JUPITER LONG DISPERSION LIGHTNING WHISTLERS THAT PROPAGATE THROUGH THE IO TORUS: JUNO OBSERVATIONS

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Abstract

The detection of lightning whistlers in planetary magnetospheres can provide valuable information about the properties of both the source lightning and the plasma environment along the whistler propagation path. The Juno spacecraft, with its multiple polar orbits, is providing a new opportunity to examine the properties of lightning and lightning whistlers at Jupiter, and to investigate the density characteristics of the plasma through which the whistlers propagate. Juno Waves has detected thousands of lightning whistlers below 20 kHz with dispersive curve time scales of a few to 10s of ms (dispersion constants D $<$ 2 sec/Hz$^{1/2}$). The small dispersion constants suggest a short propagation path from the lightning source to the spacecraft (lightning located directly below the spacecraft), which has been verified from wave propagation direction analysis. During some orbits, Juno Waves has also detected lightning whistlers exhibiting longer dispersion times of a few seconds (D $>$ 500 sec/Hz$^{1/2}$), similar to the whistlers detected by the Voyager spacecraft during its flyby of Jupiter. These longer dispersion whistlers are detected when Juno is located on magnetic field lines that map back to the equator near the orbit of Io.

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Initial analysis of these whistlers finds that D can sometimes vary by a factor of 2 in a short period of time, suggesting large variation in the plasma density on adjacent field lines. Observations of these longer dispersion whistlers are presented and the conditions under which these emissions are detected, the properties of the emissions, and the role the Io torus plays to produce the observed spectral characteristics of these dispersion whistlers discussed.

1 Introduction

Lightning whistlers observed in planetary magnetospheres exhibit a distinct frequency dispersion (decreasing frequency with increasing time) when plotted on a frequency–time spectrogram (see Figures 1, 2, 3, and 6 for examples of this characteristic dispersion for lightning whistlers detected at Jupiter by the Juno Waves instrument). The dispersion can be described by

$$t = D/f^{(1/2)} + t_0 \tag{1}$$

where t is the arrival time of the emission at frequency f, t_0 is the time of the source lightning initial flash, and D is the dispersion constant that depends on the integrated plasma density along the propagation path of the whistler (larger value for D corresponds to encountering a higher integrated density, Eckersley, 1935). D can be solved by plotting $1/f^{(1/2)}$ vs the measured arrival time of the whistler at that frequency, and fitting a straight line to the resulting points (see Figure 5 for examples of this method). The determination of D can provide valuable information about the source of the lightning and the plasma environment along the propagation path.

The presence of lightning at Jupiter was first verified by the Voyager 1 spacecraft when the Plasma Wave Subsystem detected lightning whistlers during the flyby of Jupiter (Gurnett et al., 1979; Scarf et al., 1979). A total of 167 lightning whistlers were detected during three general periods of time as Voyager passed through the Io Torus and these whistlers exhibited frequency dispersion that lasted a few hundred milliseconds to a few seconds (Gurnett et al., 1979; Kurth et al., 1985). The whistlers detected by Voyager exhibited different average dispersion constants for each of the three periods they were observed. For the first period, D averaged ∼300 sec/$Hz^{1/2}$), the second D ∼70 sec/$Hz^{1/2}$, and the third ∼500 sec/$Hz^{1/2}$ (Kurth et al., 1985). This variation in the observed dispersion was used along with density models of the Io torus (Bagenal et al., 1985) to investigate the plasma distribution along the magnetic field line that connects the lightning source to Voyager and to determine the hemisphere of Jupiter in which the lightning was occurring (Gurnett et al., 1979; Kurth et al., 1985; Menietti & Gurnett, 1980; Tokar et al., 1982b,a).

2 Juno observations

The Juno spacecraft, with its multiple polar orbits is providing a new opportunity to examine the properties of lightning whistlers at Jupiter, and to investigate the density characteristics of the plasma through which these whistlers propagate. This paper primarily uses data from the Juno Waves instrument (Kurth et al., 2017). The Juno Waves Instrument consists of a single electric dipole antenna mounted perpendicular to the Juno spin axis allowing measurement of wave electric fields from ∼50 Hz to 41 MHz, and a body–mounted search coil magnetometer oriented parallel to the Juno spin axis that measures wave magnetic fields from ∼50 to 20 kHz. The Waves instrument operates in a survey mode that usually obtains an electric and magnetic field spectrum every one second near perijove. The survey data is processed on board to produce spectra with ∼18 logarithmically spaced channels per decade at frequencies below ∼3 MHz. Waves also obtains data in a number of burst modes that send the raw digitized waveforms from the various receivers to the ground.

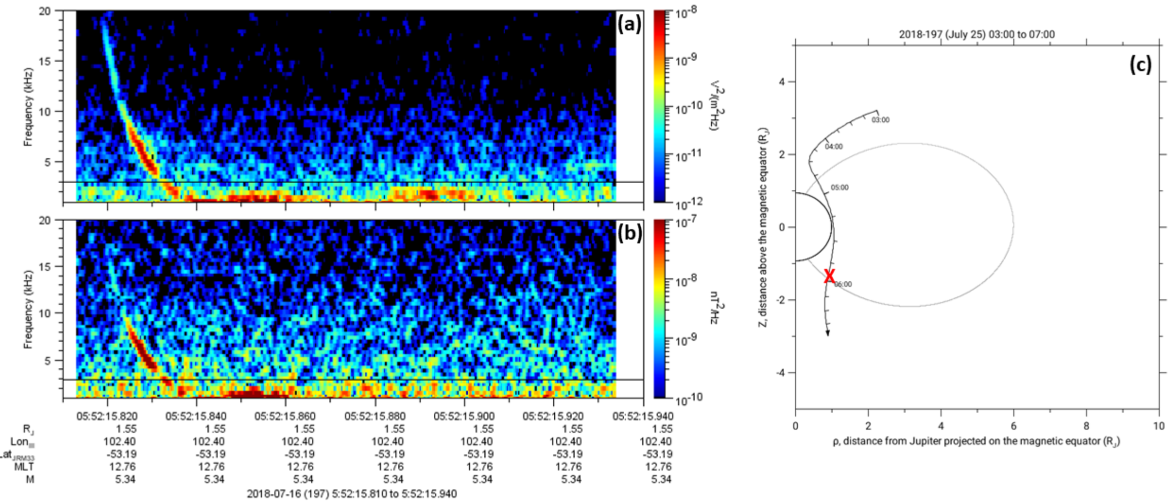

Figure 1: *Example of a shorter dispersion whistler detected by Juno on July 16, 2018. Panel (a) shows the wave electric field spectrogram and panel (b) the wave magnetic field spectrogram obtained by performing a 256 point fft on the LFR–Lo waveform burst data. Panel (c) shows the trajectory of Juno in the Jupiter magnetic Rho vs. Z coordinate system determined using the JRM33 and CS2020 models.*

Most of the Jovian whistlers are detected with the Juno Waves Low Frequency Receiver (LFR–Lo) that covers the frequency range from ∼50 Hz to ∼ 20 kHz. This receiver obtains 122.88 ms long electric and magnetic field waveform snapshots sampled at 50 kHz, typically on a cadence of once per second. Thousands of lightning whistlers have been observed by Juno Waves in the LFR–Lo Receiver, with the majority observed when Juno is very near Jupiter (<2 R_J), and exhibit frequency dispersion with times scales up to a few 10s of ms (D typically less than 1 sec/$Hz^{1/2}$) (Imai et al., 2018, 2020; Kolmašová et al., 2018). Figure 1 shows an example of this type of Jovian lightning whistler (named Jovian Rapid Whistlers by Kolmasova) detected by Juno. Panel (a) shows the wave electric field spectrogram and panel (b) the wave magnetic field spectrogram obtained by performing a 256 point sliding Fast Fourier Transform (FFT) on the LFR–Lo waveform burst data. The lightning whistler is observed from about 05:52:15.820 to 05:52:15.837 UTC and between ∼15 kHz and 2 kHz. Panel (c) shows the trajectory of Juno in the Jupiter magnetic Rho vs. Z (Z=0 is the magnetic equator) coordinate system determined using the JRM33 and CS2020 models (Connerney et al., 2020, 2022). The red X shows the approximate location of Juno when the whistler was detected.

The Juno Waves electric and magnetic antennas are mounted perpendicular to each other with the search coil magnetometer mounted parallel to the Juno spin axis. By comparing the coherence and phase difference between the simultaneously measured electric and magnetic field waveforms, the direction of propagation (parallel or anti–parallel) compared to the measured Jovian magnetic field (as determined by the Juno Magnetic Field instrument, Connerney et al., 2017) can be determined for various emissions, including lightning whistlers (see Kolmašová et al., 2018, for a detailed description of this technique). For the Jovian Rapid Whistlers detected near perijove like the one shown in Figure 1 this analysis has shown that the whistlers are propagating up from Jupiter from directly below the spacecraft, in agreement with the observed small value of D.

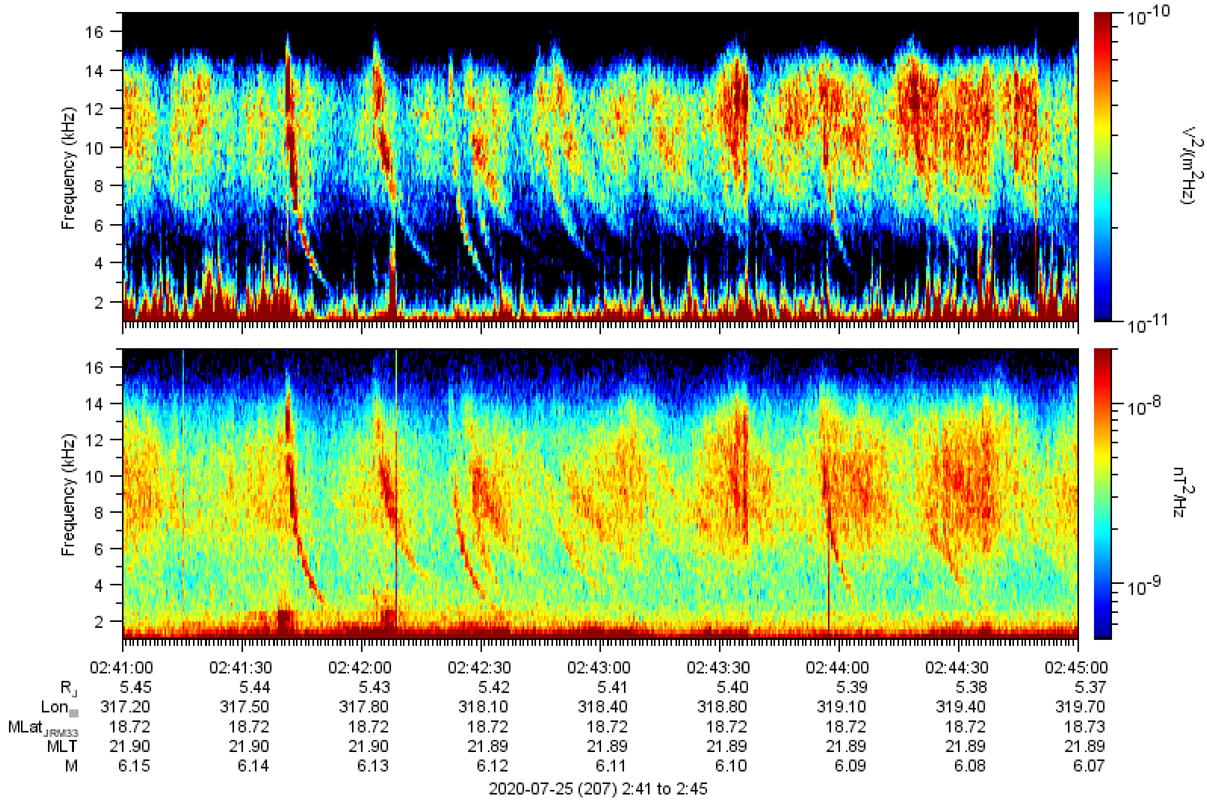

Figure 2: *Examples of a long dispersion whistlers detected by Juno on July 25, 2020. The top panel shows the wave electric field spectrogram and the bottom panel the wave magnetic field spectrogram obtained by performing a 256 point fft on the LFR–Lo waveform burst. A hiss–like emission from about 7 to 14 kHz is also observed during this period that limits the ability to resolve weaker lightning whistlers.*

During some orbits, Juno Waves has also detected lightning whistlers exhibiting longer dispersion times of a few seconds (D > 500 sec/Hz$^{1/2}$), similar to the whistlers detected by Voyager. All of these longer dispersion whistlers were detected when Juno was located on magnetic field lines that map back to the equator near the orbit of Io (M shell values of around 6). "M shell" is similar to the dipole L shell parameter but incorporates the fact that the equatorial crossing distances of the Jovian magnetic field are strongly affected by the stretched field lines caused by the Jovian current sheet. The M shell distance mapping used in this paper is derived using the JRM33 and CS2020 models. Figures 2 and 3 show two periods from July 25, 2020 (Perijove 28) when these longer dispersion whistlers were detected by the Waves LFR–Lo receiver. The top panels of both figures are the electric field spectrograms and the bottom panels are the magnetic field spectrograms obtained by performing a 256 point sliding fft on the LFR–Lo waveform burst data. Although the data shown in Figures 2 and 3 are plotted to appear to be nearly continuous in time, it should be remembered that the LFR–Lo waveforms are 122.88 ms long and obtained once per second, so there is actually an approximate 877 ms data gap between each snapshot.

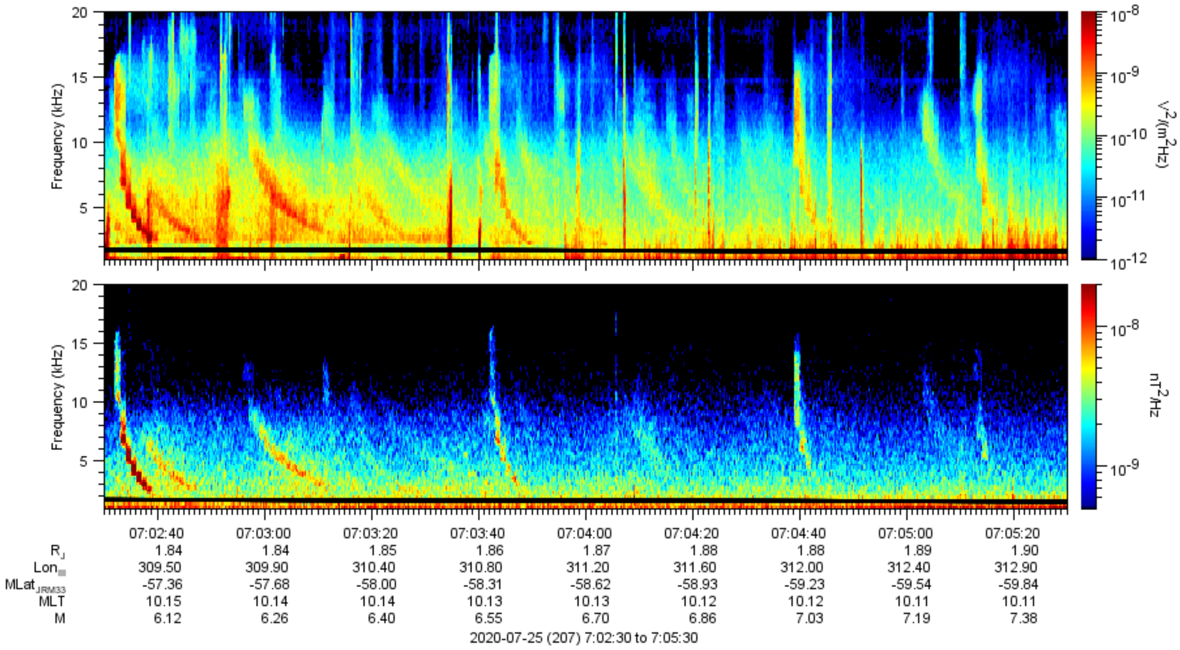

Figure 3: *Examples of a long dispersion whistler detected by Juno on July 25, 2020. The top panel shows the wave electric field spectrogram and the bottom panel the wave magnetic field spectrogram obtained by performing a 256 point fft on the LFR–Lo waveform burst data.*

Figure 4 shows the trajectory of Juno in the Jupiter magnetic Rho vs. Z coordinate system determined using the JRM33 and CS2020 models for the periods of Figures 2 and 3. The red A and B show the approximate locations of Juno when the whistlers were detected for the periods shown in Figures 2 and 3. The magnetic field line that passes through the magnetic equator at 6 R_J is also plotted to provide a representative field line that passes through the Io torus. For the period shown in Figure 2, Juno was located in the northern hemisphere ($\sim 18^\circ$ north magnetic latitude) at about 5.4 R_J from Jupiter. During this period, Juno observed a strong hiss–like emission from about 7 to 14 kHz that is often detected on field lines that map to the Io torus. At least ten lightning whistlers are also present, though the background hiss–like emission makes the determination of the exact number of whistlers difficult. The whistlers detected during this period exhibit frequency dispersion that lasts from a few seconds to about 10 seconds. Panels (a) and

(b) of Figure 5 show the determination of D for the whistlers that start at 02:41:21UTC (D=1020 sec/Hz$^{1/2}$) and 02:42:23 UTC (D=1120 sec/Hz$^{1/2}$). Determination of D for the other whistlers detected during this period range from about 900 to 2000 sec/Hz$^{1/2}$. The large values of D suggests that the source lighting was in the southern hemisphere for these whistlers, and that the whistlers passed through the high density plasma in the Io torus before arriving at Juno.

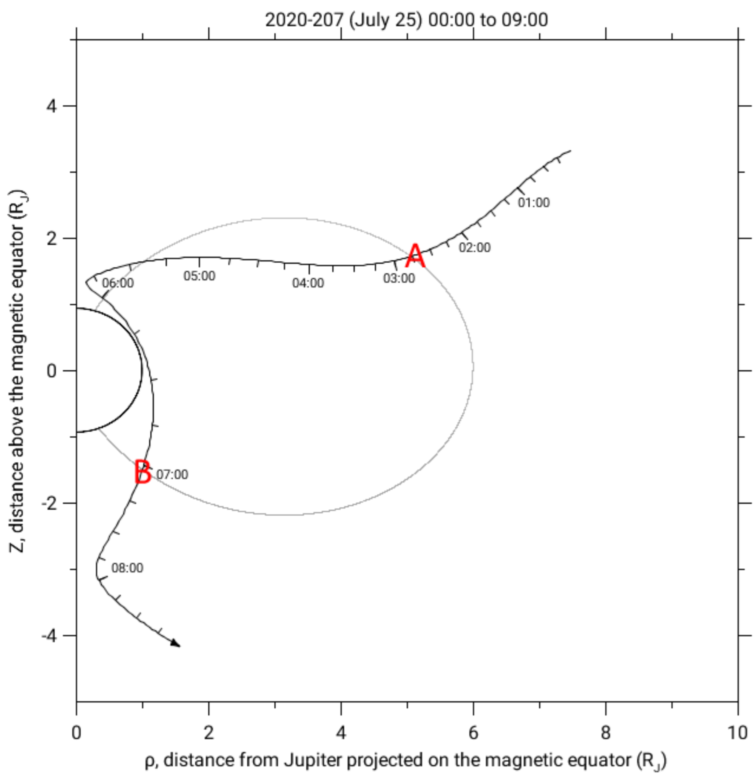

Figure 4: *The trajectory of Juno from 00:00 to 0900 UTC on July 25, 2020 in the Jupiter magnetic Rho vs. Z coordinate system determined using the JRM33 and CS2020 models. The red A and B show the approximate location of Juno when the whistlers shown in Figures 2 and 3 were detected. The magnetic field line that passes through the magnetic equator at 6* R_J *is plotted to estimate field lines that map to the Io torus.*

For the period shown in Figure 3, Juno is located at much higher magnetic latitudes ($\sim -58°$) in the southern hemisphere and much closer to Jupiter (<1.9 R_J). Typically, at this distance from Jupiter, the majority of the lightning whistlers detected by Juno are from lightning sources directly below the spacecraft and have dispersion that lasts just a few to tens of ms (e.g., the whistler shown in Figure 1). However, the lightning whistlers shown in Figure 3 exhibit dispersion times of at least a few seconds. Panel (c) of Figure 5 shows the determination of D for the whistlers that start at 07:02:32UTC (D=581 sec/Hz$^{1/2}$). Determination of D for the other whistlers detected during this period find that the majority range from about 500 to 650, with a few as high as 1750 sec/Hz$^{1/2}$. These large values for D suggest that the source lighting was in the northern hemisphere and the whistler passed through the higher density Io torus before arriving at Juno.

The wave propagation direction analysis discussed above was performed on the whistlers

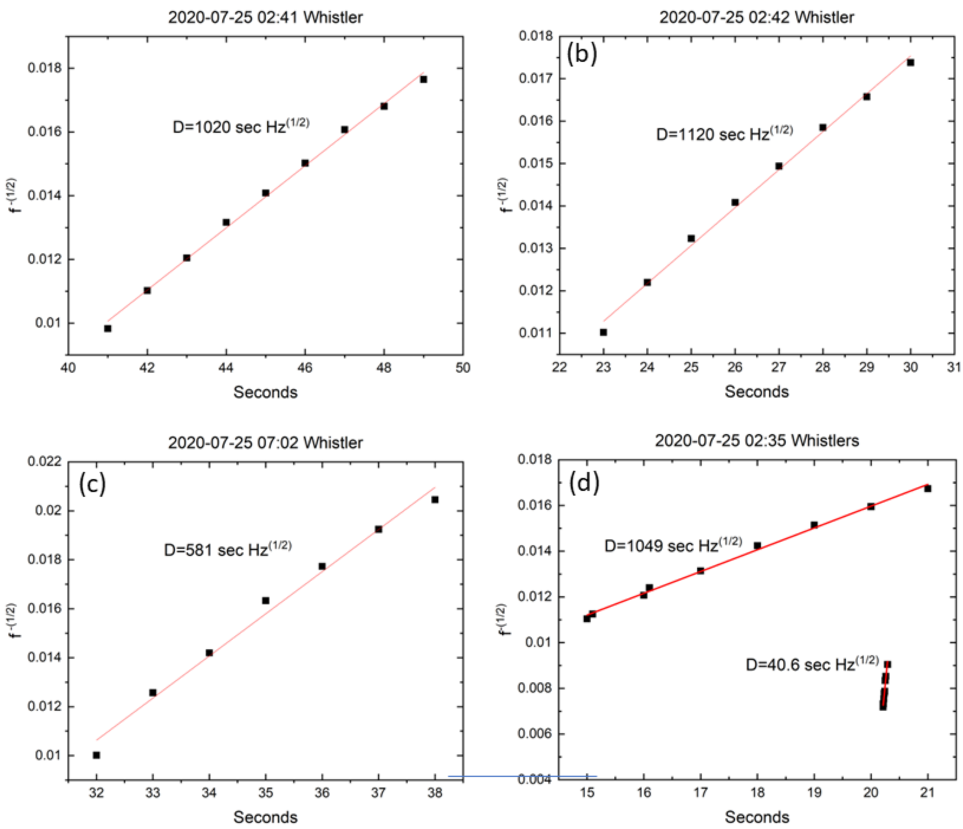

Figure 5: *Plots of $f^{-(1/2)}$ versus the arrival time for two of the whistlers in Figure 2 (panels (a) and (b)), one in Figure 3 (panel (c)), and two in Figure 6 (panel (d)). The x–axis shows the time to the nearest second of the burst capture that contains the whistlers. The slope of the best–fit straight line (red) provides 1/D.*

detected during these two periods. For the examples shown in Figure 2, the long dispersion whistlers were found to be propagating northward, away from the magnetic equator and the Io torus, suggesting the lightning source was located in the southern hemisphere of Jupiter. For the whistlers shown in Figure 3, they were found to be propagating southward towards Jupiter (again away from Io torus), suggesting a lightning location in the northern hemisphere. Both of these results agree with the measured large values of D ($>$500 sec/Hz$^{1/2}$) and the resulting requirement that the whistlers must have propagated through a region of higher plasma density. For every example of the longer (D $>$ few hundred) dispersion whistlers examined, the propagation analysis has shown the lightning originated in the opposite hemisphere from the location of Juno.

Figure 6 shows two lightning whistlers detected about six minutes earlier than those shown in Figure 2. These two whistlers are a rare example (only two cases have been found so far in the Juno Waves data) of whistlers detected in the same time period that are propagating in opposite directions relative to the background magnetic field. These two whistlers exhibit very different dispersion times and frequency ranges. The top two panels show the wave electric field and magnetic field spectrogram respectively obtained by performing a 256 point fft on the LFR–Lo waveform burst data. The third panel shows the phase difference between the electric and magnetic channels. This phase difference and the sign

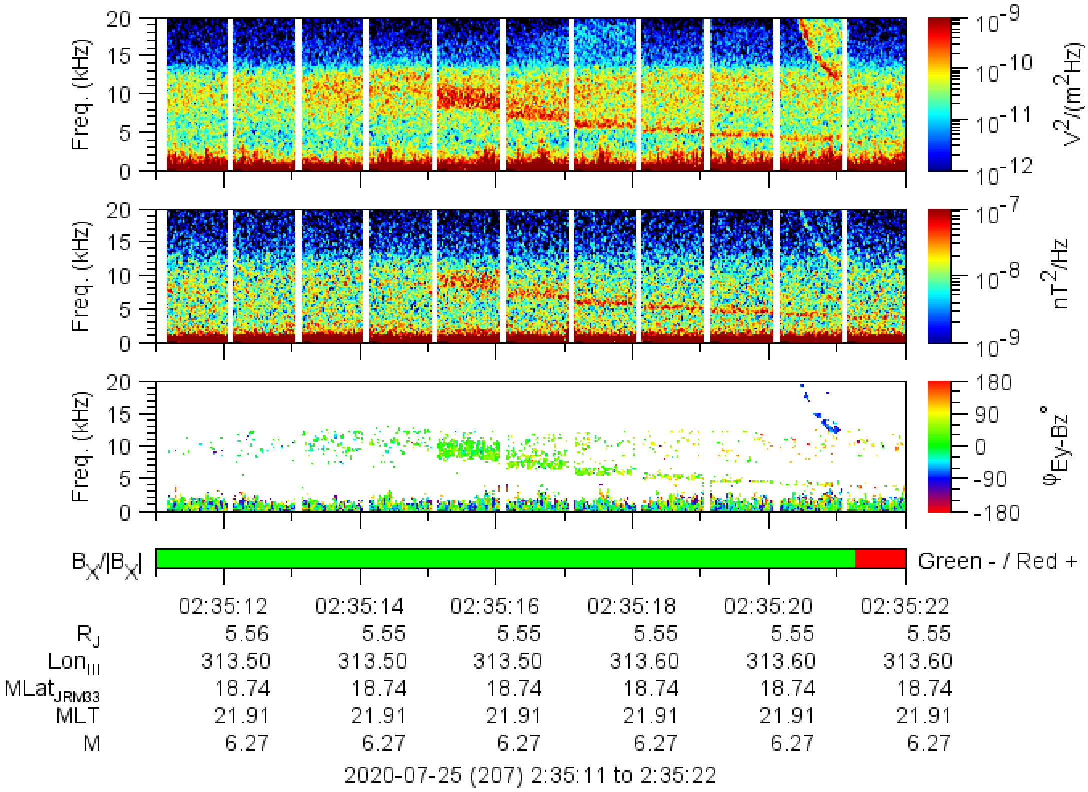

Figure 6: *Example of long and medium dispersion whistlers detected at the same time by Juno on July 25, 2020. The top panel shows the wave electric field spectrogram and the second panel the wave magnetic field spectrogram obtained by performing a 256 point fft on the LFR–Lo waveform burst data. The third panel shows the phase difference between the electric and magnetic measurements and is used along with the bottom panel to determine if the whistler is propagating in a direction parallel or anti–parallel to the Jovian magnetic field as described in Kolmašová et al. (2018).*

of the x component of the background magnetic field in spacecraft coordinates (bottom panel green/red bar), provides the parallel or antiparallel to Jupiter's field direction of propagation of the whistlers (Kolmašová et al., 2018). To better show the structure and propagation parameters of these whistlers, the ∼128 ms of burst data that is obtained every second is expanded to cover about 900 ms when plotted in the spectrogram. A long dispersion whistler similar to the ones shown in Figures 2 and 3 is observed from about 02:35:15 to 02:35:22 from about 10 kHz to 3 kHz. A second whistler is captured in a single burst snapshot at about 02:35:20 and is observed for about 80 ms from about 20 kHz to 12 kHz. Although this whistler is much shorter than the long dispersion one (∼80 ms vs 7 seconds), it is much longer than the typical few ms to a few 10s of ms for the Jovian Rapid Whistlers shown in Figure 1. Panel (d) of Figure 5 shows the determination of D for these two whistlers (1049 sec/Hz$^{1/2}$ for the first and 40.6 sec/Hz$^{1/2}$ for the second). Juno is located at the northern edge of the Io torus during this period (approximately at the red A in Figure 4), and as discussed above, the large value of D for the first whistler suggests that the source lightning is in the southern hemisphere and the whistler has propagated through the high density Io torus to reach Juno. The much smaller value of D for the second whistler suggests a lightning source in the northern hemisphere due to the required smaller integrated density along the propagation path. This difference in source locations is verified by the phase difference shown in the third panel between these two whistlers ($\sim 0°$ vs $\sim -110°$), which demonstrates that these two whistlers are propagating in opposite directions relative to the background magnetic field. The long dispersion whistler is propagating anti–parallel to the magnetic field (from the direction of the Io torus/equator) and the shorter dispersion whistler is propagating parallel to the magnetic field (from the northern hemisphere of Jupiter towards the equator).

3 Discussion and conclusions

Juno has detected thousands of lightning whistlers at Jupiter, providing new insights on the properties of the source lightning (e.g., location and flash rates), the density and uniformity of the ionosphere, and the density along the whistler propagation path. The majority of the whistlers detected by Juno have values of $D < 2$ sec/Hz$^{1/2}$, suggesting that source lightning is below the spacecraft with a short propagation path from the lightning source to Juno. On a number of orbits (12 orbits out of 46 that have been examined to date), longer dispersion whistlers ($D > 500$ sec/Hz$^{1/2}$) have also been detected, along with two medium dispersion whistlers ($D \sim 40$ sec/Hz$^{1/2}$). As the examples shown in Figures 2 and 3 demonstrate, these longer dispersion whistlers can be detected when Juno is at lower latitudes (near the Io torus) and at higher latitudes (closer to Jupiter). However, these whistlers are only observed during periods when Juno is located on magnetic field lines that map to the equator in the region of the Io torus. Although Juno usually crosses field lines that map to the torus at least twice every orbit, long dispersion whistlers are detected in only a limited number of orbits. This is likely due to two main factors. First lightning must be occurring in the correct Jovian latitude and longitude such that the magnetic field line maps from the lightning source to Juno. Magnetic field lines that pass through the Io torus map to Jovian latitudes of about 50 to 80°. These latitudes have been found to often contain lightning (Brown et al., 2018; Kolmašová et al., 2018), however the lightning must also be occurring at the longitude Juno is currently sampling. Second, the other naturally occurring plasma waves detected by Juno must be weak enough (or the lightning whistlers strong enough) such that the lightning whistlers can be detected. Often a strong hiss–like emission (see Figure 2) is detected when Juno is on field lines that map to the Io torus, limiting the ability to detect other weaker emissions during those periods.

The variation in D shown in Figure 5 between the whistlers in Figure 2 ($D \sim 1000$) and Figure 3 ($D \sim 600$) suggests that the whistlers in Figure 2 encountered a larger integrated plasma density along their propagation path than the whistlers in Figure 3, even though Juno was on magnetic field lines that mapped to similar distances from Jupiter at the equator (M shell ~ 6.1) during both periods. Because the source lightning for both periods was determined to be located in the opposite hemisphere than the Juno location, D would have been expected to be larger for the whistlers in Figure 3 due to the longer propagation path if the Io torus density was symmetric and constant. However, the larger value of D for the period in Figure 2 shows that there were variations in the integrated plasma density for similar M shell, possible due to Local Time, longitudinal, or possibly temporal variations. Furthermore, the variation in D during each period discussed in this paper (900 to 2000 sec/Hz$^{1/2}$ for the first period, and 500 to 650, with a few as high as 1750 sec/Hz$^{1/2}$ for the second) suggests small–scale variations in the density are also present along similar propagation paths.

Figure 6 shows the rare example of Juno detecting lightning whistlers propagating in opposite directions at the same time. This implies that lightning is occurring simultaneously in both the northern and southern hemispheres near the footprints of Juno's field line. The large number of long dispersion whistlers (southern hemisphere lightning) detected compared to just the two medium dispersion whistlers (northern hemisphere lightning) may suggest a more lightning active storm in the south. However, Juno may be missing many medium dispersion events due the $\sim$13% data coverage of the LFR–Lo burst data (high dispersion whistlers are detected in multiple burst snapshots while the medium dispersion whistlers are detected in only one snapshot). This variation in density plus statistics of the medium and longer dispersion whistlers will be studied in more detail in a future work.

Other future work will include determining the dispersion constants for all the long dispersion whistlers detected by Juno, investigating this variation of D with the various density models, and the possible parameters that may affect the Io torus density, including System III Longitude, Local Time, Juno's location with respect to the location of Io, radial distance, and temporal variations in the Io torus density.

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