

## On the Global Features of the 10–60-Min ULF Waves in Jovian Magnetosphere: Juno Observations

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### Special Section:

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### Key Points:

- We investigate the spatial distribution and periodic characteristics of ultra-low frequency (ULF) waves in the Jovian magnetosphere
- We examine and compare the occurrence rate of ULF waves under different solar wind compression states
- The connection between ULF waves and auroral morphology provides key constraints on wave generation mechanisms

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**Abstract** In the Jovian magnetosphere, quasi-periodic phenomena, with quasi-periods on the order of 10–60 min, are frequently identified using different data sets. These pulsations are a branch of ultra-low frequency (ULF) waves, which are believed to play a crucial role in driving the energy circulation within Jupiter's magnetosphere. In this study, we utilize magnetic field data collected by Juno between 2016 and 2022 to perform a comprehensive global statistical analysis of the spatial distribution and periodic characteristics of ULF waves in the Jovian magnetosphere. Our findings reveal distinct periodic features observed at different latitudes and distances, providing valuable insights into the generation mechanisms of ULF waves. Furthermore, we establish a close relationship between the presence of these ULF wave fluctuations and the magnetospheric state, such as under conditions of solar wind compression. By combining contemporaneous ultraviolet aurora observations from the Hubble Space Telescope (HST) and magnetic field data obtained by Juno, we have discovered that the compressed magnetospheres exhibit more pronounced ULF waves and enhanced auroral activity. These results provide a global picture of the distribution, implying potential generation of ULF waves in the Jovian magnetosphere, and shedding light on the processes behind the 10–60-min energy releases.

**Plain Language Summary** In the Jovian system, there are patterns of magnetic waves with periods of 10–60 min. These waves are part of a larger category called ultra-low-frequency waves and play an important role in how energy moves around Jupiter. Here, we study these waves using data collected by the Juno spacecraft from 2016 to 2022, investigating where these waves occur and how often they occur. The waves are different depending on the location and distance from Jupiter, which gives us clues about how they are created. These waves also appear to be more common when Jupiter's magnetic field is compressed by the solar wind. We have also combined data from the Hubble Space Telescope and Juno, and found that the compressed magnetic field leads to more of these waves and stronger auroras on Jupiter. This research helps us to understand how these 10–60-min bursts of energy work in Jupiter's magnetosphere.

## 1. Introduction

Jupiter's rapidly rotating magnetic field imparts strong electromagnetic forces on the surrounding plasma in the magnetosphere, leading to complicated particle acceleration and mass circulation. The primary source of particles in the Jovian magnetosphere is from the volcanic activity of its closest moon Io. As these charged particles are diffusing outward, they are constrained by the centrifugal force near the equatorial plane (Bagenal et al., 2016), and eventually stretch the magnetic field lines forming a magnetodisk. Within the vast Jovian magnetosphere, ultra-low-frequency (ULF) waves are abundant (Lysak, 2022; Lysak & Song, 2020; Manners & Masters, 2020). These waves play a crucial role in energy dissipation within the magnetosphere-ionosphere system, providing valuable insights into the overall dynamics of the system.

The generation of ULF pulsations in the magnetosphere can occur through various mechanisms. The resonant Alfvén wave structures are believed to be one of the major sources, including field line resonances for the shear Alfvén mode from one ionosphere to the conjugate ionosphere and cavity resonances for the fast mode in the

magnetodisk, as well as a lobe resonator in the high Alfvén speed region between the ionosphere and the magnetosphere (Lysak, 2022). Perturbations associated with the radial transport of plasma in the rapidly rotating magnetodisk also play a significant role in driving these waves (Delamere et al., 2015; Khurana et al., 2004; Krupp et al., 2004). Furthermore, internally driven magnetic reconnection in the disk and externally driven events dominated by solar wind also serve as potential sources of ULF pulsations (Dunn et al., 2017; Guo et al., 2018; Kronberg et al., 2012; Yao et al., 2017). It is crucial to consider that large-scale compressions can lead to disturbances within the magnetospheric cavity (Delamere, 2015; Delamere et al., 2014). The external perturbation from the solar wind can also excite ULF waves in the system. For example, Kelvin-Helmholtz instabilities may excite surface waves near the magnetopause propagating into the magnetosphere (Johnson et al., 2014). In order to comprehend the origins of ULF waves and understand the contributions from different sources, it is crucial to explore the distribution of ULF waves in Jupiter's magnetosphere, which can provide important constraints and insights. Manners and Masters (2020) conducted a study on the distribution using data from Pioneer 10 and 11 and Voyager 1 and 2 as well as Ulysses and Galileo. However, due to limitations in data quantity and orbital positions, our understanding of ULF waves concerning different distances and latitudes remains incomplete. In this study, we adopt a unique methodology, utilizing data from the Juno spacecraft, to gain further insights into the distribution of ULF waves and their generation mechanisms within Jupiter's magnetosphere.

In addition to the spatial presence or absence, our inquiry also extends to the periodic characteristics of ULF waves, which is pivotal for delving into their generation mechanisms and analyzing the plasma environment in Jupiter's magnetosphere. Due to the diverse wave excitation mechanisms and the intricate energy propagation processes, the magnetosphere-ionosphere system exhibits a highly dynamic behavior. In the ULF band, ubiquitous quasi-periodic oscillations (QPOs) are widely identified by multiple types of observations, including X-ray, infrared (IR), and ultraviolet (UV) auroral emissions (Dunn et al., 2016; Gladstone et al., 2002; Nichols et al., 2017; Watanabe et al., 2018), magnetic field (Khurana & Kivelson, 1989), radio waves (Arkhipov & Rucker, 2006; Hospodarsky et al., 2004; Kimura et al., 2011, 2012; MacDowall et al., 1993), and energetic particle flux (Karanikola et al., 2004). The phenomena exhibit a wide range of periods typically spanning from 1 to 100 min with a noticeable concentration in the 10–60 min range. There also appear to be several distinct ULF periods, often described as “magic frequencies,” around ~15, ~30, and ~40 min (QP-15, QP-30, and QP-40). The presence of similar periods suggests potential correlations and the common underlying physics governing these phenomena.

As one type of QPOs, the auroral emissions indeed provide a visualization of the pulsations in a global context. From 30 November 2016 to 18 July 2017, HST captured a series of ultraviolet (UV) aurora images of Jupiter. Grodent et al. (2018) categorized six aurora morphological classes (Q family, N family, U family, I family, i family, X family) based on the intensity and temporal evolution in the main auroral oval, equatorward and poleward auroras. Moreover, combining coordinated observations by HST and the Juno satellite, Yao et al. (2022) highlighted that the main auroral brightening (MAB) events (corresponding to X family events) arise from magnetospheric compression and are absent under expanded conditions. Similarly, auroral observations in multiple wavelength segments exhibit enhanced brightness (Baron et al., 1996; J. E. P. Connerney & Satoh, 2000; Dunn et al., 2016; Echer et al., 2010; Gurnett et al., 2002; Hess et al., 2014; Nichols et al., 2007, 2009; Sinclair et al., 2019; Zarka & Genova, 1983). In fact, every X-ray observation of Jupiter that is known to have occurred during a solar wind compression at the planet has shown strong periodic pulsations in the X-ray aurora with a characteristic pulsation rate of 9–14 or 24–30 min (Dunn et al., 2016, 2017, 2020; Weigt et al., 2020; Wibisono et al., 2020). Such periodic X-ray pulsations appear to be less prevalent in the aurora during intervals of more quiescent solar wind conditions (Dunn et al., 2020; Wibisono et al., 2021). Yao et al. (2021) show a strong correlation between QPO in the outer magnetosphere magnetic field measurements and X-ray auroral pulsations during July 2017. Although the exact physical mechanism is not yet fully understood, it is clear that solar wind compressions enhance the Jovian auroral emissions globally and across multiple wavebands. What's more, Macdowall et al. (1993) elucidated a correlation between QP radio bursts and the solar wind velocities through data from Ulysses, which intimated the influence of interplanetary conditions. They also emphasized that further examination of the correlations between solar winds and magnetic fields could provide more clues. It would be interesting to explore the potential differences in the occurrence possibility and periodic characteristics of ULF waves in the Jovian magnetosphere under compressed and expanded conditions, which would provide valuable insights into the mechanisms influencing ULF waves and the generation of auroras and QPOs.

On Earth, current systems and Alfvén waves play vital roles in generating auroras. Observation and simulation studies suggest that electromagnetic waves provide driving force for auroral acceleration processes and lead to energy deposition in the ionosphere (Chaston et al., 2005; Keiling et al., 2003, 2019; Lotko et al., 1998). Similarly, on Jupiter, in addition to the corotation breakdown current system (Cowley & Bunce, 2001; Hill, 2001; Southwood & Kivelson, 2001), electromagnetic waves, especially Alfvén waves, have been proposed as an important driver. Observational researches have confirmed the presence of intense Alfvén waves in regions connected to the auroral zone (Saur et al., 2003) and strong Alfvén wave activities at the tail of Io's auroral footprint (Gershman et al., 2019). Furthermore, electron distribution and magnetic perturbations in the auroral region and the magnetosphere also confirmed the importance of Alfvénic acceleration (Lorch et al., 2022; Mauk et al., 2017). Pan et al. (2021) found a strong correlation between the energy of ULF waves with periods ranging from 1 to 60 min and the energy of auroral emissions, particularly in the main aurora. However, further evidence is needed to fully understand the specific mechanisms as well as the contributions of current systems and Alfvén waves to aurora generation. In this study, we further investigate ULF waves in the Jovian magnetosphere and their correlation with auroras, thereby offering new insights into the generation mechanisms of ULF waves and the underlying energy release processes. The subsequent section provides an overview of the data and methodologies employed in this research. In the third section, we present the global distribution of ULF waves in the Jovian magnetosphere using data collected by Juno. Additionally, we explore the interrelationships among magnetospheric compression, auroral brightening and ULF waves through the joint observations of Juno and HST. Finally, we discuss the possible generation mechanisms of ULF waves in Jupiter's magnetosphere based on the statistical results.

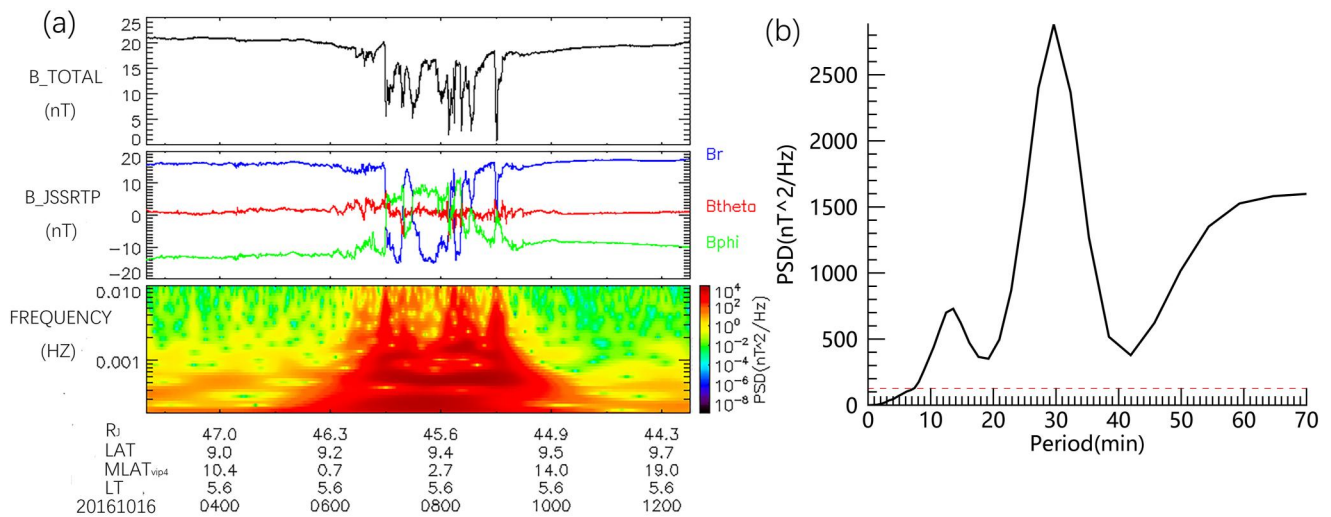
## 2. Data and Methods

This study analyzed magnetic data obtained from the Juno Magnetic Field Investigation (MAG) with 1 s resolution (J. E. P. Connerney et al., 2017). We analyze measurements from 7 July 2016 to 18 August 2022, which cover a distance range of  $\sim 1 R_J$  to  $113 R_J$ , a local time range of 6LT to 18LT through midnight, and a latitude range from  $70^\circ\text{S}$  to  $50^\circ\text{N}$  through the equator. The sequential data can then be divided into segments with the length of Jupiter's rotation period. This timescale is appropriate to capture 10–60-min fluctuations around Jupiter during one complete rotation, minimizing potential errors introduced by different locations in the Jupiter-Centered Fixed Coordinate System.

Previous studies on ULF waves typically decompose the magnetic field in the magnetic field-aligned (MFA) coordinate system. However, the data used here exhibit significant variations. The direction of the background field obtained through sliding averaging may have a large angular deviation from the true magnetic field direction, sometimes reaching  $180^\circ$ . Therefore, this study utilizes the total magnetic field data for wave analysis to obtain overall information, while in subsequent case studies, the specific directions of waves can be examined in detail.

We perform the continuous wavelet transform (CWT) on the total magnetic field data. Compared to other spectral methods, the wavelet transform has a better capacity for identifying QPOs (Manners & Masters, 2020). It provides superior simultaneous localization of non-time stationary fluctuations in both frequency and time. The CWT convolves a continuous signal with a set of wavelet basis functions at different scales and time positions to obtain the signal's distribution in the frequency and time domains. Compared to the discrete wavelet transform (DWT), CWT provides higher frequency and time resolution. To address boundary effects in wavelet analysis, we broadened the analysis window to include additional data before and after the target time segment. This strategy ensures the integrity of our analysis of wave fluctuations within the designated timeframe, avoiding distortions due to edge artifacts. We calculate the wavelet power spectral density (PSD), providing a time-frequency representation of magnetic field fluctuations. By performing a time integration, the time-average wavelet PSD distribution across frequencies can be obtained within each time window. The peaks in this distribution mark the quasi-periodic phenomena of interest. It should be noted that whenever we are talking about a period in this study, we actually mean a quasi-period, since it is not a strictly periodic signal that is recorded. By statistically analyzing these periodic peaks, we provide global characteristics of QPOs in Jupiter's magnetosphere. Figure 1 shows an example application of this process and the detection of QPO signatures in the magnetic field data. The significance levels were calculated employing the approach described in Torrence and Compo (1998).

Furthermore, this study also combines auroral observations from the HST program GO-14634 conducted with the Space Telescope Imaging Spectrograph (STIS) ultraviolet camera. The program coincides with Juno orbits 3–7,



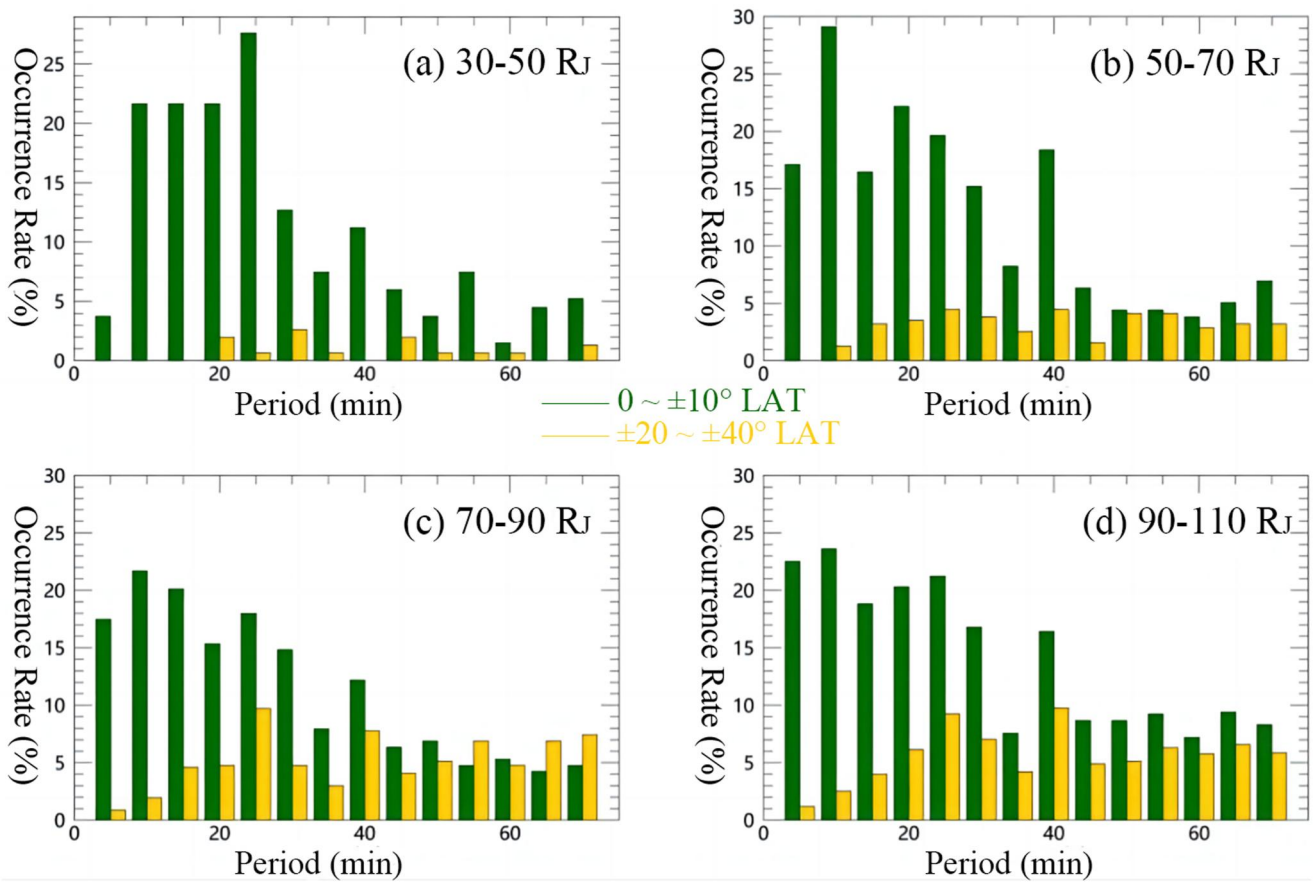
**Figure 1.** Analysis framework showing magnetometer data from the Juno spacecraft during 2:40–12:30 on 16 October 2016. (a) From top to bottom: the total magnetic field, r-theta-phi magnetic field components in Jupiter-de-Spun-Sun (JSS) coordinate, and the power spectral density (PSD) obtained by wavelet analysis. (b) The time-average wavelet PSD distribution across frequencies. The red dashed line represents the 99% significance level computed according to Torrence and Compo (1998).

providing a good opportunity for contemporaneous comparison of Jupiter's auroras with the state of the magnetosphere. Given the absence of real-time observations of solar wind conditions at Jupiter, we adopted auroral observations to estimate the level of magnetospheric compression. Our statistical study is based on the list of auroral characteristics derived by Grodent et al. (2018), and mainly focuses on the X and Q family auroras, which are considered to correspond to the compressed and the quiet magnetospheres, respectively, in Yao et al. (2022) and Grodent et al. (2018).

### 3. Results

We analyzed the total magnetic field data and collected the periodic peaks, showing the distributions of periods in different regions in Figure 2. The period range from 2.5 to 72.5 min was divided into 14 intervals of 5 min each. We count the number of events showing periodic peaks of each interval in different distance ranges (30–50  $R_j$ , 50–70  $R_j$ , 70–90  $R_j$ , and 90–110  $R_j$ ) for both low latitudes (0–10°, represented by green) and mid latitudes (20°–40°, represented by yellow) in Jupiter's planetocentric system. The statistical results were then normalized to the total number of time segments satisfying the corresponding spatial conditions, so that the relative heights of the bars indicate the occurrence probability of different quasi-periods in the described region. We categorized the total number of observation events under different distance and latitude conditions as follows: (a) 30–50  $R_j$ : 134 (low latitude), 154 (middle latitude); (b) 50–70  $R_j$ : 158 (low latitude), 314 (middle latitude); (c) 70–90  $R_j$ : 189 (low latitude), 566 (middle latitude); (d) 90–110  $R_j$ : 542 (low latitude), 1351 (middle latitude). Since some intervals do not exhibit period peaks and others show single or multiple peaks, the sum of occurrence rates may not equal 1.

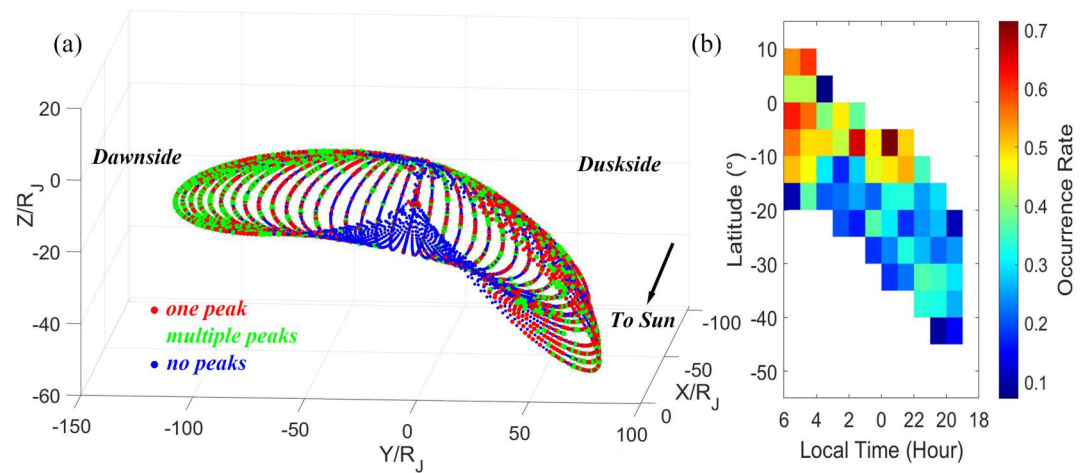
Periods span the full 5–70 min range in particular the 10–60 min range reported in the literature. In the low-latitude magnetosphere, the probability of occurrence of ULF waves appears to be largely independent of distance. There is a suggestion of peaks consistent with the “magic frequencies” QP-15, QP-30, and QP-40. The QP-15 and QP-30 appear to be widely distributed over 10–30 min range rather than two discrete peaks. Regarding the mid-latitude magnetosphere, ULF waves are increasingly obvious from 50  $R_j$  to 110  $R_j$ , and almost no fluctuations can be observed within 30–50  $R_j$ . This could be attributed to the fact that for the mid-latitude magnetosphere, being farther out implies closer proximity to the magnetopause, resulting in more disturbance events due to fluctuations near the magnetopause. Compared with low-latitude regions, the 10–30 min periods in mid-latitude regions are not always prominent, but there is a peak at 25 min. The 40 min peak can also be vaguely distinguished, and this region exhibits relatively evenly distributed 45–70 min periods similar to the low latitude. Overall, latitude appears to have a more pronounced impact on the distribution of ULF waves compared with distance. The low-latitude regions are more abundant with waves with periods of 40 min or shorter, which may indicate an extra and independent source in the magnetodisk.



**Figure 2.** Normalized histograms of significant periods in four distance sectors: (a) 30–50  $R_J$ , (b) 50–70  $R_J$ , (c) 70–90  $R_J$ , and (d) 90–110  $R_J$ . The green and yellow columns correspond to the low ( $0\text{--}10^\circ$ ) and middle ( $20\text{--}40^\circ$ ) latitude regions, respectively. The latitude seems to play a more important role than the distance.

In order to investigate the possible superposition of multiple source mechanisms and possible harmonic phenomena, we obtained the distribution of single-period and multi-period (10–60 min) events in Figure 3a, while Figure 3b displays the ratio of multi-period events to all observed ULF wave events across different regions. From dawnside to nightside to duskside, the inclination of the Juno orbits gradually increased. Observing the green-dominated dawnside and the red-dominated duskside in Figure 3a, as well as the color distribution in Figure 3b, it is evident that the proportion of multi-period wave events in the low-latitude regions far exceeds that in the mid-latitude areas, with a discrepancy reaching 50%. These results provide constraints and indications for discerning the sources of ULF waves in the magnetosphere. For the duskside of middle latitudes, the disturbance might mainly come from the magnetopause. The high proportion of multi-peak events in the low-latitude regions on the nightside suggests the potential coexistence of multiple ULF wave driving mechanisms within the magnetodisk. The dawnside of low latitudes may be influenced by both the magnetopause and the dynamic processes in the magnetodisk. Additionally, the multi-period phenomenon could also be derived from harmonic structures (Manners & Masters, 2019), especially when the present multiple periods are proportional.

In addition to the spatial distribution of ULF waves, the factors influencing their temporal variation are also important in understanding the Jovian system energy processes. Here, we mainly discuss the differences between compression and expansion conditions identified by HST observations. In the comparison of HST-Juno simultaneous observations, time correction needs to be carefully considered. First, due to the distance between Earth and Jupiter, there is a time delay from the occurrence of auroras to the observation by the telescope. At the same time, the duration of X- or Q-family auroras is, in fact, not confined solely to the HST observation time, but may extend over several hours both preceding and following the observation. In addition, it is worth noting that different events correspond to different positions of Juno in the magnetic coordinate system. The Juno was sometimes in the magnetodisk during HST's exposure, and sometimes it was not. This may introduce potential



**Figure 3.** The spatial distribution of quasi-periodic magnetic field fluctuations (10–60 min). (a) A 3-D plot in the JSS coordinate system. The red, green, and blue dots represent cases with one periodic peak, multiple peaks and no peaks on timescales of 10–60 min, respectively. (b) The ratio of multi-peak events to total ULF wave events in each region. The local time is plotted on the  $x$ -axis, while the latitude is shown on the  $y$ -axis. White areas represent regions with fewer than 10 ULF wave events.

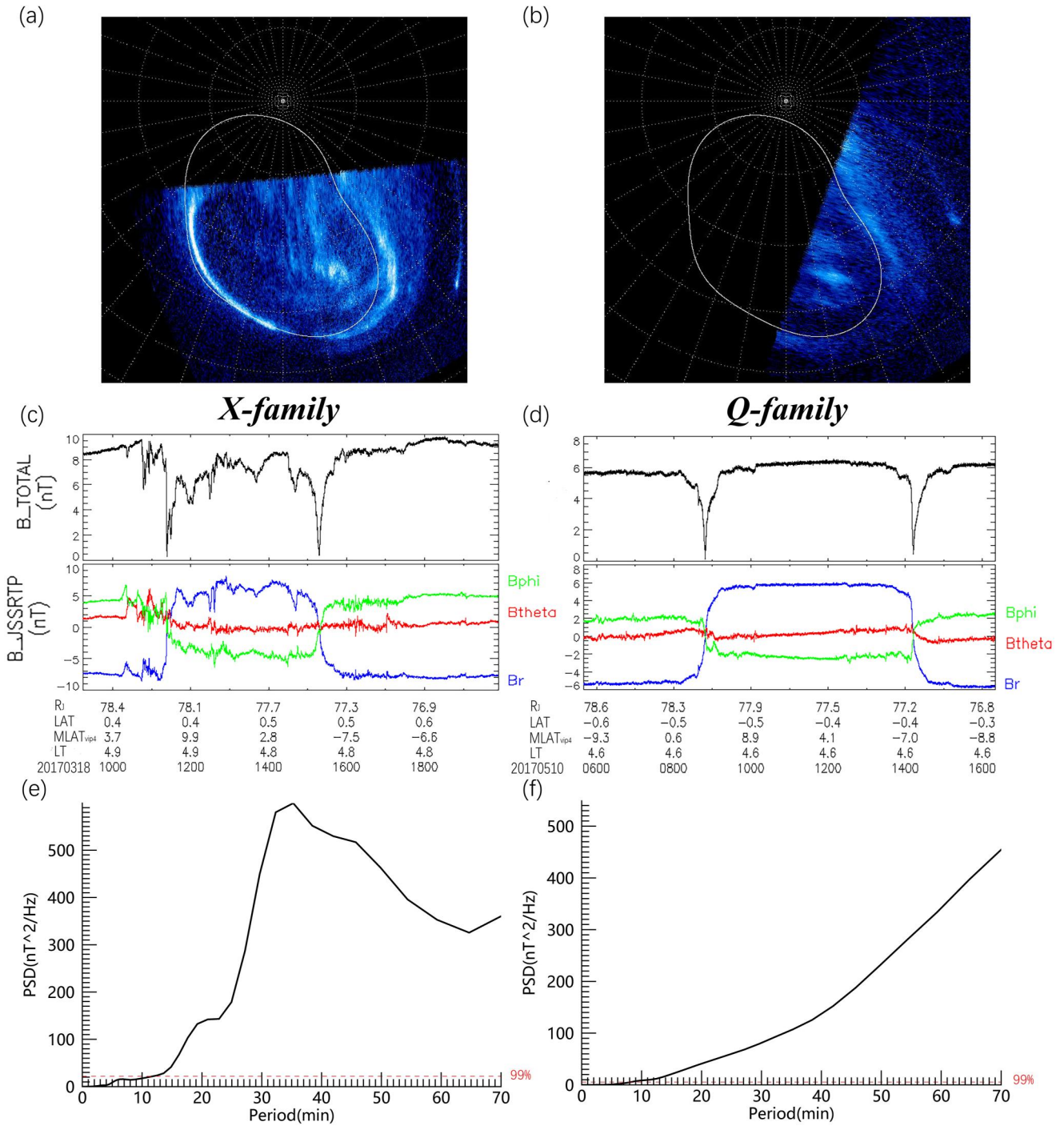
issues in our comparative analysis. To ensure comparability and involve the observations of the closest current sheet crossings, we chose to analyze the data during a period spanning several hours before and after the corrected Juno time when HST acquired the images.

The two tables provide the times when the auroral morphology was either in the Q family or the X family, respectively. Both tables display the auroral brightness, the positions of Juno, and the corresponding magnetic field wave characteristics. It can be observed that regardless of the extended time windows of 3, 6, or 10 hr (1.5, 3, or 5 hr before and after the telescope shot), the X family auroras consistently correspond to distinct quasi-periodic peaks, often showing multiple periods. On the other hand, the Q family auroras seldom occur with such quasi-periodicity, and no multi-periodic behavior has been observed. We conducted 100,000 random samplings of our database, wherein nine instances were labeled as fake X events and 11 instances were labeled as fake Q events in each iteration. The analysis revealed that the frequency of observing such imbalances randomly was found to be only 0.03%. Additionally, the chi-square test shows that there is 99.7% certainty that the occurrence possibility of ULF waves is related to the auroral family (the magnetospheric state). Figure 4 respectively gives examples of magnetic field features of X and Q-family events, between which we can see a clear contrast. During the corresponding interval of X-family auroras, magnetic field disturbances were more pronounced, whereas the magnetic field during Q-family auroras remained relatively quiet. In these two 10-hr intervals, the Juno satellite was at roughly similar locations, at a distance of 76–79  $R_J$ , a latitude of about  $\pm 0.6^\circ$ , and a local time of 4.5–4.9 LT. The similarity in location makes the temporal variations brought about by different magnetospheric states more explicit.

We display the distribution of periodic peaks obtained in 10-hr time windows in Figure 5. The periods of ULF waves during X-family auroras are clustered in the 10–30 min range. As for Q family, it is challenging to observe the distribution due to the scarcity of periodic peaks, but they seem to exhibit a higher occurrence rate in periods above 30 min compared to X-family events. In summary, this comparison suggests the different ULF wave features in the compressed and calm magnetosphere (corresponding to the X and Q auroras) from Tables 1 and 2 and Figures 4 and 5, although we note the limited data set and possible randomness.

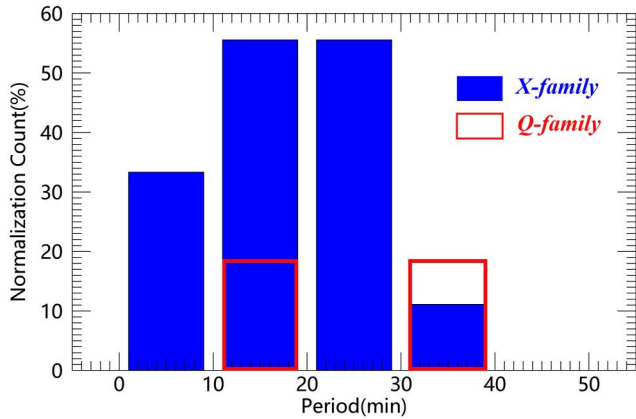
#### 4. Discussion

In this study, we utilize data gathered during 6 years by the MAG instrument onboard the Juno spacecraft to perform a statistical analysis of ULF waves in Jupiter's magnetosphere. This research marks the first time such an analysis has been performed using these specific instruments. Our investigation focuses on the global distribution of ULF waves and their periodic characteristics across various regions of the Jovian magnetosphere.



**Figure 4.** Two examples showing magnetic field features in 10-hr window of X-family (od8k42fiq observation, see Table 1) and Q-family (od8k62ogq observation, see Table 2) events, presented in (a, c, e) and (b, d, f), respectively. (a, b) Two auroral images acquired by HST. (c, d) From top to bottom: the total magnetic field and r-theta-phi magnetic field components in JSS coordinate. (e, f) The time-average wavelet PSD distribution across frequencies. The red dashed line represents the 99% significance level.

The distribution of ULF waves is a consequence of the combined influence of both internal and external driving mechanisms. It is widely accepted that under the influence of centrifugal forces, the Rayleigh-Taylor instability facilitates the outward transport of plasma, a process achieved through the interchange of magnetic flux tubes. In the magnetospheric context of rapidly rotating systems, such as Jupiter, the magnetic curvature forces often dominate over centrifugal forces (Southwood & Kivelson, 1987). Simulation-based investigations show that the



**Figure 5.** The distribution of periods identified in 10-hr windows corresponding to the Q-family (red box) and X-family (solid blue square) auroras, normalized according to the total number of selected events (11 for Q and 9 for X).

magnetodisk of Jupiter contains multiple finger-like interchange structures (Feng et al., 2023; Schok et al., 2023). These structures, influenced by planetary rotation modulation, may produce periodic perturbations in in situ measurements and result in an additional ULF wave source. The periodicity arising from these interchange structures is determined by their wave number, which may vary from several to tens, corresponding to periods of 10–60 min. Such interchange structures are also dynamically evolving. According to the analysis of quasi-interchange mode in giant planet magnetospheres by Achilleos et al. (2015), the condition of the generalized Rayleigh-Taylor frequency squared  $\omega_0^2 \geq 0$  is necessary and sufficient for the stability of the interchange mode.

$$\omega_0^2 = \left( \frac{\nabla \rho}{\rho} - 2\mathbf{c} \right) \cdot \mathbf{g} + \left[ \frac{\nabla(2P_M + P_\perp - P_\parallel)}{\rho} - (V_A^2 + C_\perp^2 - 4C_\parallel^2) \mathbf{c} \right] \cdot \mathbf{c} - \frac{[\mathbf{g} + (V_A^2 - C_\parallel^2) \mathbf{c}]^2}{V_A^2 + 2C_\perp^2}.$$

Here,  $\rho$  denotes the plasma mass density,  $g$  the effective gravity (including a centrifugal component) with unit vector  $\hat{e}_g = g/g$ ,  $c$  the magnetic curvature vector,  $C_\perp^2 = (P_\perp/\rho)$ ,  $C_\parallel^2 = (P_\parallel/\rho)$  where the corresponding plasma pressures are  $P_\perp$  (perpendicular to the magnetic field) and  $P_\parallel$  (parallel to the magnetic field).  $P_M$  denotes magnetic pressure. It also involves the Alfvén speed,  $V_A$ , and sound speeds in directions perpendicular and parallel to the magnetic field (respectively  $C_\perp$  and  $C_\parallel$ ). When Jupiter's magnetosphere is compressed by the solar wind pressure, the current sheet becomes thinner (Xu et al., 2023), leading to an increase in magnetic field curvature ( $c$ ) (Rogers et al., 2023). As a result,  $\omega_0^2$  is more likely to fall below 0, which conveys the growth of interchange instability and gives rise to more prominent structures for transporting plasma outward. Conversely, when the current sheet is relatively thick, interchange structures are less likely to emerge within the magnetodisk, leading to a reduced likelihood of observing quasi-periodic phenomena. Theoretical predictions align with observational evidence. In this study, we have observed more distinct ULF waves in the low-latitude magnetodisk during X-family auroral events corresponding to compressed conditions, whereas they were not as pronounced during Q-family auroral events.

**Table 1**  
*Quasi-Periodic Fluctuations During the X-Family Auroras*

Rootname	Date (dd/mm/yyyy)	Time (hh:mm:ss)	Auroral brightness/TW	Distance/ $R_J$	Latitude/ $^\circ$	Local time	Period (~3-hr window)/min	Period (~6-hr window)/min	Period (~10-hr window)/min
od8k01r0q	11/30/2016	14:57:23	1.5872	87.0	0.96	5.40	16, 35, 54	14, 30	14, 30
od8k02r4q	11/30/2016	16:32:45	1.40442	86.8	1.00	5.40	12, 54	14	14, 30
od8k05vniq	12/01/2016	16:23:32	1.7525	82.9	1.57	5.39	10, 23, 59	25	25
od8k11fuq	12/05/2016	18:56:58	1.65873	62.8	4.84	5.37	23	6, 21	10, 21
od8k12j9q	12/06/2016	14:02:21	1.98114	57.9	5.76	5.37	16	16	16
od8k32anq	03/17/2017	8:01:34	2.46697	82.9	-0.32	4.86	25	27	27
od8k42fiq	03/18/2017	14:14:38	2.08424	77.6	0.5	4.85	21, 46	46	35
od8k57itq	03/19/2017	9:19:18	2.59752	73.9	1.1	4.84	10	9, 16	10, 16
od8k69idq	06/18/2017	9:13:04	2.07849	111.1	-7.54	4.4	19	19	8, 19

*Note.* The first four columns of the table provide the HST archive root name, the corresponding time at Juno corrected for light travel time at the start of the exposure (dd/mm/yyyy hh:mm:ss format) and auroral brightness from Grodent et al. (2018). Subsequently, we present Juno's distance, latitude, local time, and the quasi-periods of the magnetic field within 3 hr (approximately 1.5 hr before and after), 6 hr (approximately 3 hr before and after), and 10 hr (approximately 5 hr before and after) centered around the exposure time. We exclude an X-family event from Grodent et al. (2018) due to significant differences in Juno's location, making it difficult to compare with the statistics above and other events.



**Table 2**  
*Quasi-Periodic Fluctuations During the Q-Family Auroras*

Rootname	Date (dd/mm/yyyy)	Time (hh:mm:ss)	Auroral brightness/TW	Distance/ $R_J$	Latitude/ $^\circ$	Local time	Period (~3-hr window)/min	Period (~6-hr window)/min	Period (~10-hr window)/min
od8k26q4q	12/04/2016	12:44:51	0.99415	70.0	3.63	5.38	19	19	19
od8k15qdq	12/13/2016	11:21:37	0.702831	30.2	-24.4	5.34	None	None	None
od8k16yrq	12/15/2016	7:50:44	0.919639	47.2	-19.1	5.33	None	None	None
od8k63neq	05/10/2017	5:54:33	0.776101	78.6	-0.58	4.58	None	None	None
od8k62ogq	05/10/2017	10:40:39	1.00931	77.7	-0.45	4.58	None	None	None
od8k84c6q	05/13/2017	8:36:44	1.16827	62.6	2.03	4.56	None	None	None
od8k87d1q	05/15/2017	11:28:13	0.902056	48.3	4.93	4.55	None	None	None
od8k0qldq	07/05/2017	8:05:37	0.936805	61.7	1.25	4.29	32	32	32
od8k0eqaq	07/06/2017	23:49:38	1.14375	50.7	3.46	4.28	11	None	16
od8k0twqq	07/08/2017	4:28:27	0.936659	41.0	5.84	4.27	None	32	None
od8k0fwuq	07/08/2017	6:01:24	0.923965	40.5	6.00	4.27	32	35	38

*Note.* The format is the same as in Table 1. We exclude two Q-family events from Grodent et al. (2018).

The internal sources of ULF waves include field line resonances, cavity resonances, and magnetic reconnection, while the external sources include solar wind dynamic pressure impulses and Kelvin-Helmholtz instability. These mechanisms can occur both independently and interactively, collectively influencing the excitation and characteristics of ULF waves. As discussed in Figure 3, the low-latitude magnetosphere appears to be influenced by two or more driving sources, while the mid-latitude magnetosphere is likely primarily affected by external driving factors. From this perspective, it can be conjectured that under the influence of external driving, ULF waves predominantly exhibit periodicities around 25 and 40 min in the mid-latitude regions. ULF waves primarily manifest periodicities ranging from 5 to 40 min under internal driving.

The results of the statistical research in this paper enhance our understanding of the excitation of ULF waves through field line resonances and cavity resonances within Jupiter's plasma environment. Lysak and Song (2020) employed the magnetic field model developed by J. E. P. Connerney et al. (1981) and the plasma model by Bagenal and Delamere (2011) to perform time-domain simulations of Alfvén waves propagating along Jovian magnetic field lines. They found that the model could support a diverse range of frequencies, particularly in the 10–40 min range. These findings align with our statistical results, revealing a prevalence of waves in the 10–40 min range and lower occurrence rates in the 45–70 min range within the low-latitude magnetosphere. It is likely that this phenomenon arises from the combined effects of field line resonances and cavity resonances coupling in the magnetodisk. Certain regions with specific magnetic field strengths or topologies could exert inhibitory effects on waves within the 45–70 min range. Furthermore, such wave distributions are widely spread in the region of 30–110  $R_J$ , indicating their presence throughout a substantial portion of Jupiter's magnetosphere. As posited by Lysak (2022), the Jovian tail is more conducive to supporting field line resonances at larger radial distances from the planet compared to Earth. Our statistical findings lend support to the extension of the range of field line resonances within Jupiter's magnetosphere beyond 100  $R_J$ .

Magnetic reconnection is also considered a potential internal trigger source for ULF waves. Recent research by Vogt et al. (2020) has highlighted the widespread occurrence of magnetic reconnection in Jupiter's magnetotail. We also noticed that the majority of X-type auroral events appear to be potentially associated with events listed in their magnetic reconnection catalog. Moreover, reconnection events at the magnetopause have also been invoked to account for the observed quasi-periodic phenomena. By analogy with Earth, Bunce et al. (2004) estimated that the reconnection interpulse period at Jupiter could be around 30–50 min, which may provide a plausible explanation of the pulsed X-ray emissions and the 40-min peak observed in this study. These findings suggest that magnetic reconnection plays a significant role in the generation of ULF waves in Jupiter's magnetosphere. However, further research is required to fully understand the specific mechanisms and dynamics involved in this process.

In addition to internal triggering mechanisms such as field line resonances, cavity resonances and magnetic reconnection, external driving can also impact wave generation. The increased occurrence rates under magnetospheric compression conditions and the distance-dependent distribution of ULF waves in mid-latitude regions observed on Jupiter appear to be related to external driving factors. The Kelvin-Helmholtz instability (KHI) and solar wind dynamic pressure impulses are acknowledged as two primary external sources believed to stimulate wave excitation (Zong et al., 2017). Evidence of KHI-driven waves along Jupiter's dawn flank magnetopause during the Juno prime mission (Montgomery et al., 2023). Simulation results indicate that the period of density fluctuations at the dusk terminator flank (18 magnetic local time, MLT) is approximately 1.4 hr (Zhang et al., 2018). The second harmonic (42 min) and the third harmonic (28 min) may account for the observed peaks at 40 and 25 min in the mid-latitude magnetosphere. Further research is needed to fully understand the specific mechanisms and dynamics involved in this process.

Internal and external driving mechanisms can account for the relationship between the occurrence rate of ULF waves and magnetospheric compression conditions. One scenario posits that magnetospheric compression leads to the generation of compression waves, while interactions with the solar wind induce magnetopause K-H instability, resulting in quasi-periodic fluctuations with periods of around 25 and 40 min. For another, the increased proximity of magnetic field lines facilitates the occurrence of magnetic reconnection events in the magnetotail, generating ULF waves with periods of 5–30 min. Notably, the observed periods during X-family auroras predominantly fall within the 5–30 min range, which seems to provide some additional support for the dominance of the latter mechanism.

Our findings resonate with the observations made by Macdowall et al. (1993), suggesting that solar wind conditions have a significant impact on the occurrence rate of quasi-periodic radio bursts and magnetic field fluctuations.

We also pay attention to the relationship between ULF waves and aurorae. Under compressed conditions, ULF waves with periods concentrated in the 10–30 min range exhibit consistency with the 9–14 or 24–30 min periods in the X-ray observations mentioned in the Introduction. Under quiet magnetospheric conditions, the low occurrence rate of ULF waves in this statistical analysis also aligns with the absence of observed X-ray auroral pulsations. This adds new information to the elucidation of the correlation between ULF waves and auroras. It is also comprehensible that certain time intervals corresponding to Q-family auroras display periodic peaks. Jupiter's magnetosphere is a highly intricate and dynamic system; thus, the continuous presence of ULF waves is expected, though their quantity and intensity may occasionally be diminished. Additionally, it is important to note that within the chosen 3–10-hr time intervals, the magnetospheric state may have undergone significant changes, such as transitioning from a quiet state to a more active one. Therefore, the aurora observed by HST may not fully represent the actual magnetospheric state.

## 5. Conclusion

This study provides a global perspective on the spatial distribution, periodic characteristics and potential sources of ULF waves within Jupiter's magnetosphere, contributing to a deeper understanding of the energy releases on timescales of 10–60 min. The main results are summarized as follows:

1. In the analysis of the spatial distribution and periodic features of ULF waves, it becomes evident that latitude plays a more substantial role than distance. The occurrence rate of ULF waves is observed to be higher in low-latitude regions and remains relatively constant with distance. In mid-latitude regions, the occurrence rate is relatively lower but displays a slight increase at greater distances.
2. In the mid-latitude region, a similar QP-40 and 45–70 min period distribution structure as that in the low-latitude region is observed. Additionally, another distribution peak is observed at approximately 25 min, which is also present in the low-latitude region where ULF waves in the 10–30 min range are abundant.
3. It has been consistently observed that ULF waves are present during episodes of enhanced X-family auroras that are associated with magnetospheric compression. However, this phenomenon is not evident during Q-family auroras, which correspond to quiet conditions.
4. The observed quasi-periodic magnetic field fluctuations are likely attributed to the interchange structures within the Jupiter's magnetodisc, as well as field line resonances and cavity resonances possibly triggered by concurrent processes such as magnetic reconnection and the Kelvin-Helmholtz instability.

In future studies, the combination of periods of quasi-periodic phenomena in multiple data sets (including magnetic fields, particles, auroras, etc.) may provide more evidence to reveal dynamic processes in Jupiter's magnetosphere. In the meantime, we will select typical cases for comprehensive in-depth analysis of ULF wave characteristics, hoping to be able to build a more complete picture of the energy transfer and release in Jupiter's magnetosphere.

### Data Availability Statement

The Juno data presented in this study are available at <http://pds-ppi.igpp.ucla.edu/> via the MAG instrument (J. Connerney, 2022). The auroral images are based on observations with the NASA/ESA HST (program HST GO-14634) obtained at the Space Telescope Science Institute (STScI), which is operated by AURA for NASA. These data are publicly available at STScI via <https://archive.stsci.edu/hst/>. The auroral list used is available at <https://doi.org/10.1002/2017JA025046> (Grodent et al., 2018).

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