min, suggesting a persistent low-frequency wave driver on the magnetopause (Zeng et al., 2024). A plausible interpretation for the waves is the interaction between a rotating interchange structure and the magnetopause. To date, direct examination of interchange-like structure is highly challenging due to the mixture of spatial and temporal variations.

In this study, we investigate two events with unprecedented observations from Juno, searching for direct observational evidence of the interchange-like structure in the azimuthal direction. The first event was detected between 9 and 15 May 2017, when the magnetosphere was in an extremely quiet period as evidenced by the weak auroral emissions observed by the Hubble Space Telescope (HST). We expect a low chance of temporal variations of global magnetic structure during the extremely quiet magnetospheric state, so the strong variations in measurements are likely spatial effects. The second event was detected on 28 December 2020, when Juno was located inside the plasma disc at a distance of around 35 $R_J$, where it remained for a long time (>3 hr). Magnetic curvature and plasma density were investigated, providing key insights into the understanding of azimuthal structures of the magnetodisc.

## 2. Observations

The magnetic field in the Jovian magnetosphere is obtained from Juno's Magnetic Field investigation (MAG) (Connerney et al., 2017). In this study, we present magnetic field data with 1-s resolution. Plasma data are from the Jovian Auroral Distributions Experiment (JADE) instrument on Juno, which consists of two identical electron sensors (JADE-E) and an ion sensor (JADE-I) (McComas et al., 2017). Figure 1a shows polar projections of five auroral images taken by HST/STIS in May 2017 (details are described in Grodent et al. (2018)). Both the auroral morphology and low power confirm that Jupiter's magnetosphere was under a quiet state (Grodent et al., 2018; Yao et al., 2022). The relatively steady oscillation of magnetic field and electron flux shown in Figures 1b and 1c also supports that the magnetosphere was not highly perturbed (Pan et al., 2021; Yao et al., 2019).

Taking advantage of the magnetodisc oscillation caused by the planetary rotation, we can calculate magnetic curvature near the equator for each plasmadisc crossing (Gu et al., 2024). The main results of magnetic curvature are shown in Figure 2. We first establish a local CS orientation, by transforming the magnetic field data into a CS coordinate system using Minimum Variation Analysis (MVA) (Lepping et al., 1981; Sonnerup & Scheible, 1998), based on the first CS crossing in Figure 2a, that is, from 09 May 2017/03:20 UT to 09 May 2017/05:40 UT. This is a standard technique in space plasma physics, which identifies the principal axes of magnetic field variance, and defines the natural coordinates of structures like current sheets. The time window for the MVA application is

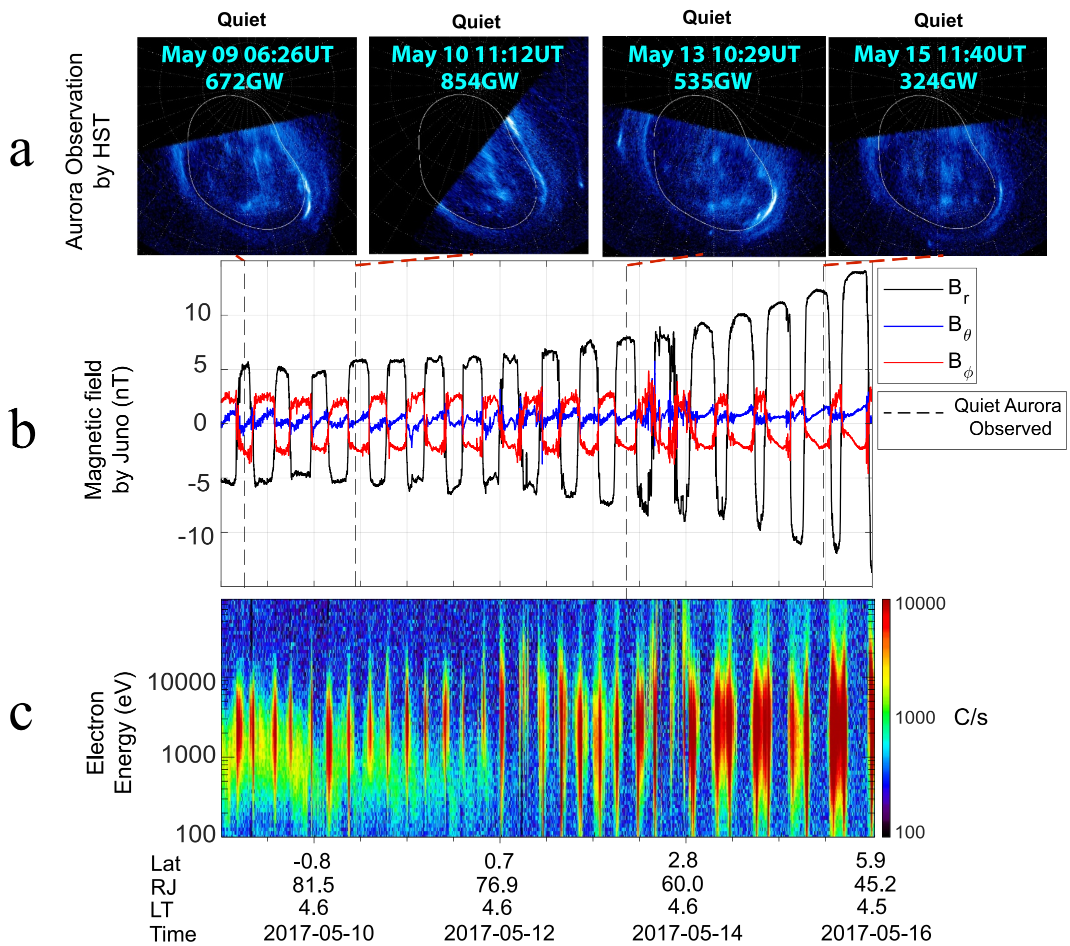


**Figure 1.** Polar projections of auroral images by the Hubble Space Telescope, magnetic field, and Jovian Auroral Distributions Experiment electrons by Juno in orbit PJ06, the magnetic field are presented in Jupiter-De-Spun-Sun (JSS) coordinate system (Wilson, 2017). Juno gradually approached Jupiter, moving from beyond 80–45 $R_J$, while the local time remained relatively stable between 4.5 and 4.6 LT on the morning side.

selected by the start and end times of the spacecraft's crossing of the CS, typically identified by the characteristic reversal of the primary tangential magnetic field component (marked as pink color in Figure S1 in Supporting Information S1), which is a widely adopted procedure for such analyses. Figure 2a shows the magnetic components in LMN coordinates (Denton et al., 2018), where $L$ representing the maximum variance eigenvector, $N$ to be the normal direction to the CS, and $M = N \times L$. For a reliable magnetic curvature reconstruction, we require that the CS can be well-fitted by the Harris CS model (Harris, 1962) and that the MVA eigenvalues, shown for all plasmadisc crossings in Figure 2b, satisfy the criteria $\lambda_1 > 10\,\lambda_2$ and $\lambda_2 > 3\,\lambda_3$. Once these conditions are met, the tangential component $B_L$ is fitted to the Harris CS model, expressed as $B_L = B_0 \tan h\left(\frac{v_n(t-t_0)}{L_{\text{model}}}\right)$, where $B_0$ is the asymptotic tangential magnetic field strength, $v_n$ is the relative normal velocity between the spacecraft and the CS, $t_0$ is the time of the CS center crossing, and $L_{\text{model}}$ is a scale length related to the CS half-thickness. Finally, the magnetic curvature ($\kappa$) is determined using the fitted tangential component $B_L$ and the measured normal component $B_N$. The magnetic curvature at the CS center, $\kappa_0$, is specifically calculated as $\kappa_0 = \frac{B_0}{B_N L_{\text{model}}}$, and the radius of magnetic curvature is then defined as $R_c = 1/\kappa$. The detailed discussion are found in Gu et al. (2024). The curvature results are shown in Figure 2c. It is obvious that the magnetic curvature could vary significantly, up to 3 orders of magnitude. As Jupiter rotates and the magnetospheric conditions remain quiet—as indicated by consistently low auroral emissions—the significant variations in magnetic curvature data suggest that the Juno spacecraft was traversing dynamic, co-rotating spatial structures, effectively sampling different azimuthal

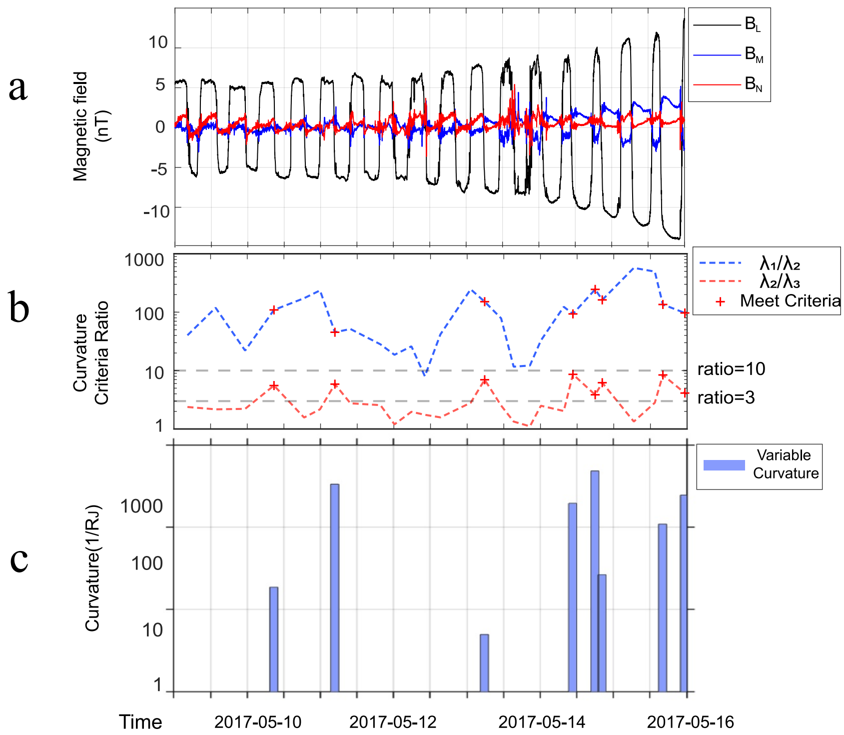


**Figure 2.** (a) Magnetic field in LMN Coordinates $B_{\mathrm{LMN}}$, (b) The ratio of lambdas which can be used to select relevant curvature events, and (c) Curvature values for selected points.

sections of the magnetodisc (see detailed discussion in Figure S2 in Supporting Information S1 and the Note in Supporting Information S1).

Due to the rapid magnetodisc oscillation, Juno often completes a plasma sheet crossing within 10s min, which is too short to resolve azimuthal structures related to interchange instability (Feng, 2023; Scudder et al., 1981; Wang, Bagenal, Wilson, Nerney, Crary, et al., 2024; Wang, Bagenal, Wilson, Nerney, Ebert, et al., 2024; Wang, Bagenal, Wilson, Valek, et al., 2024; Wang et al., 2025). Nevertheless, long duration in one plasma sheet crossing is still possible if the satellite is located in a specific location, such as near the extreme points of magnetodisc oscillation (Yao et al., 2021) where the vertical velocity is minimum. As illustrated by the schematic on the top of Figure 3, Juno would remain in the plasma sheet for a much longer time if located in the locations of the pink stars as opposed to the blue star. On 20 December, Juno stayed in the plasma sheet boundary layer from 16 to 20 UT with local time at ∼4.6, providing an unprecedented opportunity to analyze magnetodisc structure in the azimuthal direction.

Figure 3a presents magnetic field in JSS coordinate system (Wilson, 2017), showing a depression of $B_r$ for more than 3 hr, which is a direct evidence of plasma sheet boundary layer. Figures 3b and 3c show energy spectrograms for electrons and protons, both showing clear periodic variations, which can be analyzed by Fast Fourier Transform (FFT). Figures 4a and 4b show the flux intensities of electrons and ions as shown in Figures 3b and 3c. The periodicities highlighted by the FFT analysis in Figures 4c and 4d were determined from the interval where plasma flux was highest within the plasma sheet boundary layer (shaded region). This segment was chosen for analysis to clearly identify dominant frequencies; although similar periodic variations may extend beyond this specific region, this observation is consistent with the potentially widespread nature of such finger-like structures. A clear period of about 30 min was identified for all species. In a rotating system, the ∼30-min oscillations likely correspond to a Finger-like interchange structure in azimuthal direction, although we do not fully exclude temporal variation using single spacecraft measurements. If these structures co-rotate with Jupiter, their estimated azimuthal size is about 11 $R_J$, derived by multiplying the angular distance Jupiter rotates in 30 min by the spacecraft's radial distance (about 35 $R_J$ during this event). FFT analysis of the electron and ion density data was also conducted in the same region, revealing a periodicity near 0.5 hr (see Figure S3 in Supporting

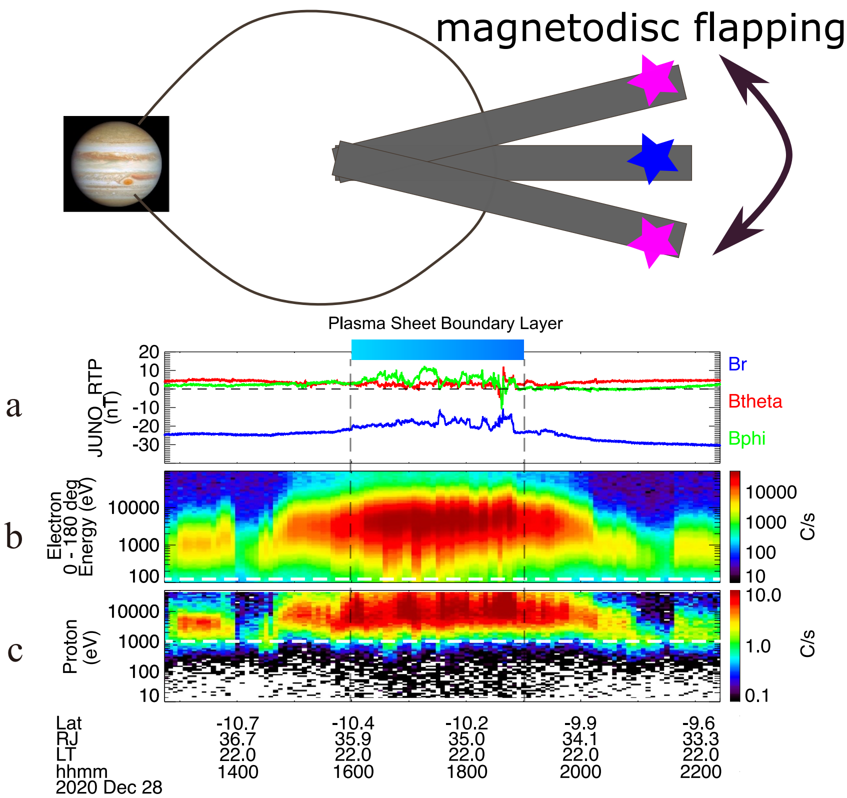


**Figure 3.** An illustration of magnetodisc flapping and varied magnetodisc crossings for spacecraft at different locations. Panels (a–c) are magnetic field, electron, and proton fluxes during a plasma sheet boundary layer event on 28 December 2020, during orbit PJ31.

Information S1). Schematics of two hypotheses of magnetodisc structures are shown in Figures 4e and 4f. Figure 4e represents a smoothed disc, from which we shall not expect either the large variations of curvature during quiet magnetosphere state, or the periodic variations of plasma density, as demonstrated by the two events shown in this study. As a contrast, the Finger-like disc picture illustrated by Figure 4f is nicely consistent the observations.

## 3. Discussion and Summary

In this study, we investigated two events providing potential evidence from two individual perspectives—magnetic field curvature and particle flux measurements—for the existence of finger-like structures in Jupiter's magnetodisc. The first case study focused on the pronounced variations in CS curvature during quiet magnetospheric conditions, where Juno measured curvature values spanning three orders of magnitude across different CS crossings during a single orbit. The second case study showed the periodicities in particle energy spectra within the plasma sheet boundary layer, revealing consistent oscillations with periods of approximately half an hour. These complementary approaches, examining both magnetic field geometry and particle characteristics, converge on a coherent picture of Jupiter's magnetodisc as a dynamic environment characterized by co-rotating finger-like structures as shown in Figure 4f.

Compared to the terrestrial magnetosphere that with an ion population of mostly solar wind protons, Jupiter's magnetosphere is mainly sourced by heavy ions from ionization of neutral clouds of volcanic gases escaping from Io (reviewed by Thomas et al. (2004), Bagenal and Dols (2020), and Roth et al. (2025)). The interchange processes in planetary magnetospheres are crucial in understanding mass and energy circulations. The interchange processes could also produce a highly stretched magnetic configuration, which could be related to magnetic reconnection, a key process in particle acceleration in space environments and laboratory (Zweibel & Yamada, 2009).

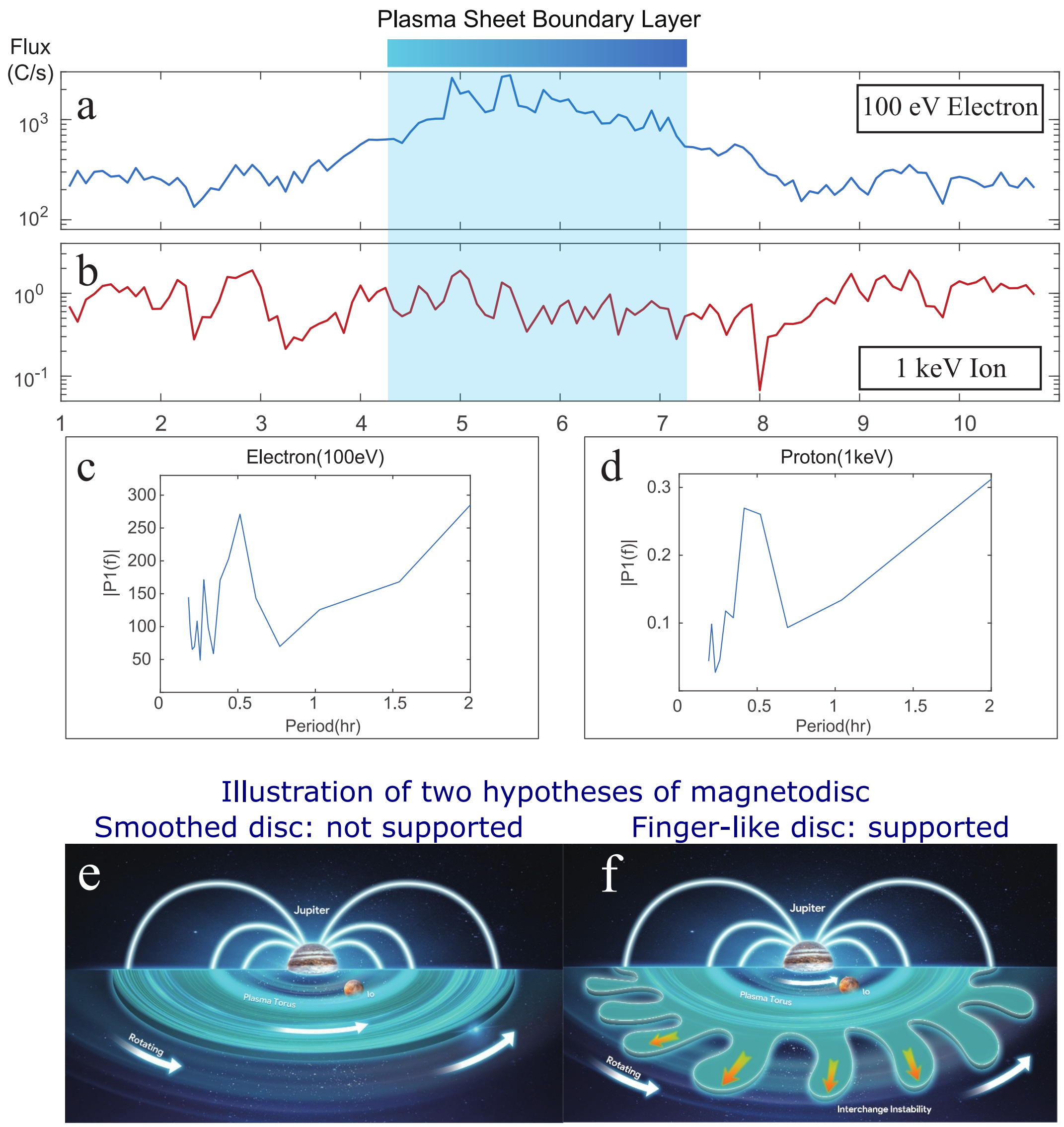


**Figure 4.** Fluxes for (a) electrons at 100 eV and (b) protons at 1 keV; panels (c, d) show Fast Fourier Transform analysis of the electron and proton fluxes in panels (a, b). Panels (e, f) are two possible magnetodisc structures, that is, smoothed disc and Finger-like disc.

Jupiter's magnetosphere is mainly dominated by the corotating electric field, resulting in a rotating magnetodisc, therefore, spacecraft measurements would couple spatial structure in the azimuthal direction to temporal variations. During 9–15 May 2017, the aurora images show very low emissions, indicating a relatively quiet magnetosphere, corresponding to a minimum temporal effect. The highly variable magnetic curvature during successive plasma sheet crossings (Figure 2c) indicates large varieties of magnetic configurations in the azimuthal direction, which is a plausible evidence of Finger-like structure in the azimuthal direction.

The magnetodisc flapping is persistent because of Jupiter's rotation, and the vertical speed during oscillation is minimal near the extreme points of magnetodisc oscillation. The event on 28 December 2020, provided an ideal opportunity for direct examination of spatial structure in the azimuthal direction. The period of about 30 min, if corresponding to a rotating azimuthal structure, would correspond to azimuthal wave number to be about 20, which is generally consistent with magnetohydrodynamic simulation results (Feng et al., 2023). We shall also not fully exclude temporal effects, such as low-frequency waves for the ~30-min variations.

It is noteworthy that a rotating spatial structure may also cause temporal effects, as interaction between the magnetospheric structure and the magnetopause could persistently produce dynamic processes. The interaction of the rotating magnetodisc with the magnetopause is highly asymmetric. We expect the dynamic interaction to be more significant on the morning side magnetopause, as the rotating magnetospheric flow would compress the morning side magnetopause. Since the near-pole magnetic field lines are mostly connected to the dawnside magnetosphere (Zhang et al., 2021, 2024); periodic dynamics in the dawnside magnetosphere are expected to result in near-pole pulsating emissions, such as the X-ray pulsations (Dunn et al., 2017; Gladstone et al., 2002; Yao et al., 2021).

## Data Availability Statement

Data from Juno MAG (Connerney, 2024) and JADE (Allegrini, 2023) used in this study are publicly available on the Planetary Data System (https://pds.mcp.nasa.gov/portal/). The auroral images are based on observations with the NASA/ESA Hubble Space Telescope (program HST GO-14634) via Yao (2025), obtained at the Space Telescope Science Institute (STScI), which is operated by AURA for NASA. All data are publicly available at STScI. The ion density data used in this study is available on Wang et al. (2025) via https://doi.org/10.1029/2024JA033454.

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