First evidence for multiple-harmonic standing Alfvén waves in Jupiter's equatorial plasma sheet

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

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

Key Points:

- We report first evidence of several simultaneous wave harmonics on the same magnetic field line in Jupiter's plasma sheet.
- The harmonic periods, elliptical polarization, and confinement to the plasma sheet all agree with predictions for standing Alfvén waves.
- Multiple-harmonic standing Alfvén waves could explain the entire range of quasi-periodic pulsations observed in Jupiter's magnetosphere.

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

Abstract

Quasi-periodic pulsations in the ultra-low-frequency band are ubiquitously observed in the jovian magnetosphere, but their source and distribution have until now been a mystery. Standing Alfvén waves on magnetic field lines have been proposed to explain these pulsations and their large range in observed periods. However, in-situ evidence in support of this mechanism has been scarce. Here we use magnetometer data from the Galileo spacecraft to report first evidence of a multiple-harmonic ultra-low-frequency event in Jupiters equatorial plasma sheet. The harmonic periods lie in the 4-22-min range, and the nodal structure is confined to the plasma sheet. Polarization analysis reveals several elliptically-polarized odd harmonics, and no presence of even harmonics. The harmonic periods, their polarization, and the confinement of the wave to the plasma sheet, are strong evidence supporting the standing Alfvén wave model. Multiple-harmonic waves therefore potentially explain the full range of periods in quasi-periodic pulsations in Jupiters magnetosphere.

1 Introduction

Unexplained quasi-periodic (QP) pulsations in the ultra-low-frequency (ULF) band have been observed throughout the jovian magnetosphere since Pioneer 10 first encountered the system in 1973 (Kivelson, 1976). Jupiter's enormous magnetosphere is capable of supporting waves of far lower frequency than the terrestrial magnetospheric ULF spectrum, and so the label ULF is often extended to $<$ 1mHz. Observations span multiple datasets, most predominately X-Ray, IR and UV auroral emission modulations (Gladstone et al., 2002; Nichols et al., 2017; Dunn et al., 2017; Watanabe et al., 2018), magnetic perturbations (Khurana & Kivelson, 1989), radio emissions (MacDowall et al., 1993; Hospodarsky et al., 2004; Arkhypov & Rucker, 2006; Kimura et al., 2011, 2012) and energetic particle flux modulations (Anagnostopoulos et al., 2001; Karanikola et al., 2004). The combined range of observed periods spans 1-100+ minutes, with several preferential 15-minutes, 30-minutes and 40-minutes periods referred to as QP15, QP30 and QP40, respectively. The topic has been well reviewed recently by Delamere (2016). Several studies have attempted to assess ULF wave activity in the middle magnetosphere, and found significant wave power within 1-100-minutes, but none spanned the full range (Khurana & Kivelson, 1989; Tsurutani et al., 1993; Schulz et al., 1993; Petkaki & Dougherty, 2001; Wilson & Dougherty, 2000; Russell et al., 2001). Most of these studies looked for travelling ULF waves (with the exception of the standing wave description in Khurana and Kivelson (1989), however Voyager 2 moved too rapidly to resolve harmonic structures). Ultimately, determining the cause of these pulsations has proven challenging. At the time of writing, whether they are the result of a single mechanism or several is yet to be confirmed.

Despite these difficulties, it is clear that perturbations should correlate between datasets in a system as highly coupled as a planetary magnetosphere. Any local departure from equilibrium in a magnetosphere creates Alfvén waves, which carry field-aligned currents (FACs). These FACs propagate along the field lines towards the ionospheric footprints and modulate the local current density and particle distributions, which are responsible for polar-region electromagnetic emissions. The evidence supports this connection, and seems to be most prevalent in the middle magnetosphere: quasi-periodic ULF magnetic perturbations in the middle magnetosphere have strong Alfvénic components (Khurana & Kivelson, 1989), and pulsations in the auroral emissions are often in regions where the magnetic field lines map to the middle magnetosphere (Gladstone et al., 2002; Nichols et al., 2017). The pulsations are therefore likely the result of a single mechanism perturbing the magnetic field that subsequently modulates other observables, exhibiting the same range of periods. As ULF periods $\gtrsim$10-mins correspond to wavelengths comparable to the size of the magnetospheric cavity, these pulsations are consistent with a global Alfvénic resonance of the magnetic field.

A well-established literature exists regarding magnetospheric resonance and ULF waves in the terrestrial magnetosphere (see Takahashi et al. (2006) for a detailed overview). It has been shown that ULF waves have an important role in the flow of energy and momentum through the terrestrial magnetosphere, and in understanding phenomena such as diffusive transport of electrons, radiation belt dynamics, ionospheric particle precipitation, and myriad wave-particle interactions. These behaviours result from trapping wave energy at low-frequencies (corresponding to large scales) on a finite timscale, providing free energy to smaller-scale processes after an initial disturbance has ceased, often far from the site of disturbance. Without analogous knowledge of ULF waves in the jovian magnetosphere a full understanding of magnetospheric dynamics cannot be expected.

The presiding paradigm in terrestrial magnetospheric literature claims that ULF waves can be explained by the field-line-resonance (FLR) mechanism. In this description, Kelvin-Helmholtz (KH) vortices or other large-scale perturbations on the magnetopause are advected around the flanks of the magnetopause and produce evanescent, circularly-polarized fast-mode MHD waves that propagate into the magnetosphere, as outlined in Chen and Hasegawa (1974). In regions of inhomogeneity, the fast-mode waves can couple to the Alfvénic MHD mode and drive standing Alfvén waves on magnetic field lines analogous to vibrating strings (D. Southwood, 1974). The plasma sheet in the jovian magnetosphere is a region of significant inhomogeneity, and so the fast and Alfvénic modes should be strongly coupled, therefore a mechanism analogous to the field-line-resonance mechanism may be activee. However, it is unclear how the established literature for terrestrial magnetospheric resonance translates to the magnetospheres of the outer planets (though comparisons have been made of the ULF wave activity between planets, e.g. Glassmeier (1995)). In addition to standing Alfvén waves, travelling fast-mode wave energy may be trapped locally by a cavity resonance mode. It has been shown that cavity resonances in the terrestrial magnetosphere provide a persistent source of energy to slowly build large amplitude standing Alfvén waves (Kivelson & Southwood, 1985). In the terrestrial magnetosphere the most notable cavity mode is between the magnetopause and the plasmapause. The jovian magnetosphere is suffused with plasma everywhere and so lacks a plasmapause, and the geometric distortion the field due to the plasma sheet makes an analogous cavity mode unlikely. However, the equatorial plasma density gradient potentially makes the plasma sheet boundaries reflective. This could create resonant cavities inside the plasma sheet, or between the ionosphere and plasma sheet boundary as suggested by Nichols et al. (2017). In either case the mode would probably be more accurately described as a wave-guide, because the wave energy is likely to be eventually lost down-tail (McPherron, 2005). As the majority of pulsation observations have been associated with Alfvénic activity, we focus on trans-hemispheric standing Alfvén waves as our primary candidate mechanism. A series of studies have built on the early work of D. Southwood (1974); Chen and Hasegawa (1974) and D. Southwood and Hughes (1982) to develop a magnetospheric box-model of standing Alfvén waves in the jovian magnetosphere (D. J. Southwood & Kivelson, 1986; Kivelson & Southwood, 1986; Khurana & Kivelson, 1989). A key difference in the jovian model from equivalent terrestrial models is the effect of the jovian equatorial plasma sheet. As the plasma density in the plasma sheet is orders of magnitude higher than in the higher-latitude regions (lobes), the Alfvén travel time is dominated by the plasma sheet thickness and Alfvén speed (see Fig. 27

in Bagenal et al. (2017)). Conservation of energy flux of also means that the magnetic perturbation amplitude is maximised inside the plasma sheet. The combination of these effects results in the MHD wave power and standing wave nodal structure being effectively confined to the equatorial region. Recently, Manners et al. (2018) used the box model first presented by Kivelson and Southwood (1986) to compare standing Alfvén wave eigenperiods to all of the QP ULF periods observed at Jupiter. They found that either due to either spatial variation in plasma sheet properties, or a superposition of harmonics on the same field line, standing Alfvén waves are consistent with the full range of observations. We can therefore explain all ULF pulsations in the jovian magnetosphere with a single mechanism. However, further analysis has been hindered by the lack of clearly resolved in-situ observations.

Here we present the first evidence for multiple harmonics of a standing Alfvén wave on the same field line, confined inside the equatorial plasma sheet.In section 2 we present an algorithm searching for ULF waves using magnetometer data from the Galileo spacecraft. In section 3 we present a multiple-harmonic standing Afvén wave discovered by our algorithm. In section 4 we discuss the implications multiple-harmonics may have for explaining the wide range of reported ULF periods.

2 Searching for Ultra-Low-Frequency Waves in Jupiter's Magnetosphere

We used data from the Galileo spacecraft (Kivelson et al., 1992), which followed an equatorial trajectory for the majority of its 34 orbits, in the vicinity of Jupiter's equatorial plasma sheet and the surrounding lobes. Galileo traversed the magnetic equator thousands of times, due to the spacecraft's equatorial orbit, Jupiter's 10-hour rotational period and the $\sim 10^\circ$ obliquity of the planet's dipole. Unfortunately, Galileo suffered damage that meant data from all instruments had to transmitted to Earth at a decimated bit-rate. Additionally, the Plasma Science (PLS) instrument suffered damage to the electrostatic analyzers (Bagenal et al., 2016). Low cadence and pointing constraints make the ion moments of limited use for this survey (see supplementary material for details). Here we use only the magnetometer data to search for magnetic perturbations close to the plasma sheet.

The magnetic perturbations fields of interest are typically of order ~ 1 nT. To inspect these small-amplitude perturbations , we rotated the data into the mean-field-aligned (MFA) coordinate system outlined in Manners et al. (2018), which uses a sliding aver-

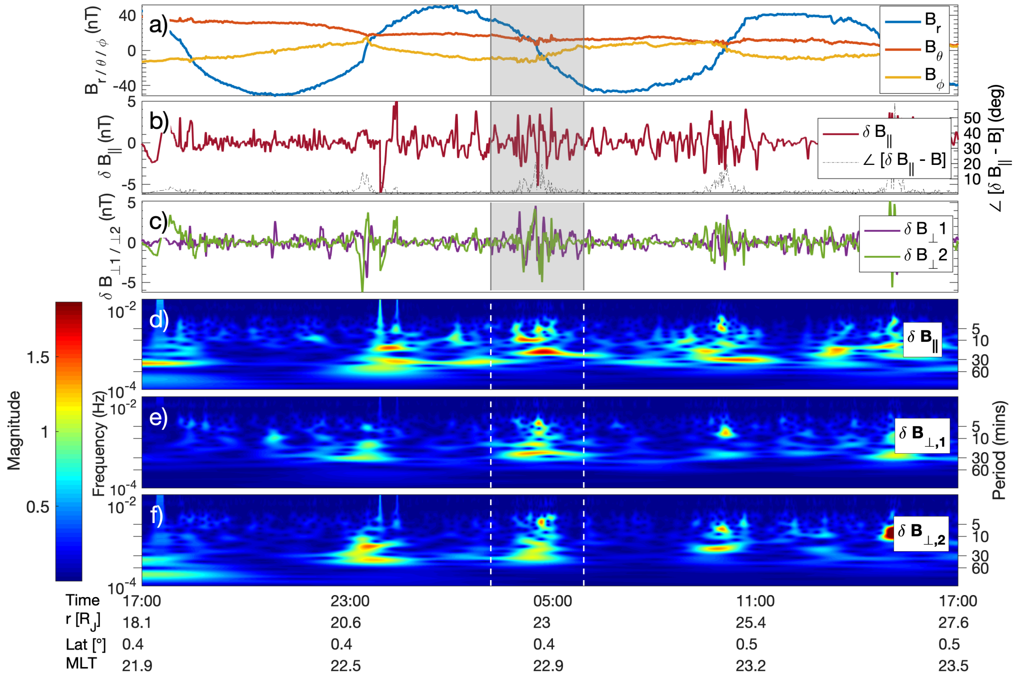

Figure 1. Magnetometer data from the Galileo spacecraft during 7th-8th November 1996, centred on a multiple-harmonic standing Alfvén wave. The event is highlighted by the grey blocks or vertical dashed white lines in each panel. a) Magnetic field data in spherical system III coordinates. b) Compressional component of the mean-field-aligned (MFA) magnetic field residual (red line), and the deviation angle between the local magnetic field vector and the MFA unit vectors (black dashed line). c) Both transverse components of the MFA magnetic field residual. d)-f) Continuous wavelet transforms for the compressional and Alfvénic MFA magnetic field residuals, respectively.

age window of width 60-mins 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 the right-handed orthogonal set and are transverse to the mean field. The rotated field components can then be detrended using the sliding average obtained during the rotation, giving the mean-field-aligned residual magnetic field components $\delta b_{||}$, $\delta b_{\perp,1}$ and $\delta b_{\perp,2}$. In regions where the background field is stable on the timescale of the sliding window, the quasi-perpendicular MFA components isolate Alfvénic MHD wave activity. However, regions of high variability such as the middle magnetosphere the background field changes significantly within the width of the sliding window, producing residuals comparable to the magnitude of the predicted ULF wave signatures. This means that signals detected beyond $\sim 30R_J$ cannot be distinguished from short-timescale change in the background magnetic field. Conversely, at radii inside Io's orbit and the inside edge of the plasma torus ($\sim 5R_J$) the latitudinal plasma density gradient is more shallow, and so the Alfvén travel time is on the order of seconds (see Fig. 27 in Bagenal et al. (2017)), and so is not a region of interest. However, in the region $\sim 10{-}30R_J$ there exists a coherent equatorial body of high-density plasma, and the plasma swept past Galileo on a timescale >1-hour, producing residuals in the MFA components of < 0.1 nT, much smaller than the wave signatures of interest. This is also the region where the time taken to transit the plasma sheet is maximised, and so is the ideal region to obtain the greatest coverage of events.

We identified many events of interest in the MFA residuals, which spanned the ULF frequency band and showed significant broadband wave power or coincident wave power maxima at discrete frequencies. For the remainder of this study we present and analyse the best resolved event, measured by Galileo on 8th November, 1996. The data and MFA residuals are shown in Figure 1 a)-c). At this time, Galileo was travelling through the midnight sector in the middle magnetosphere, at a radial distance from Jupiter of $\sim 20{-}30R_J$. To obtain details of the MFA residuals in frequency-time space, we computed the continuous wavelet transforms (CWTs) of each MFA residual component. The results are shown in Figure 1 d)-f). We assumed a Morlet wavelet to perform the computation, and the cone-of-influence (COI) regions, where edge effects dominate, lie beyond the limits of the axes. Maxima in wavelet power are evident in all three perturbation components between periods of $\sim 5{-}25$ minutes, several of which are coincident, especially in $\delta\vec{b}_{\perp,1}$. These coincident wavelet power maxima are noticeably separated into discrete frequency bands in the components transverse to the field, indicating Alfvénic activity at several ULF frequencies simultaneously. To properly identify the event we analysed its structure and polarization.

3 A Multiple-Harmonic Ultra-Low-Frequency Pulsation during 8th November 1996

We concentrate on the first transverse MFA component, $\delta b_{\perp,1}$, because it shows well-resolved coincident wave power maxima. Figure 2 a) shows a magnified view of the CWT of $\delta b_{\perp,1}$ during the pulsation at around 4:45AM (highlighted by the grey region in Figure 1). Integrating the wavelet power over the pulsation interval, we find four distinct maxima at ∼22 minutes, ∼14 minutes, ∼7 minutes and ∼4 minutes. The ratios be-

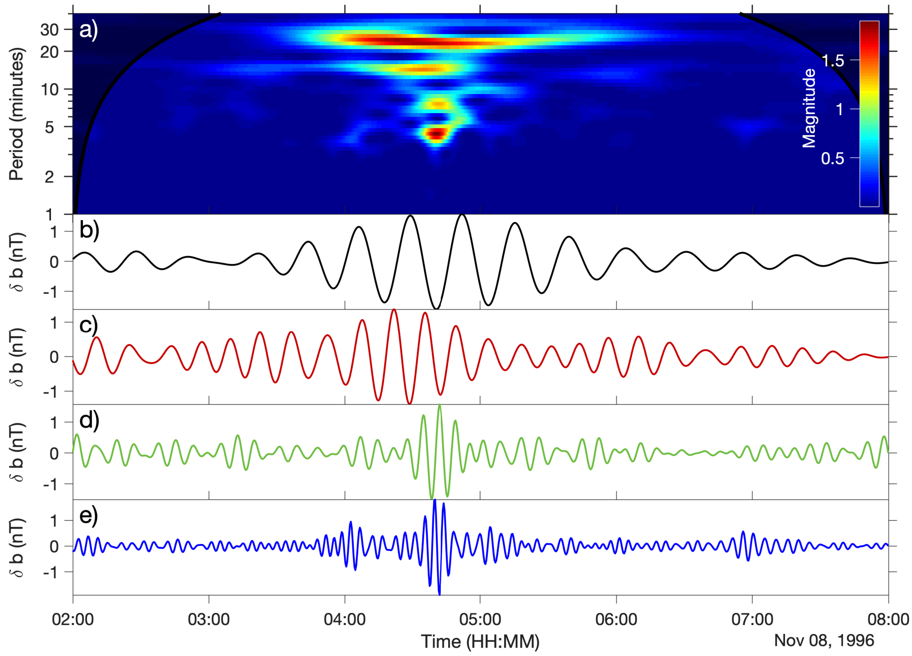

Figure 2. Processed data from the first Alfvénic MFA magnetic residual component, $\delta b_{\perp,1}$. a) Continuous wavelet transform of $\delta b_{\perp,1}$ during the event highlighted in Figure 1 (COI represented by black envelope). Four coincident wave power maxima are evident at the perturbation maximum, at around 4:45AM. b)-e) Band-pass filtered time series of $\delta b_{\perp,1}$ for the wave power maxima at ∼22 minutes, ∼14 minutes, ∼7 minutes and ∼4 minutes, respectively.

tween consecutive maxima are close to 2, indicative of a harmonic series. These results are insensitive to the frequency analysis method used, as confirmed by fast-Fourier transform and Lomb-Scargle analyses (see supplementary materials).

We isolate each period by taking the full-width-half-maximum (FWHM) of Gaussians fitted to each peak in the integrated wavelet power. Performing band-pass filters of the MFA residual time series, we obtain the decomposed time series for each peak in wavelet power, shown in Figure 2 b)-e). Each filtered time series shows a clear wave-packet structure at the pulsation maximum. The same filtering routine was applied to $\delta b_{||}$ and $\delta b_{\perp,2}$, with similar results.

The wave periods and restriction of the wave to the quasi-Alfvénic plane are insufficient to determine whether the event is the result of a superposition of travelling perturbations or a standing wave structure. However, theoretical treatment of standing Alfvén waves, e.g. Chen and Hasegawa (1974); D. Southwood (1974), predict that the wave polarization in the plane transverse to the magnetic field reverses over a magnetic perturbation maximum (plasma displacement node). We can therefore determine whether the event has a standing profile by inspecting its polarization in the field-transverse plane.

Figure 3 a), c), e) and g) show hodograms for the 22-min, 14-min, 7-min and 4-min signals, respectively, revealing them all to be elliptically polarized. Panels b), d), f) and h) show the unit vector in the direction normal to the plane created by the cross-product between transverse components of each consecutive pair of MFA magnetic field residual vectors, $\delta\vec{b}^i = \left(0,\ \delta b^i_{\perp,1},\ \delta b^i_{\perp,2}\right)$ and $\delta\vec{b}^{i+1} = \left(0,\ \delta b^{i+1}_{\perp,1},\ \delta b^{i+1}_{\perp,2}\right)$. This normal vector reverses sign when the lead/lag of the two transverse components is also reversed, corresponding to changes in handedness of the polarization. By counting the number of nodes, we can determine the wave harmonic number. Using the hodograms and normal vectors in conjunction, we find that each signal is an elliptically polarized odd harmonic. More reversals could exist outside the plasma sheet region, but those visible in the data provide a lower limit.

4 First Evidence for Multiple-Harmonic Standing Alfvén Waves in Jupiter's Plasma Sheet

Thus far we have shown several key features of the ULF pulsation centred ∼4:45AM on 8th November 1996: multiple discrete periods with each successive period doubling, confinement of the wave to the plasma sheet, and a reversal in handedness over the amplitude maxima. Combined, these features are in strong support of an equatorially-confined standing Alfvén wave on a single magnetic field line, with multiple harmonics excited simultaneously.

To compare the decomposed signals with predicted standing Alfvén wave harmonics, we refer to a magnetospheric box model previously adapted for the jovian magnetosphere (D. J. Southwood & Kivelson, 1986; Khurana & Kivelson, 1989; Manners et al., 2018). As each field line acts as a linear resonator with an independent set of harmonic periods, the model uses a 1D model field-line to solve for the field-line eigenperiods, parametrized by the Alfvén speed inside the plasma sheet, and the sheet half-thickness.

Figure 4 shows the magnetic field perturbation eigenfunctions, for the 1st, 3rd, 7th and 11th harmonics, obtained from the box model. For demonstrative purposes, we chose parameters to emphasize the equatorial confinement of the nodes by assuming a nominal plasma sheet half-thickness of 2.5 R_J, an equatorial Alfvén speed of 100 km/s, and a high-latitude Alfvén speed of $3.5{\times}10^4$ km/s (based on Fig. 27 of Bagenal et al. (2017)).

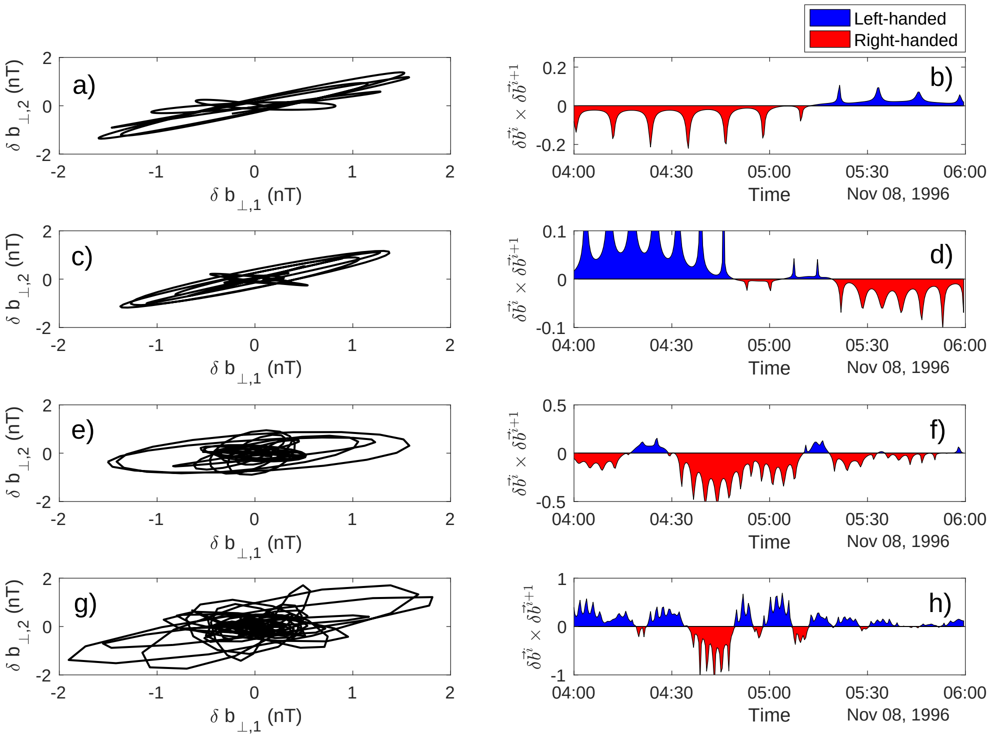

Figure 3. a), c), e), g) Hodograms of the bandpass-filtered time series for the 22 min, 14 min, 7, min and 4 min signal, showing distinct elliptical polarization. b), d), f), h) The corresponding vector cross-product of consecutive MFA magnetic residual vectors $\delta\vec{b}^i \times \delta\vec{b}^{i+1}$, where $\delta\vec{b}^i = \left(0,\ \delta b^i_{\perp,1},\ \delta b^i_{\perp,2}\right)$ for $i \in \{0, T-1\}$, where T is the total time during the interval. This produces time series for $\hat{n}\sin\theta$, where $\hat{n}$ gives the direction of the normal unit vector to the plane formed by consecutive MFA magnetic residual vectors, and θ is the angle between them.

Though the exact number of nodes in the 7-min and 4-min periods is difficult to determine, the number of nodes is odd, and so the depicted harmonics in Figure 4 give an accurate qualitative description. Periods consistent our observations can be produced by a degenerate combination of plasma sheet parameters, as shown by Fig. 4 in Manners et al. (2018). If jovian magnetospheric dynamics are conducive to exciting multiple harmonics of standing Alfvén waves on the same field line, the large range in QP ULF periods could arise not only from spatial variation of plasma sheet properties, but also due to a spectrum of harmonics generated on each field line, or a combination of both.

Inspecting Figure 1, the harmonic structure in $\delta b_{\perp,2}$ is not as well-defined as in $\delta b_{\perp,1}$. This could arise from the imperfect alignment of the MFA coordinate system, or the asym-

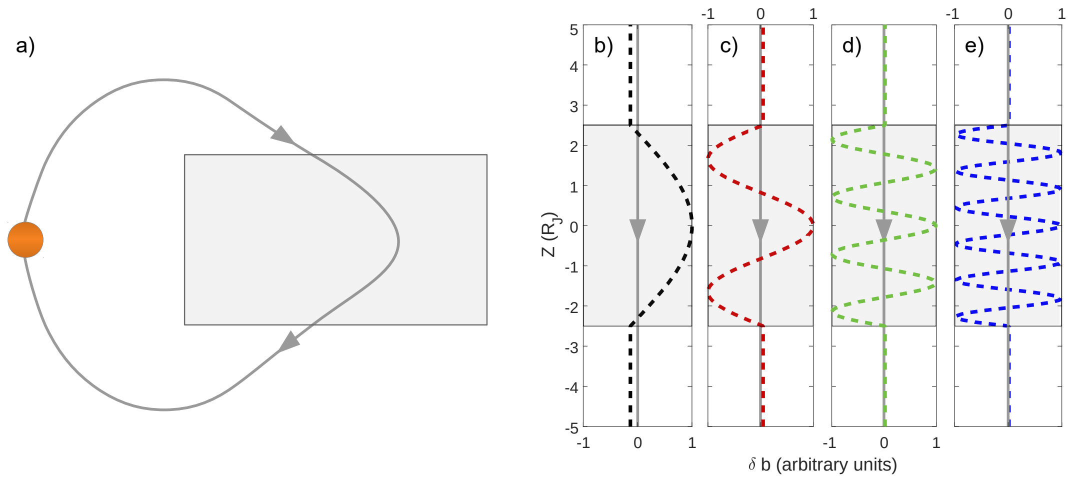

Figure 4. a) Cartoon of a typical magnetic field line (solid grey line) mapping from Jupiter (orange circle) out to the middle jovian magnetosphere at $\sim 23R_J$. The radial distension of the magnetic field is visible, especially inside the equatorial plasma sheet (light grey rectangles). b)-e) The black, red, green and blue dashed lines depict solutions of the magnetic perturbation eigenfunctions for the 1st, 3rd, 7th and 11th harmonics obtained from the magnetospheric box model developed by D. J. Southwood and Kivelson (1986). The eigenfunctions are plotted as a function of displacement along the field line from the magnetic equator, Z. The nominal field line is shown by the solid grey lines.

metry could indicate that a strict plane-wave approximation is insufficient. Alternatively, it could be evidence of decoupled poloidal and toroidal resonance modes. In the vicinity of the plasma sheet in the middle magnetosphere, the MFA coordinate system produces a $\delta b_{\perp,1}$ that is quasi-toroidal, and $\delta b_{\perp,2}$ that is quasi-poloidal. As $\delta b_{\perp,1}$ contains most of the wave power, the event periods could be evidence for a toroidal standing Alfvén wave.

The absence of even harmonics is equally significant. Modelling indicates that successive even and odd harmonics should be excited. The absence of even harmonics may be a signature of the driving mechanism. In the literature concerning terrestrial magnetospheric ULF waves, the excitation of standing Alfvén waves is thought to arise from both internal and external drivers (Oimatsu et al., 2018). Several internal mechanisms have been proposed, such as the bounce, drift-mirror and drift-bounce resonances (D. Southwood et al., 1969; Hughes et al., 1978; Khurana & Kivelson, 1989; Hasegawa & Chen, 2013). The drift-bounce resonance, however, is asymmetric about the magnetic equator, and the wavelengths involved in the drift-mirror instability are too small to match the observed ULF wave periods.

The observation critical to confirming a KH-driven FLR mechanism is the presence of a circularly-polarised travelling fast-mode wave. However, a standing Alfvén wave would persist for some time after the travelling wave front had passed. If the resonance is not critically damped, would persist for several wave periods, which indicates a potential lifetime for the wave from several hours to tens of hours. The actual characteristic lifetime is dependent on the dominant damping mechanism in the jovian magnetosphere, consideration of which is beyond the remit of this study. We speculate that the compressional component periods in $\delta b_{||}$ represent such a cavity resonance confined between the plasma sheet boundaries, feeding energy into a multiple harmonics of a standing Alfvén wave on a single field line.

It is worth noting that we found no significant wave power with periods above 22 minutes. The absence of a 40-min periodicity (QP-40) commonly observed in the jovian magnetosphere is curious. Though the significance of this cannot be determined from a single event, we speculate that that QP-40 is characteristic of a region of the magnetosphere not encountered during this event, or is globally the most commonly excited resonant period.

5 Summary

We surveyed magnetometer data from the Galileo spacecraft during its orbital tour of the jovian magnetosphere, looking for quasi-periodic ultra-low-frequency pulsations. We presented a single event confined to inside the equatorial plasma sheet. Polarization analysis revealed several elliptically polarized odd harmonics in the plane quasi-transverse to the mean field. These data represent the first observation of a multiple-harmonic standing Alfvén wave in Jupiter's equatorial plasma sheet, consistent with predictions by (Manners et al., 2018).

We showed that, in addition to spatial variation in properties of the equatorial plasma sheet producing a range in resonant periods, each resonant field line is capable of generating periodic pulsations across the full range of ULF periods. We showed that the event we analysed had a distinct absence of even modes. We have no explanation for this absence, but we speculate that it is highly relevant to determining the driving mechanism.

Several more events similar to the one we present here exist in the Galileo dataset. More work remains to be done regarding the possible resonance modes of the complex jovian magnetospheric geometry, and the driving mechanisms responsible for exciting them. The multiple-harmonic standing Alfvén wave we have presented here changes the current picture of sporadic ULF waves at Jupiter, indicative at least of a semi-permanent population of multiple-harmonic standing Alfvén waves on field lines throughout the magnetosphere. In future studies we will assess the spatial distribution of pulsations in the jovian equatorial plasma sheet, and their respective harmonic structure.

Acknowledgments

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