EVIDENCE OF FRESH INJECTIONS RELATED TO THE INTERCHANGE INSTABILITY IN THE IO TORUS

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Abstract

The Juno Waves instrument often detects brief, band-limited emissions when the spacecraft crosses magnetic fields threading Io's M-shell, or vicinity thereof, up to about 35 degrees magnetic latitude. The disturbances have durations of order one minute and are observed below the electron cyclotron frequency. While plasma densities are often not available, it is thought that the frequency of the events are below the plasma frequency of the surrounding medium. Often, the first electron cyclotron half-harmonic is weakened or disrupted at the time of the events. While the events can be seen in isolation, there are typically a few of them with temporal spacing from about 15 to 40 minutes. In this paper we suggest that the events observed by Juno are signatures of injections. Injections have been reported in the Io torus or its vicinity dating back to the Galileo mission. However, the events reported here are somewhat different in that most exhibit little or no variation in magnetic field strength and due to the radiation environment, we have minimal plasma measurements with which to compare. We show that the locations of these events are on field lines threading the dense Io torus, with several inside of Io's M-shell. We discuss reasons to believe these events are the same or similar to the earlier reported injections.

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1 Introduction

Based on studies at both Jupiter (Paranicas et al., 1990; Bolton et al., 1997; Thorne et al., 1997; Mauk et al., 1997, 1999; Haggerty et al., 2019) and Saturn (Burch et al., 2005; Menietti et al., 2008; Tao et al., 2010; Kennelly et al., 2013) injections are a manifestation of centrifugal interchange. Gold (1959); Hill (1976) and others have discussed the motion of magnetic flux tubes in a planetary magnetosphere, suggesting that flux tubes can exchange positions in order to reduce the total potential energy. In a rapidly rotating magnetosphere with a substantial population of heavy ions such as Jupiter's, heavily loaded flux tubes can exchange with lighter ones. The heavily-loaded flux tubes are subjected to centrifugal acceleration outward. However, in order to conserve flux, the flux tubes cannot leave the system. Instead, once their plasma is deposited, presumably down the magnetotail, they are accelerated inward as bouyant flux tubes that have lower densities and higher temperatures. The inward-moving particles are subject to energization by conservation of the first two adiabatic invariants as they return to the inner magnetosphere with stronger magnetic fields.

Both the terms "injections" and "interchange events" have been used to describe arguably similar magnetospheric dynamics. Some have reserved the term "injection" for larger scale (10 to 60 min.) structures and "interchange events" to refer to smaller ($\sim$1 min.) events. In this paper, while we do discuss primarily the shorter events, we use injection and interchange without distinction. The Bolton et al. (1997) and Thorne et al. (1997) papers are among the earliest reports of the phenomenon at Jupiter found in the region of the Io torus. Mauk et al. (1997) reported events at 11 Jovian Radii.

Some identifying characteristics of the observed injection signatures include decreased plasma density, higher temperatures and intensified plasma waves. Such events were observed by Galileo (Bolton et al., 1997; Thorne et al., 1997; Mauk et al., 1997, 1999; Haggerty et al., 2019). They were characterized as having depleted thermal plasma and enhanced energetic plasma with electron distributions unstable to wave modes such as enhanced whistler mode waves. Similar features were commonly seen by the Cassini radio and plasma wave instrument at Saturn and were identified as "fresh" injections or evidence of inward-moving flux tubes due to the centrifugal interchange instability (Kennelly et al., 2013). As fresh injections, the energetic particles associated with them exhibit dispersionless energy-time signatures due to relatively slow azimuthal gradient and curvature drifts. The events were observed in the plasma wave spectrum, displaying enhanced electron cyclotron harmonics (ECH) and intense chorus. The enhanced plasma waves are due to modified electron pitch-angle distributions from the conservation of the first two adiabatic invariants mentioned above (Menietti et al., 2008). There was a better correlation between signatures of injections observed in the plasma wave spectrum and those identified in the energetic particle data for recent or "fresh" events, primarily because the plasma in the inward-moving flux tubes had not had time to drift significantly. Hence, in this paper, we use the wave events as proxies for "fresh" injections. Perturbations of the magnetic field are sometimes observed as a diamagnetic effect. At Saturn, the perturbations resulted in increased magnetic field intensity near the equator also reported by Thorne et al. (1997) in the Io torus, for example. In contrast, the injections show decreased intensity at higher latitudes in the Cassini observations.

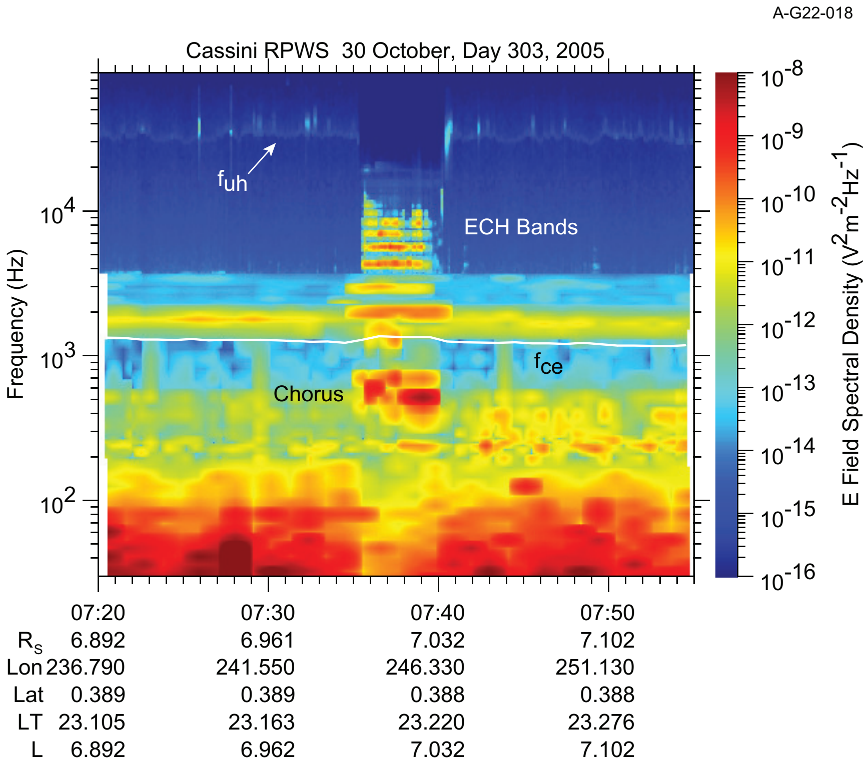

Figure 1: *Injection event at Saturn studied in Menietti et al. (2008) extending from about 07:36 to 07:40. Plotted is the electric field spectral density as a function of frequency and time with the amplitude being represented by the color bar on the right. The white line represents f_{ce}.*

Figure 1 shows an example obtained by Cassini at Saturn (Menietti et al., 2008) showing intense chorus emissions below the white line representing the electron cyclotron frequency f_{ce}. Above f_{ce} several ECH bands are observed, with the highest frequency one presumably at the upper hybrid resonance frequency f_{uh}. Surrounding the injection is a higher frequency but weaker band at the upper hybrid resonance f_{uh} indicating the injection has a lower plasma density than the surrounding medium. More detailed observations of this event are given in Menietti et al. (2008).

The wave signatures discussed herein have relatively brief durations of a few minutes or less. While there are injections having significantly longer time scales, they were not considered in this study. Haggerty et al. (2019) discusses larger scale injections observed by the Jupiter Energetic Particle Detector Instrument (JEDI, Mauk et al., 2017) at high latitudes on field lines threading the Io plasma torus. These are events that exhibit the effects of energetic particle dispersion from much earlier injections. Since the energetic particles are more dispersed, it is less likely wave signatures can be correlated with them. Hence, the wave events are most likely associated with fresh injections.

2 Methods

This study uses observations of plasma waves by Juno's radio and plasma wave instrument Waves (Kurth et al., 2017), magnetic field measurements from the Juno magnetometer investigation (Connerney et al., 2017), and the Jovian Auroral Distributions Experiment (JADE, McComas et al., 2017). The Waves instrument uses two sensors, a search coil magnetometer body-mounted to the spacecraft oriented parallel to the spin axis and a short electric dipole whose effective axis is perpendicular to the spin axis and parallel to the spacecraft y-axis. The frequency range from 50 Hz to 20 kHz is covered for both the electric and magnetic components with simultaneous sampling, preserving phases between the two. Electric fields, only, are obtained up to 40 MHz. For most times and those used herein, a spectrum is acquired every second. Survey data return a spectrum from 50 Hz to 40 MHz with ~20 channels/decade in frequency resolution using onboard spectrum analysis. The magnetic spectrum covers up to 20 kHz. A burst mode collects waveforms at a rate of 50,000 samples/s for frequencies up to 20 kHz and 375,000 samples/s for the 10 kHz to 150 kHz electric channel.

Some of the earliest events studied herein appeared during inbound legs of Juno's orbits at low-to-moderate magnetic latitudes and on M-shells spanning the Io plasma torus. This study concentrates on observations between M values of 5 to 10 and magnetic latitudes less than 35°. Because of the precession of Juno's orbit, this region was not regularly crossed until approximately orbit 14. Further, Juno's outbound orbits typically cross M-shells in the range of 5 to 10 in the southern hemisphere much closer to Jupiter in a higher field region. This would likely move the observed features into a frequency range for which Waves has reduced sensitivity, hence, this study only includes northern magnetic latitudes. The events that struck our interest were below the electron cyclotron frequency and had durations of one to a few minutes. Hence this study addresses these events with a goal of understanding whether or not they are associated with injections.

3 Observations

Figure 2 shows two examples of injections observed by Waves at 3:46 and 4:14 UT on 8 June, day 159, 2021 near M values near 6. Here, we use "M" in a similar way as the McIlwain L parameter except that M refers to the equatorial distance to a field line using the JRM09 magnetic field model with current sheet (Connerney et al., 2018, 1981). At this time, Juno is at magnetic latitudes between 11 and 12°. These events are characterized by a brief (one to two minutes) intensification of waves between about 10 and 20 kHz. Both are at frequencies below f_{ce}. The features are most intense in the electric field channel, but there is a weak response in the magnetic channel. The electron cyclotron harmonic band between f_{ce} and $2f_{ce}$ shows drop-outs or decreased amplitudes at the same times.

Figure 3 shows a high resolution burst observation of an event on 15 April, day 105, 2021 near M $\sim$ 6 and 12° magnetic latitude. There is significant frequency-time structure in this event, perhaps indicating a non-linear emission like whistler-mode chorus. As with the previous examples, this one clearly lies below f_{ce}. The $3f_{ce}/2$ band decreases in amplitude at the start of this event, but does not completely disappear.

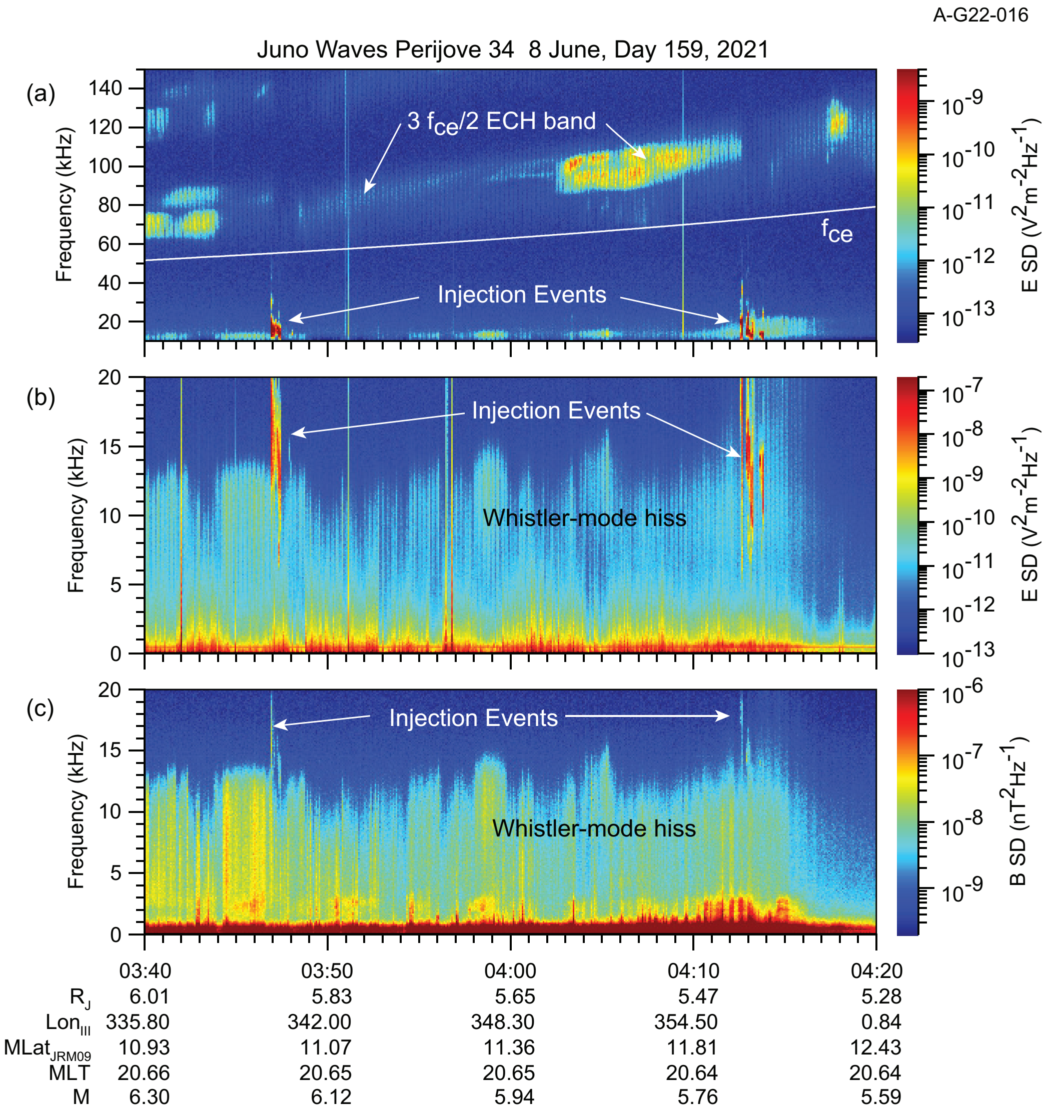

Figure 2: *Examples of injection events. (a, b, c) show two examples of such events with (a) showing the electric field spectrogram for frequencies from 10 to 150 kHz and (b and c) showing electric and magnetic spectrograms, respectively, for frequencies between 50 Hz and 20 kHz.*

The injections in the Io torus studied herein are characterized by brief (one to a few minutes), wave intensifications that are band-limited below the electron cyclotron frequency f_{ce}. They are quasi-electrostatic, because a weak magnetic component is usually present. While spectral features giving the electron plasma frequency f_{pe} are often lacking, these events are thought to be below f_{pe}. There is often a disruption in the first ECH band ($\sim 3f_{ce}/2$) that is a clue that $f_{pe} > f_{ce}$ outside the injections and the disruption could be due to the plasma frequency dropping below f_{ce} during the event. The events near Io's M shell are usually not accompanied by changes in $|B|$, but here the background magnetic field is strong and the perturbations may be negligible, in comparison. The events are on field lines threading the Io torus, and some are found inward of Io's M shell. Typically,

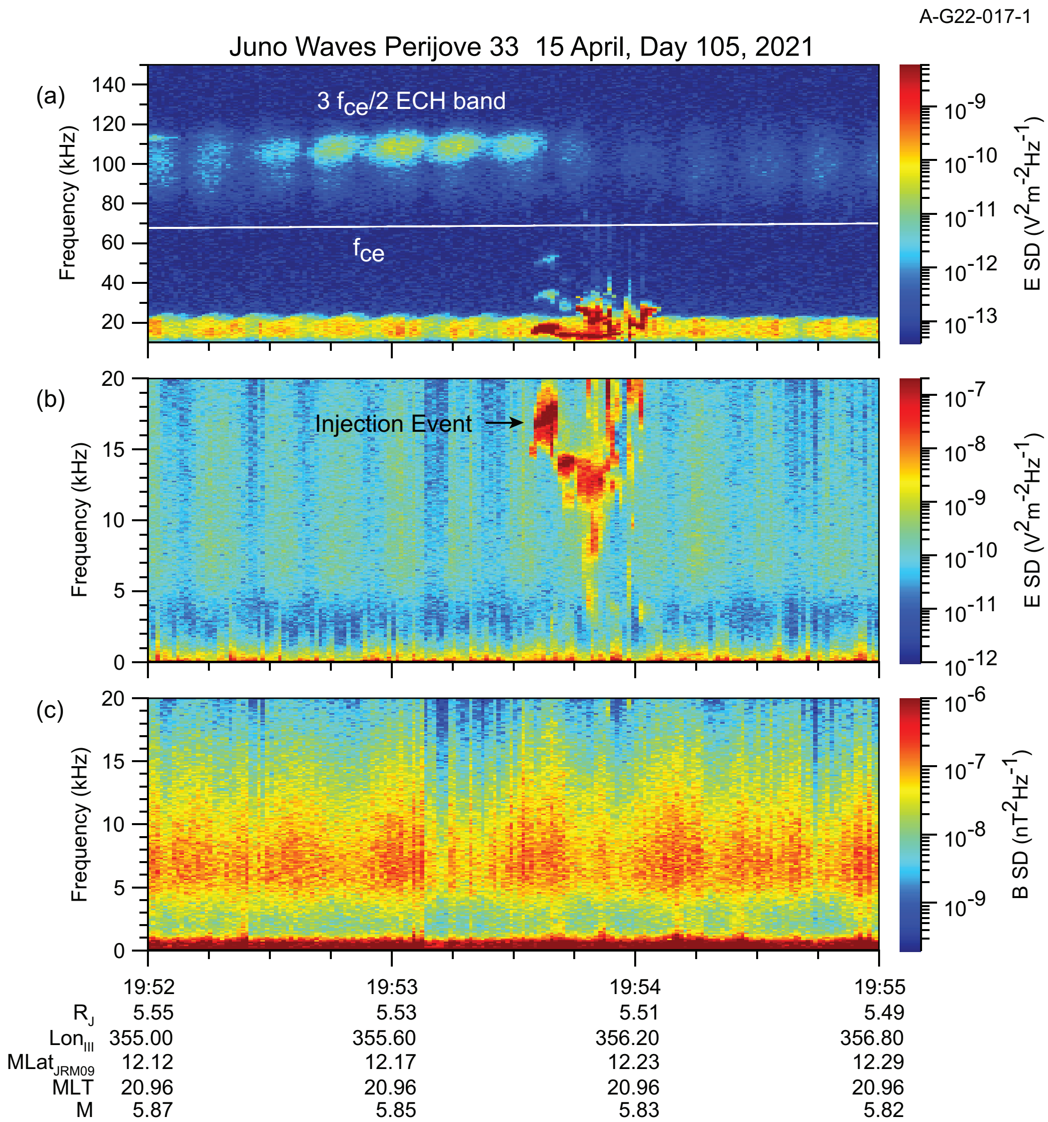

Figure 3: *Another example of an injection event with Waves burst mode data. (a) Electric field spectrogram for frequencies from 10 to 150 kHz. (b and c) Electric and magnetic spectrograms, respectively, for frequencies between 50 Hz and 20 kHz.*

a few events are observed on a given passage through field lines threading the Io torus, usually separated by 10's of minutes. However, occasionally two or three can occur in rapid succession, with temporal spacing of less than a minute.

Figure 4 shows signatures of injections in the magnetic field and JADE (McComas et al., 2017) ion and electron data, albeit at somewhat larger distances than most of the events studied here. The top panel shows the difference between the measured field and the JRM33 model with current sheet (Connerney et al., 2022, 2020), clearly showing an increase in the magnitude of the field during two closely-spaced events. The ion energy-time spectrogram in Figure 4b shows a loss of magnetospheric ions at a few keV/q (en-

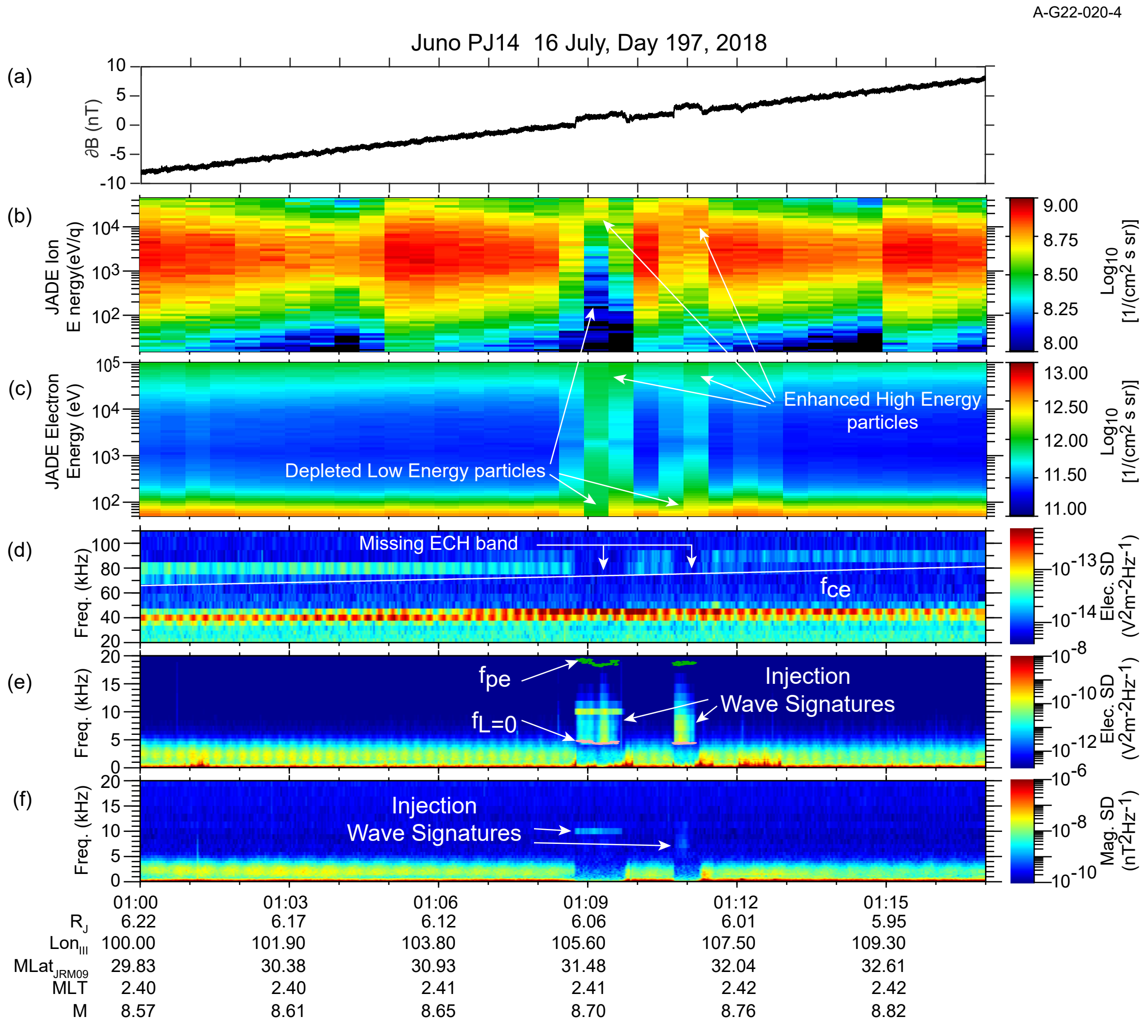

Figure 4: *Injection events near $M = 8.7$ showing effects in the magnetic field as well as JADE ion and electron data. (a) δB (difference between the measured field and the JRM33 model with current sheet (Connerney et al., 2022, 2020)). (b) Ion energy-time spectrogram. (c) Electron energy-time spectrogram. (d) Electric field spectrogram for 20 to 120 kHz). (e and f) Electric and magnetic spectrograms for 50 Hz to 20 kHz.*

ergy/charge) with evidence of higher energy ions, at least for the first event near 01:09. The electron energy-time spectrogram in Figure 4c shows a depletion of the lowest energy electrons and enhanced higher energy electrons at the two events. The JADE data have an analysis interval of 30 s, hence, the temporal correspondence with the magnetometer and Waves data is not ideal. Panel d shows the disappearance of the electron cyclotron harmonic band at the time of the two events. Panels e and f in Figure 4 show electric and magnetic spectrograms with two events we've identified as evidence of injections in the plasma wave data that exhibit enhanced electric and magnetic fields. In panel e we have identified the bottom edge of the broadband emission as the lower cutoff of z-mode emission $f_{L=0}$ similar to Daly et al. (2023) and highlighted this with a pink line. Using this and f_{ce}, we can compute f_{pe} (Sulaiman et al., 2021) and we indicate this with the green line. Hence, this emission is consistent with the z-mode. The brighter narrowband line with a weak magnetic component (panel f) could be an intensification of the z-mode or possibly whistler-mode chorus. Similar multi-instrument observations have been made at Saturn using Cassini instruments, such as in Figure 2 of Rymer et al. (2009).

4 Discussion

Figure 5a shows the locations of the 77 events identified for this study in magnetic cylindrical coordinates. The gray traces represent Juno's trajectory in this system through PJ47. The red dots are the locations of events. Their locations at northern latitudes is primarily due to Juno's orbit. The events are found on field lines threading the Io torus (indicated in gray) and a significant number are inwards of Io's M-shell. Figure 5b shows the positions rotated into the equatorial plane. That is, the M-value is preserved and the positions of the events are distributed in System-III (west) longitude. A circle at 5.9 R_J represents the Io M-shell. There is a dearth of events from about 135 to 270°, but it is clear that Juno did not sample this region near and inwards of the Io M-shell for these longitudes.

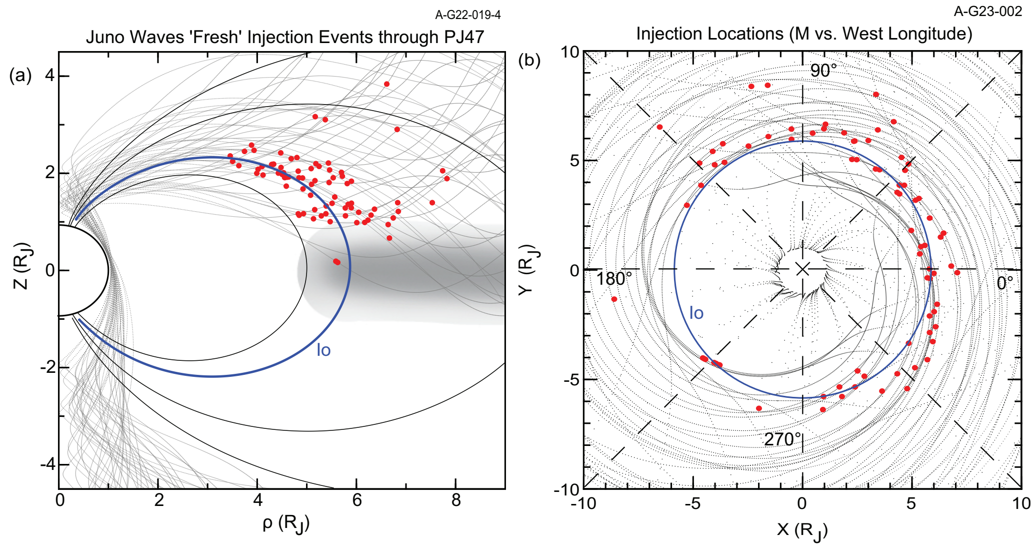

Figure 5: *(a) The distribution of "fresh" injections found in the Waves data through PJ47 in cylindrical coordinates based on a fixed magnetic dipole. Model field lines for M = 5, 10, 15... are shown for context. The Io M-shell is highlighted in blue. The gray shaded region is an artist's conception of the Io torus (not a model). (b) Locations of injection events plotted in a Jupiter-fixed coordinate system using M values and* Sys_{III} *longitudes. Again, the Io M-shell is highlighted in blue. In both panels the light gray dots show the trajectory of Juno. In (b) we have eliminated trajectories with negative magnetic latitudes for clarity.*

Figure 6 shows the distributions of the 77 wave signatures included in this study, both by M shell and by longitude. Because M is a complex function of both radial distance and magnetic latitude, we limited the following statistical study to $5 < M < 10$ and magnetic latitude between 0° and 35°. This range of parameter space seems well supported by

Figure 5. Figure 6a shows the raw number of events in 0.5M bins from 5 to 10. Panel b shows the number of observations (number of instrument cycles) obtained in each bin, effectively the observation time. Panel c normalizes the raw number of events in panel a by the effective observation time. In panel c, the peak bin is assigned a normalized rate of 1 while the other bins are scaled according to the number of events divided by the normalized observation time.

Noting that Figure 6c shows the majority of events in this study lie in the range 5.5 < M < 7, we determined the distribution of wave signature events by 45-degree longitude bins in Figure 6d in this same range of M. Panel e shows the number of observation spectra for each longitude bin for M = 5.5 to 7. Panel f shows the number of events normalized by the effective observation time. As is clear from both Figures 5b and 6e, the time spent in 135° < $\mathrm{Sys_{III}}$ longitude < 270° below M ∼ 7 is very limited. By itself, this is reason to believe the small number of events in this longitude range is likely an observational bias. To some extent, Figure 6f reflects this. However, the limited number of events overall and the orbital bias should be reason to view 6f with caution. Figure 5 on its own gives a reasonable impression on where these wave signatures are found.

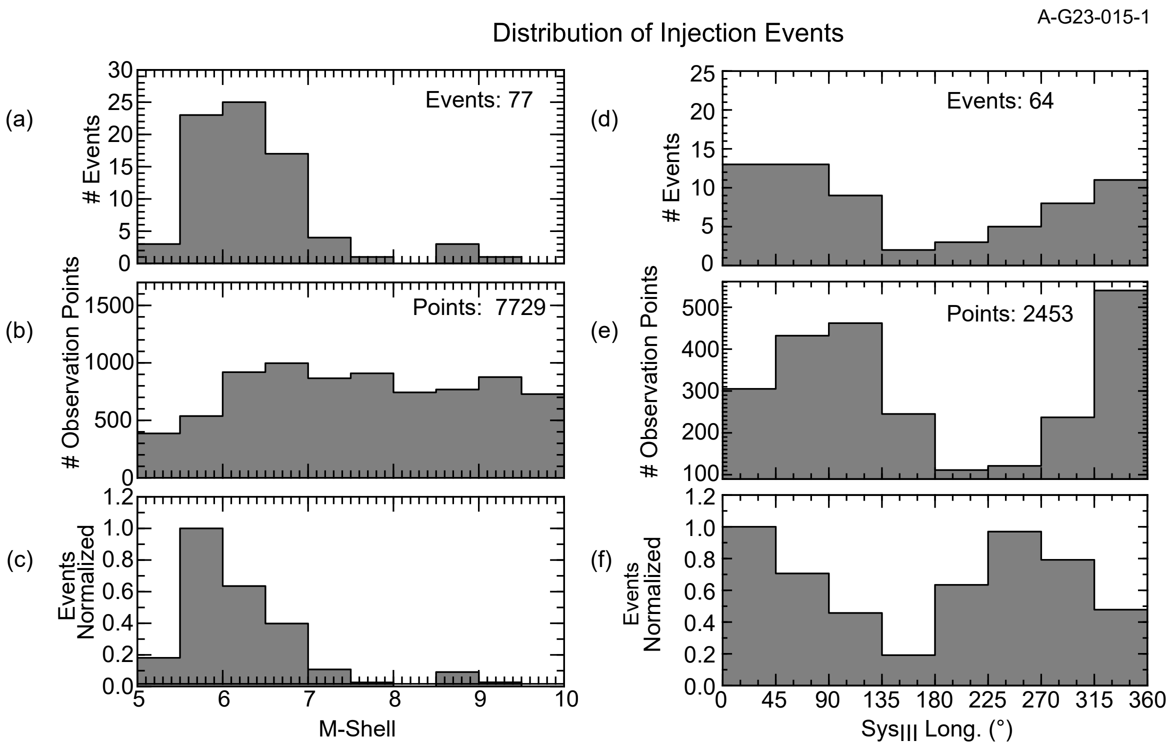

Figure 6: *Distribution of wave signatures of injection events observed in the Juno Waves data (a-c) by M-shell and (d-f) by Sys_{III} longitude. (a) Number of injection signatures vs. M shell for 5 < M < 10. (b) Number of wave spectra observed in each M shell bin. (c) Number of injection signature events normalized by the number of wave spectra (see text). (d) Number of wave injection signatures vs. System III longitude for 5.5 < M < 7. (e) Number of wave spectra observed in each longitude bin. (f) Number of wave signature events normalized by the number of spectra in the bins.*

It should be noted that this is not an exhaustive study for several reasons: 1) the trajectory has not provided uniform coverage of the region of the Io torus and near-Jupiter space,

2) there is likely some bias in the visibility of events based on receiver bandwidth and other phenomena that could mask these events, and 3) the study did not rely primarily on changes in the magnetic field intensity (as shown in Figure 1) but on plasma wave indicators. The events identified are found at mid-latitudes within about 8 R_J of Jupiter's rotational axis ($\rho < 8$ R_J). These are outside M = 5 on field lines threading the Io torus, but notably, several are inside Io's M-shell.

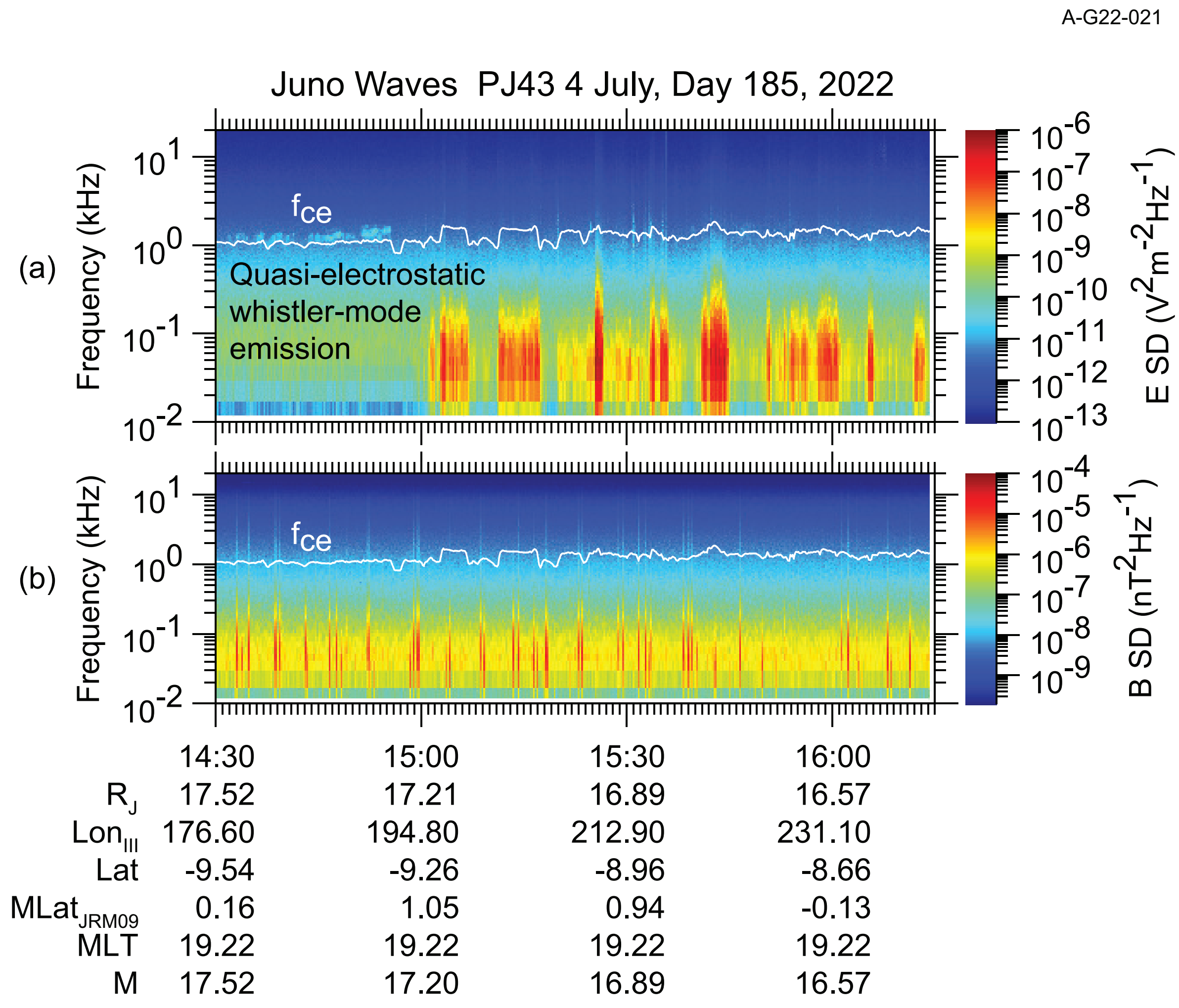

Figure 7: *Distant injections showing quasi-electrostatic waves and enhancements in the Jovian magnetic field as seen in* f_{ce}. *(a) Electric field spectrogram covering 100 Hz to 20 kHz. (b) Magnetic field spectrogram for the same frequency range. The white trace is* f_{ce} *based on the measured magnetic field intensity.*

If one assumes centrifugal interchange as the driver for these injections, one is worried by the existence of several of these events inward of Io, as interchange is thought to proceed outward from Io. For example, Hill (1976) states that the interchange instability requires the plasma content of a unit magnetic flux tube be a decreasing function of distance from the spin axis. However, Mauk et al. (2020) showed evidence of injections inward of Io based on energetic ion observations with distinct temporal variability, so ours would not be the first examples of these so close to Jupiter. And, the plasma dynamics in the inner torus may be less straightforward than expected. For instance, some studies suggest the possiblity of outward radial convection, including in the inner torus, in certain circumstances, maybe paving the way for the possibilty of injection events (cf. Russell et al., 2000; Cowee et al., 2005a,b). The older, larger scale injections reported by Haggerty et al. (2019) were observed at high latitudes on field lines threading the Io torus, but beyond Io's M-shell. The difference between these larger scale injections and the smaller, fresh ones presented here and their mutual relationships, if any, are unresolved. One possibility is that the large-scale events form farther out in the magnetosphere and pressure balance increases their extent as they move inward. The smaller features presented herein, are presumably fresh and likely form at significantly smaller radial distances.

We have identified the events discussed in this paper as indicators of injections. Similar to injections reported using Galileo and Cassini, observations these events include intensified plasma waves for brief intervals. Using the corotation speed at Io's orbit of 74 km/s and ignoring the azimuthal speed of Juno, the one- to few-minute durations suggest a size scale for these events of a few to several thousand km. The events shown herein typically are not accompanied by intensifications or depressions of $|B|$ as is typically seen in the Galileo and Cassini observations. Figure 7 shows an example of a series of injection events observed farther out in the magnetosphere (~ 17 R_J and at the magnetic equator). The injections are highlighted by bursts of quasi-electrostatic whistler mode waves, suggesting oblique propagation, as well as enhancements in the magnetic field. It may be that the mid-latitude location of the events studied herein contributes to the lack of diamagnetic effect. Alternately, it could be that the δB is too small to detect in the presence of the very strong background field. The intensification of waves in the whistler-mode frequency range ($f < f_{ce}$ and $< f_{pe}$ where known) is consistent with anisotropic distribution functions associated with adiabatic inward diffusion driven by centrifugal interchange. Given the often discrete nature of these emissions and their quasi-electrostatic nature, we're tempted to identify at least part of the spectrum as obliquely-propagating chorus. The identification of the low-frequency cutoff for some of the events as the z-mode cutoff suggests other events consist of z-mode emissions. Such emissions are commonly observed in Jupiter's inner magnetosphere (Menietti et al., 2021). A decrease in the plasma density may be responsible for the disruption of the first ECH band, although clear identification of f_{pe} within many of the events is difficult. Unfortunately, penetrating electrons and the short durations of the events make it challenging to find evidence of the events in the charged particle data, although Figure 4 is one example.

5 Conclusions

The Juno Waves instrument provides observations of wave signatures that appear to be evidence for injection events in the inner Jovian magnetosphere. Many of the events studied do not have all of the attributes of depleted, inward-moving flux tubes that have been previously observed at Jupiter such as increases or decreases in the magnetic field intensity and corresponding changes in the plasma distribution within them. The latter has to do with the intense radiation enviroment which precludes interpretation of the JADE data. However, we argue that they are of a similar class to others observed at larger distances. Given work at Saturn (Kennelly et al., 2013), this study focuses on what are thought to be fresh events, since their underlying plasma distributions have not had time to disperse to a large extent. As such, this work does not include larger, older injection events previously reported. The events in this study:

- occur at mid-latitudes on field lines threading the Io plasma torus between M of 5 to 10, peaking near M=6,
- are sometimes found inward of the Io M-shell,
- are characterized by quasi-electrostatic waves below f_{ce} and also below f_{pe} when this is known,
- are brief, of the order of one to a few minutes,
- exhibit significant structure in some events where high resolution burst observations are available, suggestive of chorus,
- sometimes have a low-frequency cutoff apparently consistent with the z-mode.

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