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Key Points:

- Large magnetic field perturbations coincide with Juno Ultraviolet Spectrograph (UVS) intense auroral arcs
- Magnetic field fluctuations on temporal scales <2 s are only resolvable above 4 R_J
- Magnetic field fluctuations at <2 s above 4 R_J coincide with auroral main emission zone

Supporting Information:

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

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Investigating Magnetic Field Fluctuations in Jovian Auroral Electron Beams

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Abstract The Juno spacecraft provides a unique opportunity to explore the mechanisms generating Jupiter's aurorae. Past analyses of Juno data immensely advanced our understanding of its auroral acceleration processes, however, few studies utilized multiple instruments on Juno in a joint systematic analysis. This study uses measurements from the Juno Ultraviolet Spectrograph (UVS), the Jupiter Energetic particle Detector Instrument (JEDI), and the Juno Magnetometer (MAG) from the first 20 perijoves. On magnetic field lines associated with the diffuse aurora, we consistently find small-scale magnetic field fluctuations with amplitudes of up to 100 nT on time scales of seconds to 1 min. On magnetic field lines directly linked to the main emission, the electron distribution is field-aligned, mostly broad-band in energy, and accompanied by large-scale magnetic field perturbations of several 100 nT on time scales of tens of min (except one case). These large-scale perturbations are generally associated with quasistatic field-aligned electric currents. Small-scale magnetic fields are not resolved over the main emission zone when the spacecraft is within four Jovian radii radial distance closer than radial distances four Jovian radii due to the digitization limit of the magnetometer. However, in all cases where Juno crosses the main auroral field lines beyond 4 R_J , the digitization limit is significantly reduced and we detect small-scale magnetic field fluctuations of 2–10 nT consistent with a turbulent spectrum. Associated energy fluxes projected to Jupiter can exceed 1,000 mW/m². The general broad-band nature of the electron distributions and the consistent presence of small-scale magnetic field fluctuations over the main emission support that wave-particle interaction can dominantly contribute to power Jupiter's auroral processes.

Plain Language Summary Jupiter possesses the brightest auroral emission of all planets in the solar system. One of the key objectives of the Juno mission to Jupiter is to better understand the processes that lead to this bright emission. In our analysis, we simultaneously use data from three instruments on Juno, that is, from the Ultraviolet Spectrograph, the Jupiter Energetic particle Detector Instrument, and the Juno Magnetometer obtained during the first 20 orbits of Juno around Jupiter. We find that on magnetic field lines connecting to auroral emission, energetic electrons and magnetic field perturbations associated with electric currents are systematically present. Magnetic field perturbations indicate that both large-scale DC electric currents and small-scale AC currents occur. We find that most auroral electrons are broad-band in nature and often travel toward and away from Jupiter, which together with the consistent presence of AC currents suggests what waves, in particular a type referred to as Alfvén waves, might play a key role in energizing auroral electrons.

1. Introduction

Jupiter possesses the most powerful aurora in the solar system. Understanding the mechanisms that energize the electrons and ions causing auroral emissions is a key objective of the Juno mission (Mauk, 2013). Initial observations based on Jupiter Energetic-particle Detector Instrument (JEDI) and Jovian Auroral Distributions Experiment (JADE) instruments of the Juno spacecraft have shown that electron energy distributions, ranging from low to high energies (30 eV–1 MeV) are often broad and follow power-law distributions with a hardtail that extends to high energies of around 1 MeV and energy fluxes exceeding 3 W/m² (Allegrini et al., 2017; Mauk et al., 2020; Mauk, Haggerty, Jaskulek, et al., 2017; Szalay et al., 2017). In a statistical analysis, the occurrence of these broad distributions was further investigated, revealing that they are present approximately 93(±3.8)% of the time above the main emission region during the first 20 perijoves (Salveter et al., 2022). In contrast, mono-energetic distributions, where intensities peak at specific energy levels, are rare and account for approximately 7

(± 3.8)% of the observed times (Clark et al., 2017; Mauk et al., 2018, 2022; Salveter et al., 2022). Another remarkable observation was the bidirectional nature of electron distributions, indicating electrons accelerated in both directions along magnetic field lines. This phenomenon is particularly prominent in the Zone II (ZII) region, identified by Mauk et al. (2020), characterized by dominant upward and bidirectional electron distributions associated with a downward electric current region. In contrast, equatorward Zone I (ZI) exhibits mostly downward-going electrons linked with upward currents and transitions further equatorward into diffuse auroral regions DifA with mostly pancake distributions. Poleward of the main emission in the polar region, a large and dynamic region, energetic electrons move primarily upward along magnetic field lines (Ebert et al., 2017; Elliott et al., 2018; Mauk et al., 2020; Paranicas et al., 2018). Distinguishing the transition from the main emission zone to the polar region proves challenging, as both inverted V and broadband distributions are frequent.

Jupiter exhibits a unique magnetosphere-ionosphere (MI) interaction with large angular momentum and energy transport between its ionosphere and the plasma of the middle magnetosphere due to the internal mass loading from Io, which is generally thought to ultimately cause the intense aurora. This contrasts with the aurora on Earth, which is powered by the solar wind (Akasofu, 1981; Baker et al., 1996). Jupiter's intense auroral emissions reach an ultraviolet brightness of several thousand kilorayleighs (kR) (Grodent et al., 2003) that exceeds the terrestrial auroral brightness by a factor of 10 (Broadfoot et al., 1979). At Earth, the dominating auroral type in contrast to Jupiter is diffusive aurora with a smaller contribution from discrete aurora. At Earth, the latter is usually caused by a larger fraction of mostly downward mono-energetic electrons compared to broad-band electron distributions (Newell et al., 2009). Another difference lies in Jupiter's downward current region ZII, which shows strong auroral emissions, unlike Earth, where such emissions are absent (Mauk et al., 2020).

Jupiter's powerful magnetic field, the rapid rotation of the planet, and Io's plasma production result in a corotating plasma sheet confined to the equatorial region. However, the plasma's corotation cannot be sustained in the middle magnetosphere, leading to magnetic field tension and Lorentz forces, enforcing corotation in the equatorial sheet. The forces are balanced in Jupiter's ionosphere through collisions with the neutral atmosphere. The associated transport of angular momentum and energy from the ionosphere into Jupiter's magnetosphere is associated with a quasi-static electric current system along Jupiter's field lines (T. Hill, 1979; Kivelson, 2005). This large-scale electric current system has traditionally been associated with the main auroral emission (T. W. Hill, 2001; Cowley & Bunce, 2001). On field lines where the upward electric current maximizes, that is, around 30 R_J , electrons are expected to accelerate toward Jupiter. Using the Knight relationship (Knight, 1973) for Jupiter, Cowley and Bunce (2001) predicted mono-energetic, unidirectional auroral electrons with energies around 100 keV. The relationship between electrostatic potential, field-aligned currents, and the resulting auroral excitation has been further studied, for example, by Nichols and Cowley (2004) and Ray et al. (2010).

Jupiter's equatorial magnetosphere also exhibits small-scale magnetic field fluctuations on the order of several nT, which show turbulent properties (Kaminker, 2024; Lorch et al., 2022; Ng et al., 2018; Saur, 2004; Saur et al., 2002; C. Tao et al., 2015). These small-scale magnetic field fluctuations have been associated with Alfvén wave packets and highly time-variable field-aligned electric currents whose dissipation at high latitudes was suggested to contribute to auroral acceleration (Saur et al., 2003). Thomas et al. (2004) and Mauk and Saur (2007) observed in the middle magnetosphere of Jupiter broadband highly field-aligned electron beams, which were argued to be related to anti-planetward auroral acceleration due to small-scale electric current systems (Mauk & Saur, 2007) similar to the findings and discussion about Saturn's magnetospheric electron beams (Masters et al., 2022; Saur et al., 2006). The highly time-variable magnetic fields and associated DC electric currents are related to plasma waves such as kinetic/inertial Alfvén waves. When these waves encounter low plasma densities in the auroral acceleration region such that the scales of the plasma wave approach typical kinetic plasma scales, that is the electron inertial length scales (Saur et al., 2018; Sulaiman et al., 2022), then wave-particle interaction can take place (e.g., Lysak & Lotko, 1996). In addition to (turbulent) Alfvénic fluctuations (Damiano et al., 2019; Saur et al., 2018) other mechanisms are also expected to lead to a strong wave-particle interaction, such as those originating from field line resonances (Lysak & Song, 2020) or the ionospheric Alfvén resonator (Lysak et al., 2021).

Although there are no direct electric field measurements to constrain auroral acceleration mechanisms (except for high-frequency plasma waves by the Waves instrument; Kurth et al., 2017), Juno's magnetic field data can suggest the presence of various types of related electric current and possibly associated electric fields. Kotsiaros et al. (2019) analyzed perpendicular magnetic field fluctuations at high latitudes, providing evidence for quasi-

steady state Birkeland currents. Such a large-scale current system might be associated with large potentials (Kotsiaros et al., 2019). The derived currents in Kotsiaros et al. (2019) are weaker than anticipated and were argued to not fully account for the expected currents related to Jupiter's aurorae, despite their amplitude matching the radial currents detected within the equatorial plane. Bonfond et al. (2020) provided multiple arguments challenging the notion that Jupiter's main aurora is primarily caused by the large-scale corotation enforcement current. For example, the aurora appears to be more intense at dusk, whereas the radial currents are more pronounced at dawn (Groulard et al., 2024). In contrast, small-scale magnetic field fluctuations and time-variable electric currents indicating wave-particle interactions have been observed at high latitudes as well (Gershman et al., 2019; Sulaiman et al., 2022). Gershman et al. (2019), for example, observed that small-scale perpendicular magnetic field fluctuations occurred along with auroral broadband emissions and the Poynting flux reaching up to 100 mW/m^2 . Small-scale magnetic field fluctuations have previously been detected primarily over diffuse auroral regions but appeared to be not present as the spacecraft passes through the main emission zone (Sulaiman et al., 2022). The authors suggested that the diminished magnetic fields resulting from very small plasma densities, known as auroral cavities, might explain the lack of fluctuations over ZI. This density drop leads to large electron inertial length scales, increasing the wave-particle interaction of kinetic/inertial Alfvén waves thereby reducing the magnetic field fluctuations while accelerating auroral particles (e.g., Lysak et al., 2021; Saur et al., 2018). However, evidence for Alfvénic turbulence at mid to high latitudes, characterized by small-scale magnetic field fluctuations and sufficient Poynting fluxes to drive auroral emissions, has been found at radial distances of $>10 R_J$ by Lorch et al. (2022).

To further shed light on the dominant mechanisms that cause Jupiter's auroral electrons associated with the diffuse and main emission, this work presents a statistical study in which we jointly analyze auroral electron intensity from Jupiter Energetic-particle Detector Instrument (JEDI), and magnetic field variations from Juno Magnetometer (MAG), and compares these with ultraviolet emissions observed by Juno Ultraviolet Spectrograph (UVS). By examining magnetic field changes, we investigate also the role of the possible electric currents associated with the observed particle distribution and auroral patterns. In Section 2, we briefly present the important properties of the JEDI, JADE, and MAG instruments, and the data and analysis tools applied in this study. In Section 3 we present the results of our data analysis, categorized by radial distance from Jupiter: within $4 R_J$ and at greater distances. At greater distances, digitization of the magnetometer significantly enhances the resolution of small-scale magnetic field fluctuations. In Section 4, we end with a summary of our main conclusions.

2. Instrument, Data, and Methods

To gain a deeper understanding of the distinctive features of Jupiter's magnetosphere at high latitudes, particularly in relation to the auroral regions, we have integrated data from three instruments aboard the Juno spacecraft. During the first 20 perijoves, the spacecraft has conducted in situ measurements while passing Jupiter at low altitudes and high latitudes above the Jupiter auroral region. These unique data enable us to gain a broader understanding by statistically analyzing observations from multiple perijoves and various magnetospheric properties, rather than focusing solely on individual observations. Now, we briefly introduce the three instruments used in this study—the Jupiter Energetic-particle Detector Instrument (JEDI), Juno Ultraviolet Spectrograph (UVS), and Juno Magnetometer (MAG)—along with the basic processing routines we employed.

2.1. Jupiter Energetic Particle Detector (JEDI)

The JEDI instrument, in conjunction with its low-energy counterpart JADE, carries out in situ observations of electron and ion distributions (Bagenal et al., 2017). JEDI measures the precipitation of energetic electrons within the energy range of 25–1,200 keV (Mauk, Haggerty, Jaskulek, et al., 2017). It is equipped with 18 solid state detectors (SSD) that simultaneously measure the rate of single electrons in different directions, providing an almost complete 360° field of view (Mauk, Haggerty, Jaskulek, et al., 2017). This allows for the measurement of all pitch angles, which is the angle between the velocity of the electrons and the magnetic field vector, and leads to a nearly full pitch angle coverage. The measurements are obtained every 0.5 s, enabling the resolution of even small structures of a few hundred kilometers because of the spacecraft's velocity of approximately 50 km/s near Jupiter. However, the pitch angle coverage of JEDI depends on the alignment of the magnetic field with the plane perpendicular to the spacecraft spin vector, which means that reasonable pitch angle coverage is sometimes only achieved over the 30 s spacecraft spin period. Given a complete population of the loss cone, the energy flux can be

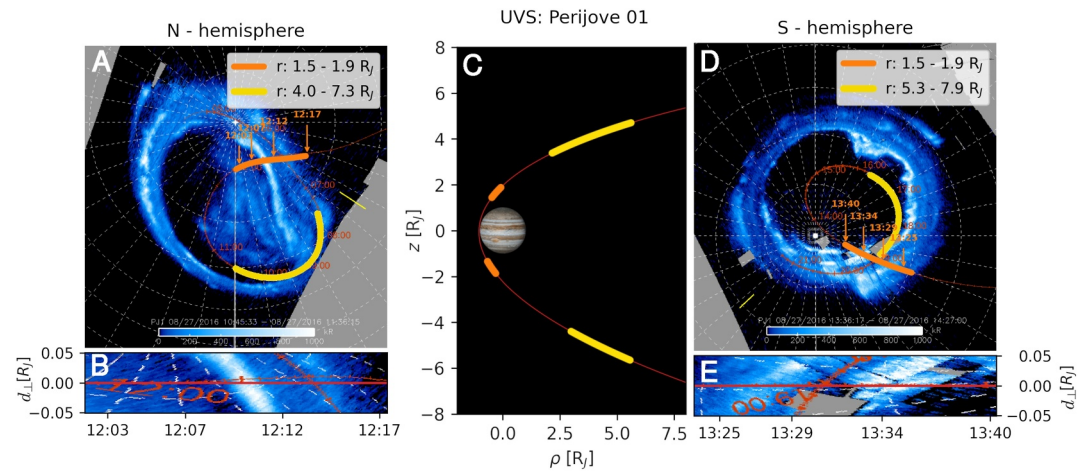


Figure 1. Overview of the flight trajectory in panel (c) of the first perijove in the rotating frame of Jupiter, expressed by the SysIII coordinates. The perpendicular distance from the spin axis is calculated by $\rho = \sqrt{x^2 + y^2}$. The spacecraft's location is mapped onto the ionosphere and marked with red lines on the left and right sides of the UVS panels. The UVS images are shown for the northern hemisphere (a) on the left and the southern hemisphere on the right side (d). The lower parts (b and e) show the UVS image slice along the flight trajectory for both hemispheres, where Juno crosses the expected auroral emission region at times indicated by the orange and yellow lines in the top plots, at low and high altitudes, respectively. Some regions may lie above the main emission region, but those beyond 8 R_J radial distance are excluded due to the resolution limits of the instrument. The perpendicular distance to the flight trajectory is given by $d_{\perp}$ in Jovian radii.

calculated and projected onto the atmosphere by adding $\pi \sum_n I_n(\alpha) E_n \Delta E_n$, where π represents the area projection-weighted size, n refers to individual energy channels with E_n as central energy, ΔE_n as the energy bandpass and I_n the measured intensity (Mauk, Haggerty, Paranicas, et al., 2017).

2.2. Juno Ultraviolet Spectrograph (UVS)

The Ultraviolet Spectrograph (UVS) observes ultraviolet emissions from Jupiter, covering wavelengths from 68 to 210 nm (Gladstone, Versteeg, et al., 2017). Bonfond et al. (2021) introduces a method for comprehensive imaging of the whole northern and southern aurora in polar projection, at an altitude of 400 km above the planet's 1-bar level, where the detector distinguishes ultraviolet photons from background interference. During approximately 50 min, the successive rotations update the Ultraviolet (UV) image by calculating the weighted average, prioritizing recent ones, resulting in a comprehensive overview of the whole polar-projected auroral region, demonstrated in panels A and D of the first perijove in Figure 1. To associate particular UV emission patterns with the spacecraft's location along magnetic field lines, a mapping technique created by Wilson et al. (2023) is used. This method utilizes both the internal Juno Reference Model through Perijove 33 (JRM33) (Connerney et al., 2022) and the external magnetic field models Connerney 2020 current sheet model (Con2020) (Connerney et al., 2020). A set of lines parallel to Juno's trajectory is determined to encompass a curved section along the trajectory of the spacecraft. This curved section is extracted from the averaged polar UVS images to create a two-dimensional rectangular representation of the averaged polar UVS along the line of flight (see panels b and e in Figure 1). The effectiveness of this method's display has been evaluated using the standard Phase Alternating Line (PAL) test pattern *Philips PM5544*. This pattern comprises elements such as color bars, grayscale, and geometric shapes, which are utilized to assess parameters like color fidelity, contrast, sharpness, alignment, and aspect ratio. Achieving a satisfactory representation requires at least 40 lines per 0.1 R_J for optimal data visualization.

Discrepancies between the location of the time-averaged observation of the ultraviolet emissions and the instantaneous in situ measurements taken by MAG and JEDI may arise due to various factors. First, the 50 min duration for capturing average polar UVS images introduces timing uncertainties for time-variable auroral UV emissions. Second, changes in the magnetic field over time may affect the accuracy of tracing field lines. Third, the curved flight path can distort UV emission structures when projected onto a rectangular shape, as is exemplarily shown in panels 1b and 1e. Nevertheless, the resulting UVS image slices offer a comprehensive view of UV emission morphology for comparison with magnetic field configurations and electron intensity.

2.3. Fluxgate Magnetometer

To observe magnetic field fluctuations along the flight trajectory, data from the Fluxgate Magnetometer (FGM) is utilized. Operating at 64 samples per second, the FGM measures magnetic field magnitude and direction, enabling observation of variations on short temporal and spatial scales in all three dimensions simultaneously (Connerney et al., 2017). Additionally, an onboard star camera observes the position of fixed stars to obtain the spacecraft orientation, achieving an accuracy of 100 ppm for magnetic field vectors.

The magnetometer is capable of sensing magnetic field strengths within a range of a few nanoteslas (nT) up to 16 Gauss (equivalent to 1.6×10^6 nT) per axis, operating in one of six dynamic ranges in response to the measured field magnitude (Connerney et al., 2017). The analog output in each range is sampled by a 16-bit analog-to-digital converter (A/D), resulting in a resolution of 0.025 nT in the instrument's most sensitive dynamic range ($\pm 1,600$ nT), increasing (by a factor of 4) as the dynamic range increases by a factor of 4, to a resolution of 25 nT in the 16 Gauss dynamic range. The Fluxgate Magnetometer (FGM) possesses a natural noise level of less than $\ll 1$ nT, which is considered negligible compared to the uncertainty due to digitization.

The calibrated magnetic field data for this study was obtained from the Planetary Data System (Connerney, 2017) in planetocentric coordinates. The data is provided with a temporal resolution of 64 samples per second near perijove, dropping to 16 samples per second further from Jupiter and ultimately eight samples per second throughout the remainder of Juno's highly elliptical orbit, to meet the telemetry allocation constraints.

2.4. Magnetic Field Fluctuations

Fluctuations in the magnetic field caused by effects of temporal or spatial variability are studied by looking closely at the residual that remains after subtraction of the model fields, typically no more than about 0.1%–1% of the ambient field. Thus, the initial data processing step involves subtracting the background magnetic field defined by the internal magnetic field model JRM33 and the external magnetic field model Con2020.

Background magnetic field data are obtained from a module developed by Wilson et al. (2023), which offers both internal and external magnetic field components in SysIII coordinates based on JRM33 and Con2020. The magnetic field variations are then given in the Jupiter coordinate system SysIII with δB_i along the longitudinal ϕ , latitudinal θ , and radial r axes.

The calibrated magnetometer data in the high dynamic ranges used in this study (ranges 4–6) have been corrected for a spacecraft field arising from Eddy currents due to the spacecraft rotation in a strong magnetic field (Kotiaros et al., 2020). The corrections applied are described in Addendum 1 to the Software Interface Specification (Connerney et al., 2017) and are a few hundred parts per million in magnitude. However, the residuals for some perijoves contain a recognizable sinusoidal component with a period of ~ 30 s, corresponding to the Juno spin period. Spin modulation can arise from a variety of sources, including induced and remanent spacecraft magnetic fields, instrument measurement errors, coordinate transformation errors, and even data quantization uncertainties. However, we make here no attempt to correct these to maintain data integrity; instead, these artifacts are carefully observed during interpretation and do not impact our results.

Changes in the magnetic field are represented by the longitudinal component δB_ϕ , the latitudinal component δB_θ , and the radial component δB_r . In a dipolar-dominated magnetic field at low altitudes and high latitudes, the radial component aligns roughly with the magnetic field direction, while the longitudinal and latitudinal components are roughly perpendicular to a dipole-dominated field. Thus, variations in the θ and ϕ components indicate magnetic field perturbations perpendicular to the background field, often associated with parallel electric currents. In the following, we will analyze magnetic field fluctuations in a broad frequency range up to 2 Hz.

2.5. Field-Aligned Static Currents

To examine the contribution of magnetic field fluctuations that indicate field-aligned current density from radial currents in the ionosphere, we apply Ampère's law, $\nabla \times \vec{B} = \mu_0 \vec{j}$, where μ_0 is the vacuum permeability while neglecting displacement currents. The resulting magnetic field changes are then associated with the field-aligned currents by

$$j_{\parallel} \approx \pm j_r = \frac{\pm 1}{\mu_0 r \sin \theta} \left(\frac{\partial(\delta B_{\phi} \sin \theta)}{\partial \theta} - \frac{\partial(\delta B_{\theta})}{\partial \phi} \right), \quad (1)$$

where δB_{ϕ} corresponds to the background subtracted latitudinal magnetic field and the $\pm$ signs to the northern and southern hemispheres, respectively. We assume in the following that the current density j_r at high latitudes and low altitudes represents the field-aligned currents. The measurements obtained by the Juno spacecraft do not permit independent determination of the θ and ϕ derivatives in Equation 1. However, assuming that the electric currents connecting Jupiter's magnetosphere with its ionosphere are structured in sheets with locally very small variability in the ϕ -direction, but only in the θ -direction (such as the MI-current system suggested by T. W. Hill (2001) and Cowley and Bunce (2001)), then we can neglect to first order $\frac{\partial(\delta B_{\theta})}{\partial \phi}$. This approximation is expected to hold for the large-scale MI-electric current system (Cowley & Bunce, 2001; T. W. Hill, 2001). It is important to note that single spacecraft observations are limited to measuring changes only along the spacecraft's path. Therefore, if the current sheet is not perfectly perpendicular to the trajectory of the spacecraft, the variations perpendicular to it could be underestimated, affecting the resulting field-aligned currents (Luhr et al., 1996). Note, we do not apply 1 in our study, but only discuss this equation to help with the interpretation of observed large-scale magnetic field perturbations.

The polarity, that is direction, of the magnetic field change is directly linked to the direction of the field-aligned current, which can either be directed toward or away from Jupiter. For measurements as a function of time in a moving spacecraft, the polarity depends on the direction of the trajectory, whether it is toward the poles or the equator, and the orientation of the magnetic field, which is upward in the northern hemisphere and downward in the southern hemisphere. Analyzing the magnetic field components in the SysIII coordinates, we find that negative magnetic field changes indicate upward currents when Juno is heading toward the poles in the northern hemisphere. Each alteration in the flight path or observation hemisphere will lead to a reversal of the sign to determine the direction of the field-aligned electric current and must be taken into account.

Substantial changes in the magnetic field with considerable amplitudes over several minutes are likely linked with field-aligned current (FAC) and will be termed *large-scale magnetic field variations*. These variations are characterized by isolated structures associated with periods greater than 1 min, corresponding to frequencies less than 0.01 Hz. Thus, Juno detects these variations in the magnetic field over distances exceeding 3,000 km. Conversely, the high-frequency magnetic field changes with periods shorter than seconds, and hence frequencies above 0.1 Hz are termed *small-scale fluctuations* henceforth. Their amplitudes are smaller and sometimes indistinguishable from background noise. However, these small-scale fluctuations can occur over an extended time interval of several minutes. The subsequent section will explore the potential physical significance and occurrence of these small-scale fluctuations.

2.6. Field-Aligned Non-Static Currents

To explore the fluctuations in the magnetic field at high frequencies, potentially arising from dynamic MI-coupling and associated time-variable field-aligned currents, it is important to distinguish between high-frequency reaching 1 Hz and low-frequency fluctuations with less than 1 mHz, as well as to filter out noise by focusing on specific frequencies of interest. To study the temporal evolution of the frequency components of a signal with N samples and the sampling interval Δt , we use the wavelet analysis which convolves the signal with localized basis functions in both the time and frequency domains. The resulting Continuous Wavelet Transform (CWT) coefficients $W_n(s)$, conserve the average signal energy during the transition from the time to the frequency domain, following Parseval's relation (Paschmann & Daly, 1998; Torrence & Compo, 1998). To ensure energy consistency across interval modifications, the Power Spectral Density (PSD) is given by $S_n = 2 \frac{N}{\Delta t} \cdot W_n(s)^2$ in units of (nT)²/Hz. A Morlet basis function $\Psi_0(\eta) = \pi^{-1/4} \exp i \omega_0 \eta \exp -\eta^2/2$ is used based on sinusoidal waves with a Gaussian envelope, with a nondimensional "time" parameter η and the nondimensional frequency ω_0 representing the number of oscillations in a wave packet. Within these studies, we choose the nondimensional frequency $\omega_0 = 6$, which establishes an almost direct relationship between the wavelet scale and the Fourier period $\lambda = 1.03$ s (refer to Table 2 for other empirical values in Torrence & Compo, 1998).

To remove any unresolved low-frequency trends/noise in the data, the data undergo pre-whitening before the wavelet transform and post-darkening afterward. Pre-whitening involves computing the time increment series of

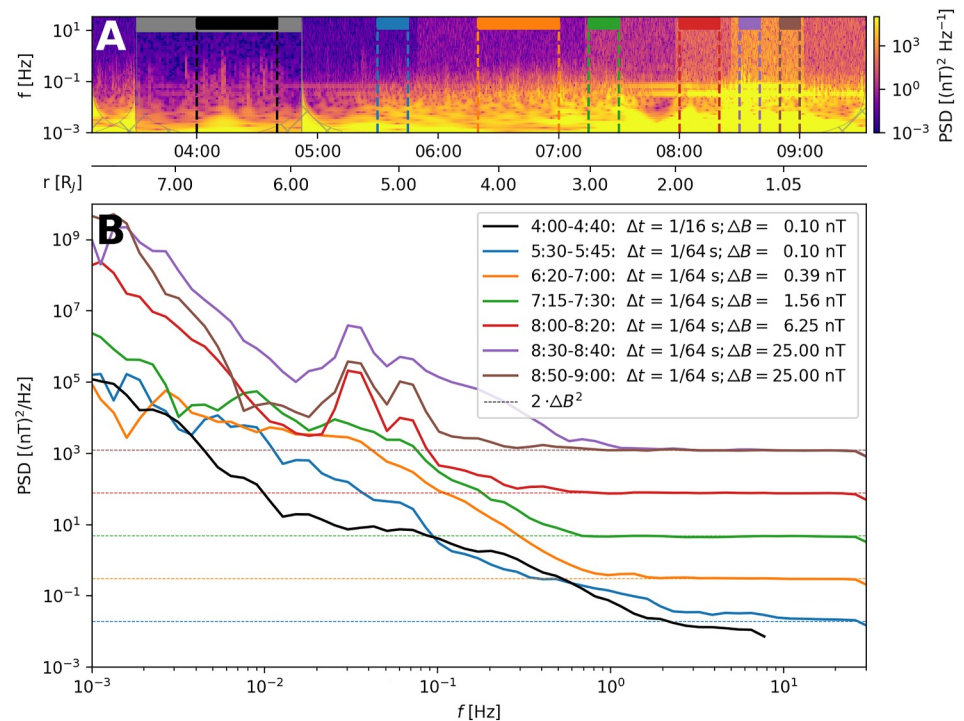


Figure 2. Wavelet spectrum of the northern flyby of Fifth Perijove are displayed over a wide temporal range of more than 6 hr in part (a). All the different digitization levels are visible. (b) Time-averaged Power Spectral Densities (PSD) during selected time intervals, with the dashed lines indicating the corresponding digitization levels.

the data as $b(t, \tau) = B(t + \tau) - B(t)$, where τ represents the time increment of the series. The post-darkening step guarantees energy conservation by multiplying the Power Spectral Density (PSD) by the factor $(4\pi \sin^2(\pi f \Delta t))^{-1}$ (Bieber et al., 1993). To reduce edge effects in the wavelet transform, zeros are added to the signal until the next power of two is reached. Yet, edge effects are visible in the Cone-of-Influence (COI), which refers to the region where the sidelobes of the Morlet wavelet exceed e^{-1} when reaching the data boundary (for detailed information Torrence & Compo, 1998). Consequently, we extend the time intervals of interest to eliminate the boundary effects on the time periods specified for the frequencies above 1 mHz.

To distinguish regions with significant fluctuations at either small or large scales, the wavelet power is averaged over specific frequency bands, indicating the average variability within a specific frequency range using Parseval's Theorem (Torrence & Compo, 1998). The root-mean-square (rms) value is derived by taking the square root of S_n the PSD. Consequently, the local power spectra for specific time windows are calculated by averaging over the frequency bands of the wavelet spectra, as illustrated in Figure 2b, with respect to time periods of various digitization levels, indicated in Figure 2a.

Resolving fluctuations associated with higher frequencies (small-scale) fluctuations is subject to limitations due to the restricted resolution of FGM data caused by digitization.

The quantization error, as described by Bennett (1948) and Gray and Neuhoﬀ (1998), exhibits little correlation with the real signal, acting as random noise with a nearly uniform white spectrum. Consequently, PSDs are constrained by the square of quantization noise ΔB , following $2 \cdot \Delta B^2$, as depicted by dotted lines in Figure 2b. This figure illustrates the average power spectral densities determined for different digitization levels in various time periods during the northern perijove 5, marked by colored regions in Figure 2a, showing limits within each digitization level. For most levels, frequencies above approximately 0.5 Hz are mainly affected by quantization noise. However, the smallest digitization level of 0.072 nT can detect changes in amplitude down to $0.1 \text{ (nT)}^2/\text{Hz}$, allowing the observation of frequencies up to around 3 Hz on average. The relationship between the quantization error ΔB and the lowest detectable Power Spectral Density $PSD_{\min}$ is shown in Figure 3a, where the equation $PSD_{\min} = \Delta B^2 \cdot 2$ delineates the minimum detectable Power Spectral Density.

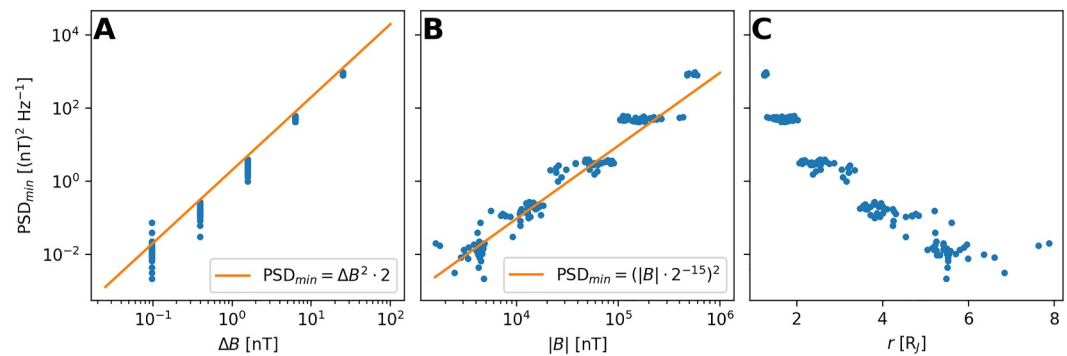


Figure 3. The minimum resolvable Power Spectral Density PSD_{min} is analyzed for each digitization level (panel a), demonstrating its correlation with the total magnetic field strength (panel b) and the radial distance to Jupiter (panel c). The orange slopes in panels (a) and (b) indicate the expected minimum resolvable Power Spectral Density PSD_{min} for the digitization level ΔB and the total magnetic field strength $|B|$, respectively.

The magnetic field strength is associated with the least resolvable Power Spectral Density PSD_{min} through expression $PSD_{min} = (B \cdot 2^{-15})^2$, and thus is related to the radial distance to Jupiter, as seen in Figure 3b. Consequently, observations at radial distances less than $4 R_J$ are unlikely to be able to resolve possible magnetic field fluctuations with amplitudes less than 1 nT, which are mostly related to wavelengths less than 2 s. Thus, only observations at a greater radial distance than $4 R_J$ can resolve sufficient frequencies up to 3 Hz. The highest resolution of magnetic field data is achieved with a quantization step of 0.025 nT (Connerney et al., 2017), typically used during flybys at radial distances greater than $\sim 6 R_J$. Although this is expected to improve the resolution of higher frequencies, we did not use this range since we focused on examining magnetic field perturbations near Jupiter's poles and above the main emission region.

3. Results

Only about half of all flybys are suitable for a joint analysis of the magnetic fields, energetic electrons, and auroral UV emission at high latitudes. This is because the spacecraft did not cross field lines connected to the main emission—particularly at higher altitudes—or because the field of view is restricted by the spacecraft's rotation. In particular, the spacecraft's rotation can cause restrictions on the measurements of the magnetometer and particle instrument. Therefore, some auroral crossings do not provide sufficient data resolution to investigate the correlation between the different instrument observations. However, the trajectory of the spacecraft passes through the magnetic field lines mapping to the primary auroral emission multiple times throughout the flybys, as illustrated in Figure 4 by the radial and L-shell coverage of the various flybys.

To compare the time-averaged UVS observations with the instantaneous magnetic field and particle observations, we use the L-shell parameter to localize auroral intensities and acceleration processes. This parameter was computed using the routine developed by Wilson et al. (2023), which maps the magnetic field lines according to the internal model JRM33 introduced by Connerney et al. (2022). Since the isolines of the L-shell parameter closely match the auroral shape, it offers a quantitative means of comparing auroral regions across all longitudes.

For comparison of auroral electron distributions and magnetic field perturbations mapped to specific auroral features, we focus on the L-shell parameter, which approximates the internal field, but neglects Jupiter's current sheet. We use the L-shell for the purpose of associating in situ observations close to Jupiter with auroral features in Jupiter's upper atmosphere, but not for mapping these observations into equatorial regions of Jupiter's magnetosphere. Previous studies have shown that the L-shell parameter is more robust than the M-shell parameter for our purpose (see Salveter et al., 2022, and specifically Supporting Information S1 of this work, which demonstrates spurious effects that can occur when applying the M-shell parameter).

The closest crossing occurs at a jovian radial distance ranging from $1.25 R_J$ to $3 R_J$, while the second closest crossing occurs at a radial distance between $1.6 R_J$ to $8.2 R_J$. The closest approach to the main emission region typically lasts around 15–20 min, whereas the subsequent closest approach extends much longer, averaging 111 min due to the alignment of the spacecraft's trajectory with the magnetic field. In these encounters, the

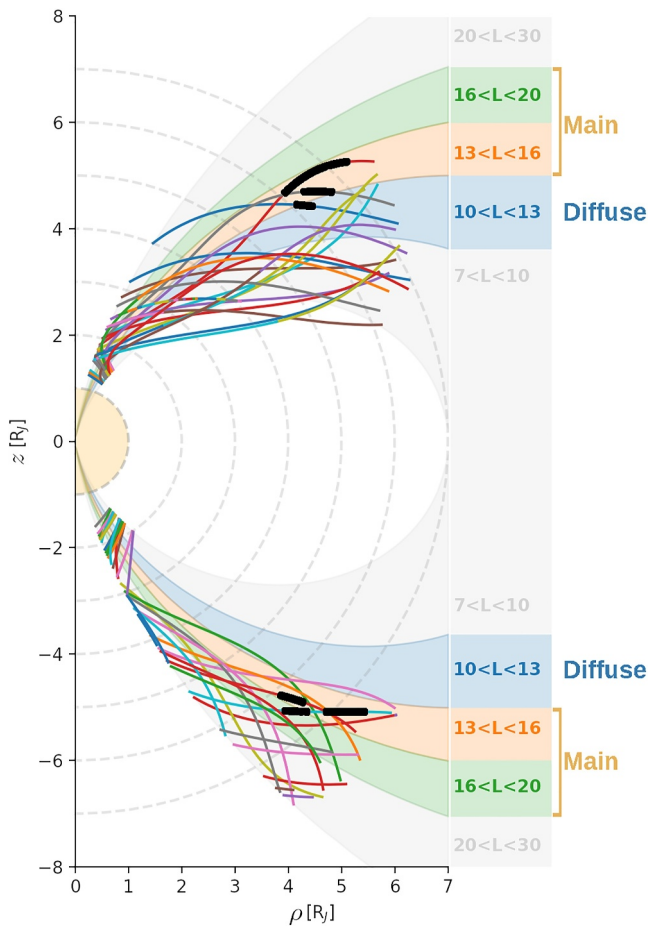


Figure 4. The Figure illustrates the data coverage in SysIII coordinates, where the line plots outline the paths observed in the initial 20 perijoves. ρ represents the distance perpendicular and z represents the distance along the axis aligned with magnetic dipole. The circular dashed lines on the graphs represent radial distances. The green, orange, and blue segments signify regions between the L-shell values of 10, 13, and 16, respectively, indicating the DifA, ZI, and ZII regions. The L-shell approximates the internal magnetic field and neglects the current sheet. It is used as a simple and transparent method to map the magnetic field into Jupiter's atmosphere. Furthermore, black lines indicate observations of small-scale magnetic field fluctuations detected at higher altitudes.

spacecraft traverses magnetic field lines with L-shell values ranging from 8 to 20 shown in Figure 4, allowing observation of the three primary emission zones: Diffuse aurora (DifA), ZI, and ZII, indicated by blue, orange, and green areas. These regions are roughly indicated using L-shell values, providing a reference for comparing different auroral zones. These definitions are based on observations from the perijoves, where typical L-shell parameters were identified by electron distribution types and UV emission characteristics. However, the L-shell parameter alone is insufficient for precisely delineating the true boundaries of these regions, as they are strongly influenced by spatial and temporal variations in magnetospheric conditions (L. A. Head et al., 2024). However, Jupiter's rotation beneath the spacecraft causes more pronounced azimuthal motion along the main emission region at higher altitudes, resulting in fewer perpendicular passes through all three regions, with some flybys remaining either poleward or equatorward of the main emission region without crossing it. Additionally, certain perijoves do not provide sufficient resolution to encompass the entire electron pitch angle space, yet they are still utilized to examine the correlation between UV emissions and magnetic field fluctuations.

An important advantage of analyzing magnetic field measurements at higher altitudes is the lower digitization level of 1 nT, which is significantly better than the lower resolution of 25 nT within radial distances below 3 R_J . By examining auroral crossings at radial distances ranging from 1.25 R_J to 8.2 R_J , a thorough qualitative investigation can be conducted to understand the correlations between electron distributions, magnetic field variations, and ultraviolet emissions in the three distinct regions outlined in the following sections.

3.1. The Polar Region

The polar region exhibits minimal magnetic field variations at radial distances between 1.25 R_J and 3 R_J , except for some minor noise-related signals, as shown in Figure 5 before 4:35 UTC. Furthermore, the high-altitude polar cap crossings between 3 R_J and 8 R_J radial distance, which occur mainly in the southern hemisphere due to the flight trajectory, do not show significant small-scale magnetic field fluctuations, as shown in Figure S5 in Supporting Information S1. This suggests that any magnetic fluctuations are likely too small to be observed but could still influence acceleration processes through, for example, whistler-mode waves.

Electron intensities are very low, indicating weak or absent local acceleration, with only a few electrons moving upward or in both directions, or none

detected at all. Furthermore, Ultraviolet emissions are faint or absent, suggesting that the spacecraft is in an area with little to no accelerated auroral particles. These observations indicate a quiet magnetospheric environment during the observed periods.

3.2. The Diffuse Auroral Region

L-shell values smaller than $L < 8$ show no evidence of magnetic-field fluctuations or UV emission, and are typically characterized by isotropic electron distributions, as seen in Figure 5 after to 4:47 UTC. However, L-shells between 10 and 13 sometimes reveal faint and indistinct UVS emission, lacking a clear structure. The azimuthal magnetic field shows minimal fluctuations, usually comparable to background noise levels. The electron pitch angle distributions typically show pancake distributions characterized by empty loss cones, at times, reduced intensity near 90° resembling a butterfly distribution. The loss cones are typically empty; however, pitch-angle scattering of the trapped particles can lead to partial filling of the loss cones. In such cases, the downward loss cone becomes populated, while the upward loss cone remains relatively empty as those particles

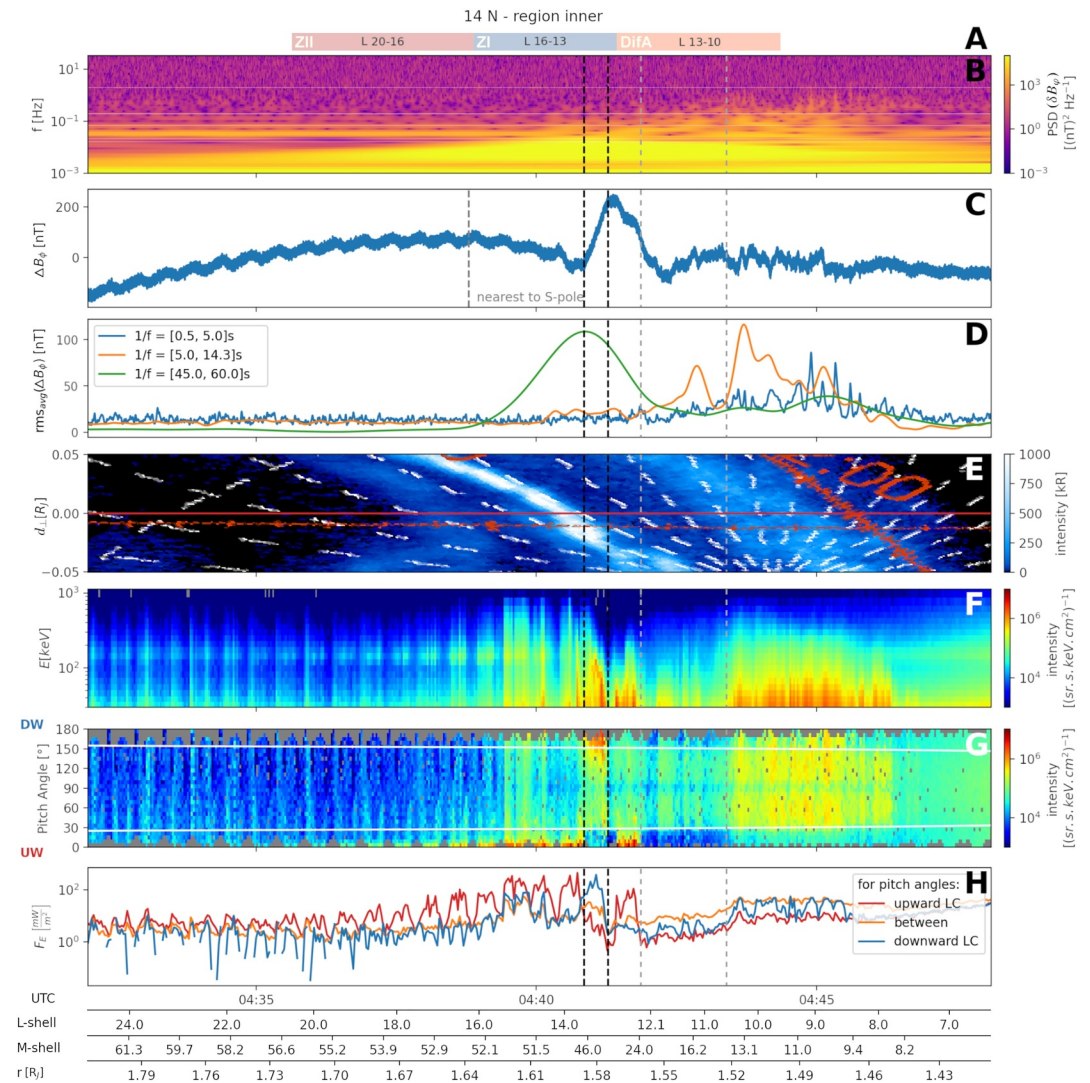


Figure 5. Overview of the instrument data from Perijove 14, which crossed the northern hemisphere at altitudes lower than 1 R_J . Panel (a) displays the L-shell value color-coded in red, blue, and orange, representing the three anticipated auroral regions: ZII, ZI, and DifA from Mauk et al. (2020), respectively. (b) Wavelet spectrum of the δB_ϕ component. (c) Azimuthal magnetic field component δB_ϕ obtained by subtracting the JRM33 + Con2020 model values from the full magnetic field. Panel (d) shows the rms obtained from the averaged PSD between the frequency ranges, labeled in the legend. Panel (e) shows the UVS observations projected along the Juno flight trajectory. Panels (f) and (g) provide the electron intensity distribution through energy and pitch angles, respectively. The white line in panel (g) corresponds to the loss-cone boundary, which was calculated from the ratio between the magnetic field at the spacecraft and the magnetic footprint in the atmosphere. Lastly, panel (h) provides the mean energy flux for each resulting pitch angle within the loss cones and between. The vertical dashed black lines indicate regions of intense aurora and correspond to strong magnetic field changes. The vertical dashed gray lines indicate regions of empty loss cones and low auroral intensities in the UV, but still some magnetic field variations.

are lost to the atmosphere. The energy flux carried by trapped electrons outside of the loss cones typically ranges from 10 to 100 mW/m^2 at radial distances of approximately 1.3 R_J to 1.6 R_J , as exemplarily shown in Figure 5. These regions appear to show very limited auroral activity.

On average, at L-shells between approximately 10 and 13, accelerated auroral electrons intermittently occupy the downward loss cone, with energy fluxes peaking around $\approx 100 \text{ mW/m}^2$, both inside and outside the loss cone. This behavior, shown in Figure 5, occurs at lower L-shells between 8 and 11 and highlights the challenge of identifying precise boundaries. Nonetheless, the L-shell boundaries are introduced as a rough reference to compare the observations through all perijoves. However, the regions between approximately 10 and 13 exhibit a consistent

luminosity of about 200 kR, along with sporadic patchy UV glows, albeit less bright compared to regions associated with higher L-shells. Concurrently, these areas are dominated by small-scale magnetic field fluctuations occurring at intervals between 0.5 and 60 s with rms values ranging from 50 to 100 nT. The large amplitude magnetic field fluctuations on field lines associated with diffuse aurora are attributed to whistler-mode chorus waves and lead to pitch-angle scattering of trapped electrons (Elliott et al., 2021). Sometimes, an intermediate region with empty loss cones separates the dim UV radiations of diffuse aurorae from the intense and luminous auroral emissions originating from ZI.

3.3. Strong Electron Beams Connected to Auroral Arcs

Between L-shells 13 to 16, marked by the blue bar at the top of Figure 5, strong magnetic field deviations are observed from a few nT to several hundreds of nT. These substantial deviations are mainly mapped to intense auroral lines in the UVS images, as seen in Figure 5e, marked by the black vertical dashed lines. In a duration of 2 min, the magnetic field δB_ϕ increases by 260 nT and then drops by 300 nT as it approaches smaller L-shell values down to 12. The passage of the spacecraft through strong changes in the magnetic field consistent with a curl of $\vec{B}$ (as discussed in Section 2.5) is indicative of a large-scale current region. Small-scale magnetic field fluctuations are hardly seen throughout this region at low altitudes.

The positive slope indicates an upward current region with a characteristic downward filled electron loss cone and mono-energetic high electron intensities of 100 keV, within an inverted V structure, commonly associated with a static electric potential. These structures are mapped to UVS a bright auroral arc in the UVS image. The negative slope at 04:42 in Figure 5 indicates a downward current region, mapping to dim UV emissions, and demonstrates a filled upward loss cone but with a wide range of energy levels and high intensities, described as a broadband distribution.

Although this is a compelling example, most unidirectional pitch angle distributions in the downward direction exhibit broadband energy distributions rather than monoenergetic structures. Unidirectional pitch angle distributions are commonly seen when the spacecraft crosses intense auroral regions, especially when they cover a small latitudinal range. The auroral crossings at greater radial distances also show mostly unidirectional magnetic field changes accompanied by intense auroral UV emissions matching upward currents. Those magnetic field perturbations are smaller than those at low altitudes, usually observed with amplitudes ranging from a few tens of nT to no more than 100 nT.

Not every magnetic field variation exceeding an amplitude of 50 nT leads to unidirectional electron pitch angle distributions or increased particle intensities. For example, during the first perijove crossing of the northern auroral zone, a notable magnetic field variation of -200 nT observed at 12:12 signifies an upward electric current, but the loss cones of the pitch angle distribution are vacant at that time, as shown in Figure S3 in Supporting Information S1. Concurrently, the UVS images exhibit intense auroral emissions. Hence, it is crucial to remember that the time discrepancy between instantaneous and time-averaged measurements, as well as the inaccuracy of the magnetic field-line mapping, might distort the comparison of different observations. Although unlikely, it is possible that the JEDI might fail to detect electrons that have already moved to radial distances closer than the spacecraft's location or penetrated the atmosphere. Moreover, JEDI might not detect electrons that are strongly aligned with the magnetic field within the resolved pitch angle distribution.

Bidirectional pitch angle distributions are often observed in the smooth transition from ZI to ZII, as seen in Figure S6 in Supporting Information S1 at 01:15. These regions are indicated by the red bar at the top of the Figures from L-shell 16 to 20. These distributions exhibit a comparable energy flux in both cones, exceeding that outside the cones. Interestingly, bidirectional distributions often coincide with magnetic field changes indicating downward currents, alongside very intense auroral UV emissions, as seen in Perijove 3 at 17:38 in Figure 6. This contradicts the idea that a static potential mainly accelerates the electrons since the electrons move in both directions independently of the possible current direction determined by the magnetic field change. The considerable amount of particles that are accelerated downward can cause the most intense auroral emission. Thus, bidirectional acceleration in an area connected to downward currents significantly contributes to the intense UV emissions.

These bidirectional distributions are also observable poleward through even higher L-shells. The UV emissions show intensities that are bright and patchy with high intensities or diffuse with intermediate intensities. The

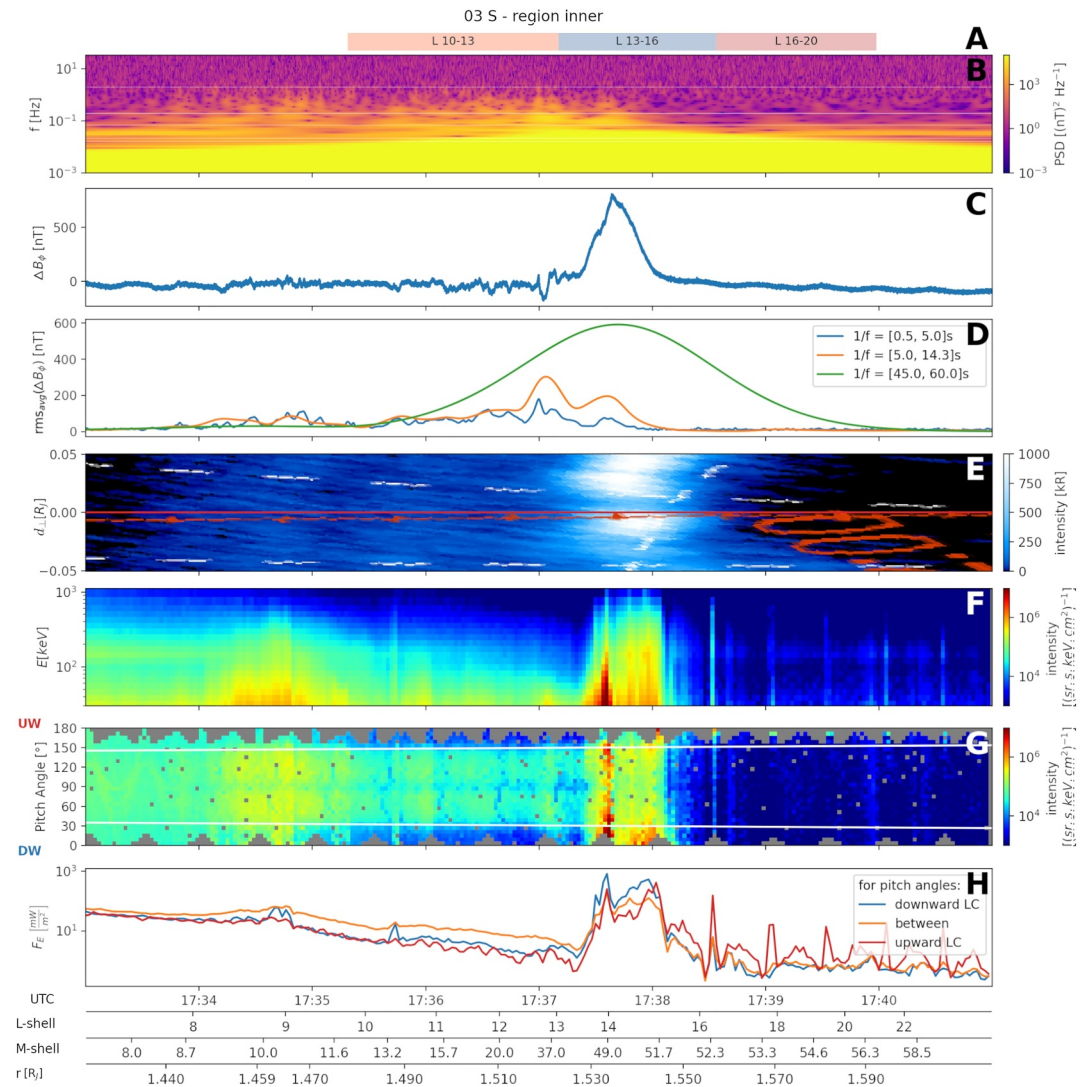


Figure 6. This figure gives an overview of the instrument data from perijove 3 over the southern hemisphere passing at altitudes lower than 1 R_J . Further details for each panel are similar to those provided in the caption of Figure 5.

magnetic field shows mainly negative changes of several 100 nT, corresponding to a downward current. The electron distributions in these areas are similar in intensity to those of ZI. However, the pitch angle distributions are usually bidirectional, sometimes almost isotropic, or unidirectional in an upward direction. At the same time during which the electron beams appear, negative magnetic field changes, accompanied by intense UV radiation, are observed. As already observed in ZI, if the pitch angle distributions are bidirectional, this UV radiation is present (see Figure S5 in Supporting Information S1 at 06:58), but when the electrons only fill the upward loss cone, nearly no UV emissions are visible (see Figure S4 in Supporting Information S1 at 09:47).

The bidirectional distribution weakens in intensity toward the poles and sometimes transitions into distributions that are solely directed upward. However, electrons with energies up to 1 MeV can reach the detectors at higher latitudes, as evidenced by the minimum ionizing effect observed at 150 keV. Despite the bidirectional acceleration of the electrons, only faint UV emissions are detected. Surprisingly, there are no observations of either small-scale magnetic field fluctuations or significant magnetic field changes. The acceleration in both directions could be attributed to small fluctuations that are too weak to be identified in the inner radial regions.

3.4. Small-Scale Magnetic Field Fluctuations

During all perijove observations, fluctuations in the magnetic field were detected on short time scales of a few seconds to several minutes and across various radial distances, particularly at L shells below 13. These regions predominantly exhibited pancake distributions along with some diffuse auroral beams. The magnitude of these magnetic field fluctuations ranged from a few nT and tens of nT at higher altitudes (above 1 R_J) to 30–600 nT at lower altitudes (below 1 R_J). These high amplitude changes occur distinct from the Io-Alfvén wing crossings and are exemplarily shown in Figure S1 in Supporting Information S1 between 9:36 and 9:39.

Most low-altitude crossings did not detect small-scale fluctuations in ZI and ZII. Nevertheless, particular powerful electron beams could not be correlated to any perturbation in the magnetic field, thus providing no direct insight into the acceleration mechanisms of these intense beams. In some cases, the magnetic field showed small-scale fluctuations of several seconds at low altitudes that directly contributed to intense emissions above the main emission zone, as seen in the Juno Ultraviolet Spectrograph (UVS) observations, Figure S1 (B) in Supporting Information S1 between 17:26 and 17:27. Unfortunately, the electron distribution during this perijove was not fully captured, especially the upward loss cone. However, pitch angle distribution indicates diffuse emissions, with the upward loss cone empty and the downward loss cone and pitch angles outside the cone filled, as depicted in Figure S1 in Supporting Information S1 between 17:26 and 17:30. In particular, at 17:25, the electron energy distribution displays a beam with an inverted V structure, yet no magnetic changes indicative of field-aligned currents are detected. Additionally, no magnetic field fluctuations accompany downward or bidirectional electron beams, suggesting either insufficient resolution of magnetic field components to discern an acceleration mechanism or the spacecraft's position lying below the acceleration region. Only six other perijoves show small-scale fluctuations for higher L shells that map to intense UV emissions at these small radial distances. The amplitudes of the fluctuations are very small, almost equivalent to the high noise level of 25 nT at these small radial distances.

MAG observations at small radial distances with less than 2 R_J do not allow observation of fluctuations with less than 10 (nT)²/Hz, mostly corresponding to frequencies greater than 0.8 Hz. However, beyond a distance of 4 R_J , digitization by the FGM results in noise levels below 0.1 nT (as illustrated in Figure 3b), allowing the detection of smaller amplitudes associated with small-scale fluctuations. A drawback of observations at larger radial distances is the changing temporal resolution of MAG data, which sometimes decreases from 64 to 16 Hz.

Hence, small-scale fluctuations along higher radial distances $>3 R_J$ typically show a rolling rms of a few nT between 0.5 and 15 s. In particular, the fifth perijove, depicted in Figure 7b (3:10–4:50) at radial distance of $\sim 7 R_J$, demonstrates small amplitude magnetic field fluctuations at temporal scales as short as 0.5 s when the noise level is low (0.024 nT). The rms values of these fluctuations within 0.5 to 5 s is about 2–5 nT, which are too small to be resolved at low altitudes due to the higher noise level.

We estimate the corresponding energy flux at Jupiter's ionosphere using $F_E = \frac{(\delta B)^2}{\mu_0} \cdot c \cdot \frac{B}{B_m}$, where B is the local magnetic field and B_m is the traced ionospheric magnetic field. We approximate the Alfvén velocity with the speed of light, as expected for the densities observed in the previous paragraph (Bagenal et al., 2014). Based on the observed magnetic field fluctuations of approximately 2–5 nT at a radial distance of $\sim 7 R_J$ (as described above), this yields a range of about 380 to 2370 mW/m². While these energy fluxes represent simplified estimates, it suggests that the observed magnetic field fluctuations can carry sufficient energy to drive structured auroral emissions—particularly since some fluctuations reach amplitudes of up to 10 nT (see Figure S5 in Supporting Information S1 at 11:15). Lorch et al. (2022) report magnetic field fluctuations in the range of 0.16–0.675 nT, corresponding to projected ionospheric energy fluxes of approximately 6.8 to 196 mW/m², which are already sufficient to generate aurora. In our case, we estimate comparable or even significantly higher fluxes of several hundred mW/m² up into the range of mW/m², indicating that the observed fluctuations are well within the energetic range required to support structured auroral processes, assuming effective transmission. Similar small-scale fluctuations are observed shown in Figure S2 in Supporting Information S1 between 10:30 and 11:15.

Broadly distributed electron populations at large radial distances $>3 R_J$ are associated with higher rms values in the magnetic field fluctuations on the 8–20 s scale. At high altitudes, distributions such as pancake, butterfly, and isotropic populations are difficult to distinguish from one another, as the loss cone is extremely small at these distances. However, the magnetic field fluctuations for these populations are large enough to remain visible despite the high noise levels. This is shown in Figure 7 between 5:30 and 7:40.

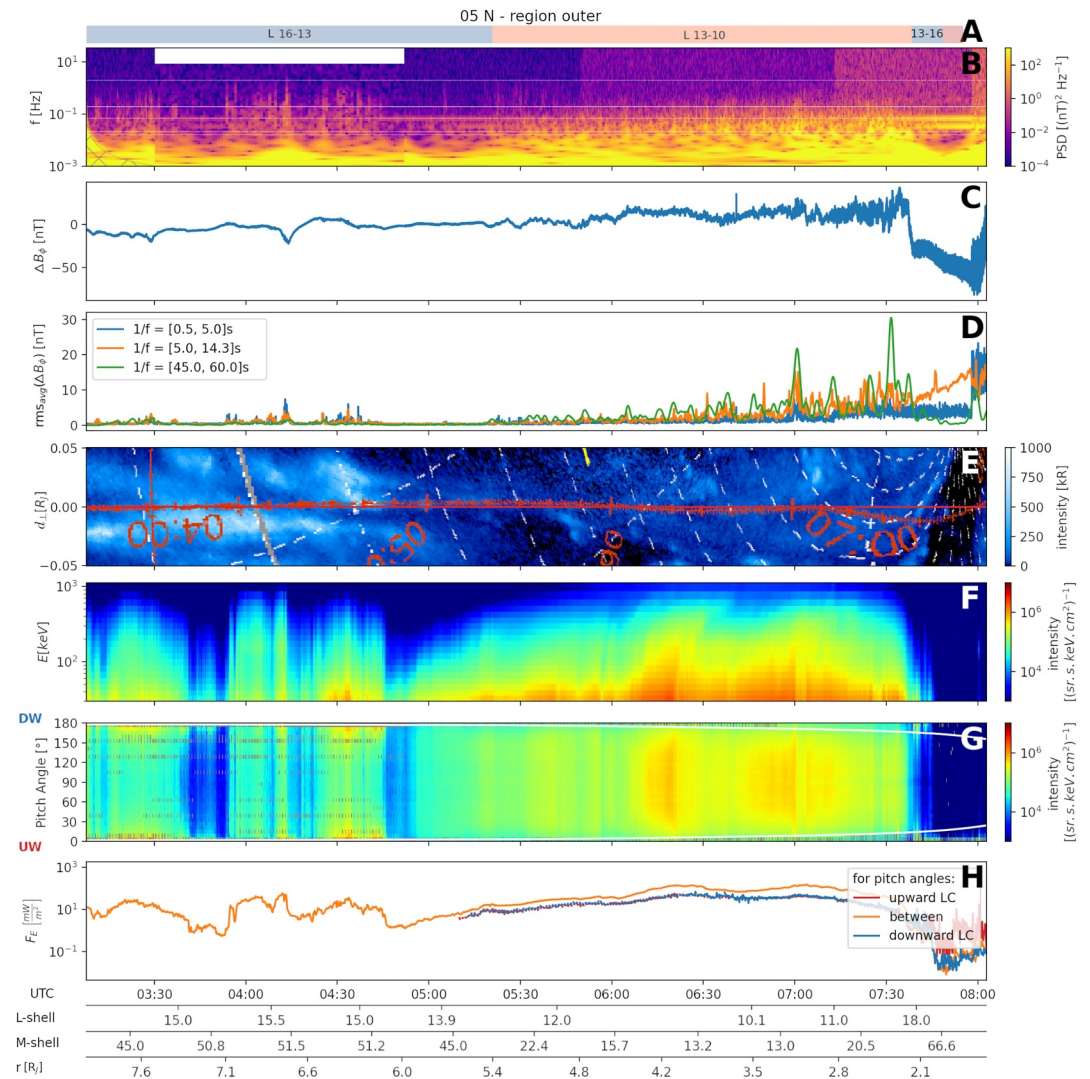


Figure 7. This figure gives an overview of the magnetic field, energetic electrons, and UV emission data from Perijove 5, which passed through the northern hemisphere at altitudes higher than 1 R_J . Further details of each panel are provided in the caption of Figure 5.

We used wavelet analysis to examine the fluctuations in the magnetic field perpendicular to the magnetic field by categorizing their strength according to different time scales. The identified frequency bands strongly depend on the time that Juno spent within the main emission region, the constraints imposed by digitization, and the notable influence of the spacecraft's rotation. This influence becomes more pronounced with higher magnetic field strengths at smaller radial distances where digitization levels are already high, resulting in significant Power Spectral Densities of around 1×10^3 (nT)²/Hz.

Measurements obtained with a digitization level of 0.1 nT are possible at radial distances greater than 5 R_J . The spacecraft rarely crosses the main emission region at these altitudes. Nevertheless, six distinct time intervals for observing intense ultraviolet emissions are available, as marked by the black lines within the orange zone of Figure 4. Figure 8 illustrates the power spectral densities measured over these periods, which exhibit a power-law like distribution with fluctuations reaching into high-frequency ranges. The corresponding slopes, shown on the right, range between 1.71 and 2.33, with a power spectral density (Power Spectral Density) between 0.03 (nT)²/Hz to 0.45 (nT)²/Hz at a frequency of 1 Hz. The gray and black dashed lines in Figure 8 show the digitization level and the corresponding boundary of the resolved frequencies. Certain time periods exhibit significant magnetic

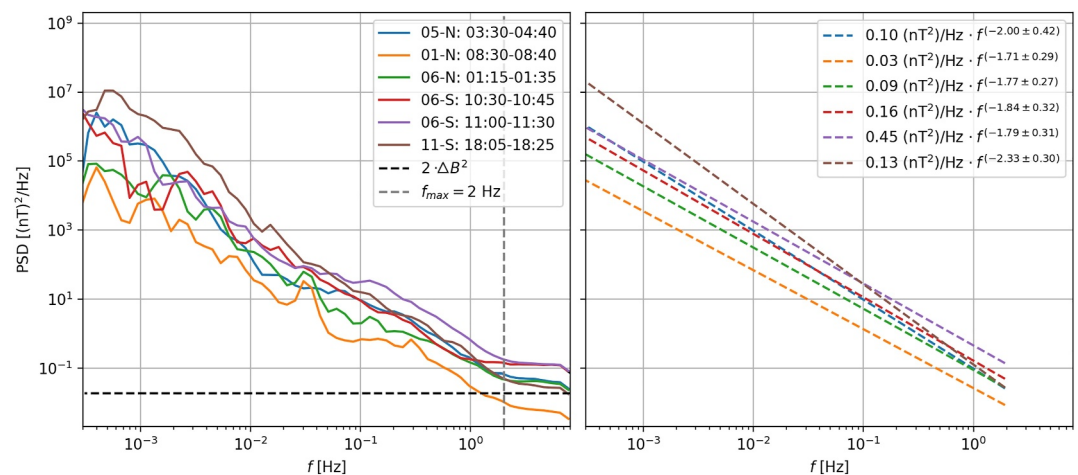


Figure 8. Six distinct time spans at high radial between $6 R_J$ to $7.5 R_J$ distances crossing the main emission zone. The power spectra of magnetic field fluctuations measured during these time periods are shown, each providing evidence for small-scale fluctuations up to the highest frequencies. The right-hand side displays the linear regression of the time-averaged spectra on the left. The black and gray dashed line indicate the boundary to unresolved frequencies for the corresponding digitization levels.

field fluctuations at lower frequencies with amplitudes reaching up to 50 nT. As a result, the corresponding spectra are steeper, offering greater power at frequencies below 0.1 Hz.

All of the 6 time intervals at larger distances have bidirectional electron distributions or isotropic distributions with unresolved loss cones. The energy distribution is broad and the ultraviolet emission is intense, reaching up to 1,000 kR. The energy fluxes are mostly in the range of a few tens of mW/m² but can reach a few hundred mW/m² when amplitudes of the magnetic field fluctuations are greater than 10 nT.

These perijoves display small-scale fluctuations at the lowest digitization levels at a radial distance between approximately $6 R_J$ to $7.5 R_J$ and L-shell between 12.5 and 17, each time the digitization level allows to resolve them. This suggests that small-scale fluctuations might be an omnipresent feature of Jupiter's magnetosphere-ionosphere coupling. This would further stress the importance of stochastic acceleration, consistent with the wide range of auroral particle observations at low altitudes.

4. Summary and Conclusions

In this study, a comprehensive analysis was conducted on the Juno observations during the first 20 flybys where magnetic fields, electron intensities, and UV emission were systematically compared. Our findings confirm the characterization by Mauk et al. (2020) of the auroral emission region in the three zones but provide an additional new and significant understanding of MI-coupling processes associated with magnetic field fluctuations.

Polewards of the main emission, predominantly upward and bidirectional electron beams are detected, with occasional faint ultraviolet emissions. No magnetic field fluctuations were detected at radial distances between $1.25 R_J$ to $3 R_J$, suggesting that any fluctuations might be too small to observe, though they may contribute to acceleration via whistler-mode waves, as noted by Elliott et al. (2020).

However, luminous emissions are also observed in the polar region area, where three distinct bright auroral spots have been examined by Haewsantati et al. (2023). Juno's observations traced along the magnetic field lines to these spots revealed an enhanced upward flow of energetic electrons, increased whistler-mode wave activity, and fluctuations in the magnetic field. The results suggest that beneath Juno, particle acceleration occurs, and wave-particle interactions play a role in creating UV aurora, consistent with observations by Mauk et al. (2020). This is consistent with Gérard et al. (2019), who observed an inconsistency between electron flux and UV brightness.

The diffuse auroral emission zone is characterized by pancake-shaped electron distributions. In the diffuse emission zone, field lines demonstrate minimal significant fluctuations in the magnetic field perpendicular to the background field, when considering the noise level. Electron intensities sometimes fill the downward loss cone,

along with magnetic field fluctuations that are perpendicular to the background field and occur at frequencies between 1/60 and 0.5 Hz. The amplitudes of these fluctuations show a radial dependence, reaching several hundred nanoteslas (nT) at radial distances less than 4 R_J and tens of nT beyond 4 R_J .

The main emission zone shows large-scale magnetic field variations correlated with unidirectional and bidirectional electron distributions, as defined in Mauk et al. (2020). The changes in the magnetic field perpendicular to the background magnetic field occur on large scales corresponding to tens of minutes with magnetic field amplitudes of several 100 nT and are consistent with quasi-static large-scale electric currents. Consequently, the downward electron distributions align with the upward current regions, which are linked to strong UV emissions. In contrast, areas with downward currents sometimes show only upward-moving electrons without UV emissions. However, most of the time regions with downward currents exhibit electrons moving in both directions, leading to significant UV emissions. Therefore, the prevalence of broadband distributions and the dominance of bidirectional electron flow in these regions seem inconsistent with the explanation of static potential drops (Salveter et al., 2022).

Fluctuations in the magnetic field on smaller temporal scales manifest exclusively in areas linked to diffuse auroral regions at lower altitudes and diminish upon entering regions connected to the main emission zone (Sulaiman et al., 2022). Sulaiman et al. (2020) has proposed that this lack of fluctuations could be due to significant reductions in density above the main emission zone, resulting in large electron inertial lengths scales and thus more efficient wave-particle interaction (Lysak et al., 2021; Saur et al., 2018). On the other hand, the absence of magnetic field fluctuations might be attributed to the inability to detect minor fluctuation amplitudes. This occurs as a result of the reduction in density when considering the same Poynting flux $\delta B^2/\mu_0 \cdot v_A$ and leading to significant increases in the Alfvén speed and therefore decrease in δB .

An extensive analysis of the power spectrum has revealed that the transition from analog to digital measurement (i.e., digitization) significantly restricts the observable temporal scales of the magnetic field data. Specifically, when observing radial distances greater than 4 R_J as opposed to radial distances less than 2 R_J , the magnetic field strength decreases by approximately two magnitudes. As a result, there is an improvement in the resolution of the magnetic field measurements from 25 to 0.1 nT. Thus, the digitization level with the highest resolution (i.e., the lowest digitization level) is capable of detecting frequency changes above 0.5 Hz. This level of resolution is only used at radial distances larger than 4 R_J . Consequently, the identification of small magnetic field fluctuations can occur only at greater radial distances.

Throughout the mission, the trajectory of the Juno spacecraft evolves due to the gravitational influence of Jupiter's oblateness, which causes Juno's perijove latitude to shift northward by approximately 1° per orbit, starting with a near-equatorial perijove. This results in relatively brief observation periods connected to the main emission at higher altitudes in the north and extended periods connected to high latitudes during Juno's outward passages.

However, the perpendicular component of the magnetic field consistently exhibits small-scale fluctuations at radial distances larger than 4 R_J , when mapping to intense UV emissions in the main emission zone. The slope of the PSD resembles a power law with a slope ranging from -1.7 to -2.2 , extending to higher frequencies of up to 2 Hz, which is consistent with the power spectral densities discovered by Lorch et al. (2022) at radial distances greater than 10 R_J . A power law in the spectral energy density is indicative of turbulent fluctuations (Saur et al., 2002; X. Tao et al., 2011). Amplitudes of 2–10 nT of these fluctuations carry very large energy fluxes on the order of 0.1 W/m² to several W/m² when mapped to Jupiter.

We conclude that electrostatic field-aligned currents, as well as wave-particle interaction, may contribute significantly to intense auroral arcs on Jupiter. A stochastic acceleration process seems to drive the dominant amount of particle observation (Damiano et al., 2019, 2023; Gershman et al., 2019; Lorch et al., 2022; Salveter et al., 2022; Saur et al., 2018). The coexistence of these accelerations underscores Jupiter's magnetospheric variability. Enhancing this analysis in spatial and temporal coverage using the Juno data and using the full range of Juno instruments would be valuable.

Our study investigates the occurrence of large-scale magnetic field variations associated with quasi-static field aligned Direct Currents (DC) and small-scale magnetic field fluctuations associated with highly time-variable Alternating Currents (AC). We find in most cases large-scale current systems over the main auroral emission are present but also detect that alternating currents are always present when they can be measured. The latter observations in conjunction with the fact that the dominant electron distribution functions are broadband over the

main emission zone suggestive of wave-particle interaction being the dominant acceleration mechanism (Damiano et al., 2019, 2023; Gershman et al., 2019; Lorch et al., 2022; Lysak et al., 2021; Salveter et al., 2022; Saur et al., 2018). Further theoretical and observational studies based on a large suite of Juno instruments and extending it to further perijoves will help to bring further light into understanding Jupiter's enigmatic auroral emissions.

Abbreviation

FAC	Field-aligned current
DifA	Diffuse aurora
ZI	Zone I
ZII	Zone II
MI	Magnetosphere-ionosphere
JEDI	Jupiter Energetic-particle Detector Instrument
JADE	Jovian Auroral Distributions Experiment
UVS	Juno Ultraviolet Spectrograph
MAG	Juno Magnetometer
FGM	Fluxgate Magnetometer
UV	Ultraviolet
JRM09	Juno Reference Model through Perijove 9
JRM33	Juno Reference Model through Perijove 33
SysIII	Jupiter System III coordinates
Con2020	Connerney 2020 current sheet model
PSD	Power Spectral Density
rms	Root-mean-square

Data Availability Statement

The Juno-JEDI data (Mauk, 2020) as well as the Juno-Magnetometer data (Connerney, 2017) were obtained from the website of the NASA Planetary Data System: Planetary Plasma Interactions (<https://pds-ppi.igpp.ucla.edu/mission/JUNO/JNO/JEDI> and <https://pds-ppi.igpp.ucla.edu/mission/JUNO/JNO/FGM>). The Juno-UVS calibrated data (Gladstone, Persyn, et al., 2017; Trantham, 2014) can be utilized from https://pds-atmospheres.nmsu.edu/cgi-bin/getdir.pl?dir=DATA%26volume=jnouv3_3001 to obtain the polar projection images described by Bonfond et al. (2021). Juno footprints are available using Juno Reference Model through Perijove 9 (JRM09) and Con2020 models at https://lasp.colorado.edu/home/mop/files/2020/04/20190412_Imai_MagFootReader_UIowa_rev.pdf. The tracking of the magnetic field lines with JRM33 and Con2020 is provided by Wilson et al. (2023). The classification results for calculating the precipitation budget of the different electron distributions are provided as supplementary material in Salveter et al. (2022).

References

- Akasofu, S.-I. (1981). Energy coupling between the solar wind and the magnetosphere. *Space Science Reviews*, 28(2), 121–190. <https://doi.org/10.1007/BF00218810>
- Allegrini, F., Bagenal, F., Bolton, S., Connerney, J. E. P., Clark, G., Ebert, R., et al. (2017). Electron beams and loss cones in the auroral regions of Jupiter. *Geophysical Research Letters*, 44(14), 7131–7139. <https://doi.org/10.1002/2017GL073180>
- Bagenal, F., Adriani, A., Allegrini, F., Bolton, S. J., Bonfond, B., Bunce, E. J., et al. (2014). Magnetospheric science objectives of the Juno mission. *Space Science Reviews*, 213(1), 219–287. <https://doi.org/10.1007/s11214-014-0036-8>

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- Bagenal, F., Adriani, A., Allegrini, F., Bolton, S. J., Bonfond, B., Bunce, E. J., et al. (2017). Magnetospheric science objectives of the Juno mission. *Space Science Reviews*, 213(1), 219–287. <https://doi.org/10.1007/s11214-014-0036-8>
- Baker, D. N., Pulkkinen, T. I., Angelopoulos, V., Baumjohann, W., & McPherron, R. L. (1996). Neutral line model of substorms: Past results and present view. *Journal of Geophysical Research*, 101(A6), 12975–13010. <https://doi.org/10.1029/95JA03753>
- Bennett, W. R. (1948). Spectra of quantized signals. *The Bell System Technical Journal*, 27(3), 446–472. <https://doi.org/10.1002/j.1538-7305.1948.tb01340.x>
- Bieber, J. W., Chen, J., Matthaeus, W. H., Smith, C. W., & Pomerantz, M. A. (1993). Long-term variations of interplanetary magnetic field spectra with implications for cosmic ray modulation. *Journal of Geophysical Research*, 98(A3), 3585–3603. <https://doi.org/10.1029/92JA02566>
- Bonfond, B., Yao, Z., & Grodent, D. (2020). Six pieces of evidence against the corotation enforcement theory to explain the main aurora at Jupiter. *Journal of Geophysical Research: Space Physics*, 125(11), e2020JA028152. <https://doi.org/10.1029/2020JA028152>
- Bonfond, B., Yao, Z. H., Gladstone, G. R., Grodent, D., Gérard, J.-C., Matar, J., et al. (2021). Are dawn storms Jupiter's auroral substorms? *AGU Advances*, 2(1). <https://doi.org/10.1029/2020AV000275>
- Broadfoot, A. L., Belton, M. J. S., Takacs, P. Z., Sandel, B. R., Shemansky, D. E., Holberg, J. B., et al. (1979). Extreme ultraviolet observations from Voyager 1 encounter with Jupiter. *Science*, 204(4396), 979–982. <https://doi.org/10.1126/science.204.4396.979>
- Clark, G., Mauk, B. H., Haggerty, D., Parancas, C., Kollmann, P., Rymer, A., et al. (2017). Energetic particle signatures of magnetic field-aligned potentials over Jupiter's polar regions. *Geophysical Research Letters*, 44(17), 8703–8711. <https://doi.org/10.1002/2017GL074366>
- Connerney, J. E. P., Benn, M., Bjarnø, J. B., Denver, T., Espley, J., Jørgensen, J., et al. (2017). The Juno magnetic field investigation. *Space Science Reviews*, 213(1–4), 39–138. <https://doi.org/10.1007/S11214-017-0334-Z>
- Connerney, J. E. P. (2017). Juno fluxgate magnetometer calibrated data v1.0 [Dataset]. <https://doi.org/10.17189/1519711>
- Connerney, J. E. P., Timmins, S., Hecceg, M., & Jørgensen, J. L. (2020). A Jovian magnetodisc model for the Juno era. *Journal of Geophysical Research: Space Physics*, 125(10). <https://doi.org/10.1029/2020JA028138>
- Connerney, J. E. P., Timmins, S., Oliverson, R. J., Espley, J. R., Jørgensen, J. L., Kotsiaros, S., et al. (2022). A new model of Jupiter's magnetic field at the completion of Juno's prime mission. *Journal of Geophysical Research: Planets*, 127(2), e2021JE007055. <https://doi.org/10.1029/2021JE007055>
- Cowley, S., & Bunce, E. (2001). Origin of the main auroral oval in Jupiter's coupled magnetosphere–ionosphere system. *Planetary and Space Science*, 49(10), 1067–1088. [https://doi.org/10.1016/S0032-0633\(00\)00167-7](https://doi.org/10.1016/S0032-0633(00)00167-7)
- Damiano, P. A., Delamere, P. A., Kim, E.-H., Johnson, J. R., & Ng, C. S. (2023). Electron energization by inertial Alfvén waves in density depleted flux tubes at Jupiter. *Geophysical Research Letters*, 50(5), e2022GL102467. <https://doi.org/10.1029/2022GL102467>
- Damiano, P. A., Delamere, P. A., Stauffer, B., Ng, C.-S., & Johnson, J. R. (2019). Kinetic simulations of electron acceleration by dispersive scale Alfvén waves in Jupiter's magnetosphere. *Geophysical Research Letters*, 46(6), 3043–3051. <https://doi.org/10.1029/2018gl081219>
- Ebert, R., Allegrini, F., Bagenal, F., Bolton, S., Connerney, J. E. P., Clark, G., et al. (2017). Spatial distribution and properties of 0.1–100 keV electrons in Jupiter's polar auroral region. *Geophysical Research Letters*, 44(18), 9199–9207. <https://doi.org/10.1002/2017GL075106>
- Elliott, S., Gurnett, D., Kurth, W., Clark, G., Mauk, B. H., Bolton, S., et al. (2018). Pitch angle scattering of upgoing electron beams in Jupiter's polar regions by whistler mode waves. *Geophysical Research Letters*, 45(3), 1246–1252. <https://doi.org/10.1002/2017GL076878>
- Elliott, S., Gurnett, D., Yoon, P. H., Kurth, W., Mauk, B. H., Ebert, R., et al. (2020). The generation of upward-propagating whistler mode waves by electron beams in the Jovian polar regions. *Journal of Geophysical Research: Space Physics*, 125(6). <https://doi.org/10.1029/2020JA027868>
- Elliott, S., Sulaiman, A., Kurth, W., Faden, J., Allegrini, F., Valek, P., et al. (2021). The high-latitude extension of Jupiter's Io torus: Electron densities measured by Juno waves. *Journal of Geophysical Research: Space Physics*, 126(8). <https://doi.org/10.1029/2021JA029195>
- Gérard, J., Bonfond, B., Mauk, B. H., Gladstone, G., Yao, Z., Greathouse, T., et al. (2019). Contemporaneous observations of Jovian energetic auroral electrons and ultraviolet emissions by the Juno spacecraft. *Journal of Geophysical Research: Space Physics*, 124(11), 8298–8317. <https://doi.org/10.1029/2019JA026862>
- Gershman, D. J., Connerney, J. E. P., Kotsiaros, S., DiBraccio, G. A., Martos, Y. M., Viñas, A. F., et al. (2019). Alfvénic fluctuations associated with Jupiter's auroral emissions. *Geophysical Research Letters*, 46(13), 7157–7165. <https://doi.org/10.1029/2019GL082951>
- Gladstone, G. R., Persyn, S. C., Eterno, J. S., Walther, B. C., Slater, D. C., Davis, M. W., et al. (2017). The ultraviolet spectrograph on NASA's Juno mission. *Space Science Reviews*, 213(1–4), 447–473. <https://doi.org/10.1007/s11214-014-0040-z>
- Gladstone, G. R., Versteeg, M. H., Greathouse, T. K., Hue, V., Davis, M. W., Gérard, J.-C., et al. (2017). Juno-UVS approach observations of Jupiter's auroras. *Geophysical Research Letters*, 44(15), 7668–7675. <https://doi.org/10.1002/2017gl073377>
- Gray, R., & Neuhoﬀ, D. (1998). Quantization. *IEEE Transactions on Information Theory*, 44(6), 2325–2383. <https://doi.org/10.1109/18.720541>
- Grodent, J. T., Clarke, J. H., Waite, S. W. H., Cowley, J.-C., Gérard, J. K., & Kim, J. (2003). Jupiter's polar auroral emissions. *Journal of Geophysical Research*, 108(A10). <https://doi.org/10.1029/2003ja010017>
- Groulard, A., Bonfond, B., Grodent, D., Gérard, J.-C., Greathouse, T., Hue, V., et al. (2024). Dawn-dusk asymmetry in the main auroral emissions at Jupiter observed with Juno-UVS. *Icarus*, 413, 116005. <https://doi.org/10.1016/j.icarus.2024.116005>
- Haesantati, K., Bonfond, B., Wannawichian, S., Gladstone, R., Hue, V., Greathouse, T., et al. (2023). Juno's multi-instruments observations during the flybys of auroral bright spots in Jupiter's polar aurorae. *Journal of Geophysical Research: Space Physics*, 128(8). <https://doi.org/10.1029/2023JA031396>
- Head, L. A., Grodent, D., Bonfond, B., Moirano, A., Benmahi, B., Sicorello, G., et al. (2024). Effect of magnetospheric conditions on the morphology of Jupiter's ultraviolet main auroral emission as observed by Juno-UVS. *Astronomy & Astrophysics*, 688, A205. <https://doi.org/10.1051/0004-6361/202450253>
- Hill, T. (1979). Inertial limit on corotation. *Journal of Geophysical Research*, 84(A11), 6554–6558. <https://doi.org/10.1029/JA084iA11p06554>
- Hill, T. W. (2001). The Jovian auroral oval. *Journal of Geophysical Research*, 106(A5), 8101–8107. <https://doi.org/10.1029/2000JA000302>
- Kaminker, V. (2024). Examination of magnetic field signatures and local plasma distribution variations in Jupiter's magnetosphere. *Journal of Geophysical Research: Space Physics*, 129(5), e2024JA032572. <https://doi.org/10.1029/2024JA032572>
- Kivelson, M. G. (2005). The current systems of the Jovian magnetosphere and ionosphere and predictions for Saturn. *Space Science Reviews*, 116(1), 299–318. <https://doi.org/10.1007/s11214-005-1959-x>
- Knight, S. (1973). Parallel electric fields. *Planetary and Space Science*, 21(5), 741–750. [https://doi.org/10.1016/0032-0633\(73\)90093-7](https://doi.org/10.1016/0032-0633(73)90093-7)
- Kotsiaros, S., Connerney, J. E. P., Clark, G., Allegrini, F., Gladstone, G., Kurth, W., et al. (2019). Birkeland currents in Jupiter's magnetosphere observed by the polar-orbiting Juno spacecraft. *Nature Astronomy*, 3(10), 1–6. <https://doi.org/10.1038/s41550-019-0819-7>
- Kotsiaros, S., Connerney, J. E. P., & Martos, Y. M. (2020). Analysis of eddy current generation on the Juno spacecraft in Jupiter's magnetosphere. *Earth and Space Science*, 7(7). <https://doi.org/10.1029/2019EA001061>
- Kurth, W. S., Hospodarsky, G. B., Kirchner, D. L., Mokrzycki, B. T., Averkamp, T. F., Robison, W. T., et al. (2017). The Juno waves investigation. *Space Science Reviews*, 213(1–4), 347–392. <https://doi.org/10.1007/s11214-017-0396-y>

- Lorch, C. T. S., Ray, L. C., Wilson, R. J., Bagenal, F., Cray, F., Delamere, P. A., et al. (2022). Evidence of Alfvénic activity in Jupiter's mid-to-high latitude magnetosphere. *Journal of Geophysical Research: Space Physics*, 127(6), e2021JA029853. <https://doi.org/10.1029/2021JA029853>
- Luhr, H., Warnecke, J., & Rother, M. (1996). An algorithm for estimating field-aligned currents from single spacecraft magnetic field measurements: A diagnostic tool applied to Freja satellite data. *IEEE Transactions on Geoscience and Remote Sensing*, 34(6), 1369–1376. <https://doi.org/10.1109/36.544560>
- Lysak, R. L., & Lotko, W. (1996). On the kinetic dispersion relation for shear Alfvén waves. *Journal of Geophysical Research*, 101(A3), 5085–5094. <https://doi.org/10.1029/95JA03712>
- Lysak, R. L., & Song, Y. (2020). Field line resonances in Jupiter's magnetosphere. *Geophysical Research Letters*, 47(18), e2020GL089473. <https://doi.org/10.1029/2020GL089473>
- Lysak, R. L., Song, Y., Elliott, S., Kurth, W., Sulaiman, A. H., & Gershman, D. (2021). The Jovian ionospheric Alfvén resonator and auroral particle acceleration. *Journal of Geophysical Research: Space Physics*, 126(12), e2021JA029886. <https://doi.org/10.1029/2021JA029886>
- Masters, A., Sergis, N., Sulaiman, A. H., Palmaerts, B., & Hunt, G. J. (2022). Near-magnetic-field-aligned energetic electrons above Saturn's dark polar regions. *Journal of Geophysical Research: Space Physics*, 127(11). <https://doi.org/10.1029/2022ja030924>
- Mauk, B. H. (2013). Analysis of EMIC-wave-moderated flux limitation of measured energetic ion spectra in multispecies magnetospheric plasmas. *Geophysical Research Letters*, 40(15), 3804–3808. <https://doi.org/10.1002/grl.50789>
- Mauk, B. H. (2020). Juno Jedi Jupiter standard calibrated products (Jno J Jed 3 Cdr V1.0). <https://doi.org/10.17189/1519713>
- Mauk, B. H., Allegrini, F., Bagenal, F., Bolton, S., Clark, G., Connerney, J. E. P., et al. (2022). Loss of energetic ions comprising the ring current populations of Jupiter's middle and inner magnetosphere. *Journal of Geophysical Research: Space Physics*, 127(5). <https://doi.org/10.1029/2022JA030293>
- Mauk, B. H., Clark, G., Gladstone, G., Kotsiaros, S., Adriani, A., Allegrini, F., et al. (2020). Energetic particles and acceleration regions over Jupiter's polar cap and main aurora: A broad overview. *Journal of Geophysical Research: Space Physics*, 125(3). <https://doi.org/10.1029/2019JA027699>
- Mauk, B. H., Haggerty, D., Paranicas, C., Clark, G., Kollmann, P., Rymer, A., et al. (2017). Discrete and broadband electron acceleration in Jupiter's powerful aurora. *Nature*, 549(7670), 66–69. <https://doi.org/10.1038/nature23648>
- Mauk, B. H., Haggerty, D., Paranicas, C., Clark, G., Kollmann, P., Rymer, A., et al. (2018). Diverse electron and ion acceleration characteristics observed over Jupiter's main aurora. *Geophysical Research Letters*, 45(3), 1277–1285. <https://doi.org/10.1002/2017GL076901>
- Mauk, B. H., Haggerty, D. K., Jaskulek, S., Schlemm, C., Brown, L., Cooper, S., et al. (2017). The Jupiter energetic particle detector instrument (Jedi) investigation for the Juno mission. *Space Science Reviews*, 213(1), 289–346. <https://doi.org/10.1007/S11214-013-0025-3>
- Mauk, B. H., & Saur, J. (2007). Equatorial electron beams and auroral structuring at Jupiter. *Journal of Geophysical Research*, 112(A10). <https://doi.org/10.1029/2007JA012370>
- Newell, P. T., Sotirelis, T., & Wing, S. (2009). Diffuse, monoenergetic, and broadband aurora: The global precipitation budget. *Journal of Geophysical Research*, 114(A9). <https://doi.org/10.1029/2009JA014326>
- Ng, C. S., Delamere, P. A., Kaminker, V., & Damiano, P. A. (2018). Radial transport and plasma heating in Jupiter's magnetodisc. *Journal of Geophysical Research: Space Physics*, 123(8), 6611–6620. <https://doi.org/10.1029/2018JA025345>
- Nichols, J. D., & Cowley, S. W. H. (2004). Magnetosphere-ionosphere coupling currents in Jupiter's middle magnetosphere: Effect of precipitation-induced enhancement of the ionospheric Pedersen conductivity. *Annales Geophysicae*, 22(5), 1799–1827. <https://doi.org/10.5194/angeo-22-1799-2004>
- Paranicas, C., Mauk, B. H., Haggerty, D., Clark, G., Kollmann, P., Rymer, A., et al. (2018). Intervals of intense energetic electron beams over Jupiter's poles. *Journal of Geophysical Research: Space Physics*, 123(3), 1989–1999. <https://doi.org/10.1002/2017JA025106>
- Paschmann, G., & Daly, P. W. (1998). Analysis methods for multi-spacecraft data ISSI Scientific Reports Series SR-001, ESA/ISSI. In *ISSI Scientific Reports Series, 1* (Vol. 1). ISBN 1608-280X, 1998.
- Ray, L. C., Ergun, R. E., Delamere, P. A., & Bagenal, F. (2010). Magnetosphere-ionosphere coupling at Jupiter: Effect of field-aligned potentials on angular momentum transport. *Journal of Geophysical Research*, 115(A9). <https://doi.org/10.1029/2010JA015423>
- Salveter, A., Saur, J., Clark, G., & Mauk, B. H. (2022). Jovian auroral electron precipitation budget—A statistical analysis of diffuse, monoenergetic, and broadband auroral electron distributions. *Journal of Geophysical Research: Space Physics*, 127(8). <https://doi.org/10.1029/2021JA030224>
- Saur, J. (2004). Turbulent heating of Jupiter's middle magnetosphere. *The Astrophysical Journal*, 602(2), L137–L140. <https://doi.org/10.1086/382588>
- Saur, J., Janser, S., Schreiner, A., Clark, G., Mauk, B. H., Kollmann, P., et al. (2018). Wave-particle interaction of Alfvén waves in Jupiter's magnetosphere: Auroral and magnetospheric particle acceleration. *Journal of Geophysical Research: Space Physics*, 123(11), 9560–9573. <https://doi.org/10.1029/2018JA025948>
- Saur, J., Mauk, B. H., Mitchell, D. G., Krupp, N., Khurana, K. K., Livi, S., et al. (2006). Anti-planetward auroral electron beams at Saturn. *Nature*, 439(7077), 699–702. <https://doi.org/10.1038/nature04401>
- Saur, J., Politano, H., Pouquet, A., & Matthaeus, W. H. (2002). Evidence for weak MHD turbulence in the middle magnetosphere of Jupiter. *Astronomy & Astrophysics*, 386(2), 699–708. <https://doi.org/10.1051/0004-6361:20020305>
- Saur, J., Pouquet, A., & Matthaeus, W. H. (2003). An acceleration mechanism for the generation of the main auroral oval on Jupiter. *Geophysical Research Letters*, 30(5). <https://doi.org/10.1029/2002GL015761>
- Sulaiman, A. H., Allegrini, F., Clark, G., Gladstone, R., Kotsiaros, S., Kurth, W. S., et al. (2022). Jupiter's low-altitude auroral zones: Fields, particles, plasma waves, and density depletions. *Journal of Geophysical Research: Space Physics*, 127(8). <https://doi.org/10.1029/2022JA030334>
- Sulaiman, A. H., Hospodarsky, G., Elliott, S., Kurth, W. S., Gurnett, D., Imai, M., et al. (2020). Wave-particle interactions associated with Io's auroral footprint: Evidence of Alfvén, ion cyclotron, and whistler modes. *Geophysical Research Letters*, 47(22). <https://doi.org/10.1029/2020GL088432>
- Szalay, J., Allegrini, F., Bagenal, F., Bolton, S., Clark, G., Connerney, J. E. P., et al. (2017). Plasma measurements in the Jovian polar region with Juno/Jade. *Geophysical Research Letters*, 44(14), 7122–7130. <https://doi.org/10.1002/2017GL072837>
- Tao, C., Kimura, T., Badman, S. V., André, N., Tsuchiya, F., Murakami, G., et al. (2015). Variation of Jupiter's aurora observed by Hisaki/exceed: 2. Estimations of auroral parameters and magnetospheric dynamics. *Journal of Geophysical Research: Space Physics*, 121(5), 4055–4071. <https://doi.org/10.1002/2015JA021272>
- Tao, X., Thorne, R. M., Horne, R. B., Ni, B., Menietti, J. D., Shprits, Y. Y., & Gurnett, D. A. (2011). Importance of plasma injection events for energization of relativistic electrons in the Jovian magnetosphere. *Journal of Geophysical Research*, 116(A1). <https://doi.org/10.1029/2010ja016108>

- Thomas, N., Bagenal, F., Hill, T., & Wilson, J. (2004). The Io neutral clouds and plasma torus. In *Jupiter. The planet, satellites and magnetosphere* (Vol. 1, pp. 561–591).
- Torrence, C., & Compo, G. P. (1998). A practical guide to wavelet analysis. *Bulletin of the American Meteorological Society*, 79(1), 61–78. [https://doi.org/10.1175/1520-0477\(1998\)079<0061:APGTWA>2.0.CO;2](https://doi.org/10.1175/1520-0477(1998)079<0061:APGTWA>2.0.CO;2)
- Trantham, B. (2014). *Juno Jupiter UVS calibrated data archive v1.0*. NASA Planetary Data System.
- Wilson, R. J., Vogt, M. F., Provan, G., Kamran, A., James, M. K., Brennan, M., & Cowley, S. W. H. (2023). Internal and external Jovian magnetic fields: Community code to serve the magnetospheres of the outer planets community. *Space Science Reviews*, 219(1), 15. <https://doi.org/10.1007/s11214-023-00961-3>