The Global Distribution of Ultra-Low-Frequency Waves in Jupiter's Magnetosphere

H. Manners[1], A. Masters[1]

[1]Space and Atmospheric Physics Group, Blackett Laboratory, Imperial College London, London, UK

Key Points:

- We used heritage magnetometer data to produce the first global statistical survey of ultra-low-frequency waves in Jupiters magnetosphere.
- The waves have periods spanning ∼5-60 min, dominated by ∼15, ∼30 and ∼40 min pulsations, consistent with periods reported in the literature.
- The population of waves have a diverse spatial distribution, indicating multiple driving mechanisms and several distinct resonant cavities.

Corresponding author: Harry Manners, `h.manners17@imperial.ac.uk`

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 ultra-low-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 & 2, Pioneer 10 & 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 waveguides.

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 (Bolton et al., 2002; Bagenal & Delamere, 2011a; B. Mauk & Bagenal, 2013). This complex environment represents an analogue 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 (Barbosa et al., 1979; K. Khurana et al., 2004; Went et al., 2011; Achilleos et al., 2015). This is because Jupiter rotates on its axis in just ten hours; 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; B. H. Mauk et al., 2017a, 2017b; Gershman et al., 2019). 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 ultra-low-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, infra-red (IR) and ultra-violet (UV) auroral emissions (Gladstone et al., 2002; Nichols et al., 2017; Dunn et al., 2017; Watanabe et al., 2018), magnetic field (K. Khurana & Kivelson, 1989), radio waves (MacDowall et al., 1993; Hospodarsky et al., 2004; Arkhypov & Rucker, 2006; Kimura et al., 2011, 2012) 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 sub-band of the ULF spectrum (e.g. Tsurutani et al. (1993); Schulz et al. (1993); Petkaki and Dougherty (2001); Wilson and Dougherty (2000); Russell et al. (2001)), and collectviely

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 Alfvn modes communicate the new stress distribution imposed by the perturbation. MHD waves in the ULF band travelling 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 behaviour of QPOs is consistent with non-stationary 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 (Tamao, 1965; D. J. Southwood, 1974; Chen & Hasegawa, 1974; D. Southwood & Hughes, 1983). D. J. Southwood and Kivelson (1986) and K. 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 1D as transverse displacements on a 'magnetic string', where magnetic tension acts as a restoring force, and the ionospheric footprints represent fixed bound-

aries 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 sub-set of QPOs are 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 analyse 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 & 11, Voyager 1 & 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 dusk-ward 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 Sci-
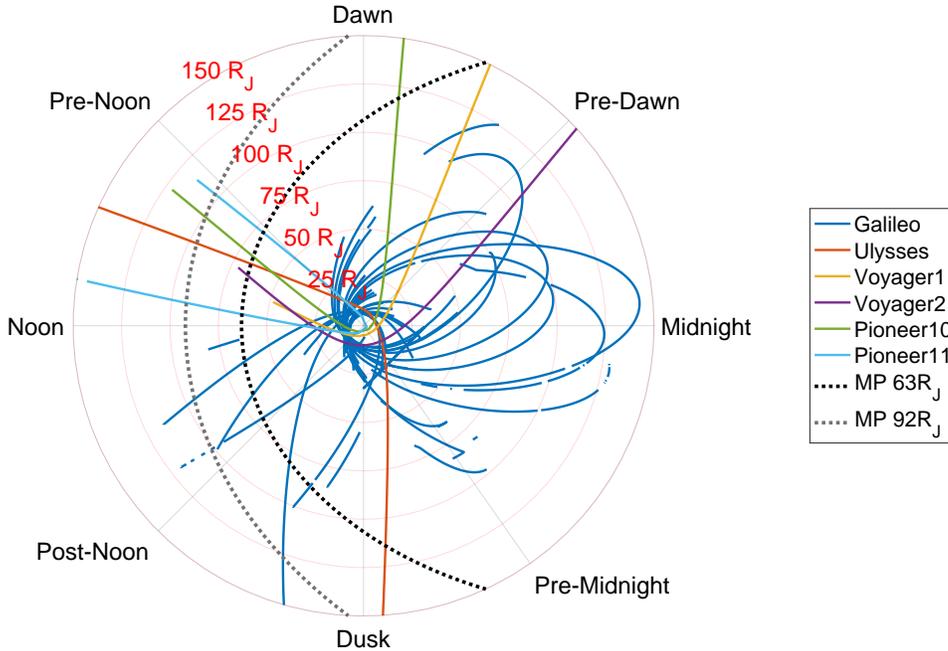
Figure 1. Portions of spacecraft trajectories during intervals where magnetometer data was suitable for inclusion in the survey, shown in equatorial cross-section. Data are omitted where the sampling cadence falls below the 2 min threshold required to capture the full ULF spectrum. The dotted lines show the bi-modal statistical position of the magnetopause (Joy et al., 2002).

ence 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); 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 cut-off in cadence above which low data-rates effectively constitute a data-gap. The lowest resolvable period τ_{min} is given by the Nyquist condition $\tau_{min} = 2\tau_s$, where τ_s is the sampling cadence. We chose a cut-off 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 ∼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 & 11, Voyager 1 & 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 analysed. 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 & 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 which were measured with a sufficient sampling cadence less than 2 min. Any gaps in the trajectories correspond to times when the magnetometers were offline 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 catalogue 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 dataset. 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 analysed using a framework presented in Fig. 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 Fig. 2.a) show perturbations of periods on the order tens of min super-
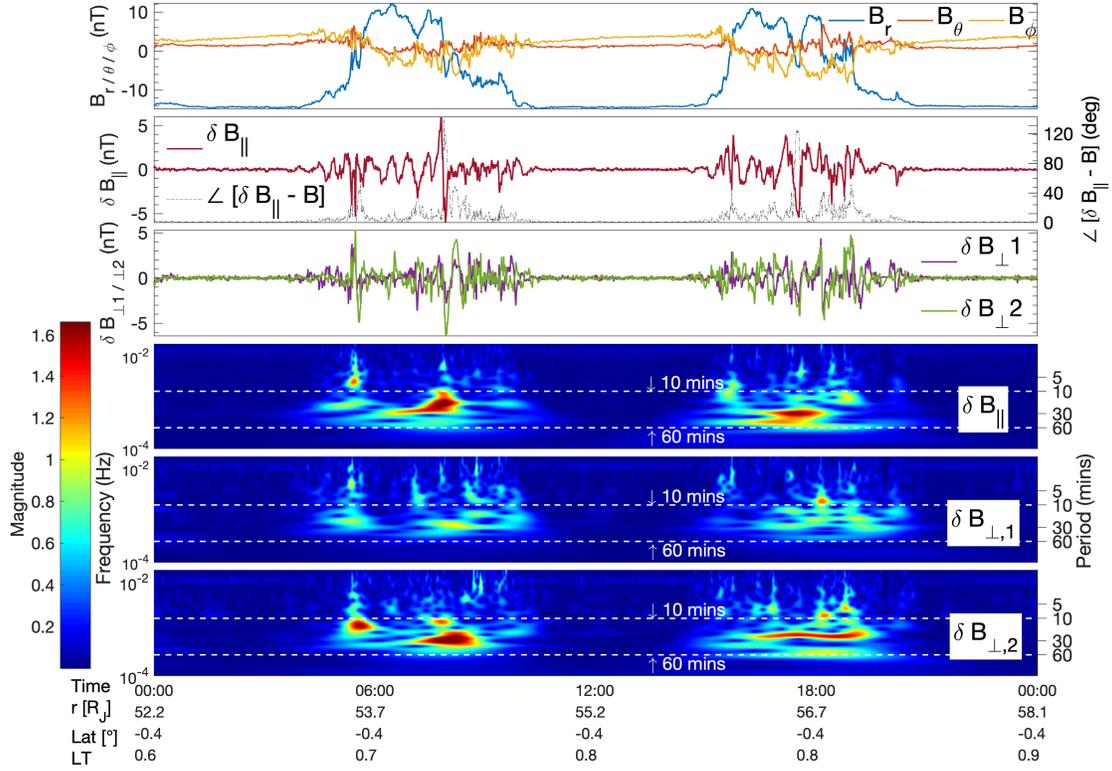
Figure 2. Analysis framework showing magnetometer data from the Galileo spacecraft during 13th-14th September 1996. a) Magnetic field data in spherical system III coordinates. b) Field-aligned component of the mean-field-aligned (MFA) magnetic field residual (red line), and angle of deviation between 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.

posed on top of the long-timescale evolution of the field. To inspect these small-amplitude perturbations, we rotated the data into mean-field-aligned (MFA) coordinate system (see K. Khurana and 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 $\hat{b}_{\perp,1}$ and $\hat{b}_{\perp,2}$ 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 $\delta b_{||}$, $\delta b_{\perp,1}$ and $\delta b_{\perp,2}$, shown in figure 2.b-c). Further examples of intervals analysed using this framework in different parts of the magnetosphere can be found in Supplementary Materials.

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

$$\sigma\left(B_i\right) = \frac{1}{2wB_i} \sum_{j=-w}^{w} \left(\bar{B}_{i+j} - \bar{B}_i\right)^2, \tag{1}$$

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_i} 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 Fig. 2b). We imposed a limit on the acceptable angle of deviation to a cone-angle subtending 45 degrees from the local magnetic field vector. This constraint almost invariably removes intervals where the spacecraft is travelling through the centre-most region of the plasma sheet, which is expected to be the primary locus of ULF wave-power. However, while the latitudinal plasma-density gradient is large, the waves are unlikely to be perfectly confined to the centre-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.

Fig. 2.b-c) 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 Fig. 2d-f. 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 Supplementary Materials 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

$$P_{ULF} = \frac{1}{\nu_{max} - \nu_{min}} \int_{\nu_{min}}^{\nu_{max}} P(\nu)\, \delta\nu, \tag{2}$$

where ν is frequency, P is power spectral density and $\nu_{min/max}$ 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 refered to as significant periods.

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 by over range of spacecaft velocities on waves with rest-frame periods between ∼10-60 mins shows that the effect is minimal, introducing a typical shift of a few mins, and around 10 mins in the extreme. As the availability of bulk-velocity measurements from plasma moments is very limited, and a shift of several mins 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 catalogue 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 hour and most events were 1-3 hours in duration, with a minority lasting up to 8 hours. As events shorter than 1 hour were included in the survey 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 ∼-10 degrees, confirming the success of the quality control measures imposed by the selection algorithm. For more details, the interested reader may refer to the Supplementary Material.

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. Fig. 3 a) through d) 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 grey.
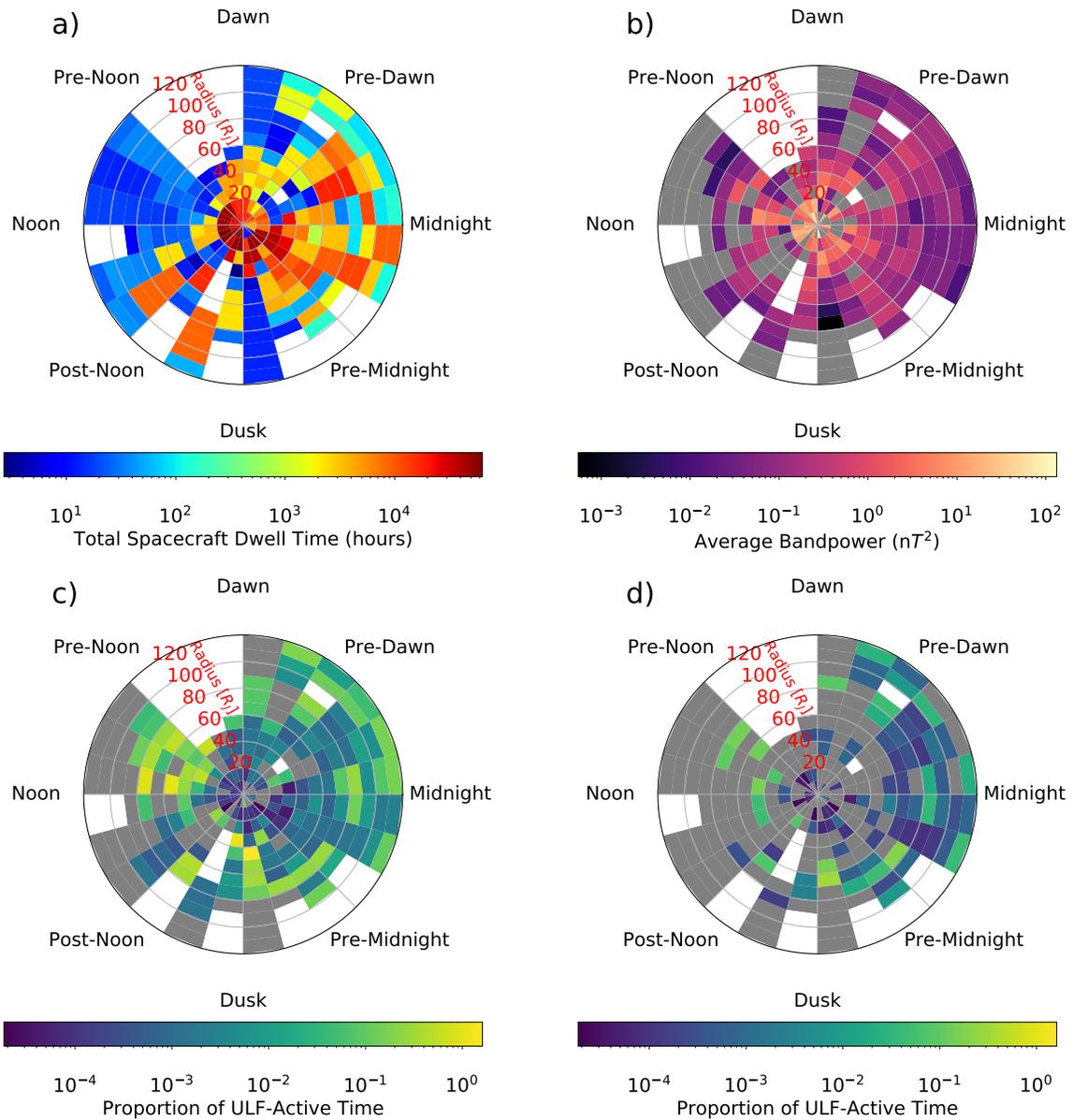
Figure 3. Histograms using field-transverse events gathered using data from all the spacecraft magnetometers, in an equatorial-plane projection: a) the total time spacecraft spent in each bin; b) the ULF bandpower averaged over the events in each bin; c) the proportion of time spacecraft spent in each region where significant ULF-activity was observed; d) same as c) for the subset of events where only a single significant period was observed. White bins signify where there are no available data, and grey bins signify regions where spacecraft visited but observed no events.

The ULF-active proportion of spacecraft dwell-time in Fig. 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 Fig. 3d). Globally the majority of ULF activity appears to consist of multiple simultaneous discrete periods.

The distributions of periods in different components is shown in Fig. 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 $\sim$ 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 K. Khurana and Kivelson (1989); these periods also have a systematically smaller power than 30 min 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 events field-transverse events showed the same significant spectral behaviour 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 Fig. 2 in Supplementary Materials).

Fig. 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 towards periods less than 30 min, and the dusk sector is skewed towards periods longer than 30 min.

Localized deviations from the global distribution of periods are evident in several places: Fig. 6 compares the region of the plasma torus at Io's orbit with the region close to the magnetopause at the sub-solar point. The broadband periods close to the plasma torus appear to consist of three harmonics at $\sim$ 30, 60 and 90 min, whereas the distribution close to the dayside magnetopause is much more narrowband and centred around 30 min. The MFA magnetic field residuals shown in Fig. 6c) and d), and their respective wavelet transforms in e) and f), are representative of the two regions. Events close to the torus are variable in profile, whereas the outer magnetospheric signals have a more
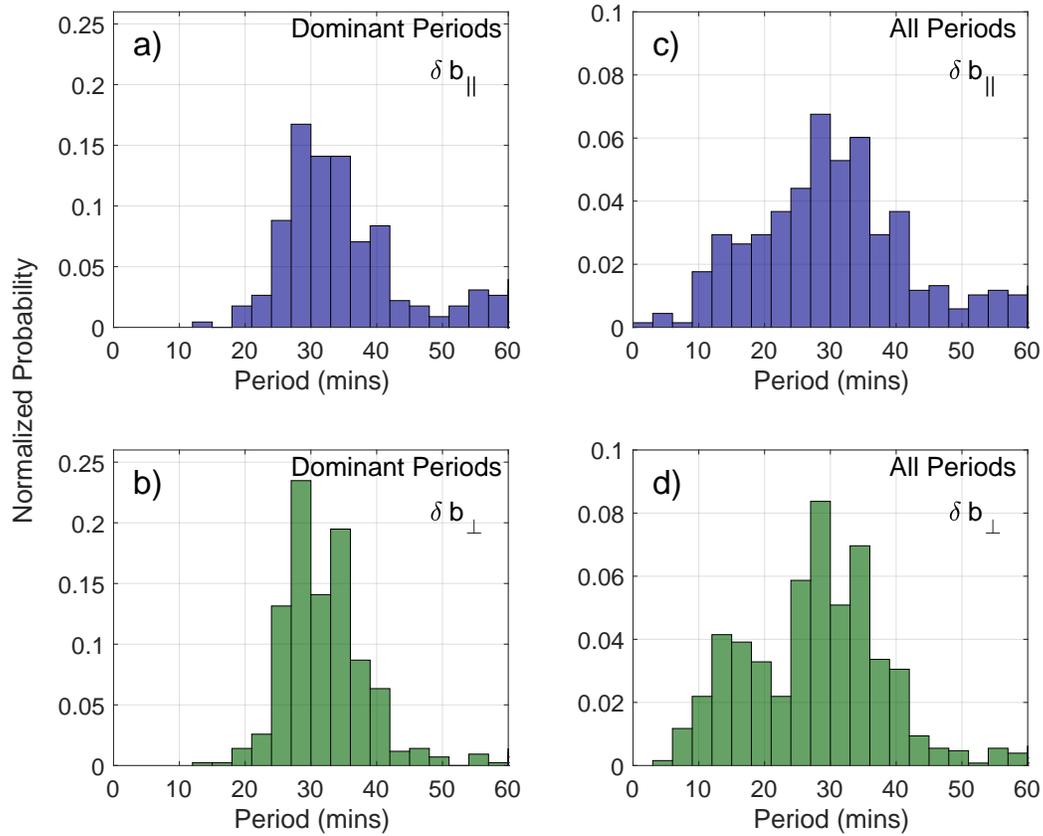
Figure 4. Normalized histograms of significant periods during all events identified in the survey: a) the distribution of events where only one significant period was identified in the field-parallel component or the dominant period when multiple significant periods were identified in the field-parallel component; b) same as a) for the field-transverse components; c) the distribution of all significant periods of events in the field-parallel component; d) same as c) for the field-transverse components. The 15 min, 30 min and 40 min 'magic frequencies' are evident in d), and the 30 min periods appears to dominate throughout.

regular 'saw-tooth' profile, which could possibly indicate a more homogeneous region or monochromatic source.
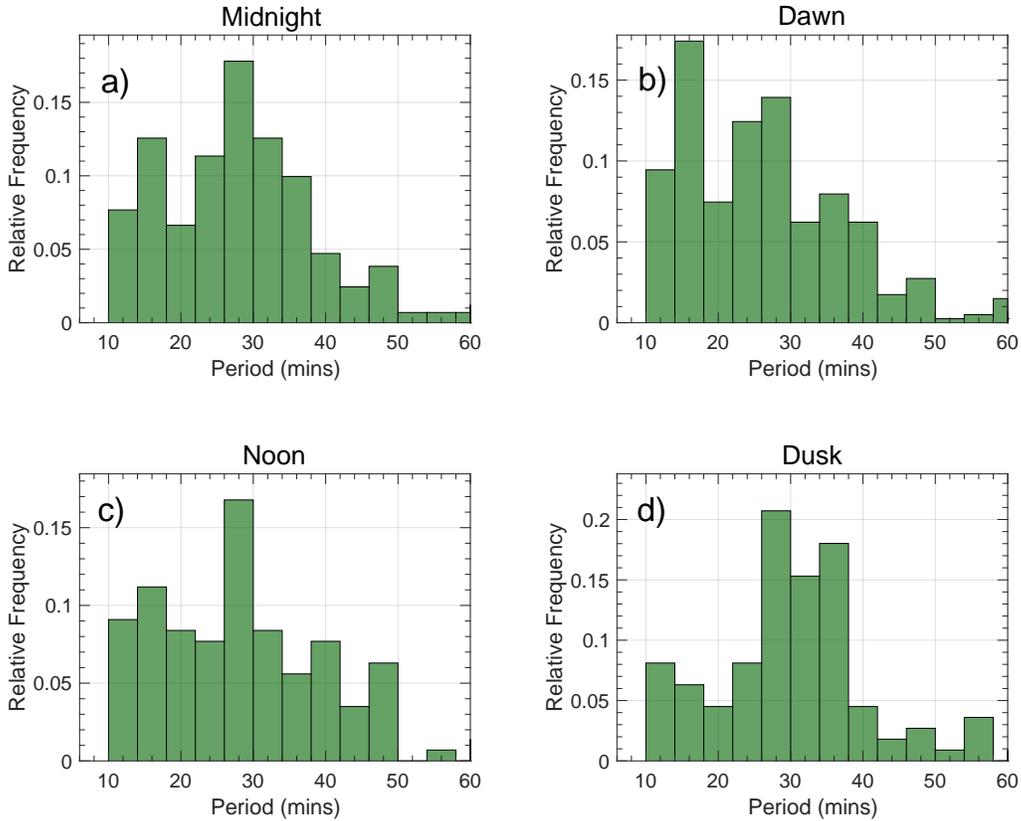
Figure 5. The distribution of periods in four local-time sectors: a) midnight, b) dawn, c) noon and d) dusk. We show only the field-transverse events, and have normalized each histogram for consistent comparisons of relative frequency. Clear skews are evident in dusk and dawn about the dominant 30 min period at noon and midnight, with dusk periods shifted to <30 min and dawn shifted to >30 min.

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 Fig. 3. For example, the magnetotail appears to have significantly different spectral proper-ties to the dayside, and there is some evidence of a dawn-dusk asymmetry. This is con-sistent 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 (Kivelson & Khu-
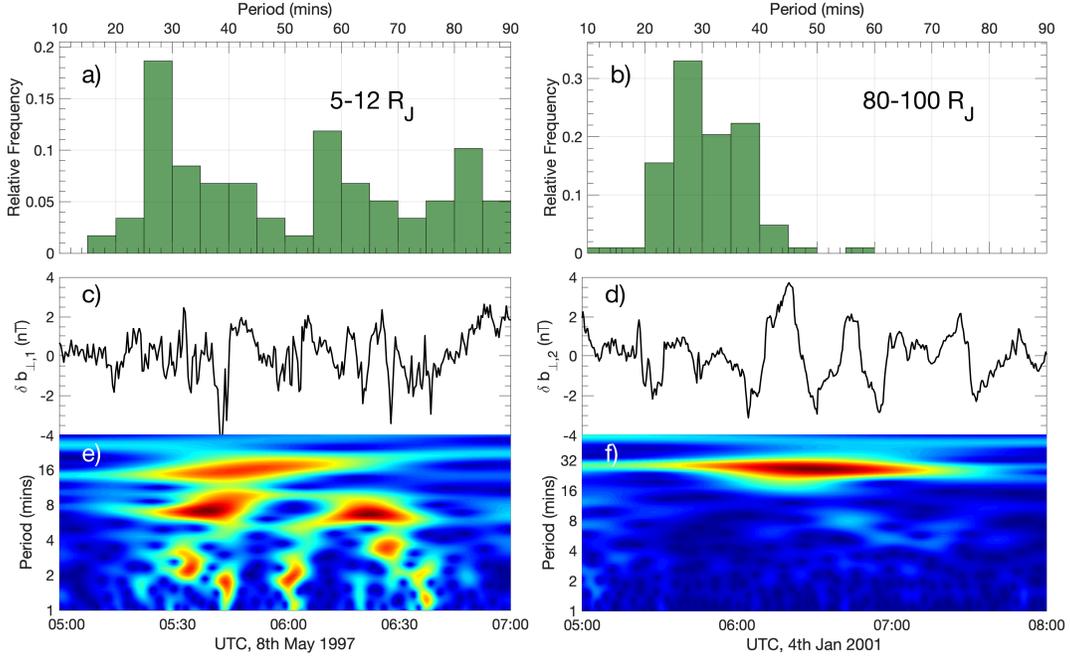
Figure 6. Case study comparing ULF waves a/c/e) near the plasma torus around Io's orbit, and b/d/f) the vicinity of the magnetopause in the noon local-time sector; a) and b) show the distributions of periods in this regions; c) and d) show the time series of MFA residual perturbations representative of events in these regions, obtained using a 100 min sliding window; and e) and f) show the wavelet transforms of c) and d), respectively.

rana, 2002; K. Khurana et al., 2004). 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 ($<10\ R_J$) is several orders of magnitude greater than in the outer magnetosphere ($>40\ R_J$). 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 in-

346 ner magnetosphere with a much larger energy-density than drivers in the outer magne-

347 tosphere. The most likely causes of these systematic differences can be considered us-

348 ing analogues in the terrestrial magnetosphere for comparison.

349 ## 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 magneto-
spheric compressibility was derived by Glassmeier et al. (2004), expressed as

$$\kappa = \frac{1}{R_{MP}} \frac{dR_{MP}}{dP_{Dyn}}, \tag{3}$$

350 where R_{MP} is the magnetopause stand-off distance at the subsolar point as calculated

351 using the Chapman-Ferraro approximation, and P_{Dyn} is the solar wind dynamic pres-

352 sure. At Jupiter κ is much larger than for the other magnetospheres in the solar system,

353 and so the magnetopause can be compressed by tens of jovian radii due to a relatively

354 small change in the dynamic pressure of the solar wind. This enhanced susceptibility to

355 compression is mostly due to the plasma pressure contribution from iogenic plasma (Went

356 et al., 2011), and the presence of a 'cushion region' close to the magnetopause, charac-

357 terised by plasma-depletion and more dipolar field lines (K. Khurana et al., 2004). Kelvin-

358 Helmholtz instabilities (KHIs) also grow on the magnetopause and have been shown to

359 introduce ULF waves into the terrestrial magnetosphere (Hasegawa et al., 2004). Mod-

360 elling of the magnetopause at Jupiter has revealed an enhanced KHI region close to the

361 equator, due to the presence of the equatorial plasma sheet (Masters, 2017). KHI-driven

362 ULF waves are therefore preferentially launched into the plasma sheet. The density gra-

363 dients at the northern and southern boundaries of the plasma sheet cause partial reflec-

364 tion of the waves, such that the plasma sheet acts as a waveguide. This means that com-

365 pressional ULF waves become trapped in the region where MHD mode-coupling is strongest,

366 and so transfer to energy to the Alfvén mode in the resonance region (leading to SAWs)

367 is likely to be more efficient than at Earth. This is potentially of great importance to

368 an understanding of wave-wave and wave-particle interactions in the plasma sheet: (Saur,

369 2004) suggested that the the long-standing question of why the plasma sheet temper-

370 ature increases with distance from Jupiter may be due to an Alfvénic turbulent cascade

371 leading to heating in the plasma sheet in the middle magnetosphere; more recently, (Saur

372 et al., 2018) suggested that the main mode of damping due to wave-particle interactions

373 beyond $\sim$30 R_J is the ion-cylclotron mode, facilitated by such an Alfvénic cascade. A

374 constant supply of large spatial-scale perturbations such as ULF waves could ensure that

375 such a cascade is always active, and SAWs could present a method of further confining

376 Alfvén wave energy in a relatively small region for a long times, allowing waves to break

377 up into smaller scales and enhance this dissipation effect.

378 Constant perturbations of the magnetopause injecting broadband ULF waves into

379 the magnetosphere is consistent with the frequent ULF activity in the outer magneto-

380 sphere on the dayside and dusk-flank sectors (see Fig. 3c). However, if it can be assumed

381 that this activity is the result of SAWs, a constant supply of energy from the magnetopause

382 should permit the amplitude of SAWs to increase over time, such that the amplitude of

383 SAWs on field lines closest to the magnetopause is greater than SAWs on field lines far-

384 ther from the boundary. Instead, the data suggest the converse: the lowest ULF-power

385 is found in the most ULF-active regions. This could represent large variability of the mag-

386 netic field topology in the resonance region over long timescales. Large-amplitude SAWs

387 require an accumulation of energy in a region where there is persistent fast-mode energy

388 available and the MHD modes are consistently coupled by strong inhomogeneity. Any

389 SAWs in the outer magnetosphere during a large compression of the magnetopause would

390 be discohered and dissipated, before sufficient time has elapsed to build up large-amplitude

391 Alfvén waves.

392 Resonant absorption occurs only at harmonics of the natural frequency of the lo-

393 cal magnetic field line, and so a small portion of the broadband wave-energy is converted

394 to the Alfvén mode (Glassmeier et al., 1999). Remaining wave energy is free to prop-

395 agate to the middle magnetosphere. The waves may propagate as far as the inner mag-

396 netosphere, where local conditions are more stable and so large-amplitude SAWs can be

397 established. The efficiency of this radial transport of ULF energy is enhanced by the pres-

398 ence of the plasma-sheet waveguide. Assuming that the thickness of the plasma sheet

399 can be considered small compared to the length scales of the magnetosphere, the wave-

400 energy-density should scale with the inverse square of the radius from the planet. Fit-

401 ting the radial dependence of bandpower of the events identified in the survey with a power

402 law yields an exponent of the radius of -2.18 $\pm$ 0.16 for the field-transverse components

403 and -1.53 $\pm$ 0.21 for the field-parallel components (see Fig.3 in Supplementary Materi-

als). 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 min (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 ∼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 hours, 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 sub-corotation 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 and 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 wavenumbers), 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.

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, 2011b). 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 outwards and replaced by inward-travelling 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 (Thorne et al., 1997; Kivelson 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 Fig. 3c) and d): while the majority of events contain a superposition of multiple significant periods, waves in the magnetotail from post-dusk to pre-dawn predominately only contain one significant period. However, the same arguments regarding transport of the waves shoud 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 (K. K. 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 pre-dawn sector are of systematically greater power than those post-dusk. 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 dawn-side of midnight and Vasyliunas is dominant dusk-side. The clear asymmetry in power pre- and post-midnight in Fig. 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. Mishin et al. (2002); Volwerk et al. (2005); Liang et al. (2009)). Vogt et al. (2014) found the mean plasmoid duration to be 6.8 min, but the distribution spanned $\sim$ 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 Fig. 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 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 (Watt et al., 2011; Jonathan Rae et al., 2018), 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. 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 (Rankin et al., 2007; Jonathan Rae et al., 2018). ULF energy is also known
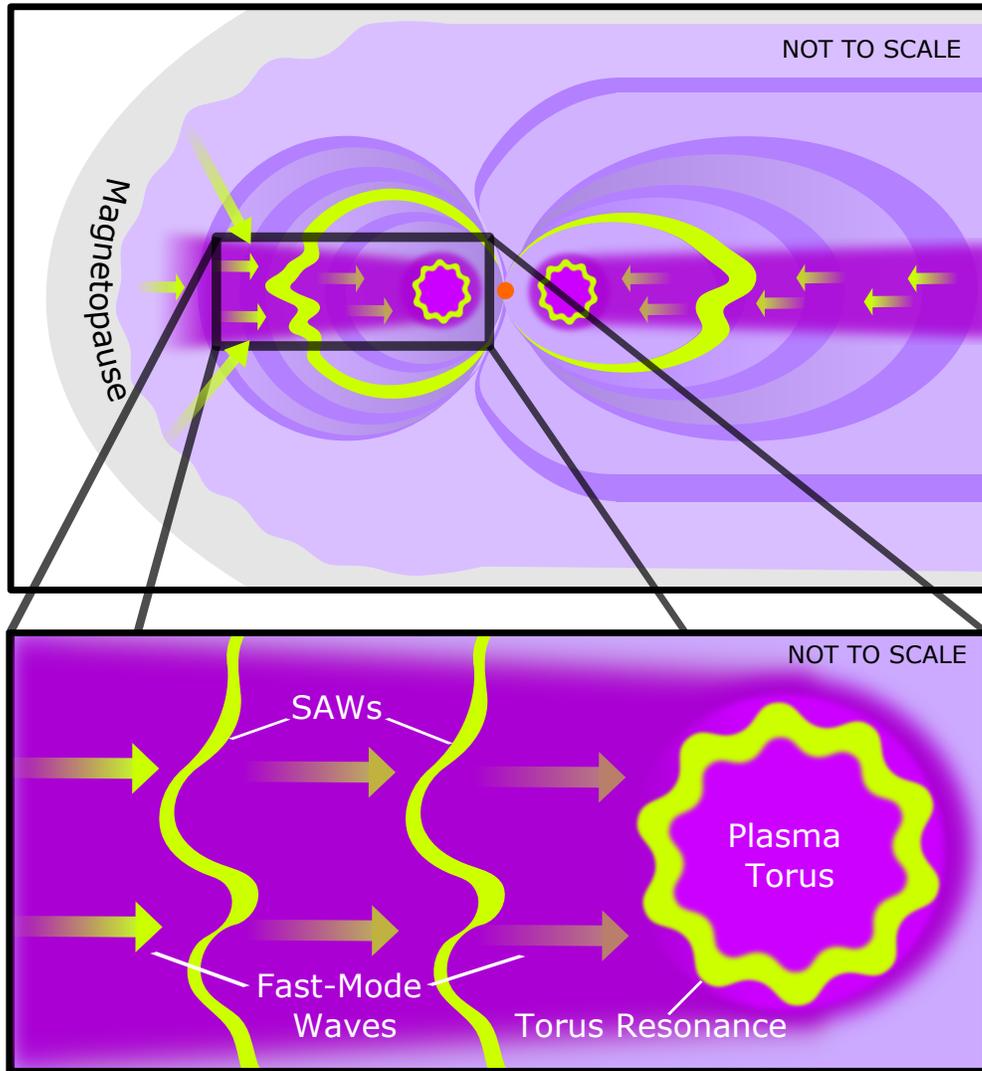
Figure 7. A cartoon of the chain of processes responsible for ULF wave generation in the magnetosphere. The magnetospheric cavity is shown in light purple, and magnetic field lines are represented in dark purple. Perturbations on the magnetopause create compressional fast-mode waves (green arrows) that 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.

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 anti-sunward 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. Bagenal and Delamere (2011b)). 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); B. H. Mauk et al. (2017a, 2018)). Non-steady 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 et al., 2002; Saur, 2004). 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 non-trivial 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

564 with the ULF spectrum obtained from the survey: a distribution spanning 5 - 60 min,

565 dominated by 15, 30 and 40 min. The population is well described by a large popula-

566 tion of transhemispheric SAWs confined to the plasma sheet. The magnetotail plasma-

567 sheet appears to host a separate population of quasi-monochromatic ULF waves, which

568 we interpreted as evidence of a different driving mechanism dominated by reconnection

569 and dipolarization of the magnetic field. ULF waves are a key element in understand-

570 ing both the global processes which redistribute energy through the magnetosphere, and

571 resonant cavities that act as localized reservoirs of energy. Answering questions of how

572 these cavities contribute to particle energization, stochastic acceleration and energy/momentum

573 transport in the magnetosphere will require a detailed analysis of ULF wave-modes and

574 the wave-particle interactions in which they participate.

583 **References**

584 Achilleos, N., André, N., Blanco-Cano, X., Brandt, P. C., Delamere, P. A., &

585 Winglee, R. (2015). 1. Transport of Mass, Momentum and Energy in

586 Planetary Magnetodisc Regions. *Space Sci. Rev.*, *187*(1-4), 229–299. doi:

587 10.1007/s11214-014-0086-y

588 Acuna, M. H., & Ness, N. F. (1980). The Magnetic Field of Saturn: Pioneer 11 Ob-

589 servations. *Science (80-.).*, *207*(4429), 444–446. doi: 10.1126/science.207.4429

590 .444

591 Allegrini, F., Bagenal, F., Bolton, S., Connerney, J., Clark, G., Ebert, R. W., . . .

592 Zink, J. L. (2017). Electron beams and loss cones in the auroral regions of

593 Jupiter. *Geophys. Res. Lett.*, *44*(14), 7131–7139. doi: 10.1002/2017GL073180

594 Anagnostopoulos, G., Aggelis, A., Karanikola, I., & Marhavilas, P. (2001). Ener-

getic ion (>∼50keV) and electron (>∼40keV) bursts observed by Ulysses near Jupiter. *Adv. Sp. Res.*, *28*(6), 903–908. doi: 10.1016/S0273-1177(01)00514-2

Arkhypov, O. V., & Rucker, H. O. (2006). Ultra low frequencies phenomena in Jovian decametric radio emission. *Astron. Astrophys.*, *452*(1), 347–350. doi: 10.1051/0004-6361:20054334

Bagenal, F. (1983). Alfvén wave propagation in the Io plasma torus. *J. Geophys. Res. Sp. Phys.*, *88*(A4), 3013–3025. Retrieved from http://dx.doi.org/10.1029/JA088iA04p03013 doi: 10.1029/JA088iA04p03013

Bagenal, F., Adriani, A., Allegrini, F., Bolton, S. J., Bonfond, B., Bunce, E. J., . . . Zarka, P. (2017). Magnetospheric Science Objectives of the Juno Mission. *Space Sci. Rev.*, *213*(1-4), 219–287. doi: 10.1007/s11214-014-0036-8

Bagenal, F., & Delamere, P. A. (2011a). Flow of mass and energy in the magnetospheres of Jupiter and Saturn. *J. Geophys. Res. Sp. Phys.*, *116*(A5), 1–17. doi: 10.1029/2010JA016294

Bagenal, F., & Delamere, P. A. (2011b). Flow of mass and energy in the magnetospheres of Jupiter and Saturn. *J. Geophys. Res. Sp. Phys.*, *116*(5), 1–17. doi: 10.1029/2010JA016294

Bagenal, F., Wilson, R. J., Siler, S., Paterson, W. R., & Kurth, W. S. (2016). Survey of Galileo plasma observations in Jupiter's plasma sheet. *J. Geophys. Res. Planets*, *121*(5), 871–894. doi: 10.1002/2016JE005009

Barbosa, D. D., Gurnett, D. A., Kurth, W. S., & Scarf, F. L. (1979). Structure and properties of Jupiter's magnetoplasmadisc. *Geophys. Res. Lett.*, *6*(10), 785–788. doi: 10.1029/GL006i010p00785

Bolton, S. J., Janssen, M., Thorne, R., Levin, S., Klein, M., Gulkis, S., . . . West, R. (2002). Ultra-relativistic electrons in Jupiter's radiation belts. *Nature*, *415*(6875), 987–991. doi: 10.1038/415987a

Chen, L., & Hasegawa, A. (1974). A theory of long-period magnetic pulsations: 1. Steady state excitation of field line resonance. *J. Geophys. Res.*, *79*(7), 1024–1032. doi: 10.1029/JA079i007p01024

Clark, G., Mauk, B. H., Haggerty, D., Paranicas, C., Kollmann, P., Rymer, A., . . . Valek, P. (2017). Energetic particle signatures of magnetic field-aligned potentials over Jupiter's polar regions. *Geophys. Res. Lett.*, *44*(17), 8703–8711. doi: 10.1002/2017GL074366

628 Connerney, J. E., Adriani, A., Allegrini, F., Bagenal, F., Bolton, S. J., Bonfond,

629   B., ... Waite, J. (2017). Jupiter's magnetosphere and aurorae observed by

630   the Juno spacecraft during its first polar orbits. *Science (80-.).*, *356*(6340),

631   826–832. doi: 10.1126/science.aam5928

632 Cowley, S. W. H., Bunce, E. J., Stallard, T. S., & Miller, S. (2003). Jupiter's polar

633   ionospheric flows: Theoretical interpretation. *Geophys. Res. Lett.*, *30*(5), n/a–

634   n/a. doi: 10.1029/2002GL016030

635 Delamere, P. A. (2016). A Review of the Low-Frequency Waves in the Gi-

636   ant Magnetospheres. *Low-Frequency Waves Sp. Plasmas*, 365–378. doi:

637   10.1002/9781119055006.ch21

638 Delamere, P. A., & Bagenal, F. (2010). Solar wind interaction with Jupiter's mag-

639   netosphere. *J. Geophys. Res. Sp. Phys.*, *115*(A10), n/a–n/a. doi: 10.1029/

640   2010JA015347

641 Dunn, W. R., Branduardi-Raymont, G., Ray, L. C., Jackman, C. M., Kraft, R. P.,

642   Elsner, R. F., ... Coates, A. J. (2017). The independent pulsations of Jupiter's

643   northern and southern X-ray auroras. *Nat. Astron.*, *1*(11), 758–764. doi:

644   10.1038/s41550-017-0262-6

645 Ebert, R. W., Allegrini, F., Bagenal, F., Bolton, S. J., Connerney, J. E., Clark, G.,

646   ... Wilson, R. J. (2017). Spatial Distribution and Properties of 0.1100keV

647   Electrons in Jupiter's Polar Auroral Region. *Geophys. Res. Lett.*, *44*(18),

648   9199–9207. doi: 10.1002/2017GL075106

649 Frank, L. A., Ackerson, K. L., Lee, J. A., English, M. R., & Pickett, G. L. (1992).

650   The plasma instrumentation for the Galileo Mission. *Space Sci. Rev.*, *60*(1-4),

651   283–304. doi: 10.1007/BF00216858

652 Gershman, D. J., Connerney, J. E. P., Kotsiaros, S., DiBraccio, G. A., Martos,

653   Y. M., Viñas, A. F., ... Bolton, S. J. (2019). Alfvénic Fluctuations Associated

654   With Jupiter's Auroral Emissions. *Geophys. Res. Lett.*, *46*(13), 7157–7165. doi:

655   10.1029/2019GL082951

656 Gladstone, G. R., Waite, J. H., Grodent, D., Lewis, W. S., Crary, F. J., Eisner,

657   R. F., ... Cravens, T. E. (2002). A pulsating auroral X-ray hot spot on

658   Jupiter. *Nature*, *415*(6875), 1000–1003. doi: 10.1038/4151000a

659 Glassmeier, K. H., Klimushkin, D., Othmer, C., & Mager, P. (2004). ULF waves at

660   Mercury: Earth, the giants, and their little brother compared. *Adv. Sp. Res.*,

33(11), 1875–1883. doi: 10.1016/j.asr.2003.04.047

Glassmeier, K.-H., Ness, N. F., Acuña, M. H., & Neubauer, F. M. (1989). Standing hydromagnetic waves in the Io plasma torus: Voyager 1 observations. *J. Geophys. Res.*, *94*(A11), 15063. doi: 10.1029/JA094iA11p15063

Glassmeier, K. H., Othmer, C., Cramm, R., Stellmacher, M., & Engebretson, M. (1999). Magnetospheric field line resonance: A comparative planetology approach. *Surv. Geophys.*, *20*(1), 61–109. doi: 10.1023/A:1006659717963

Goertz, C. (1980). Io's interaction with the plasma torus. *J. Geophys. Res.*, *85*(A6), 2949. doi: 10.1029/JA085iA06p02949

Greenwald, R. A., & Walker, A. D. M. (1980). Energetics of long period resonant hydromagnetic waves. *Geophys. Res. Lett.*, *7*(10), 745–748. doi: 10.1029/ GL007i010p00745

Hasegawa, H., Fujimoto, M., Phan, T.-D., Rème, H., Balogh, A., Dunlop, M. W., . . . TanDokoro, R. (2004). Transport of solar wind into Earth's magnetosphere through rolled-up KelvinHelmholtz vortices. *Nature*, *430*(7001), 755–758. doi: 10.1038/nature02799

Hospodarsky, G. B., Kurth, W. S., Cecconi, B., Gurnett, D. A., Kaiser, M. L., Desch, M. D., & Zarka, P. (2004). Simultaneous observations of Jovian quasi-periodic radio emissions by the Galileo and Cassini spacecraft. *J. Geophys. Res. Sp. Phys.*, *109*(A9), 1–13. doi: 10.1029/2003JA010263

Jonathan Rae, I., Murphy, K. R., Watt, C. E. J., Halford, A. J., Mann, I. R., Ozeke, L. G., . . . Singer, H. J. (2018). The Role of Localized Compressional Ultra-low Frequency Waves in Energetic Electron Precipitation. *J. Geophys. Res. Sp. Phys.*, *123*(3), 1900–1914. doi: 10.1002/2017JA024674

Joy, S. P., Kivelson, M. G., Walker, R. J., Khurana, K. K., Russell, C. T., & Ogino, T. (2002). Probabilistic models of the Jovian magnetopause and bow shock locations. *J. Geophys. Res. Sp. Phys.*, *107*(A10), 1–17. doi: 10.1029/2001JA009146

Karanikola, I., Athanasiou, M., Anagnostopoulos, G. C., Pavlos, G. P., & Preka-Papadema, P. (2004). Quasi-periodic emissions (15- 80 min) from the poles of Jupiter as a principal source of the large-scale high-latitude magnetopause boundary layer of energetic particle. *Planet. Space Sci.*, *52*(5-6), 543–559. doi: 10.1016/j.pss.2003.10.002

Kepko, L. (2003). Observations of discrete, global magnetospheric oscillations directly driven by solar wind density variations. *J. Geophys. Res.*, *108*(A6), 1257. doi: 10.1029/2002JA009676

Khurana, K., & Kivelson, M. (1989). Ultralow frequency MHD waves in Jupiter's middle magnetosphere. *J. Geophys. Res.*, *94*(A5), 5241. doi: 10.1029/JA094iA05p05241

Khurana, K., Kivelson, M., Vasyliunas, V., Krupp, N., Woch, J., Lagg, A., ... Kurth, W. (2004). The Configuration of Jupiter's Magnetosphere. *Jupiter Planet, Satell. Magnetos.*, 593–616. doi: 10.1007/s00216-006-0600-5

Khurana, K. K., Sheng Hsien Chen, Max Hammond, C., & Kivelson, M. G. (1992). Ultralow frequency waves in the magnetotails of the Earth and the outer planets. *Adv. Sp. Res.*, *12*(8), 57–63. doi: 10.1016/0273-1177(92)90377-A

Kimura, T., Cecconi, B., Zarka, P., Kasaba, Y., Tsuchiya, F., Misawa, H., & Morioka, A. (2012). Polarization and direction of arrival of Jovian quasiperiodic bursts observed by Cassini. *J. Geophys. Res. Sp. Phys.*, *117*(11), 1–15. doi: 10.1029/2012JA017506

Kimura, T., Tsuchiya, F., Misawa, H., Morioka, A., Nozawa, H., & Fujimoto, M. (2011). Periodicity analysis of Jovian quasi-periodic radio bursts based on Lomb-Scargle periodograms. *J. Geophys. Res. Sp. Phys.*, *116*(3), 1–10. doi: 10.1029/2010JA016076

Kivelson, M. G. (2016). Planetary Magnetodiscs: Some Unanswered Questions. In *The magnetodiscs and aurorae of giant planets* (pp. 5–21). New York, NY: Springer. doi: 10.1007/978-1-4939-3395-2_2

Kivelson, M. G., & Khurana, K. K. (2002). Properties of the magnetic field in the Jovian magnetotail. *J. Geophys. Res. Sp. Phys.*, *107*(A8), SMP 23–1–SMP 23–9. doi: 10.1029/2001JA000249

Kivelson, M. G., Khurana, K. K., Means, J. D., Russell, C. T., & Snare, R. C. (1992). The Galileo magnetic field investigation. *Space Sci. Rev.*, *60*(1-4), 357–383. doi: 10.1007/BF00216862

Kivelson, M. G., Khurana, K. K., Russell, C. T., & Walker, R. J. (1997). Intermittent short-duration magnetic field anomalies in the Io torus: Evidence for plasma interchange? *Geophys. Res. Lett.*, *24*(17), 2127–2130. doi: 10.1029/97GL02202

Kohlhase, C., & Penzo, P.   (1977).   Voyager mission description.   *Space Sci. Rev.*,
        21(2), 77–101. doi: 10.1007/BF00200846

Kotsiaros, S., Connerney, J. E. P., Clark, G., Allegrini, F., Gladstone, G. R., Kurth,
        W. S., ... Levin, S. M.   (2019).   Birkeland currents in Jupiter's magneto-
        sphere observed by the polar-orbiting Juno spacecraft.   *Nat. Astron.*.   doi:
        10.1038/s41550-019-0819-7

Liang, J., Liu, W. W., Donovan, E. F., & Spanswick, E.   (2009).   In-situ obser-
        vation of ULF wave activities associated with substorm expansion phase
        onset and current disruption.   *Ann. Geophys.*, *27*(5), 2191–2204.   doi:
        10.5194/angeo-27-2191-2009

MacDowall, R. J., Kaiser, M. L., Desch, M. D., Farrell, W. M., Hess, R. A., & Stone,
        R. G.   (1993).   Quasiperiodic Jovian Radio bursts: observations from the
        Ulysses Radio and Plasma Wave Experiment.   *Planet. Space Sci.*, *41*(11-12),
        1059–1072. doi: 10.1016/0032-0633(93)90109-F

Manners, H., & Masters, A.   (2019).   First Evidence for MultipleHarmonic Stand-
        ing Alfvén Waves in Jupiter's Equatorial Plasma Sheet.   *Geophys. Res. Lett.*,
        2019GL083899. doi: 10.1029/2019GL083899

Manners, H., Masters, A., & Yates, J. N. (2018). Standing Alfvén Waves in Jupiter's
        Magnetosphere as a Source of ∼10- to 60-Min Quasiperiodic Pulsations.   *Geo-
        phys. Res. Lett.*, *45*(17), 8746–8754. doi: 10.1029/2018GL078891

Masters, A.   (2017).   Model-Based Assessments of Magnetic Reconnection and
        Kelvin-Helmholtz Instability at Jupiter's Magnetopause.   *J. Geophys. Res. Sp.
        Phys.*, *122*(11), 11,154–11,174. doi: 10.1002/2017JA024736

Mauk, B., & Bagenal, F.   (2013).   Comparative Auroral Physics: Earth and Other
        Planets.   *Auror. Phenomenol. Magnetos. Process. Earth Other Planets*, 3–26.
        doi: 10.1029/2011GM001192

Mauk, B. H., Haggerty, D. K., Paranicas, C., Clark, G., Kollmann, P., Rymer,
        A. M., ... Valek, P.   (2017a).   Discrete and broadband electron accel-
        eration in Jupiter's powerful aurora.   *Nature*, *549*(7670), 66–69.   doi:
        10.1038/nature23648

Mauk, B. H., Haggerty, D. K., Paranicas, C., Clark, G., Kollmann, P., Rymer,
        A. M., ... Valek, P.   (2017b).   Juno observations of energetic charged par-
        ticles over Jupiter's polar regions: Analysis of monodirectional and bidi-

rectional electron beams. *Geophys. Res. Lett.*, *44*(10), 4410–4418. doi: 10.1002/2016GL072286

Mauk, B. H., Haggerty, D. K., Paranicas, C., Clark, G., Kollmann, P., Rymer, A. M., . . . Valek, P. (2018). Diverse Electron and Ion Acceleration Characteristics Observed Over Jupiter's Main Aurora. *Geophys. Res. Lett.*, *45*(3), 1277–1285. doi: 10.1002/2017GL076901

Mishin, E. V., Foster, J. C., Potekhin, A. P., Rich, F. J., Schlegel, K., Yumoto, K., . . . Friedel, R. (2002). Global ULF disturbances during a stormtime substorm on 25 September 1998. *J. Geophys. Res. Sp. Phys.*, *107*(A12), SMP 40–1–SMP 40–11. doi: 10.1029/2002JA009302

Nichols, J. D., Yeoman, T. K., Bunce, E. J., Chowdhury, M. N., Cowley, S. W. H., & Robinson, T. R. (2017). Periodic emission within Jupiter's main auroral oval. *Geophys. Res. Lett.*. doi: 10.1002/2017GL074824

Petkaki, P., & Dougherty, M. K. (2001). ULF wave observations in Jupiter's magnetosphere. *Adv. Sp. Res.*, *28*(6), 909–914. doi: 10.1016/S0273-1177(01)00517-8

Rae, I. J., C. E. J., Fenrich, F. R., Mann, I. R., Ozeke, L. G., & Kale, A. (2007). Energy deposition in the ionosphere through a global field line resonance. *Ann. Geophys.*, *25*(12), 2529–2539. doi: 10.5194/angeo-25-2529-2007

Rankin, R., Watt, C. E. J., & Samson, J. C. (2007). Self-consistent wave-particle interactions in dispersive scale long-period field-line-resonances. *Geophys. Res. Lett.*, *34*(23), n/a–n/a. doi: 10.1029/2007GL031317

Russell, C. T., Blanco-Cano, X., & Strangeway, R. J. (2001). Ultra-low-frequency waves in the Jovian magnetosphere: Causes and consequences. *Planet. Space Sci.*, *49*(3-4), 291–301. doi: 10.1016/S0032-0633(00)00150-1

Saur, J. (2004). Turbulent Heating of Jupiter's Middle Magnetosphere. *Astrophys. J.*, *602*(2), L137–L140. doi: 10.1086/382588

Saur, J., Janser, S., Schreiner, A., Clark, G., Mauk, B. H., Kollmann, P., . . . Kotsiaros, S. (2018). WaveParticle Interaction of Alfvén Waves in Jupiter's Magnetosphere: Auroral and Magnetospheric Particle Acceleration. *J. Geophys. Res. Sp. Phys.*, *123*(11), 9560–9573. doi: 10.1029/2018JA025948

Saur, J., Politano, H., Pouquet, A., & Matthaeus, W. H. (2002). Evidence for weak MHD turbulence in the middle magnetosphere of Jupiter. *Astron. Astrophys.*, *386*(2), 699–708. doi: 10.1051/0004-6361:20020305

793   Schulz, M., Blake, J., Mazuk, S. M., Balogh, A., Dougherty, M. K., Forsyth, R. J.,

794   . . . Bame, S. J. (1993). Energetic particle, plasma and magnetic field signa-

795   tures of a poloidal pulsation in Jupiter's magnetosphere. *Planet. Space Sci.*,

796   *41*(11-12), 967–975. doi: 10.1016/0032-0633(93)90101-7

797   Smith, E. J., Wenzel, K. P., & Page, D. E. (1992). Ulysses at Jupiter: An Overview

798   of the Encounter. *Science (80-.).*, *257*(5076), 1503–1507. doi: 10.1126/science

799   .257.5076.1503

800   Southwood, D., & Hughes, W. (1983). Theory of hydromagnetic waves in the mag-

801   netosphere. *Space Sci. Rev.*, *35*(4), 301–366. doi: 10.1007/BF00169231

802   Southwood, D. J. (1974). Some features of field line resonances in the magneto-

803   sphere. *Planet. Space Sci.*, *22*(3), 483–491. doi: 10.1016/0032-0633(74)90078

804   -6

805   Southwood, D. J., & Kivelson, M. G. (1986). The effect of parallel inhomogeneity on

806   magnetospheric hydromagnetic wave coupling. *J. Geophys. Res.*, *91*(A6), 6871.

807   doi: 10.1029/JA091iA06p06871

808   Tamao, T. (1965). Transmission and Coupling Resonance of Hydromagnetic Distur-

809   bances in the Non-uniform Earth's Magnetosphere. *Sci. reports Tohoku Univ.*

810   *Ser. 5, Geophys.*, *17*(2), 43–72.

811   Thorne, R. M., Armstrong, T. P., Stone, S., Williams, D. J., McEntire, R. W.,

812   Bolton, S. J., . . . Kivelson, M. G. (1997). Galileo evidence for rapid inter-

813   change transport in the Io torus. *Geophys. Res. Lett.*, *24*(17), 2131–2134. doi:

814   10.1029/97GL01788

815   Torrence, C., & Compo, G. P. (1998). A Practical Guide to Wavelet Analysis. *Bull.*

816   *Am. Meteorol. Soc.*, *79*(1), 61–78. doi: 10.1175/1520-0477(1998)079⟨0061:

817   APGTWA⟩2.0.CO;2

818   Tsurutani, B. T., Southwood, D. J., Smith, E. J., & Balogh, A. (1993). A Survey

819   of Low Frequency Waves at Jupiter: The Ulysses Encounter. *J. Geophys. Res.*,

820   *98*(A12), 21203–21216. doi: 10.1029/93JA02586

821   Van Allen, J. A., Baker, D. N., Randall, B. A., & Sentman, D. D. (1974). The mag-

822   netosphere of Jupiter as observed with Pioneer 10: 1. Instrument and principal

823   findings. *J. Geophys. Res.*, *79*(25), 3559–3577. doi: 10.1029/JA079i025p03559

824   Vogt, M. F., Jackman, C. M., Slavin, J. A., Bunce, E. J., Cowley, S. W. H., Kivel-

825   son, M. G., & Khurana, K. K. (2014). Structure and statistical properties

of plasmoids in Jupiter's magnetotail. *J. Geophys. Res. Sp. Phys.*, *119*(2), 821–843. doi: 10.1002/2013JA019393

Volwerk, M., Zhang, T. L., Nakamura, R., Runov, A., Baumjohann, W., Glassmeier, K.-H., . . . Rème, H. (2005). Plasma flow channels with ULF waves observed by Cluster and Double Star. *Ann. Geophys.*, *23*(8), 2929–2935. doi: 10.5194/angeo-23-2929-2005

Walker, R., & Kivelson, M. (1981). Multiply reflected standing Alfven waves in the IO torus: Pioneer 10 observations. *Geophys. Res. Lett.*, *8*(12), 1281–1284. doi: 10.1029/GL008i012p01281

Wang, C., Rankin, R., & Zong, Q. (2015). Fast damping of ultralow frequency waves excited by interplanetary shocks in the magnetosphere. *J. Geophys. Res. Sp. Phys.*, *120*(4), 2438–2451. doi: 10.1002/2014JA020761

Watanabe, H., Kita, H., Tao, C., Kagitani, M., Sakanoi, T., & Kasaba, Y. (2018). Pulsation Characteristics of Jovian Infrared Northern Aurora Observed by the Subaru IRCS with Adaptive Optics. *Geophys. Res. Lett.*, 547–554. doi: 10.1029/2018GL079411

Watt, C. E. J., Degeling, A. W., Rankin, R., Murphy, K. R., Rae, I. J., & Singer, H. J. (2011). Ultralow-frequency modulation of whistler-mode wave growth. *J. Geophys. Res. Sp. Phys.*, *116*(A10). doi: 10.1029/2011JA016730

Went, D. R., Kivelson, M. G., Achilleos, N., Arridge, C. S., & Dougherty, M. K. (2011). Outer magnetospheric structure: Jupiter and Saturn compared. *J. Geophys. Res. Sp. Phys.*, *116*(4), 1–14. doi: 10.1029/2010JA016045

Wilson, R. J., & Dougherty, M. K. (2000). Evidence provided by galileo of ultra low frequency waves within Jupiter's middle magnetosphere. *Geophys. Res. Lett.*, *27*(6), 835–838. doi: 10.1029/1999GL006070

Wright, A. N., & Mann, I. R. (2013). Global MHD Eigenmodes of the Outer Magnetosphere. *Magnetos. ULF Waves Synth. New Dir.*, *169*, 51–72. doi: 10.1029/169GM06

Zhang, X. Y., Zong, Q.-G., Wang, Y. F., Zhang, H., Xie, L., Fu, S. Y., . . . Pu, Z. Y. (2010). ULF waves excited by negative/positive solar wind dynamic pressure impulses at geosynchronous orbit. *J. Geophys. Res. Sp. Phys.*, *115*(A10), n/a–n/a. doi: 10.1029/2009JA015016

Figure.
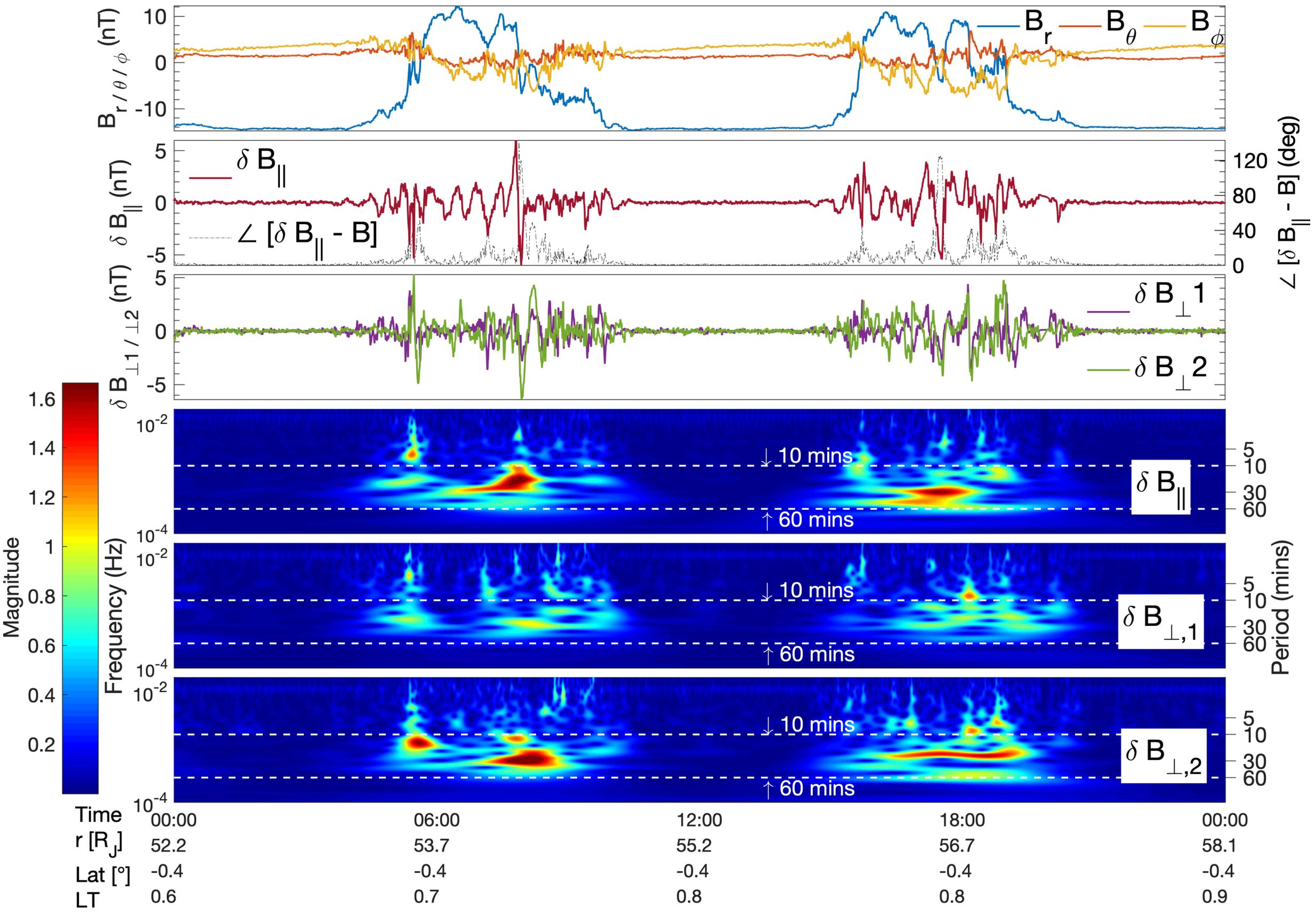
Figure.
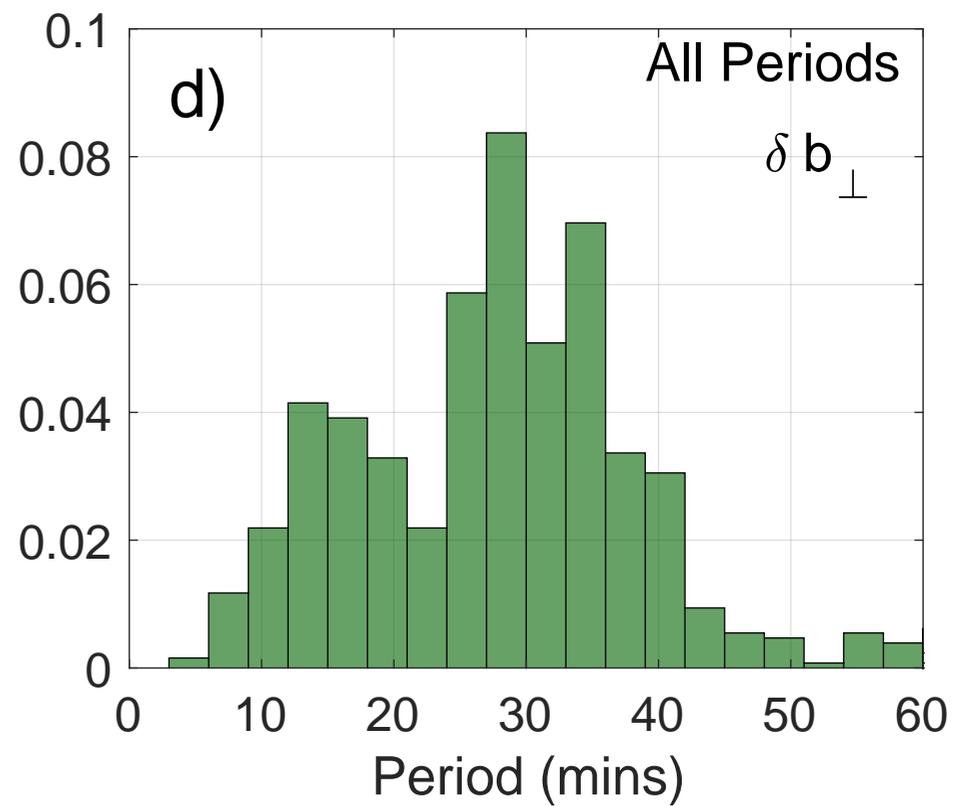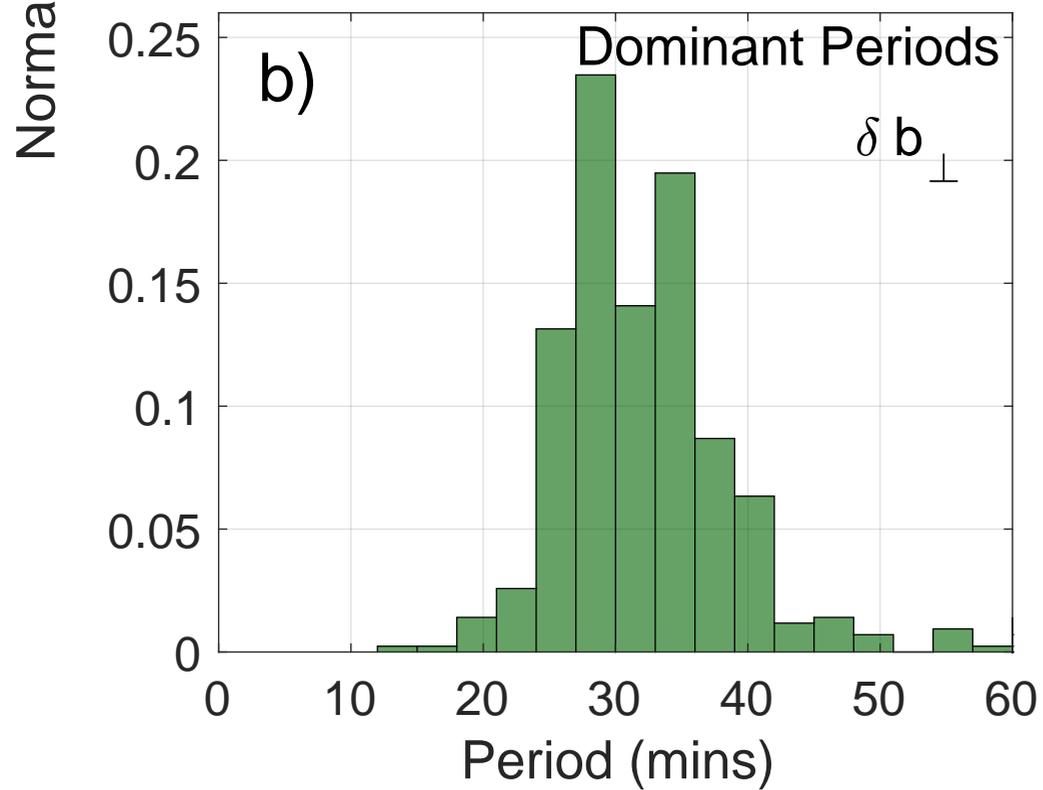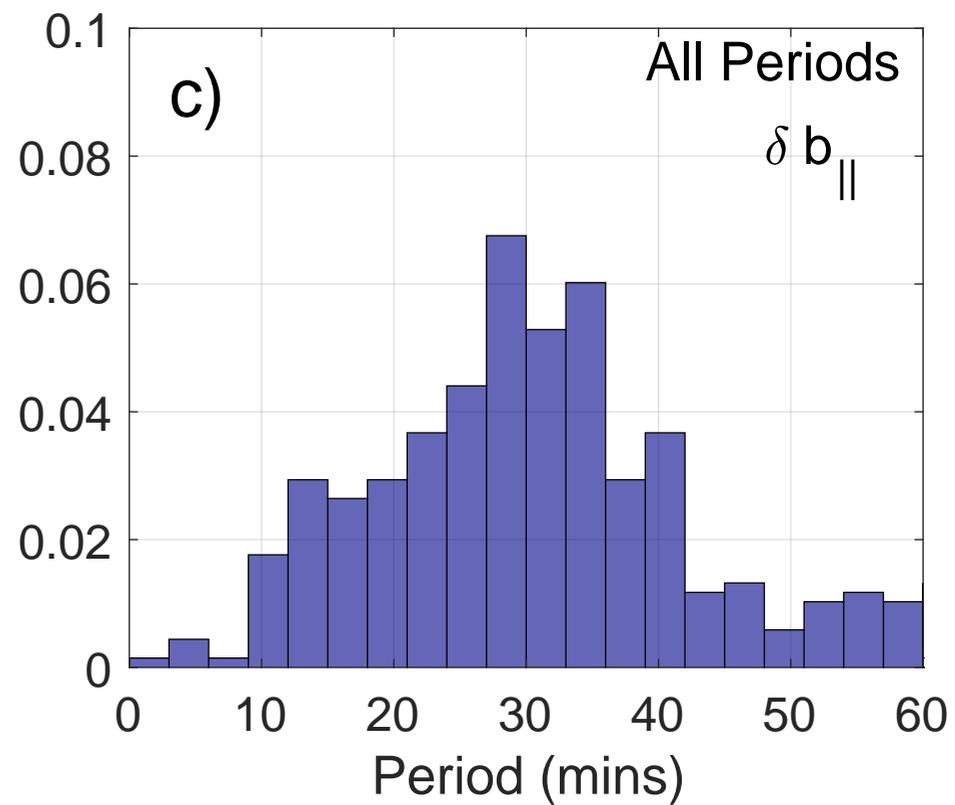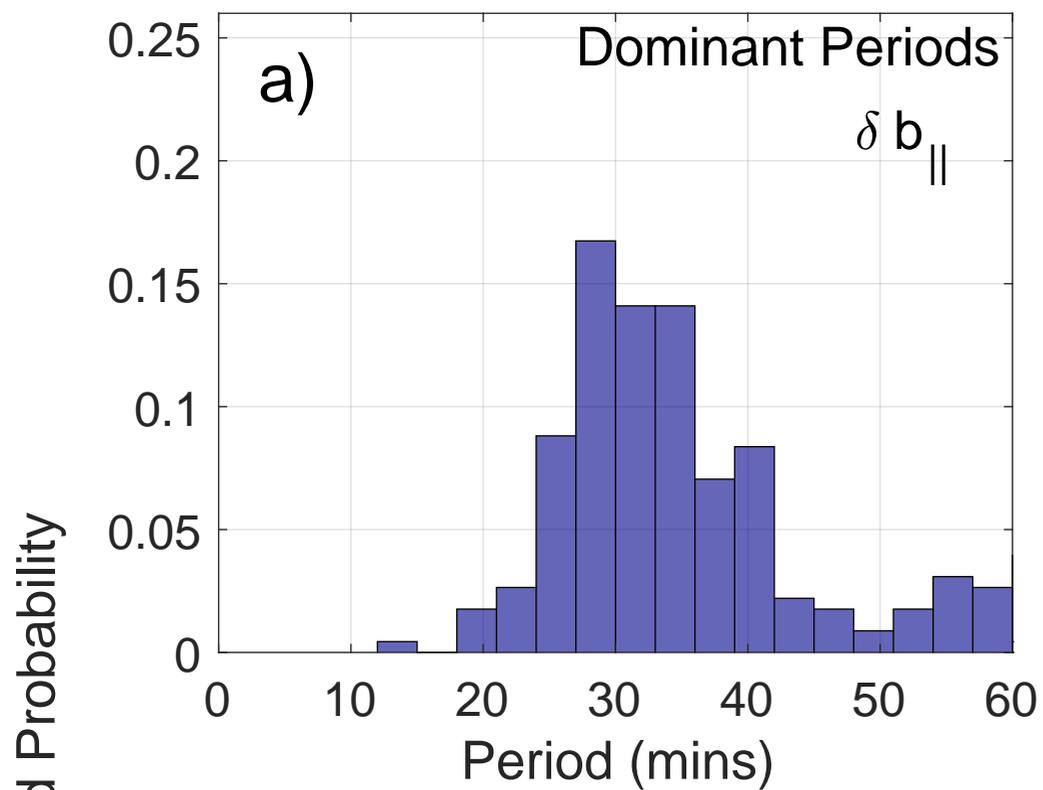
Figure.
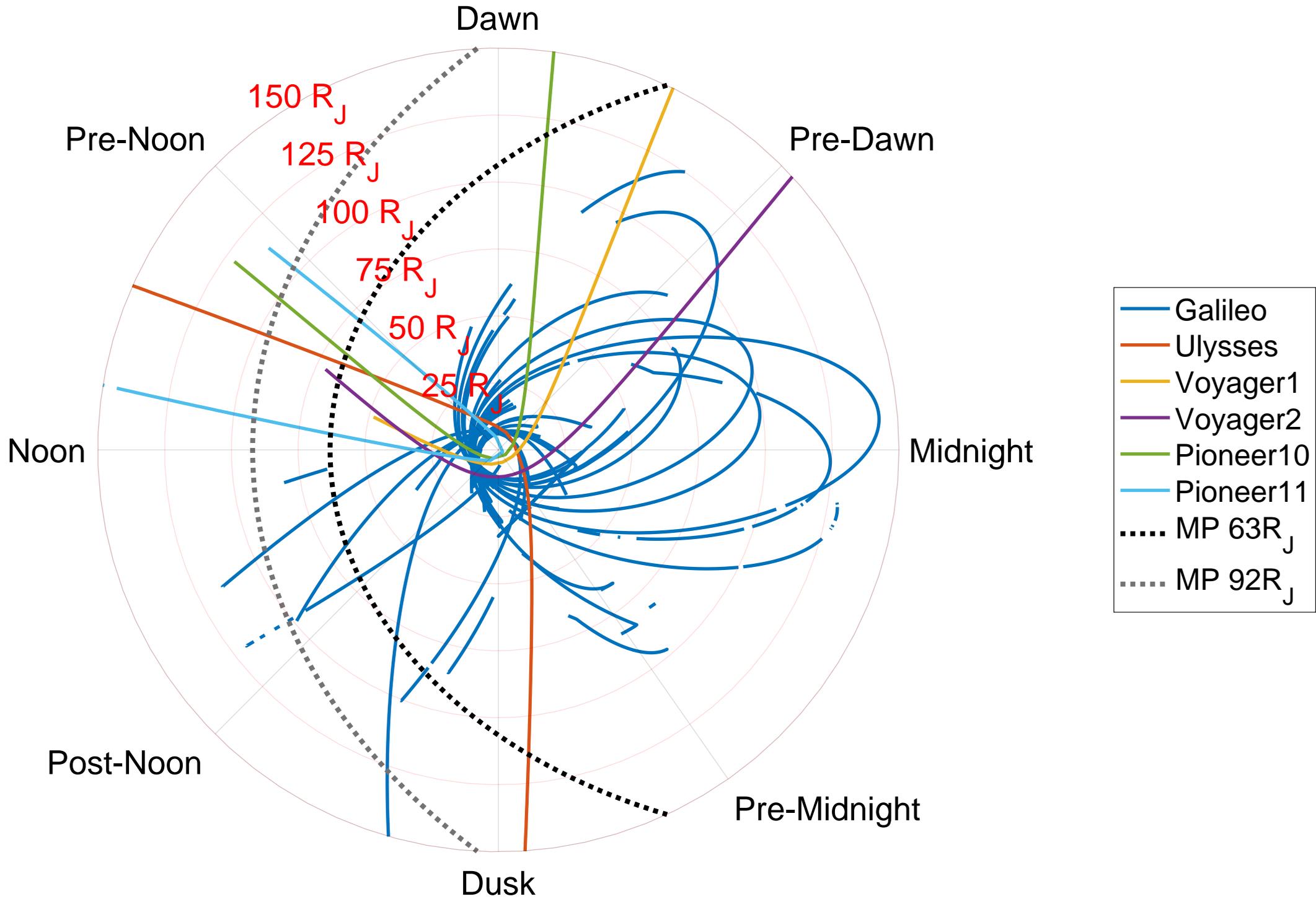
**Figure.**

NOT TO SCALE

Magnetopause
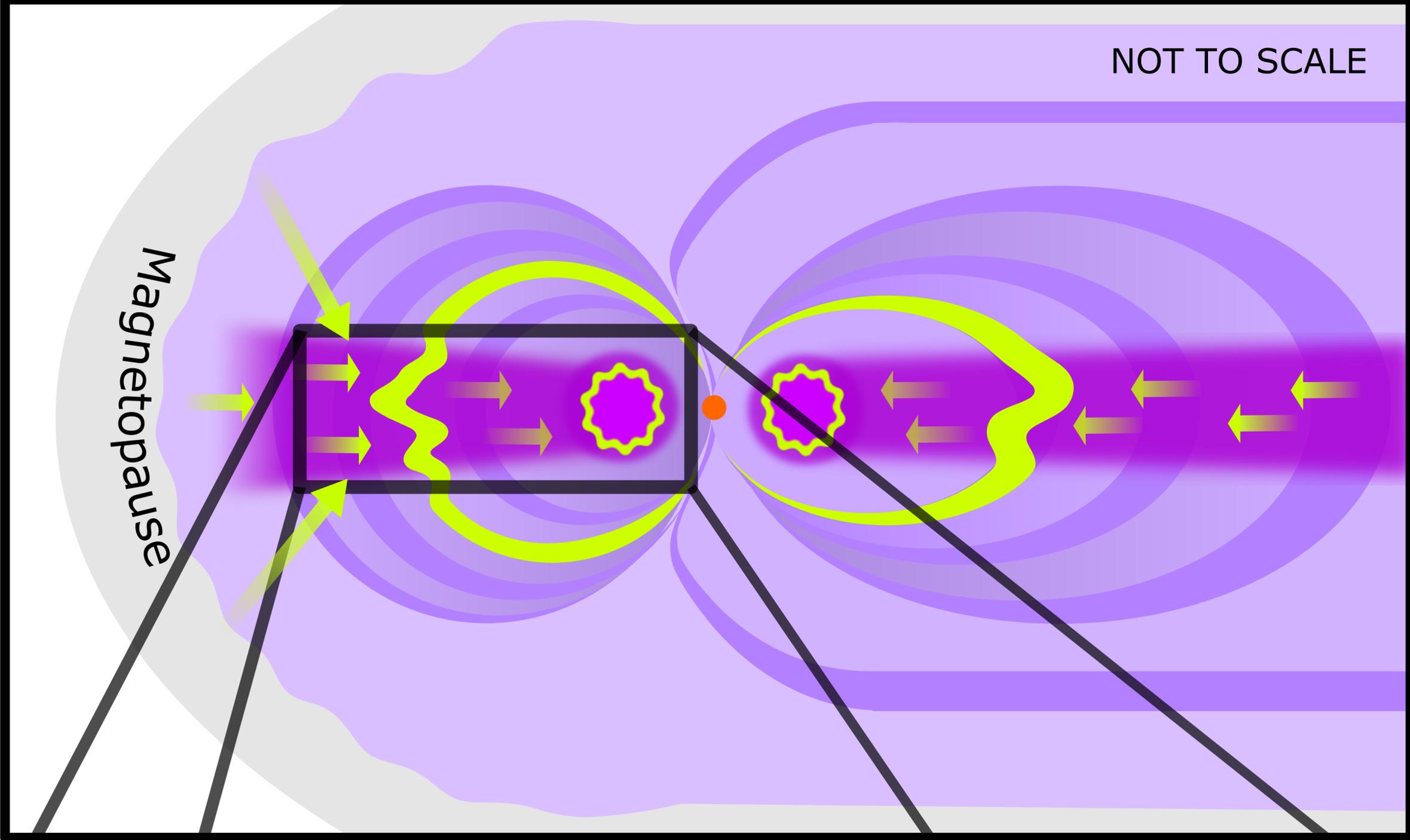
NOT TO SCALE

SAWs

Plasma
Torus

Fast-Mode
Waves

Torus Resonance

Figure.

a) 5-12 R_J

b) 80-100 R_J

Figure.

a) Dawn / Pre-Noon / Pre-Dawn / Noon / Midnight / Post-Noon / Pre-Midnight / Dusk

Radius [R_J]: 120, 100, 80, 60, 40, 20

Total Spacecraft Dwell Time (hours)
10^1 10^2 10^3 10^4

b) Dawn / Pre-Noon / Pre-Dawn / Noon / Midnight / Post-Noon / Pre-Midnight / Dusk

Radius [R_J]: 120, 100, 80, 60, 40, 20

Average Bandpower (nT^2)
10^{-3} 10^{-2} 10^{-1} 10^0 10^1 10^2

c) Dawn / Pre-Noon / Pre-Dawn / Noon / Midnight / Post-Noon / Pre-Midnight / Dusk

Radius [R_J]: 120, 100, 80, 60, 40, 20

Proportion of ULF-Active Time
10^{-4} 10^{-3} 10^{-2} 10^{-1} 10^0

d) Dawn / Pre-Noon / Pre-Dawn / Noon / Midnight / Post-Noon / Pre-Midnight / Dusk

Radius [R_J]: 120, 100, 80, 60, 40, 20

Proportion of ULF-Active Time
10^{-4} 10^{-3} 10^{-2} 10^{-1} 10^0

Figure.