The Global Distribution of Ultralow-Frequency Waves in Jupiter’s Magnetosphere

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Abstract  Jupiter’s giant magnetosphere is a complex system seldom in a configuration approximating steady state, and a clear picture of its governing dynamics remains elusive. Crucial to understanding how the magnetosphere behaves on a large scale are disturbances to the system on length-scales comparable to the cavity, which are communicated by magnetohydrodynamic waves in the ultralow-frequency band (<1 mHz). In this study we used magnetometer data from multiple spacecraft to perform the first global heritage survey of these waves in the magnetosphere. To map the equatorial region, we relied on the large local-time coverage provided by the Galileo spacecraft. Flyby encounters performed by Voyager 1 and 2, Pioneer 10 and 11, and Ulysses provided local-time coverage of the dawn sector. We found several hundred events where significant wave power was present, with periods spanning ~5–60 min. The majority of events consisted of multiple superposed discrete periods. Periods at ~15, ~30, and ~40 min dominated the event-averaged spectrum, consistent with the spectra of quasi-periodic pulsations often reported in the literature. Most events were clustered in the outer magnetosphere close to the magnetopause at noon and dusk, suggesting that an external driving mechanism may dominate. The most energetic events occurred close to the planet, though more sporadically, indicating an accumulation of wave energy in the inner magnetosphere or infrequent impulsive drivers in the region. Our findings suggest that dynamics of the system at large scales is modulated by this diverse population of waves, which permeate the magnetosphere through several cavities and wave guides.

1. Introduction

The magnetosphere of Jupiter is the largest structure embedded inside the heliosphere, yet an understanding of its dynamics remains elusive. The magnetospheric cavity is host to many dynamical processes occurring on energy scales exceeding their terrestrial equivalents by several orders of magnitude (Bagenal & Delamere, 2011; Bolton et al., 2002; Mauk & Bagenal, 2013). This complex environment represents an analog to high-energy astrophysical environments that is relatively local to Earth, offering a vast natural laboratory to test plasma-physics theory. A persistent ongoing problem is an incomplete understanding of how energy and momentum are exchanged between different regions, especially between the magnetosphere and ionosphere. This prohibits a clear picture of global dynamics, which are markedly different from the solar wind-dominated planetary magnetospheres (Achilleos et al., 2015; Barbosa et al., 1979; Khurana et al., 2004; Went et al., 2011). This is because Jupiter rotates on its axis in just 10 hr; this fast rotation, coupled with the planet’s large intrinsic magnetic field, means that the magnetosphere derives the majority of its energy and momentum budget from the planet’s core via electromagnetic coupling. By contrast, the magnetospheres of the other magnetized planets are driven mainly by the solar wind, and so ultimately by the Sun.

The aurora at Jupiter’s poles provide a proxy for this novel high spatial and temporal variability. Results from the JUNO spacecraft have shown the associated particle flux and electromagnetic emissions to be even more complex than previously thought, suggesting equally complex dynamics out in the magnetosphere, which drive these emissions (Allegrini et al., 2017; Clark et al., 2017; Gershman et al., 2019; Mauk et al., 2017a; Went et al., 2017b). As argued recently by Saur et al. (2018), the long-standing paradigm of a quasi-steady-state magnetosphere dominated by static, powerful field-aligned currents (FACs) has fallen into question, given that these FACs have been observed to be weaker than anticipated, and filamentary in structure, with evidence of stochastic acceleration producing broadband auroral signatures (Ebert et al., 2017; Kotsiaros et al., 2019). It is likely that time variable phenomena in the magnetosphere are responsible for the fine structure of the aurora, little of which has been studied in detail.
Prominent among these unexplained temporal phenomena are ubiquitous quasi-periodic oscillations (QPOs) in the ultralow-frequency (ULF) band. Reports span multiple data sets and cover a wide range of periods, encompassing ~1–100 min, though concentrated around 10–60 min. The full list of observations span modulations in the X-Ray, infrared (IR), and ultraviolet (UV) auroral emissions (Dunn et al., 2017; Gladstone et al., 2002; Nichols et al., 2017; Watanabe et al., 2018), magnetic field (Khurana & Kivelson, 1989), radio waves (Arkhypov & Rucker, 2006; Hospodarsky et al., 2004; Kimura et al., 2011, 2012; MacDowall et al., 1993), and energetic particle flux (Anagnostopoulos et al., 2001; Karanikola et al., 2004). There also appear to be several preferential ULF periods, often referred to in the literature as “magic frequencies,” around ~15, ~30, and ~40 min (also sometimes called QP-15, QP-30, and QP-40). Several studies have surveyed ULF wave activity in the middle magnetosphere using a subset of the available data and a subband of the ULF spectrum (e.g., Petkaki & Dougherty, 2001; Russell et al., 2001; Schulz et al., 1993; Tsurutani et al., 1993; Wilson & Dougherty, 2000) and collectively found significant wave power within 1–60 min. A recent comprehensive review of the topic by Delamere (2016) contains more detail on the history of research featuring QPOs at Jupiter.

The driving mechanisms of these phenomena have remained a mystery for decades. However, it is well established that the majority of QPOs are associated with magnetic field lines that map to the middle and outer magnetosphere and Alfvénic activity. When the magnetosphere is perturbed on a length scale similar to the size of the system, magnetohydrodynamic (MHD) waves in the fast-compressional and Alfvén modes communicate the new stress distribution imposed by the perturbation. MHD waves in the ULF band traveling at typical Alfvén speeds have length scales comparable to the scale of the magnetosphere, and so an Alfvénic resonance of the magnetic field may be responsible for the observed QPOs. The quasi-periodic behavior of QPOs is consistent with nonstationary resonances or localized resonances created by the complex structure of the magnetosphere.

ULF waves in the terrestrial magnetosphere have received significant attention in the literature. Early work demonstrated a mechanism for exciting a global resonance mode of the magnetosphere known as a field-line resonance (FLR), whereby propagating fast-mode ULF waves excite magnetic field lines at their natural frequencies. Trans-hemispheric standing Alfvén waves (SAWs) are subsequently established via a transfer of energy from compressional to Alfvén modes in the resonance region (Chen & Hasegawa, 1974; Southwood, 1974; Southwood & Hughes, 1983; Tamao, 1965). Southwood and Kivelson (1986) and Khurana and Kivelson (1989) postulated that a similar mechanism is active at Jupiter but that the waves are likely confined to the equatorial region by the distribution of plasma along the field line, which is dominated by the equatorial plasma sheet. Regions away from the plasma sheet are plasma depleted, and so the Alfvén speed rapidly becomes relativistic. The wave therefore spends the majority of its transit time in the plasma sheet, and so to first order the transit time is determined by the properties of this region.

Manners et al. (2018) showed that QPOs at Jupiter are well described to first order by SAWs and, given conservative variations in the plasma sheet Alfvén speed and thickness, the periods span 1–60 min for the first half-dozen harmonics. These SAWs can be depicted in 1-D as transverse displacements on a “magnetic string,” where magnetic tension acts as a restoring force and the ionospheric footprints represent fixed boundaries of the string. Multiple harmonics can be established in superposition along the field line, provided the compressional wave forcing the resonance has a bandwidth spanning several harmonic frequencies of the field line. The magnetosphere can therefore be treated as an infinite set of independent resonators, each with its own natural frequency and so its own set of harmonics (Wright & Mann, 2013). A case study by Manners and Masters (2019) presented a multiple-harmonic SAW confined to the plasma sheet in the Jovian magnetotail, with spectral properties consistent with frequently observed QPO periods. This demonstrates that at least a subset of QPOs is described by SAWs.

Progressing from these theories to a fuller understanding of ULF waves at Jupiter requires a heritage survey of all the available data to capture the systematic spatial distribution of QPOs in the magnetosphere. Here we present such a heritage survey, using the in situ magnetic field data from multiple spacecraft. In section 2 we discuss the data used in the survey, and an algorithm used to analyze the data and identify ULF events of interest. In section 3 we present the results of the survey, featuring the spatial distribution of QPOs. In section 4 we discuss potential drivers of SAWs at Jupiter and the implications they have for energy and momentum transfer through the system.
2. Spacecraft Data and an Algorithm for Identifying ULF Pulsations

2.1. Magnetometer Data From Multiple Encounters With Jupiter

To date, seven spacecraft have crossed the magnetopause and transited the Jovian magnetosphere: Pioneer 10 and 11, Voyager 1 and 2, and Ulysses flew by the system, Galileo was the first dedicated orbiter, and JUNO is currently in orbit at the time of writing. The majority of the pre-JUNO spacecraft trajectories were close to the equatorial plane, with the exception of Ulysses and Pioneer 11, which traversed the duskward southern hemisphere and the noon sector northern hemisphere, respectively. We expect ULF wave power and any SAWs to be concentrated in the equatorial plasma sheet, and so near-equatorial data are of particular interest. Data from Galileo covered a broad span of local time, except for dawn; data from the flybys contributed the majority of coverage of this region.

While Galileo provided the most data, the spacecraft experienced significant telemetry problems after the high-gain antenna sustained damage. Measurements from all instruments were downlinked at a variable data rate throughout the orbital tour, with the exception of high-interest intervals such as moon flybys. Additionally, the Plasma Science instrument (PLS) (Frank et al., 1992) suffered damage, preventing analysis of the thermal electrons, and poor pointing constraints limited the quality of calculated plasma parameters for the ions (Bagenal et al., 2016). We therefore limit our survey to exclusively using magnetometer data. As the primary focus of the survey is to inspect global resonance modes inside the magnetosphere, we excluded data measured outside the magnetopause, though ULF power in the magnetosheath or the solar wind may warrant inspection in a later study. Detailed information about the magnetometer instrument design on each spacecraft can be found in Van Allen et al. (1974), Acuna and Ness (1980), Kohlhase and Penzo (1977), Smith et al. (1992), and Kivelson et al. (1992), listed in chronological order of when the spacecraft encountered Jupiter. As JUNO is in a polar orbit, it spends minimal time close to the plasma sheet, and so we do not include these data in the survey.

The nominal cadence of magnetometer data throughout the Galileo mission was 24 s, but for portions of the tour the rate was significantly lower. A compromise is required between capturing the full ULF frequency band and retaining as much data as possible. To reach this compromise, we imposed a cutoff in cadence above which low data rates effectively constitute a data gap. The lowest resolvable period $\tau_{\text{min}}$ is given by the Nyquist condition $\tau_{\text{min}} = 2\tau_s$, where $\tau_s$ is the sampling cadence. We chose a cutoff at a sampling cadence of 2 min, which retains 97.5% of data from the Galileo magnetometer and gives a lower bound on the resolvable periods of 4 min. Given that the lowest observed periods in QPOs were $\sim$2–3 min, this eliminates only the extreme lower limit of the range of interest, which in future could be made the subject of a dedicated study using a subset of the available data. We downsampled the remaining data to the modal cadence over each day to ensure that spectral analysis was performed at a consistent data rate. Magnetometer data from Pioneer 10 and 11, Voyager 1 and 2, and Ulysses required minimal processing, as in each case magnetic field vectors were sampled at least once per min, allowing the full ULF band to be analyzed. The choice of a 4 min lower bound on the ULF spectrum also avoids the issue of detecting spin tones of the rotating spacecraft (Galileo rolled with a 19 s spin period, and the other spacecraft were similar except for Voyager 1 and 2, which did not roll). Figure 1 shows an equatorial-plane projection of the trajectories of the six spacecraft included in the survey. The data shown are those that were measured with a sufficient sampling cadence less than 2 min. Any gaps in the trajectories correspond to times when the magnetometers were off-line or in low data rate modes. Once processed, the data were then passed through an algorithm for analysis, where intervals of interest in ULF activity could be identified.

2.2. An Algorithm for Identifying ULF Waves

We used an algorithm to survey the large volume of data and construct a catalog of ULF “events.” Due to the highly dynamic nature of the magnetosphere and the variable digitization-noise floors of each magnetometer, field perturbations with amplitudes below 1 nT cannot be unambiguously separated from statistical fluctuations for the entire data set. To ensure robust results, we only identified pulsations with amplitudes of several nT during relatively quiet magnetospheric conditions, a process that we now describe in detail.

The data were analyzed using a framework presented in Figure 2. During this interval, Galileo traversed the tail plasma sheet close to midnight, 50–60 $R_J$ from Jupiter. The magnetic field data in spherical coordinates corotating with Jupiter (known as Jupiter System III) in Figure 2a show perturbations of periods on the order tens of minutes superposed on top of the long-timescale evolution of the field. To inspect
Figure 1. Portions of spacecraft trajectories during intervals where magnetometer data were suitable for inclusion in the survey, shown in equatorial cross section. Data are omitted where the sampling cadence falls below the 2 min threshold required to capture the full ULF spectrum. The dotted lines show the bimodal statistical position of the magnetopause (Joy et al., 2002).

These small-amplitude perturbations, we rotated the data into mean-field-aligned (MFA) coordinate system (see Khurana & Kivelson, 1989; Manners et al., 2018), using a moving-average window of 60 min to produce a principal unit vector $\hat{b}$ aligned with the average background magnetic field. The unit vectors $\hat{b}_r$ and $\hat{b}_θ$ complete a right-handed orthogonal set and are transverse to the mean field. The 60-min background field is then removed, producing the MFA residual magnetic field components $δb_r$, $δb_θ$, and $δb_φ$, shown in Figures 2b and 2c). Further examples of intervals analyzed using this framework in different parts of the magnetosphere can be found in the supporting information.

Transient or impulsive phenomena unlikely to be MHD waves, or changes in instrumentation dynamic ranges, occur often. To filter out these intervals, we used a threshold in the normalized moving-variance $σ$ of the magnetic field magnitude

$$σ (B_i) = \frac{1}{2wB_i} \sum_{j=-w}^{w} (B_{ij} - \bar{B}_i)^2,$$

where $w$ is the window half-width and $\bar{B}_i$ is the mean magnetic field over a 60 min interval. We neglected intervals when $σ_B$ exceeded 1 nT, using a moving-variance window half-width 10 min. This filter is particularly effective for isolating Alfvénic activity, as Alfvén waves do not perturb the magnetic field magnitude.

There are also geometric constraints to consider. The radial distension of the magnetic field is greatest near the magnetic equator in the middle magnetosphere, due to centrifugal forces acting on the equatorially confined plasma. This causes reversals in the radial and azimuthal components of the magnetic field over a spatial length scale on the order of several Jovian radii. The velocity of each spacecraft with respect to the plasma sheet normal direction was variable, but the average time taken to traverse the plasma sheet was around 30 min. This timescale is shorter than the width of the moving window used to obtain the MFA basis vectors; in this region the fidelity of these vectors in capturing the mean-field direction is poor, and they are no longer field-parallel/transverse across the whole interval. In these instances, field-aligned and Alfvénic activity are impossible to distinguish, and so they were removed from the analysis. To remove these intervals, we calculated the angle of rotation between the local magnetic field vector and the computed instantaneous MFA unit vector, which is shown by the black dotted line in Figure 2b. We imposed a limit on the acceptable angle of deviation to a cone angle subtending 45° from the local magnetic field vector. This constraint almost invariably removes intervals where the spacecraft is traveling through the center-most region of the plasma sheet, which is expected to be the primary locus of ULF wave power. However, while the
Figure 2. Analysis framework showing magnetometer data from the Galileo spacecraft during 13–14 September 1996. (a) Magnetic field data in Spherical System III coordinates. (b) Field-aligned component of the mean-field-aligned (MFA) magnetic field residual (red line) and angle of deviation between the local magnetic field vector and the computed MFA unit vector (black dashed line). (c) Both transverse components of the MFA magnetic field residual. (d–f) Continuous wavelet transforms for the field-parallel and field-transverse MFA magnetic field residuals, respectively. The white dotted lines in (d)–(f) demonstrate that most of the ULF power is concentrated within 10 and 60 min.

Latitudinal plasma-density gradient is large, the waves are unlikely to be perfectly confined to the center-most region. Consequently, this central plasma sheet “blind-spot” is assumed to diminish the number of identified events without introducing bias to the resulting distribution of wave periods.

Figures 2b and 2c show several enhancements in the amplitudes of magnetic field perturbations while Galileo crossed the equatorial plasma sheet. To obtain spectral information of the wave packets in frequency-time space, we computed the wavelet transforms of each MFA residual component using a Morlet wavelet (Gaussian-modulated plane wave), the results of which are shown in Figures 2d–2f. The region where edge effects are large is beyond the limits of the plotted data. The wavelet transform offers superior simultaneous localization of non-time stationary fluctuations in both frequency and time compared to other spectral methods, a capacity crucial for identifying QPOs, which are time variable by nature. We nevertheless validated the results of the wavelet transform by comparison to fast Fourier transform (FFT) and Lomb-Scargle spectra (see the supporting information for examples).

To classify an ULF active interval as an event, we used a threshold in the wavelet power integrated over the ULF band, which we call the ULF bandpower $P_{ULF}$, defined as

$$P_{ULF} = \frac{1}{v_{max} - v_{min}} \int_{v_{min}}^{v_{max}} P(v) \delta v,$$

where $v$ is frequency, $P$ is power spectral density, and $v_{min/max}$ are the minimum and maximum frequencies of the ULF band. We set the threshold as twice the daily mean bandpower. The longest resolvable period is given by the length of the time series, and so to capture the full ULF band up to 60 min, we considered only events where this threshold was exceeded for longer than an hour. Within each event any statistically significant discrete maxima in power were identified. We used Monte Carlo simulations of the magnetic field data during each interval of interest to perform the significance test at a 95% confidence threshold, using 10,000 random reshuffles of the data, where we assumed the background spectrum is well approximated by a red-noise process (Torrence & Compo, 1998). Any intervals where power at a given period exceeded this significance level are hereafter referred to as significant periods.
Figure 3. Histograms using field-transverse events gathered using data from all the spacecraft magnetometers, in an equatorial-plane projection: (a) the total time spacecraft spent in each bin; (b) the ULF bandpower averaged over the events in each bin; (c) the proportion of time spacecraft spent in each region where significant ULF activity was observed; (d) the same as (c) but for the subset of events where only a single significant period was observed. White bins signify where there are no available data, and gray bins signify regions where spacecraft visited but observed no events.

The spectra of waves identified by the algorithm are subject to doppler shift, due to the relative motion of the spacecraft and the plasma rest frame. A simple calculation of the frequency shift introduced to waves with rest-frame periods between \( \sim 10 \) and 60 min shows that the effect is minimal for a large range of spacecraft velocities. The result is a typical shift of a few minutes, and around 10 min in the extreme. As the availability of bulk-velocity measurements from plasma moments is very limited, and a shift of several minutes is small compared to the 10–60 min range of interest, we neglect this effect from our analysis—though the reader should remain aware of this bias.

The framework outlined above was applied to the magnetometer data from all six spacecraft, resulting in a catalog of events of at least an hour in duration, with at least one statistically significant enhancement in ULF power, providing the first global distribution of ULF waves in the magnetosphere.

3. Survey Results and Analysis

We found a combined total of around 650 events where significant ULF power was present, mostly in the Galileo data. The duration of events peaked at 1 hr, and most events were 1–3 hr in duration, with a minority lasting up to 8 hr. As events shorter than 1 hr were excluded from the survey, it is likely that many more events exist in the data, which can be the subject of a future study on shorter-period ULF waves. The average MFA angle of deviation during events was \( \sim 10^\circ \), confirming the success of the quality control measures imposed by the selection algorithm. For more details, the interested reader may refer to the supporting information.
The large number of events provides far greater spatial and spectral detail than previous studies. An analysis of the full extent of the information spans a wide range of topics at various spatial scales and is best explored in separate future works. The dominant outstanding question at the time of writing regarding these waves is their effect on energy flow through the magnetosphere, and their connection with the quasi-periodic signatures observed throughout the literature. Therefore, in the following sections we will focus on the implications of the sampled distribution for large-scale magnetospheric dynamics.

In the events successfully identified, power was predominately concentrated in the field-transverse components, but several hundred field-parallel events were also identified. The field-parallel events are difficult to interpret unambiguously, so we focus on the field-transverse events, which can be reasonably assumed to be caused by Alfvén waves and therefore representative of natural periods of the system in each region. Figures 3a–3d show several histograms of the field-transverse events in an equatorial plane projection: (a) the total dwell time of spacecraft in each bin; (b) the ULF bandpower averaged over the events in each bin; (c) the fraction of total time the spacecraft spent in each bin when significant ULF wave power was present; and (d) the same as (c) but for the subset of events where only one significant period was present. Unsampled regions are shown in white, and inactive regions where no significant ULF wave power was detected are shown in gray.

The ULF-active proportion of spacecraft dwell time in Figure 3c demonstrates ULF waves occur most often in the outer magnetosphere, especially in the noon sector and along the dusk flank. There is also regular activity in the magnetotail, where events with only a single significant period are concentrated and where there also appears to be a dawn/dusk asymmetry in the bandpower (see Figure 3d). Globally, the majority of ULF activity appears to consist of multiple simultaneous discrete periods.

The distributions of periods in different components are shown in Figure 4. Periods span the full 5–60 min observed in the literature, and there is suggestion of peaks consistent with the “magic frequencies” QP-15, QP-30, and QP-40. The 30 min period appears to dominate, and there also may be an intermediate ~35 min period. The QP-15 period appears to be spread more widely over 10–20 min than one discrete period, consistent with the 10–20 min ULF power found by Khurana and Kivelson (1989); these periods also have a systematically smaller power than 30 and 40 min periods and mostly appear only during events where multiple simultaneous periods were observed. The field-transverse and field-parallel events have periods largely coincident in time and space, consistent with compressional wave-driven FLRs, where energy is being transferred from fast mode to the resonant Alfvén mode.

The majority of field-transverse events showed the same significant spectral behavior in both transverse components, but there is some evidence of independent decoupled periods in the minority of cases; this may also be due to only one field-transverse component being present, caused by linearly polarized waves (see Figure S2).

Figure 5 shows the distribution of periods in local time for all the field-transverse events. The 30 min period is prominent in all local-time sectors, as is the 40-min period, though the latter appears most prominent in the dusk sector. There is a noticeable dawn-dusk asymmetry in the distributions: The dawn sector is skewed toward periods less than 30 min, and the dusk sector is skewed toward periods longer than 30 min.

Localized deviations from the global distribution of periods are evident in several places: Figure 6 compares the region of the plasma torus at Io’s orbit with the region close to the magnetopause at the subsolar point. The broadband periods close to the plasma torus appear to consist of three harmonics at ~30, 60, and 90 min, whereas the distribution close to the dayside magnetopause is much more narrowband and centered around 30 min. The MFA magnetic field residuals shown in Figures 6c and 6d, and their respective wavelet transforms in Figures 6e and 6f, are representative of the two regions. Events close to the torus are variable in profile, whereas the outer magnetospheric signals have a more regular “saw-tooth” profile, which could possibly indicate a more homogeneous region or monochromatic source.

4. Discussion

A wealth of information is contained in the survey results, a full analysis of which is beyond the scope of this study. We will focus our discussion on the most informative consequences for large-scale dynamics of the magnetosphere.
The most striking feature of the results is the distribution of events shown in Figure 3. For example, the magnetotail appears to have significantly different spectral properties to the dayside, and there is some evidence of a dawn-dusk asymmetry. This is consistent with expectations for the periods of SAWs excited on magnetic field lines in these local-time sectors. A persistent systematic asymmetry in magnetic field has been observed in the magnetotail, with flux tubes less stretched at dusk than at dawn (Khurana et al., 2004; Kivelson & Khurana, 2002). This means that the plasma sheet is thicker at dusk and thinner at dawn. SAWs at Jupiter spend the majority of their bounce period transiting the dense plasma sheet, and so a systematic asymmetry in plasma sheet thickness should correspond to an asymmetry in SAW periods. The distributions in the midnight and noon local-time sectors are similar, consistent with compressional ULF waves excited on the dayside being advected around the dusk flank to the nightside. However, this does not rule out other driving mechanisms common to the midnight and noon sectors, or some other method of globally generating broadband spectrum ULF waves. Conversely, on the dayside there is a clear radial trend, where bandpower of the average event in the inner magnetosphere (<10 RJ) is several orders of magnitude greater than in the outer magnetosphere (>40 RJ). Two interpretations are available: First, energy density is enhanced closer to the planet due to a focusing effect, whereby inbound MHD waves collect in the inner magnetosphere; second, separate driving mechanisms exist in the inner magnetosphere with a much larger energy density than drivers in the outer magnetosphere. The most likely causes of these systematic differences can be considered using analogs in the terrestrial magnetosphere for comparison.

4.1. Driving Mechanisms External to the Magnetosphere

ULF compressional waves in planetary magnetospheres can be externally driven by frequent perturbations on the magnetopause, some of which can be of considerable amplitude (Kepko, 2003; Zhang et al., 2010). The magnetopause is often perturbed by the solar wind, both coherently on a global scale such as during interplanetary shocks and also locally by small-scale dynamic-pressure fluctuations. A measure of magnetospheric compressibility was derived by Glassmeier et al. (2004), expressed as
Figure 5. The distribution of periods in four local-time sectors: (a) midnight, (b) dawn, (c) noon, and (d) dusk. We show only the field-transverse events and have normalized each histogram for consistent comparisons of relative frequency. Clear skews are evident in dusk and dawn about the dominant 30 min period at noon and midnight, with dusk periods shifted to <30 min and dawn shifted to >30 min.

Figure 6. Case study comparing ULF waves (a/c/e) near the plasma torus around Io's orbit and (b/d/f) the vicinity of the magnetopause in the noon local-time sector; (a and b) the distributions of periods in this regions; (c and d) the time series of MFA residual perturbations representative of events in these regions, obtained using a 100 min sliding window; and (e and f) the wavelet transforms of (c) and (d), respectively.
If the majority of power is driven at the magnetopause, then this suggests that ULF waves have a long lifetime in the magnetosphere and can transit the enormous distance between the magnetopause and the inner magnetosphere, consistent with the mechanism of resonant absorption into the Alfvén mode, which should continue to occur during transit of the waves, as long as the resonance conditions are met.

The density gradients at the northern and southern boundaries of the plasma sheet cause partial reflection of the waves, such that the plasma sheet acts as a waveguide. This means that compressional ULF waves become trapped in the region where MHD mode coupling is strongest and transfer to energy to the Alfvén mode in the resonance region (leading to SAWs) is likely to be more efficient than at Earth. This is potentially of great importance to an understanding of wave-wave and wave-particle interactions in the plasma sheet: Saur (2004) suggested that the long-standing question of why the plasma sheet temperature increases with distance from Jupiter may be due to an Alfvénic turbulent cascade leading to heating in the plasma sheet in the middle magnetosphere; more recently, Saur et al. (2018) suggested that the main mode of damping due to wave-particle interactions beyond ~30\(R_J\) is the ion-cyclotron mode, facilitated by such an Alfvénic cascade. A constant supply of large spatial-scale perturbations such as ULF waves could ensure that such a cascade is always active, and SAWs could present a method of further confining Alfvén wave energy in a relatively small region for a long times, allowing waves to break up into smaller scales and enhance this dissipation effect.

Constant perturbations of the magnetopause injecting broadband ULF waves into the magnetosphere are consistent with the frequent ULF activity in the outer magnetosphere on the dayside and dusk-flank sectors (see Figure 3c). However, if it can be assumed that this activity is the result of SAWs, a constant supply of energy from the magnetopause should permit the amplitude of SAWs to increase over time, such that the amplitude of SAWs on field lines closest to the magnetopause is greater than SAWs on field lines farther from the boundary. Instead, the data suggest the converse: The lowest ULF power is found in the most ULF-active regions. This could represent large variability of the magnetic field topology in the resonance region over long timescales. Large-amplitude SAWs require an accumulation of energy in a region where there is persistent fast-mode energy available and the MHD modes are consistently coupled by strong inhomogeneity. Any SAWs in the outer magnetosphere during a large compression of the magnetopause would be disordered and dissipated, before sufficient time has elapsed to build up large-amplitude Alfvén waves.

Resonant absorption occurs only at harmonics of the natural frequency of the local magnetic field line, and so a small portion of the broadband wave energy is converted to the Alfvén mode (Glassmeier et al., 1999). Remaining wave energy is free to propagate to the middle magnetosphere. The waves may propagate as far as the inner magnetosphere, where local conditions are more stable and so large-amplitude SAWs can be established. The efficiency of this radial transport of ULF energy is enhanced by the presence of the plasma sheet waveguide. Assuming that the thickness of the plasma sheet can be considered small compared to the length scales of the magnetosphere, the wave energy density should scale with the inverse square of the radius from the planet. Fitting the radial dependence of bandpower of the events identified in the survey with a power law yields an exponent of the radius of \(-2.18 \pm 0.16\) for the field-transverse components and \(-1.53 \pm 0.21\) for the field-parallel components (see Figure S3). This indicates that the enhanced Alfvénic ULF power in the inner magnetosphere is consistent with inbound energy being focused into a smaller volume. The \(-1.5\) exponent for the field-parallel component suggests that less energy penetrates into the inner magnetosphere, consistent with the mechanism of resonant absorption into the Alfvén mode, which should continue to occur during transit of the waves, as long as the resonance conditions are met.

If the majority of power is driven at the magnetopause, then this suggests that ULF waves have a long lifetime in the magnetosphere and can transit the enormous distance between the magnetopause and the
plasma torus at Io's orbit—in stark contrast with the terrestrial magnetosphere, where ULF waves have been observed to dissipate in tens of minutes (Wang et al., 2015). We can compare this to an estimate of how far fast-mode waves could penetrate into the magnetosphere over a Jovian rotation by assuming conservative ranges in the Alfvén and sound speed in the plasma sheet of 100–300 km/s (Bagenal et al., 2017; Kivelson, 2016). Using the expression for magnetosonic speed for oblique propagation

\[ c_{ms} = \sqrt{c_s^2 + v_A^2} \]

where \( c_s \) is the plasma sound speed, we obtain a fast-mode speed of \( \sim 140–420 \) km/s. For a nominal magnetopause standoff position of 75 \( R_J \) and assuming the waves are moving radially in the plasma sheet waveguide, this gives a transit time of 3.5–10 hr, between roughly a third and one whole Jovian rotation. This suggests that while moving radially through the system, the waves may also be carried through all local times—though this is something of an overestimate, due to subcorotation of the plasma sheet in the middle and outer magnetosphere. Nevertheless, it is feasible that at least occasionally, the fast-mode ULF waves are convected through all local times; assuming a near-constant supply of such waves from the magnetopause or other processes, the plasma sheet could be considered to contain a bath of ULF MHD wave energy at all radii and local times.

Where this energy collects is a prime question to investigate: The rapid radial drop-off in bandpower in the survey results suggests the energy collects in a localized resonator in the inner magnetosphere. Distinguishing a system-wide transport of energy and separate resonant cavities and drivers in the inner magnetosphere requires a detailed inspection of the local environment, specifically the plasma tori around Io and Europa.

4.2. Driving Mechanisms in the Plasma Tori

Since Pioneer 10 and Voyager 1 passed through the plasma torus around Io's orbit in the 1970s, strong Alfvénic activity has been observed inside the torus (e.g., Walker & Kivelson, 1981). Bagenal (1983) demonstrated that the magnetic perturbation produced in Io's wake results in a system of SAWs that propagate azimuthally around the torus. Like the equatorial plasma sheet, the northern and southern edges of the torus have a sharp plasma-density gradient, and so the torus acts a waveguide, trapping wave energy, such that the torus can sustain eigenoscillations. This “Io Alfvén resonator” produces Alfvén energy a thousand times greater than contained in a typical ULF (Pc5) wave in the terrestrial magnetosphere (Greenwald & Walker, 1980; Goertz, 1980) and so makes a significant contribution to the total ULF activity in the magnetosphere. Glassmeier et al. (1989) showed evidence for decoupled transverse and compressional MHD waves in the torus, possibly indicating that the source is the Io-plasma interaction. They also produced estimates for the power produced by the Alfvén waves generated by the Io-plasma interactions, which are energetically consistent with decoupled toroidal (field-twisting) eigenmodes of the magnetic field lines and poloidal (radial breathing) eigenmodes of the whole torus. However, the interaction is unlikely to produce spectral signatures of large azimuthal spatial scales (small azimuthal wave numbers), and so whether the interaction is responsible for coherent resonances of the whole torus is uncertain. Given that wave energy from externally driven sources may collect in the inner magnetosphere, it is also possible that the torus resonantly couples to inbound compressional waves, effectively coupling perturbations on the magnetopause to eigenoscillations inside the torus. We have included this potential mechanism in Figure 7, where it is referred to as the “torus resonance.”

Another possible driving mechanism is large-scale flux-tube interchange motion close to the torus. The radial diffusion of the torus plasma out into the equatorial plasma sheet is driven by the centrifugal-force differential across adjacent flux tubes (Bagenal & Delamere, 2011). The rapid decrease in centrifugal potential of the torus plasma with radial distance from the planet provides free energy for the instability, whereby mass-loaded flux tubes are transported outward and replaced by inward-traveling mass-depleted flux tubes. As the process is unlikely to occur at a constant rate, a heterogeneous environment is created sporadically in the torus where regions of cold, dense plasma are adjacent to regions of hot, diffuse plasma. The interactions between these regions may result in nonlinear wave-particle interactions that provide free energy for coherent eigenoscillations of the torus (Kivelson et al., 1997; Thorne et al., 1997).

4.3. ULF waves in the Magnetotail

The ULF events in the tail plasma sheet typically have spectral properties significantly different from those in the rest of the magnetosphere. The difference is evident when contrasting Figures 3c and 3d: While the majority of events contain a superposition of multiple significant periods, waves in the magnetotail from postdusk to predawn predominately only contain one significant period. However, the same arguments
regarding transport of the waves should apply, as the tail plasma sheet should also act as a waveguide for MHD waves. Analysis of magnetometer data from both Voyager spacecraft showed significant ULF power close to the magnetic equator in the magnetotails of the outer planets, and very little in the lobes between the magnetopause and the plasma sheet boundary layer (Khurana et al., 1992). However, it cannot be assumed that SAWs can explain the main population of magnetotail events. Not all of the field lines are closed in the far-tail region, and the Alfvén bounce time is too long to provide a strong coupling to the planet’s ionosphere. It is likely that a different mechanism is responsible for the tail events.

The bandpower of events in the predawn sector is of systematically greater power than those postdusk. The statistical reconnection X-line in the nightside decreases in radial distance from Jupiter moving from dusk to dawn. Cowley et al. (2003) discussed the relative contribution of Dungey-type and Vasyliunas-type (centrifugally driven) reconnection and posited that Dungey-type is expected to be dominant dawnside of midnight and Vasyliunas is dominant duskside. The clear asymmetry in power premidnight and postmidnight in Figure 3b may be evidence of different dominant reconnection mechanisms. A lower wave power at dusk sector is consistent with mass-loaded flux tubes undergoing reconnection “drizzle” as suggested by Delamere and Bagenal (2010), wherein reconnection occurs in more frequent, more localized events. ULF waves can be produced by the resultant plasmoid formation, return plasma flow sunward, and corresponding dipolarization of the planetary magnetic field. Similar ULF wave production has been observed during magnetic substorms in the terrestrial magnetosphere (e.g., Liang et al., 2009; Mishin et al., 2002; Volwerk et al., 2005). Vogt et al. (2014) found the mean plasmoid duration to be 6.8 min, but the distribution spanned ~5–15 min, consistent with the lower end of the ULF distribution throughout the magnetosphere. They also observed the “chain” reconnection bursts observed at Earth, Saturn, and Mercury; over half the plasmoids they studied occurred within 90 min of a subsequent reconnection signature. This suggests that though the reconnection-mechanism probably differs at Jupiter, return flows and dipolarizations of the field result nevertheless, and so reconnection in the magnetotail is probably a source of quasi-periodic ULF power.

### 4.4. Redistribution of Energy in the Magnetosphere

The foremost notable characteristic of magnetospheric ULF waves is their ability to redistribute energy on a global scale. The structures and processes involved in the production of ULF waves on which we have speculated are presented in Figure 7, highlighting the connection between compressional ULF waves and SAWs, as well as the different hypothesised resonant cavities. The key element facilitating a connection between these processes are SAWs, which act as energy-storage channels, trapping energy from perturbations in localized regions on timescales longer than the lifetime of the initial perturbation.

The relative proportion of ULF wave energy that is transferred to SAWs and the relative proportion of the global energy budget that is contributed by ULF waves are both important for developing a better understanding of global dynamics—and which until now have been impossible to estimate with limited data. Rae et al. (2007) estimated that the proportion of SAW energy dissipated by joule heating and injected into the Earth’s ionosphere could be as high as 30% during large substorms. While the applicability of the concept of substorms at Jupiter remains unclear, the findings of this study indicate that during times of significant perturbations to the magnetospheric configuration, SAWs may be a viable channel for transferring a large amount of energy from the solar wind to disparate parts of the magnetosphere and into the ionosphere.

The importance of wave-particle interactions is paramount in the further study of ULF waves and their relation to these dynamics. ULF wave-particle interactions have been studied extensively in the terrestrial magnetosphere (Jonathan Rae et al., 2018; Watt et al., 2011) and have been shown to modulate precipitation of energetic electrons into the ionosphere and growth rates of kinetic-scale waves, both of which have important implications for the highly variable aurora at Jupiter. For an extensive review, see Zong and Zhou (2017). The dissipation of SAWs has been shown to consist of a complex interplay between properties of the wave, ambient plasma, and the ionosphere; joule heating in the ionosphere, landau damping, and electron trapping in quasi-static field-parallel electric fields have all been shown to contribute to damping (Jonathan Rae et al., 2018; Rankin et al., 2007). ULF energy is also known to be redistributed around the flanks of the terrestrial magnetosphere by a magnetotail waveguide (see Wang et al., 2015, and references therein), whereby compressional ULF waves are advected antisunward while reflecting between the magnetopause and an inner turning point closer to the planet.

The outer planets have multiple energy crises within their magnetosphere-ionosphere-thermosphere systems, such as the heating of the plasma sheet with increasing radial distance from the planet (see, e.g.,
Figure 7. A cartoon of the chain of processes responsible for ULF wave generation in the magnetosphere. The magnetospheric cavity is shown in light purple, and magnetic field lines are represented in dark purple. Perturbations on the magnetopause create compressional fast-mode waves (green arrows) that propagate planetward, confined to the plasma sheet waveguide (pink). SAWs are generated locally where the inbound compressional waves match the field line eigenperiods (distorted green field lines). Remaining propagating wave energy collects in the inner magnetosphere where it is resonantly absorbed by the Io plasma torus. Reconnection processes in the magnetotail create a separate population of monochromatic SAWs, also confined to the equatorial waveguide.

Bagenal & Delamere, 2011). In the aftermath of JUNO’s first traversals of Jupiter’s polar regions, the established paradigm of quasi-static current systems transporting energy and angular momentum from the planet out into the mass-loaded magnetosphere cannot provide a full explanation of global dynamics. The broadband bidirectional electron beams frequently observed in regions where strong FACs are expected suggest that stochastic acceleration plays a large role in particle heating and auroral precipitation (e.g., Clark et al., 2017; Connerney et al., 2017; Mauk et al., 2017a, 2018). Nonsteady processes have also been suggested elsewhere in the magnetosphere: The plasma sheet is known to exhibit MHD turbulence that may be responsible for heating of the middle- and outer-magnetospheric plasma (Saur, 2004; Saur et al., 2002). A recent study by Saur et al. (2018) highlighted the importance of Alfvénic turbulent cascades and dissipation in the magnetosphere as a source of particle acceleration, specifically that the dominant mode of dissipation varies in different regions of the magnetosphere. Given the ubiquitous presence of QPOs, ULF waves are very likely to play a role in the modulation of wave growth and scattering processes, and direct energization of ambient plasma.

4.5. Summary

Transplanting existing ULF wave theory to the Jovian magnetosphere remains nontrivial and ongoing, but the heritage survey of magnetometer data we have presented here provides the first look at the systematic global distribution of waves in the equatorial plane. The results demonstrate that ULF waves occur most
often in the outer magnetosphere on the dayside and along the dusk flank, but ULF wave energy is concentrated in the inner magnetosphere. We speculated that this may be due to a combination of different resonant cavities, one in the equatorial plasma sheet and another in the plasma torus around Io’s orbit, though this hypothesis cannot be verified using these data alone. Spectral properties of QPOs previously observed throughout the system are consistent with the ULF spectrum obtained from the survey: a distribution spanning 5–60 min, dominated by 15, 30, and 40 min. The population is well described by a large population of transhemispheric SAWs confined to the plasma sheet. The magnetotail plasma sheet appears to host a separate population of quasi-monochromatic ULF waves, which we interpreted as evidence of a different driving mechanism dominated by reconnection and dipolarization of the magnetic field. ULF waves are a key element in understanding both the global processes, which redistribute energy through the magnetosphere, and resonant cavities that act as localized reservoirs of energy. Answering questions of how these cavities contribute to particle energization, stochastic acceleration and energy/momentum transport in the magnetosphere will require a detailed analysis of ULF wave modes and the wave-particle interactions in which they participate.

Data Availability Statement

Magnetometer data from all of the spacecraft data used in this study can be obtained from the NASA Planetary Data System (https://pds.nasa.gov). Data required to reproduce the results shown is stored in the Zenodo repository (https://doi.org/10.5281/zenodo.3898560).

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