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[1] Jovian quasiperiodic (QP) radio bursts are suspected to be associated with relativistic particle accelerations occurring with a quasiperiodicity between a few minutes and a few tens of minutes in Jupiter's polar magnetosphere. Understanding the excitation and propagation of QP bursts could help us to better understand this periodic energization process. A first necessary step is to measure the wave mode, source location, and directivity of QP bursts. For that purpose, we performed a statistical analysis of goniopolarimetric measurements of QP bursts made with the Radio and Plasma Wave Science investigation (RPWS) onboard Cassini spacecraft during the Jupiter flyby of 2000–2001. We studied two groups of QP bursts on 22 and 23 December 2000, and we found consistent source directions about 50 R_J north of Jupiter with an error bar ≤20 R_J. Statistics of the Stokes parameters indicate that QP bursts are partially left-handed polarized ($V > 0$, Q, $U < 0$). Together with the direction finding results, these polarization statistics imply that QP bursts observed from low latitudes are L-O mode waves which have been excited in the northern polar source, have propagated toward high latitudes, and then got refracted equatorward in the magnetosheath. Dependence of the Stokes parameters on the longitude indicates that QP bursts are excited within a particular phase range of the planetary rotation, when the system III longitude of the sub-solar point is between 260° and 480°. This implies that QP radio bursts and associated particle accelerations always occur within the same rotational sector, suggesting the existence of a recurrent magnetospheric disturbance at the planetary rotation period. Finally, we propose a possible scenario for the generation and propagation of QP bursts by combining the results of the present study with those of other recent observational and theoretical studies.

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1. Introduction

[2] Jovian quasiperiodic (QP) radio bursts are impulsive VLF radio bursts occurring quasiperiodically at intervals of a few minutes to a few tens of minutes. They were discovered in Voyager data [*Kurth et al.*, 1989]. Their occurrence characteristics have been investigated in detail using observations made by the Ulysses spacecraft [*MacDowall et al.*, 1993]. During Ulysses' first flyby of Jupiter in 1992, two classes of QP bursts were identified: one was observed in the 1–50 kHz range at low latitudes during the inbound phase, and the other was observed in the 1–200 kHz range at high latitudes during the outbound phase. Statistical analysis based on periodograms revealed that a 30–50 min quasiperiodic modulation affects the amplitudes of both classes of QP bursts [*Kimura et al.*, 2011a]. Although a fair number of observations were recorded in the inbound phase, the spacecraft attitude configuration prevented Ulysses to perform a goniopolarimetric (GP) study of QP bursts observed at low latitudes. Thus, their wave mode and source location could not be determined reliably.

[3] Conversely, when the spacecraft was at high southern latitudes (about −40°) near Jupiter's dusk terminator during the outbound pass, GP analyses revealed a right-handed (RH) circular polarization and a source altitude of at least a few R_J (R_J: Jovian radius = 71,492 km) above the south pole [*MacDowall et al.*, 1993].

[4] For radio emissions emitted from Jupiter's magnetic circumpolar regions, the polarization state relative to the

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k-vector and the wave mode defined with respect to the magnetic field in the source are related to each other as follows: waves emitted from the northern hemisphere with a given circular polarization (left-handed – LH – or right-handed – RH) are detected with the same polarization sense, whereas waves emitted from the southern hemisphere with a given circular polarization are detected with the opposite polarization sense. Thus, the above observed RH circularly polarized waves originating from a southern source suggest that the emission was on the LH ordinary – or L-O – mode.

[5] In the outbound phase, Ulysses observed QP bursts correlated with relativistic electron outbursts with energies larger than 9 MeV, both recurring with a ~40-min periodicity [*MacDowall et al.*, 1993; *Simpson et al.*, 1992; *McKibben et al.*, 1993; *Zhang et al.*, 1995]. Analysis of particle measurements indicated that these energetic electron bursts were accelerated outwards from the Jovian south polar region during typical intervals of 120 s [*McKibben et al.*, 1993]. *Zhang et al.* [1995] also detected relativistic proton populations with an anisotropy in the outward direction relative to Jupiter. These results suggest that QP radio bursts may be related to periodic electron acceleration to high energies, but the acceleration process as well as the detailed relationship with QP bursts remain unclear.

[6] Characteristics and occurrence of QP bursts observed at high latitudes were studied by Ulysses during its second encounter with Jupiter in February 2004 [*Kimura et al.*, 2008]. The spacecraft approached within ~0.81 AU of Jupiter, incoming from high northern latitudes (~+80°) and passing through the equator during the encounter. Analysis of QP bursts occurrence versus Central Meridian Longitude (CML) and magnetic latitude (MLAT) of the observer showed that most of the bursts were observed at high magnetic latitudes (MLAT >+30°) in the northern hemisphere. A ray tracing analysis concluded that these bursts were emitted on the L-O mode from a source located at an altitude of 0.4–1.4 R_J along $L > 30$ field lines.

[7] Characteristics of QP bursts observed at low latitudes were studied using Galileo and Cassini spacecraft data [*Hospodarsky et al.*, 2004; *Kimura et al.*, 2010]. Based on simultaneous observations of QP bursts by Galileo and Cassini *Hospodarsky et al.* [2004] showed they have a strobe-like behavior and a broad beaming. They also performed a GP analysis of one QP burst event and found apparent directions of arrival (DoA) very distant from the direction of Jupiter and consistent with a source in the magnetosheath. In that region, local cyclotron (f_c) and plasma (f_p) frequencies are much lower than measured QP burst frequencies. This discrepancy led the authors to suggest that QP bursts were produced close to Jupiter but scattered during their propagation through the magnetosheath, where the plasma frequency can be up to twice larger than in the surrounding solar wind. Measured DoA would thus correspond to the exit points of QP bursts from the magnetosheath into the solar wind. However, no statistical study of GP results at low latitudes was performed beyond this case study.

[8] Occurrence statistics by *Kimura et al.* [2010] revealed the existence of a "shadow zone", where QP bursts cannot be detected, within 30 R_J from Jupiter at $|MLAT| < 10°$. A ray tracing analysis suggested the following wave mode, source location, and directivity of the QP radio emissions: (1) RH extraordinary – R-X – mode generated by the Cyclotron Maser Instability (CMI) [*Wu and Lee*, 1979], (2) source located at an altitude of ~10 to 20 R_J above the polar region, (3) source field line with *L*–value >20, and (4) radio emission beaming within "filled cones" if the sources are restricted to a limited range of *L*–shells, or "hollow cones" if the sources extends over a broad range of *L*–shells. These results imply that QP bursts observed at low latitudes are generated at $f \sim f_c$ in the polar regions, from where they propagate to the equatorial region.

[9] *Kimura et al.* [2010] summarized these results by proposing that QP bursts could be produced from two kinds of sources: one at high altitudes ($f \sim f_c$) emitting R-X mode waves, and the other at lower altitudes ($f \sim f_p$) emitting L-O mode waves.

[10] The generation process of QP bursts was investigated in a theoretical study in the frame of the linear cyclotron resonance theory [*Kimura et al.*, 2011b]. Assuming a "ring beam" anisotropy for the relativistic electron beams detected by Ulysses [*McKibben et al.*, 1993], these authors demonstrated that, due to relativistic effects, strong L-O mode waves could be excited with a broad beaming at altitudes where $f \leq f_c$ above the polar regions, whereas the growth of R-X mode waves was not significant. It was also found that these L-O mode waves illuminate space in a way similar to the R-X mode waves from the $f \sim f_c$ surface suggested by *Kimura et al.* [2010], and that they can reproduce the observed shadow zone in the equatorial region. This implies that L-O mode waves with a broad beaming from a high altitude source (where $f < f_c$) are consistent with QP burst occurrence at low latitudes as well as with the CMI generation theory. But, as mentioned above, previous observations by Ulysses and Galileo did not constrain the wave mode of QP bursts observed at low latitudes, due to an inadequate spacecraft attitude or the absence of polarization measurement capability, respectively.

[11] *Kimura et al.* [2011b] also found that relativistic electron beams can directly excite Z-mode waves propagating toward the polar ionosphere, which could be converted to free-space L-O mode waves at a steep density gradient above the polar ionosphere, via the Mode Conversion (MC) process [*Oya*, 1974; *Jones*, 1977]. This is consistent with QP bursts observed at high latitudes, which could have low source altitudes near the $f \sim f_p$ surface as suggested by *Kimura et al.* [2008].

[12] Table 1 summarizes the QP burst source characteristics inferred in the above previous studies.

[13] The conclusion of *Kimura et al.* [2010] in favor of R-X mode waves poses the problem of different emission modes for QP bursts observed at high and low latitudes. This is not a problem for the terrestrial Auroral Kilometric Radiation (AKR), for which the emission mode may change between L-O and R-X modes depending on the source altitude [see, e.g., *Mellott et al.*, 1984, 1986]. These reversals are attributed to MC process from R-X to L-O mode (and vice versa) at the boundaries of the auroral cavity which commonly exists in the auroral acceleration region at Earth [see, e.g., *Calvert*, 1981; *Hilgers*, 1992]. But for Jovian QP bursts, the occurrence of MC seems unlikely because the value of f_p/f_c is significantly lower than unity in and around

Table 1. Summary of Suggested Source Characteristics of QP Bursts

S/C Latitude	Mode	Source Altitude	Frequency	Process	Reference
Low latitude	not known	high (magnetosheath)	$f \neq f_p, f_c$	unknown	*Hospodarsky et al.* [2004]
High latitude	L-O	low (0.4–1.4 R_J)	$f \sim f_p$	MC	*Kimura et al.* [2008]
Low latitude	R-X	high (10–20 R_J)	$f \sim f_c$	CMI	*Kimura et al.* [2010]
Low latitude	L-O	high (5–10 R_J)	$f \leq\sim f_c$	CMI	*Kimura et al.* [2011b]

the strongly magnetized polar source regions. QP bursts excited on the L-O mode at $f \sim f_c$ or $f \leq f_c$ (but in both cases $f \gg f_p$) cannot "see" a cavity boundary even if a steep density gradient is present. Thus they cannot be converted to R-X mode. Direct excitation of both of R-X and L-O modes by the CMI is also unlikely because *Kimura et al.* [2011b] found that, with the considered energetic electron populations, the growth rate of L-O mode waves is larger than that of R-X mode waves at all altitudes. Thus the R-X mode derived in *Kimura et al.* [2010] cannot be explained by either MC or CMI processes. One possible solution of this problem is that L-O mode emission only is produced at all altitudes along the source field line, although its generation process (MC or CMI) is still uncertain.

[14] It should be noted that these considerations remain inconsistent with the results of *Hospodarsky et al.* [2004], who found DoA for QP burst waves significantly far from the $f \sim f_c$ or $f \sim f_p$ surfaces, and thus invoked scattering in the magnetosheath. However, as mentioned above, the GP analysis in *Hospodarsky et al.* [2004] was performed for one event only and the DoA accuracy was not addressed. Thus we need accurate estimates of QP burst DoA at low latitudes, which will then be compared with theoretical source altitudes.

[15] In addition to the existence of quasiperiodic radio bursts and relativistic electron beams, the Chandra X-ray Observatory observed a pulsating X-ray "hot spot" with 45-min. periodicity in Jupiter's northern hemisphere [*Gladstone et al.*, 2002]. This hot spot is located significantly poleward of the main oval, where magnetic field lines are connected to the outermost regions of the magnetosphere. The ~45 min. period suggested a possible relationship with QP bursts and relativistic electron outbursts at a period of ~40 minutes. X-ray spectroscopic observations and related theoretical interpretations suggested that the hot spot is excited by precipitations of relativistic heavy magnetospheric ions with high charge states (e.g., O^{6+} and O^{7+}), energized by potential drops of more than 8 megavolts [*Cravens et al.*, 2003; *Elsner et al.*, 2005; *Branduardi-Raymont et al.*, 2004, 2007, 2008; *Bhardwaj et al.*, 2006]. Recently, quasiperiodic ultraviolet aurora with 2–3 min period was found in the polar cap region from time-tagged HST imaging [*Bonfond et al.*, 2011]. Similar short periodicities of a few minutes were also reported for QP bursts by *Hospodarsky et al.* [2004].

[16] These multiple observations and inferences of energetic electrons and protons imply the existence of relativistic, quasiperiodic particle accelerations in the Jovian magnetosphere, that could be accompanied by the emission of QP radio bursts above the polar regions. Various candidates have been proposed for driving these QP accelerations: magnetic reconnection in the cusp which may cause strong field-aligned potential in the presence of two-cell ionospheric vortices [*Bunce et al.*, 2004], and acceleration by Alfvén waves similar to those occurring at Earth [*Kimura et al.*, 2011a]. But, due to the lack of *in-situ* plasma measurements in the polar magnetosphere, the fundamental properties of QP accelerations have not been determined yet: location of the acceleration region, energy source, and cause of the periodicity.

[17] The present study focusses on QP bursts that have been observed remotely and frequently by multiple spacecraft. We address the generation and propagation processes of QP bursts, with the purpose of constraining the QP acceleration mechanism, by studying the statistical properties of QP burst polarization and DoA based on near-equator measurements by the Radio and Plasma Wave Science Investigation (RPWS) [*Gurnett et al.*, 2004] onboard Cassini. Polarization statistics should reveal the average characteristics of the wave mode of QP burst observed at low latitudes. Estimation of the accuracy of DoA of QP bursts from low latitudes is performed for the first time.

2. Data Set

[18] One of the RPWS subsystems is the High Frequency Receiver (HFR) which measures electric fields (in units of $V^2/m^2/Hz$) from 3.5 kHz to 16.125 MHz with three electric monopole antennas (E_u, E_v, E_w). We analyze here the HFR swept-frequency data, whose time resolution varies from 0.1 to 10 sec per spectrum.

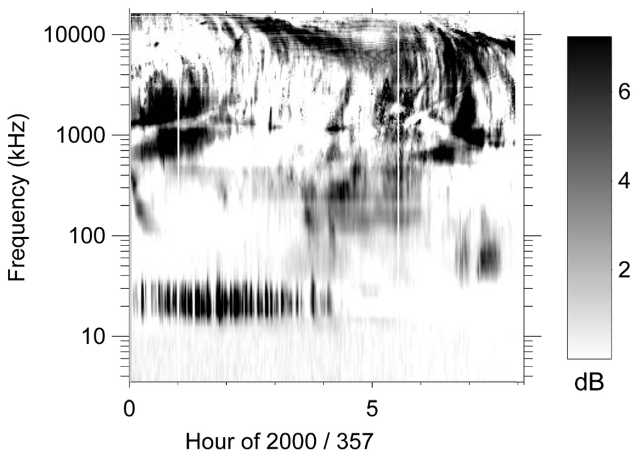

Figure 1. Dynamic spectrum recorded by RPWS between 0000 and 0800 UT on 22 Dec. 2000 (day of year 357) during Cassini's flyby of Jupiter, en route to Saturn. Cassini was located at a distance of ~175 R_J from Jupiter and at a local time of 13.3 h. The horizontal axis shows time in hours and the vertical axis shows frequency in kHz. Increasing power is represented by increasing darkness according to the scale on the right side (in dB).

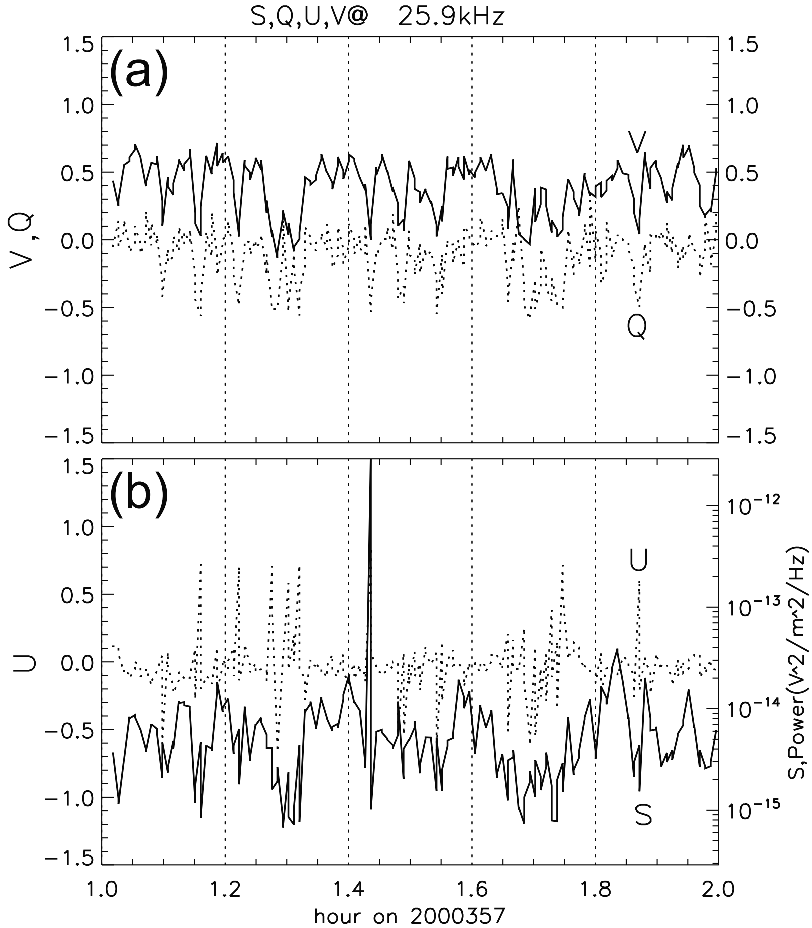

Figure 2. Stokes parameters of the QP bursts at 25.9 kHz observed from 0100 to 0200 UT on 22 Dec. 2000, corresponding to the event in Figure 1. Solid and dotted lines in Figure 2a represent V and Q, whereas those in Figure 2b represent S and U, respectively. Data points are plotted for all signal-to-noise ratio. The peak around 1.44 hr may be an interference.

[19] The interval studied goes from 1 Oct. 2000 to 31 Mar. 2001, though Cassini's closest approach to Jupiter on 30 Dec. 2000. During this flyby Cassini approached Jupiter at a minimum distance of 137 R_J and explored the dusk sector.

[20] Within the above interval, we detected QP bursts according to the following criteria: (1) frequency range from 10 to 30 kHz, and (2) DoA from within an apparent distance from Jupiter ≤100 R_J. The first criterion corresponds to the frequency range in which QP bursts observed from around the equator have flux densities higher than the Jovian continuum emission [*MacDowall et al.*, 1993]. The second criterion restricts source directions of QP bursts, which are actually expected to lie at altitudes ≤20 R_J from Jupiter. Based on these criteria, 44 groups of QP bursts were identified during the analysis period from 1 Oct. 2000 to 31 Mar. 2001.

3. Polarization Measurements

3.1. Polarization Measurements at Low Latitudes

[21] Using goniopolarimetric inversions [*Cecconi and Zarka*, 2005] it is possible to derive the polarization and DoA of electromagnetic waves from HFR measurements of complex auto- and cross-correlation of the signals received on the $E_x(x = u, v)$ and E_w antennas. Application of GP to the study of Saturn's Kilometric Radiation (SKR) permitted to derive its main characteristics: source location, wave mode, directivity …[see, e.g., *Lamy et al.*, 2008; *Cecconi et al.*, 2009].

[22] Wave polarization state and DoA are obtained by solving a system of GP equations that relate the HFR measurements to the 6 parameters that fully describe the incoming radio wave: the two spherical angles ϕ and θ (e.g., in the antenna coordinate system) defining the DoA, and the four Stokes parameters S, Q, U, V. S (in $V^2/m^2/Hz$) is related to the modulus of the Poynting vector $\vec{P}$ via the impedance of free space Z_o: i.e., $S = Z_o|\vec{P}|$. Q and U characterize the degree of linear polarization, and V the degree of circular polarization. For example, $(Q,U,V) = (0, 0, +1)$ or $(0, 0, -1)$ indicates that the received wave is completely LH or RH circularly polarized in the wave electric field plane perpendicular to the wave vector $\vec{k}$. Alternately, if $(Q \neq 0, U = (1 - Q^2)^{1/2}, V = 0$, the wave is fully linearized polarized in the wave electric field plane [see *Kraus*, 1986]. Details of GP inversions of Cassini data are

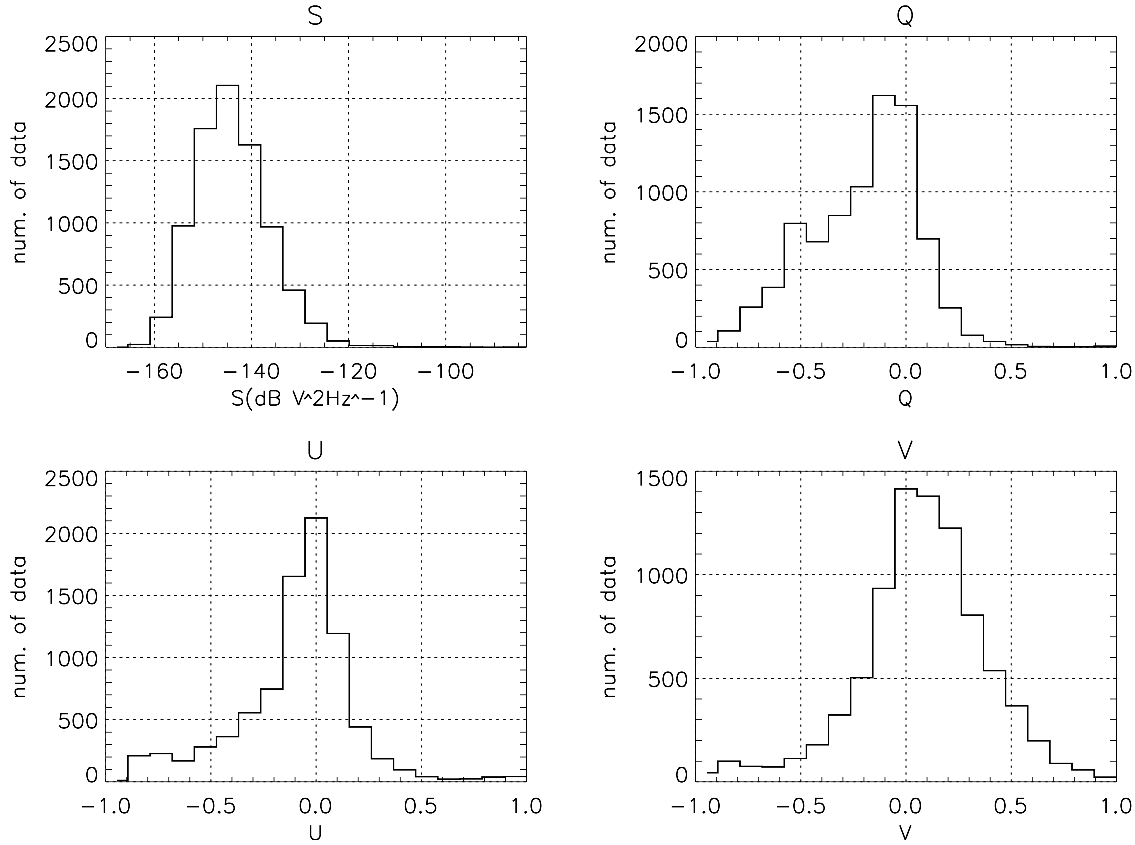

Figure 3. Histograms of Stokes parameter of QP bursts in the 10–30 kHz range, that have apparent DoA within 100 R_J from Jupiter and power $S > -200$ dB. 44 events were detected between 1 Oct. 2000 and 31 Mar. 2001. Vertical axis indicates the number of the data whereas horizontal axes show Stokes parameter value.

described in *Ladreiter et al.* [1995], *Vogl et al.* [2004], and *Cecconi and Zarka* [2005].

[23] Figure 1 is the dynamic spectrum of a typical QP bursts event recorded by RPWS during Cassini's interplanetary cruise just before its closest approach to Jupiter, on 22 Dec. 2000. QP bursts were observed between 20 and 30 kHz from about 0000 to 0415 UT, while Cassini was ~175 R_J away from Jupiter at a local time (LT) of 13.3 hours.

[24] The GP analysis of these bursts resulted in the four Stokes parameters displayed in Figure 2 for the interval 0100 to 0200 of Figure 1. Stokes parameters V and Q at 25.9 kHz are plotted in Figure 2a, and U and S in Figure 2b. During intense QP bursts emission ($S/N > 20$dB), Stokes parameters V, Q, and U were found in the following range: $V = +0.1$ to $+0.7$, $Q = -0.4$ to $+0.2$, and $U = -0.5$ to $+0.1$. These results indicate that during this event, QP bursts have a dominant LH circular polarization.

3.2. Statistical Analysis

[25] Quasi-continuous observations by RPWS around the closest approach allowed us to derive statistics of QP burst Stokes parameters. The distribution of the four Stokes parameters derived during the 44 groups of QP bursts studied is displayed in Figure 3. The vertical axes indicate the number of measurements and the horizontal axes show the value of each Stokes parameter. The distribution of wave power S is found to peak at -155 dB. Panels Q and U show that these parameters were most often close to zero, and present an excess toward negative values. Panel V peaks around zero but also reveals a significant excess of positive values (65%), versus ~35% of negative values. These distributions of Q, U, and V indicate that QP bursts observed by Cassini at low latitudes are partly LH circularly polarized.

[26] Next, we redistributed these measurement points in longitude-Stokes parameter planes within 60 × 60 bins, and counted up of the measurements in each bin. The resolution in longitude is 6°. Note that cumulative observation time is sensibly equivalent in each bin (~4000 min) because the 6 month analysis interval is long compared to Jupiter's rotation period and RPWS observations are nearly continuous, thus cover all longitudes with equal probability. Figure 4 represents the distribution of the measurement points versus each Stokes parameters and the CML of Cassini when QP bursts were observed. The same data set as in Figure 3 is used. The distributions appear to be significantly dependent on the CML, with most of the data points in the range from 180° to 480° (i.e., 180°–360° and 0°–120°). QP bursts were thus mainly observed in this CML range. This result is similar to that obtained by Galileo at low latitudes in the Jovian magnetosphere [*Kimura et al.*, 2010]. In the interval of maximum occurrence, the received power S can reach -120 dB, and the distributions of Q and U depart from zero

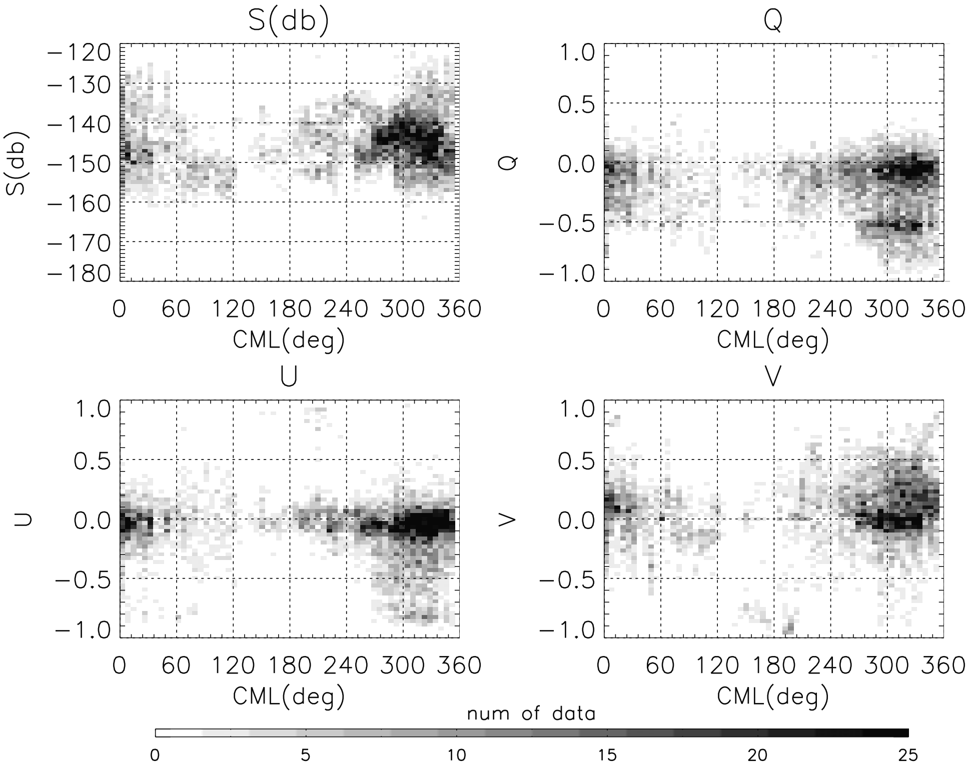

Figure 4. Statistical distribution of QP bursts' Stokes parameters versus the Central Meridian Longitude (CML) of Cassini for the 44 events of Figure 3. Each CML-Stokes parameter plane was divided in 60 bins × 60 bins. Horizontal axis is the CML of Cassini whereas vertical axes show Stokes parameter value. Darkness represents the number of data points in the bin, according to the scale on the bottom.

toward negative values whereas while that of V departs from zero toward positive values. QP bursts thus appear to have an intensity that depends on the CML, whereas their polarization is partly LH circular at all longitudes.

[27] Figure 5 represents the distribution of the same data versus the Stokes parameters and the sub-solar longitude (SSL, i.e., the longitude of the sub-solar point in System III), in the same format as Figure 4. The dependence of QP burst occurrence on the SSL is also obvious, with measurements grouped in the SSL range from 260° to 480° (i.e., 260°–360° and 0°–120°). One clearly sees that the data are better organized versus SSL than versus CML, similar to the results obtained with Galileo observations (QP bursts were found to occur at SSL = 300°–480° [*Kimura et al.*, 2010]). Again, in the interval of maximum occurrence, $< Q >, < U > < 0$ and $< V > > 0$ imply that QP burst polarization is partly LH circular at all SSL.

4. Direction Finding

4.1. Estimation of the Angular Error

[28] Before studying the DoA of QP bursts, we want to estimate the angular error on the DoA. *Cecconi and Zarka* [2005] performed a detailed analysis of the errors affecting GP inversions. Here, we estimate the angular error by analyzing the observations of another Jovian radio component, that has a large intensity and spatially compact source locations near Jupiter: the Hectometric radiation (HOM) [see, e.g., *Zarka*, 2004]. HOM is emitted in the 0.3–3 MHz range, and it has been found to originate from high-latitude $f \sim f_c$ surfaces, a few R_J above the Jovian surface [see, e.g., *Ladreiter et al.*, 1994]. We performed the GP analysis of two HOM events observed by Cassini simultaneously with QP bursts at lower frequencies. We assume that the HOM source can be considered as a point source located at Jupiter's position (as viewed from the large distance of Cassini). As a consequence, the measured spread and offset of DoA of HOM are interpreted as DoA errors. These error estimates are then applied in the next section to the analysis of the two simultaneous QP burst events.

[29] As *Cecconi and Zarka* [2005] showed that DoA errors increase for incoming rays close to the plane of Cassini's receiving antennas, we selected here measurements for which the DoA makes an angle >20° with each receiving antenna.

[30] The HOM emission detected on 22 Dec. 2000 shows up on the dynamic spectrum of Figure 1, that includes one of the QP burst events discussed in section 3.2. For estimating the angular error on DoA, we focused on the HOM intensification between 0100 and 0200 UT at frequencies around 1 MHz.

[31] Figure 6 displays the results of the GP analysis of HOM at 1075 kHz between 0100 and 0200 UT on 22 Dec. 2000, when Cassini was located at a distance of ~175 R_J from Jupiter and at 13.3 LT. Figure 6a is the dynamic spectrum recorded by RPWS and Figure 6b displays the deduced Stokes parameters at 1075 kHz. Figure 6c is the DoA at 1075 kHz averaged between 0100 and 0200 UT, with its associated error bars. The horizontal axis shows angular distances (arcmin) from Jupiter in the east-west

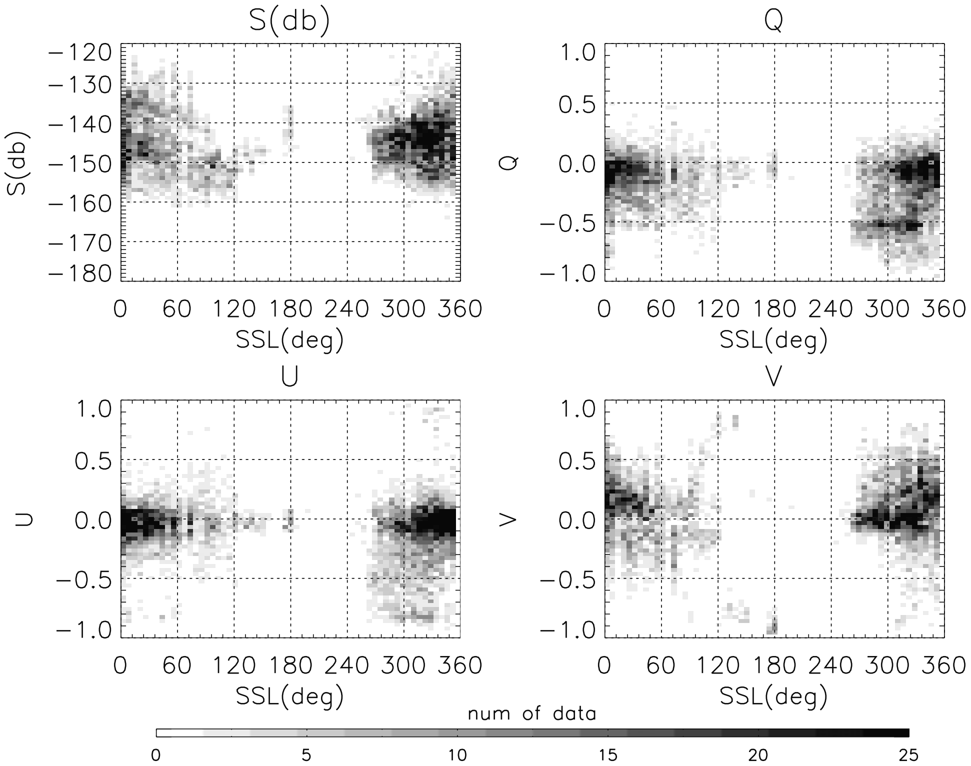

Figure 5. Statistical distribution of QP bursts' Stokes parameters versus the Sub Solar Longitude (SSL) of Cassini for the 44 events of Figure 3. Each SSL-Stokes parameter plane was divided in 60 bins × 60 bins. Horizontal axis is the SSL of Cassini whereas vertical axes show Stokes parameter value. Darkness represents the number of data points in the bin, according to the scale on the bottom.

direction and the vertical axis corresponds to the north-south direction. Jupiter is located at the origin (0,0). One R_J corresponds to an angular distance of 19.5 arcmin as seen from Cassini at the time of the observation. Figure 6d displays the corresponding histograms of DoA at 1075 kHz over the interval studied, in terms of angular distance to the direction of Jupiter. The dashed line (resp. the dotted line) represents the angular distance in the longitudinal – i.e., East-West – direction (resp. in the latitudinal – i.e., North-South – direction). The solid line represents the absolute (total) angular distance to Jupiter. Horizontal error bars correspond to $\pm 1\sigma$ (with σ the standard deviation) spread around the average value of each distribution, marked "*".

[32] From Figure 6d, we conclude that DoA of the HOM event studied are subject to systematic and random errors. The systematic error is an offset of 567 arcmin ($\sim$29 R_J) of the total angular distance to Jupiter of the average HOM DoA (the longitudinal offset is +128 arcmin and the latitudinal offset is -216 arcmin). The random error corresponds to the spread of HOM DoA with standard deviation σ = 710 arcmin ($\sim$36 R_J). It is dominated by the latitudinal error (853 arcmin or 44 R_j), while the longitudinal error is only 187 arcmin ($\sim$ 9.6 R_J).

[33] For reducing the DoA error, we assumed the incoming waves to be 100% circularly polarized by imposing Q and U to be zero. This assumption reduces the unknowns of the GP inversion from (S,Q,U,V,θ,ϕ) to (S,V,θ,ϕ) and improves the accuracy of the DoA determination. The improved results are represented on Figure 7 with the same format as Figure 6. The offset and random errors are both reduced significantly. The total angular distance to Jupiter of the average HOM DoA is reduced from 567 arcmin to 256 arcmin ($\sim$ 13R_J), while the random error is reduced from σ = 710 arcmin to σ = 157 arcmin ($\sim$8 R_J). All errors in latitude and longitude are reduced, except the random longitudinal error.

[34] Similar error estimates were performed for the data set of 23 Dec. 2000. Figure 8 shows the second HOM event analyzed, as well as one of the QP burst event studied in the next section. Tables 2 to 5 summarize the results of the error analyzes performed on DoA of HOM events of 22 and 23 Dec. 2000. From these results, we conclude that DoA errors are reduced significantly when Stokes parameters Q and U are assumed to be zero, i.e., incoming waves are assumed 100% circularly polarized. This assumption is actually consistent with the polarization deduced from the full GP inversion of HOM measurements: on Figure 6, Q and U are nearly equal to zero during the occurrence of HOM. The same is observed for the HOM event of 23 Dec. 2000 (not shown). In the worst case (23 Dec. 2000), the offset and random errors on the total angular distance to Jupiter are reduced 490 arcmin and 410 arcmin, respectively.

4.2. Direction of Arrival of QP Bursts

[35] We present in detail below the analysis of two groups of QP bursts out of the 44 identified during our analysis period. For these two groups, on 22 and 23 Dec. 2000, DoA were derived with the best accuracy due to the high intensity

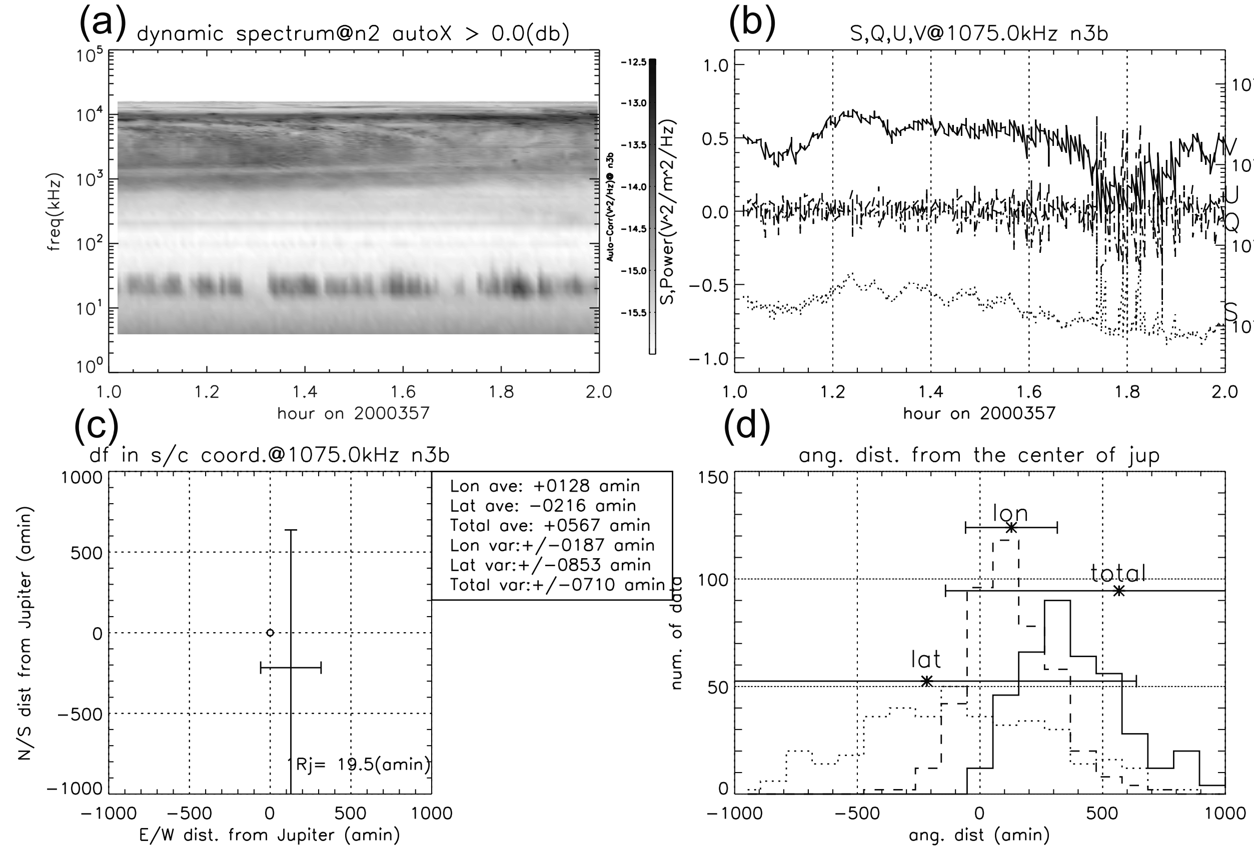

Figure 6. Polarization and DoA measurements of HOM at 1075 kHz on 22 Dec. 2000. (a) Dynamic spectrum recorded by RPWS between 0100 and 0200 UT on 22 Dec. 2000 when Cassini was located at $\sim$175 R_J from Jupiter at 13.3 LT. (b) Stokes parameters of HOM emission at 1075 kHz during the same time interval. (c) Average DoA at 1075 kHz over the same time interval. Angular distance (arcmin) from Jupiter is represented in the east-west direction along the horizontal axis, and in the north-south direction along the vertical axis. One Jovian radius (1 R_J = 71492 km) corresponds to an apparent distance of 19.5 arcmin as seen from Cassini. (d) Histograms of the angular distances between instantaneous DoA and Jupiter at 1075 kHz from 0100 to 0200 UT on 22 Dec. 2000. Horizontal axis is the angular distance (arcmin) and vertical axis is the number of the data. The solid line represents total angular distances from Jupiter, with an associated $\pm 1\sigma$ error bar labeled "total" around an average DoA value marked "*". Dashed and dotted lines represent angular distances in the longitudinal (east-west) and latitudinal (north-south) directions.

of the bursts. Figure 9 shows DoA results for the QP bursts detected at 25.9 kHz between 0100 and 0200 UT on 22 Dec. 2000. This is the same event as in Figures 1 and 2 and *Hospodarsky et al.* [2004]. The format of Figure 9 is the same as Figures 6c and 6d. Note that DoA for this event were derived by *Hospodarsky et al.* [2004], but without discussing their accuracy. We focus here on the accuracy of DoA determinations in order to decide if the obtained DoA of QP bursts are consistent or not with the direction of Jupiter.

[36] Cassini was located at 13.3 LT and at a distance of $\sim$175 R_j from Jupiter during this event, so that negative longitudinal shifts (to the left on Figure 9 (top)) correspond to the sunward direction, and positive longitudinal shifts (to the right) to the tailward direction. Figure 9 shows that apparent DoA of QP bursts are shifted to the north-west direction from Jupiter, i.e., they seem to come from the dayside high latitude region of Jupiter's magnetosphere.

[37] Because the bulk of Q and U values for QP bursts concentrate around 0 on Figure 3, we assumed Q, $U = 0$ for reanalyzing the QP burst event of 22 Dec. 2000. Under this assumption, DoA errors are found to be considerably reduced as shown in Figure 10. The average of QP burst DoA is at a total angular distance to Jupiter of 850 arcmin, i.e., a distance of $\sim$46 R_J projected on the sky. This distance largely exceeds the systematic error (offset) estimate of 256 arcmin derived from the analysis of the simultaneous HOM event (see Table 3). The 1σ spreads of QP burst DoA are 280 arcmin ($\sim$14 R_J) in longitude and 190 arcmin ($\sim$10 R_J) in latitude (180 arcmin in total angular distance to Jupiter), similar to random errors on HOM DoA (see Table 3). This implies that QP bursts during the 22 Dec. 2000 event apparently arrived from a well-defined region very distant ($\sim$46 R_J) from Jupiter, as reported by *Hospodarsky et al.* [2004].

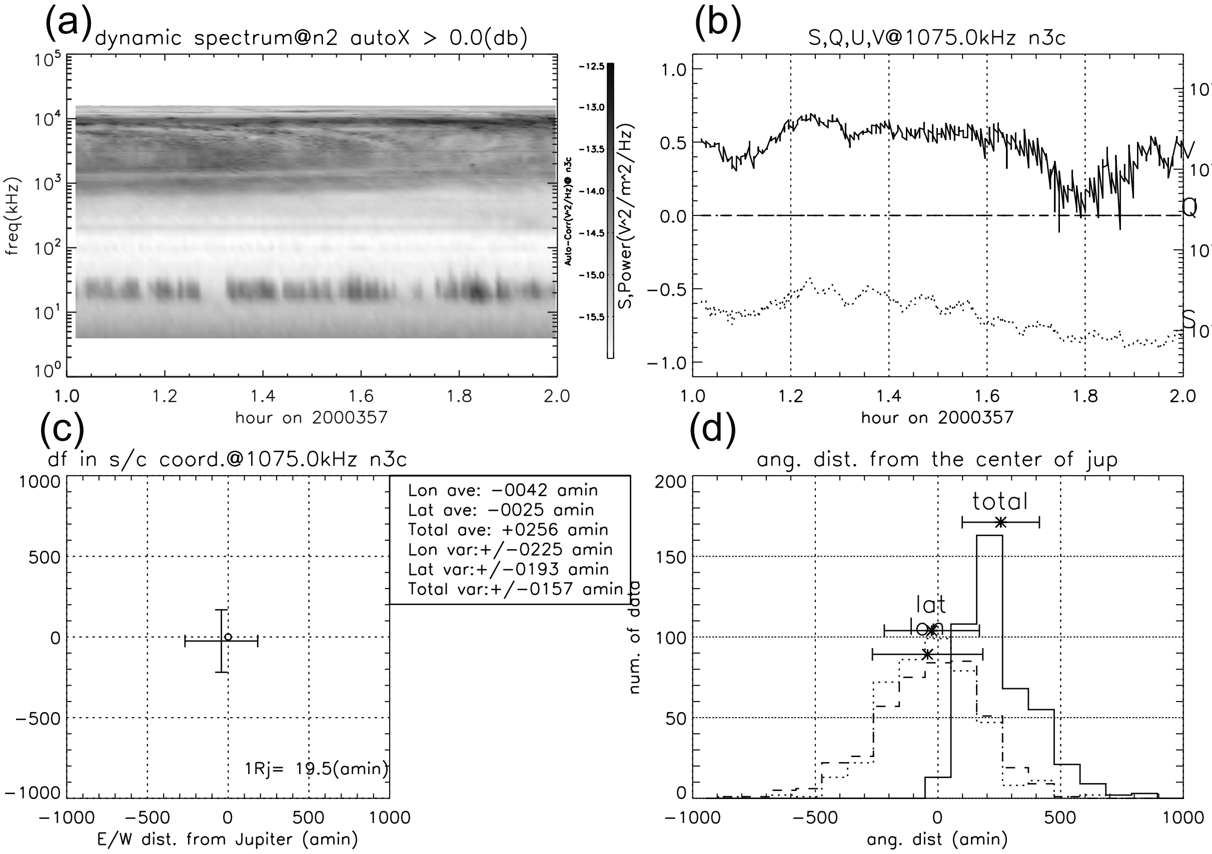

Figure 7. Polarization and DoA measurements of HOM at 1075 kHz on 22 Dec. 2000, under the assumption Q, $U = 0$ (100 % circularly polarized emission), with the same format as Figure 6.

[38] DoA results for the QP burst group of 23 Dec. 2000 are displayed in Figures 11 and 12. This event was observed when Cassini was at a distance of 166 R_J from Jupiter at 13.6 LT. Under the assumption Q, $U = 0$, the average DoA was found to be at a total angular distance to Jupiter of 1200 arcmin ($\sim$58 R_J), with spread of individual DoA of 410 arcmin ($\sim$20 R_J). The average value is significantly larger than the estimated offset error in Table 5, while the spread is comparable to the random error on HOM DoA.

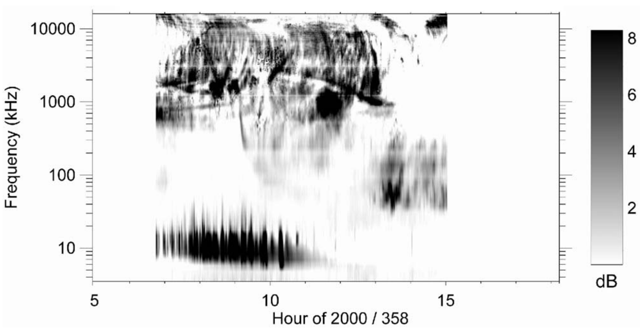

Figure 8. Dynamic spectrum recorded by RPWS on 23 Dec. 2000 (day of year 358). Cassini was located at a distance of $\sim$166 R_J from Jupiter and at a local time of 13.6 h. Increasing power is represented by increasing darkness according to the scale on the right side (in dB).

[39] From above results, we conclude that for these two QP burst events observed from low Jovian latitudes in the interplanetary space, DoA indicate a source significantly northward and far from Jupiter.

5. Discussion and Conclusions

5.1. Wave Mode, Propagation, and Source Location

[40] Our statistical analysis of QP bursts observed at low latitudes by Cassini around its closest approach to Jupiter in late 2000 indicates that QP burst occurrence depends on CML and even more clearly on SSL (with maximum occurrence at $260° \leq$ SSL $\leq 480°$), and that emission is partly LH polarized ($V > 0$ and Q, $U \leq 0$). This unique dominant sense of circular polarization (LH) at low latitudes can be explained by L-O mode generation from the northern hemisphere and/or R-X mode generation from the southern hemisphere, followed by propagation to the equatorial region.

[41] For two particular QP events (including the one studied by *Hospodarsky et al.* [2004]), we derived DoA unambiguously offset from Jupiter's center by $\sim 50R_J$, pointing at an apparent source in the northern polar magnetosheath. In order to explain the dispersive time-frequency structure of QP bursts (longer emission tail at lower frequencies), *Kaiser et al.* [2004] and *Desch* [1994] also suggested that QP bursts could be refracted tailward at the magnetopause or in the magnetosheath (because of the plasma density jump in the magnetosheath, from $2f_{psw}$ at the nose of the magnetosphere to f_{psw} at the flanks of the

Table 2. Accuracy of the Direction Finding at 1075 kHz on 22 Dec. 2000 With No Assumption on Stokes Parameters

	Offset (arcmin)	1σ (arcmin)
Total	567	710
Longitude	+128	187
Latitude	−216	853

Table 3. Accuracy of the Direction Finding at 1075 kHz on 22 Dec. 2000 Under the Assumption Q, U = 0

	Offset (arcmin)	1σ (arcmin)
Total	256	157
Longitude	−42	225
Latitude	−25	193

distant tail, with f_{psw} the local plasma frequency of solar wind), before escaping into the interplanetary space.

[42] Theoretical studies generally propose, e.g., for auroral radio emissions from planetary circumpolar regions, that emissions are generated at the altitude where the emission frequency matches the local f_c or f_p [see, e.g., *Zarka*, 2004, and references therein]. However, the DoA we found for QP bursts correspond to minimum distances to Jupiter of 46 R_J (at 25.9 kHz) or 58 R_J (at 14.7 kHz) from Jupiter. This is much higher than the typical altitudes of f_c and f_p deduced from Jovian magnetic field and plasma distribution models: for example, f_c = 20 kHz corresponds to an altitude about 10 R_J while f_p = 20 kHz corresponds to an altitude about 2 R_J, as mentioned in *Hospodarsky et al.* [2004].

[43] Ray tracing analyses in the Jovian magnetosphere suggest that emissions produced in a given hemisphere will generally escape the magnetosphere from this same hemisphere [see, e.g., *Kimura et al.*, 2011b, Figure 9], possibly after anti-sunward refraction or scattering at the magnetopause or in the magnetosheath [*Kaiser et al.*, 2004]. Thus, it is very unlikely that an emission from southern high latitudes will escape from an exit point in the magnetosheath at 50 R_J north from Jupiter. Thus, we conclude that the two QP events of the present study, having DoA from the northern magnetosheath, probably have their source regions in the northern polar magnetosphere. Combined with their observed dominant LH polarization, this leads us to suggest that QP busts observed at low latitudes by Cassini are L-O mode waves from the northern polar region.

[44] *Steinberg et al.* [2004] performed a ray tracing study of the so-called “LF bursts” emitted from the terrestrial magnetosphere at low frequencies. Assuming a distribution of density fluctuations in the solar wind as given by *Lacombe et al.* [1988, 1997], they found that the part of the LF bursts near the local f_{psw} is stochastically scattered and thus strongly dispersed. Could this effect also apply to Jovian QP bursts, whose frequencies are near f_{psw} or $2f_{psw}$ (QP bursts frequencies cover a typical range $f \leq 25.9$ kHz on 22 Dec. 2000 and $f \leq 14.7$ kHz on 23 Dec. 2000, whereas their LF cutoff, between f_{psw} and $2f_{psw}$, was respectively 15 kHz and 6 kHz)? As we found for the two events DoA concentrated around a specific distance from Jupiter, we conclude that QP bursts are probably little scattered in the solar wind and more refracted and scattered in the magnetosheath, leading to escape points far from Jupiter.

[45] Over the 6 month-interval studied, only two QP burst events were intense enough for permitting an accurate determination of DoA. Even for these two events, observed both from the post-noon sector, DoA are blurred by the magnetosheath and possibly by the solar wind (emission frequency is not far above f_{psw}), and Cassini being located at a large distance from Jupiter ($\sim$170 R_J) it could not discriminate between source altitudes of 2 or 10 R_J. Due to these limitations and the specific geometry of the observations (remote observer at near-equatorial latitude and post-noon LT), we cannot claim at the statistical generality of our results. Further investigations by an orbiter of Jupiter will provide invaluable, high spatial resolution results.

[46] In the frame of the cyclotron resonance (CMI) theory, *Kimura et al.* [2011b] found that linear growth rates of L-O mode waves at $f < f_c$ are higher than those of R-X mode waves, and that Z-mode waves could be excited toward the Jovian polar ionosphere and be converted to $f \sim f_p$ L-O mode waves at steep f_p gradients, e.g., at the top of the polar ionosphere. This could explain the above deduction that QP bursts are L-O mode waves from a northern near-polar source. Stronger wave growth in the northern hemisphere could be related to the fact that the quasiperiodic relativistic electron outbursts were observed to have a more unstable velocity distribution in the northern hemisphere than in the southern one [*Kimura et al.*, 2011b]. These conclusions are also consistent with the detection by Chandra of a northern X-ray hot spot showing a quasiperiodic pulsation [*Gladstone et al.*, 2002].

[47] Figure 13 proposes a possible picture of the generation and propagation of QP bursts consistent with the present results as well as with previous works. Intermittent cusp reconnections [*Bunce et al.*, 2004] and/or Alfvén waves [*Kimura et al.*, 2011a] cause the existence of periodically-varying parallel electric fields in the Jovian polar regions. These electric fields accelerate electrons up to relativistic energies in the anti-Jupiter direction [*MacDowall et al.*, 1993], and drive heavy ion and electron precipitations toward Jupiter responsible for QP X-ray and UV auroral

Table 4. Accuracy of the Direction Finding at 1475 kHz on 23 Dec. 2000 With No Assumption on Stokes Parameters

	Offset (arcmin)	1σ (arcmin)
Total	900	926
Longitude	−7	289
Latitude	+53	1259

Table 5. Accuracy of the Direction Finding at 1475 kHz on 23 Dec. 2000 Under the Assumption Q, U = 0

	Offset (arcmin)	1σ (arcmin)
Total	490	410
Longitude	−79	475
Latitude	+50	417

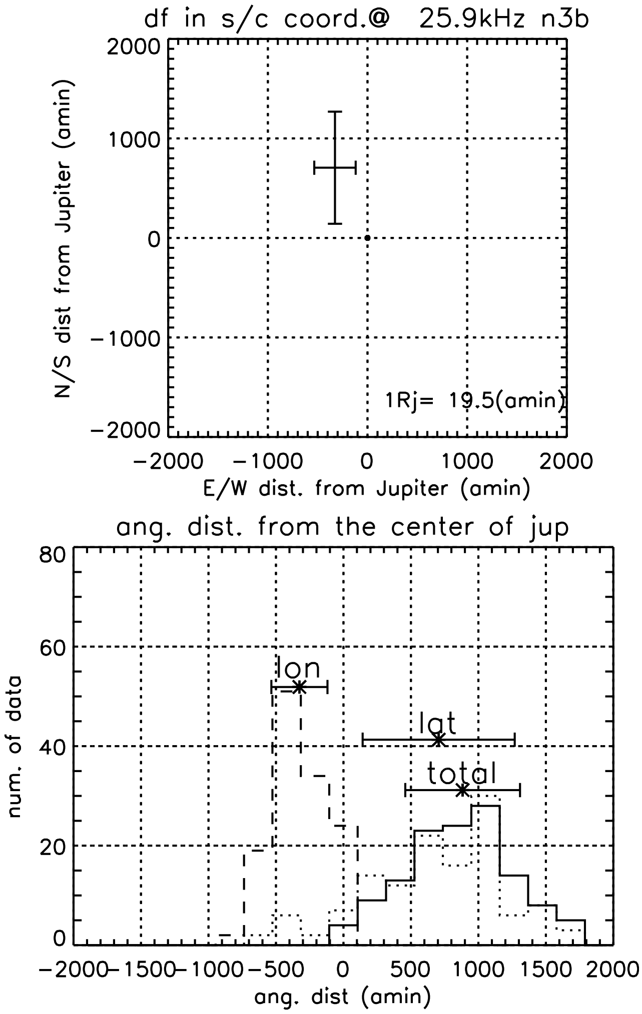

Figure 9. (top) Average DoA of QP bursts at 25.9 kHz between 0100 and 0200 UT on 22 Dec. 2000 (corresponding to the event shown in Figures 1 and 2), when Cassini was located at $\sim$175 R_J from Jupiter at 13.3 LT. Angular distance (arcmin) from Jupiter is represented in the east-west direction along the horizontal axis, and in the north-south direction along the vertical axis. Jupiter is located at the origin (0,0). One R_J corresponds to an apparent distance of 19.5 arcmin as seen from Cassini. (bottom) Histograms of the angular distances between instantaneous DoA and Jupiter at 25.9 kHz over the same time interval. Horizontal axis is the angular distance (arcmin) and vertical axis is the number of the data. The solid line represents total angular distances from Jupiter, with an associated $\pm 1\sigma$ error bar labeled "total" around an average DoA value marked "*". Dashed and dotted lines represent angular distances in the longitudinal (east-west) and latitudinal (north-south) directions.

emissions [*Gladstone et al.*, 2002; *Bonfond et al.*, 2011] (Figure 13a). The relativistic outward-going electron outbursts directly excite L-O mode radio waves via the CMI at $f < f_c$ (displayed in blue on Figure 13b). These waves subsequently propagate toward low latitudinal regions [*Kimura et al.*, 2010, 2011b]. The same electron bursts also excite Z-mode waves propagating toward the polar ionosphere [*Kimura et al.*, 2011b], which can in turn convert to L-O mode waves (MC, in red) at the top of the polar ionosphere. These L-O mode waves then propagate toward high latitudes [*Kimura et al.*, 2008]. The low frequency part of QP bursts ($f < 2f_{psw}$) are refracted and scattered in the magnetosheath, and escape it at high latitudes [*Hospodarsky et al.*, 2004; *Kaiser et al.*, 2004; *Desch*, 1994; this study]. Cassini, Galileo, and Ulysses during its inbound phase in 1992 could detect these low frequency waves (1 to 50 kHz) with LH circular polarization [*MacDowall et al.*, 1993; this study]. Higher frequency waves ($f > 2f_{psw}$) from the MC source can cross the magnetosheath while sustaining little or no refraction. Ulysses in its outbound phase in 1992 and its distant Jupiter's encounter in 2004 could detect these waves at high latitudes (from 1 to 200 kHz) [*MacDowall et al.*, 1993]. Polarization senses denoted with "?" in Figure 13b means that they have not yet been confirmed by observations. Dotted raypaths in the southern hemisphere symbolize the weaker intensity inferred for southern sources.

5.2. Rotational Phase Dependence

[48] We have found that QP burst occurrence is better organized in SSL than in CML, confirming the results

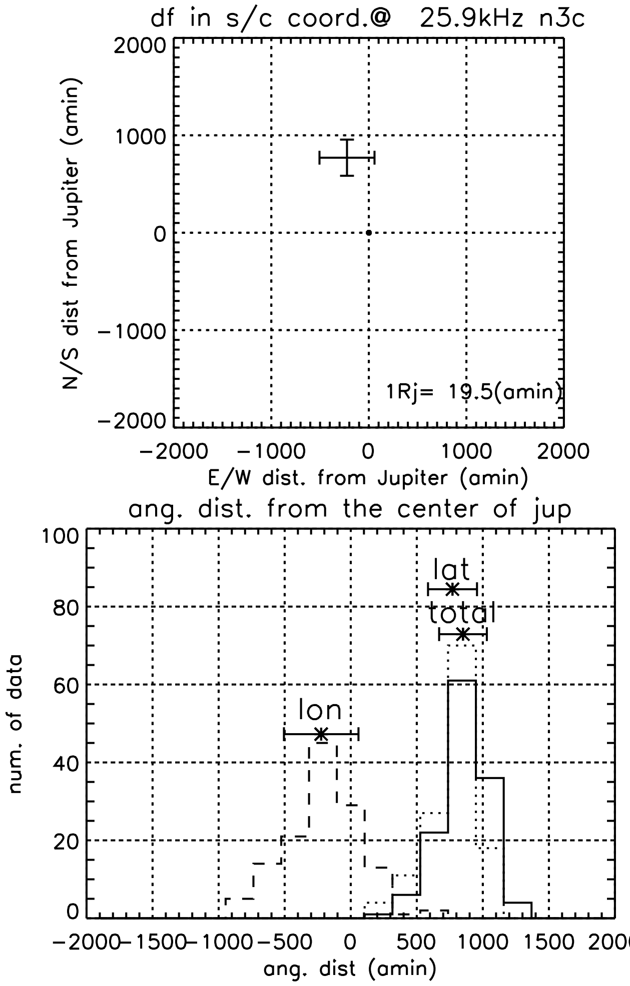

Figure 10. DoA measurements of QP bursts at 25.9 kHz on 22 Dec. 2000, under the assumption Q, $U = 0$ (100 % circularly polarized emission), with the same format as Figure 9.

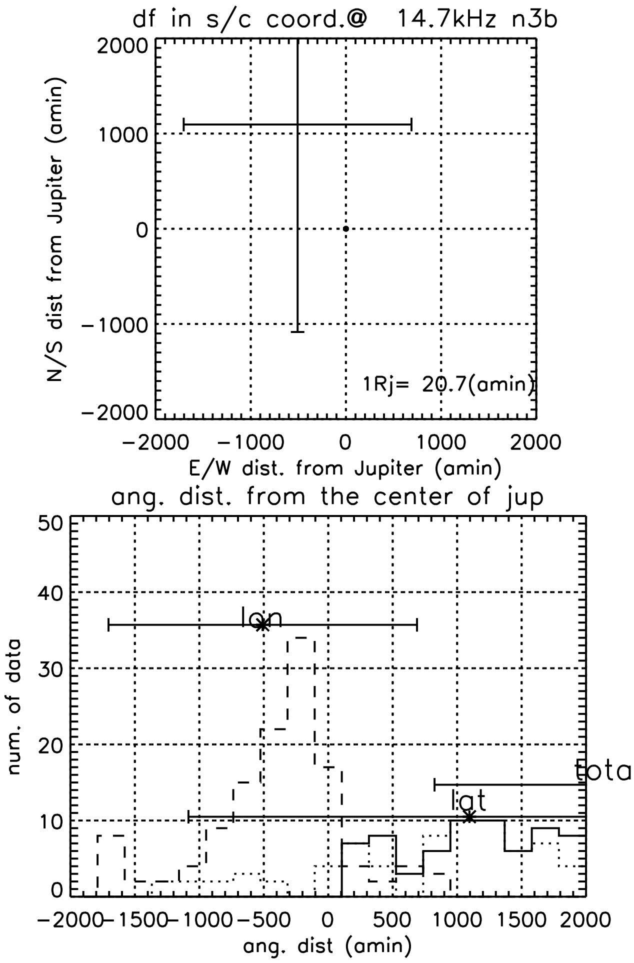

Figure 11. Results of the direction finding at 14.7 kHz performed at 0800 to 0900 UT on 23 Dec 2000 with the same format as that of Figure 9. One Jovian radius corresponds to an apparent distance of 20.7 arcmin as seen from Cassini.

obtained with Galileo from 1995 to 2003 [*Morioka et al.*, 2006; *Kimura et al.*, 2010]. This long-term dominant SSL dependence suggests that QP bursts (and possibly associated energetic electron outbursts) occur at a particular phase of the Jovian rotation, not depending of the observer's LT nor on long-term variations such as seasonal or related to the solar cycle.

[49] QP bursts dependence on the CML may be attributed to the facts that CML and SSL are related to each other at a given observer's LT (CML = SSL − (LT − 12) × 15°), and that during the interval studied Cassini spent most of time at two LT positions (~11 LT inbound and ~21 LT outbound). As a consequence, a dependence on the SSL will translate in a partial dependence on the CML.

[50] Observed occurrence of QP bursts also depends on their directivity, but one cannot deduce the true emission directivity and CML or SSL dependence on the basis of observations by a single spacecraft. But from simultaneous observations by Galileo and Cassini, *Hospodarsky et al.* [2004] showed that QP bursts are a strobe-like emission illuminating a broad angular range and not a search light beam. The theoretical study of QP burst generation by *Kimura et al.* [2011b] comforted the result of *Hospodarsky et al.* [2004] as high linear growth rates were found to be distributed over a broad angular range (tens of degrees) with respect to the source magnetic field. As a consequence, even for a corotating radio sources, the occurrence variations caused by such a beam would be of secondary importance as compared to the on/off nature of the QP burst generation mechanism. This again supports QP burst excitation at the sidereal planetary rotation period which, combined to the bimodal distribution of Cassini's LT around the closest approach to Jupiter, is responsible for the apparent CML dependence.

[51] *Morioka et al.* [2006] and *Kimura et al.* [2008, 2010] showed from Galileo and Ulysses data that the occurrence of QP burst groups depends on the SSL at both high and low latitudes of the observer. At low latitudes, QP burst groups start at SSL = 260° to 320° [*Morioka et al.*, 2006] and remain active across the SSL interval from = 300° to 480° [*Kimura et al.*, 2010], while those observed at high northern latitudes are active across the SSL interval from =90° to 300° [*Kimura et al.*, 2008]. The SSL ranges of QP burst

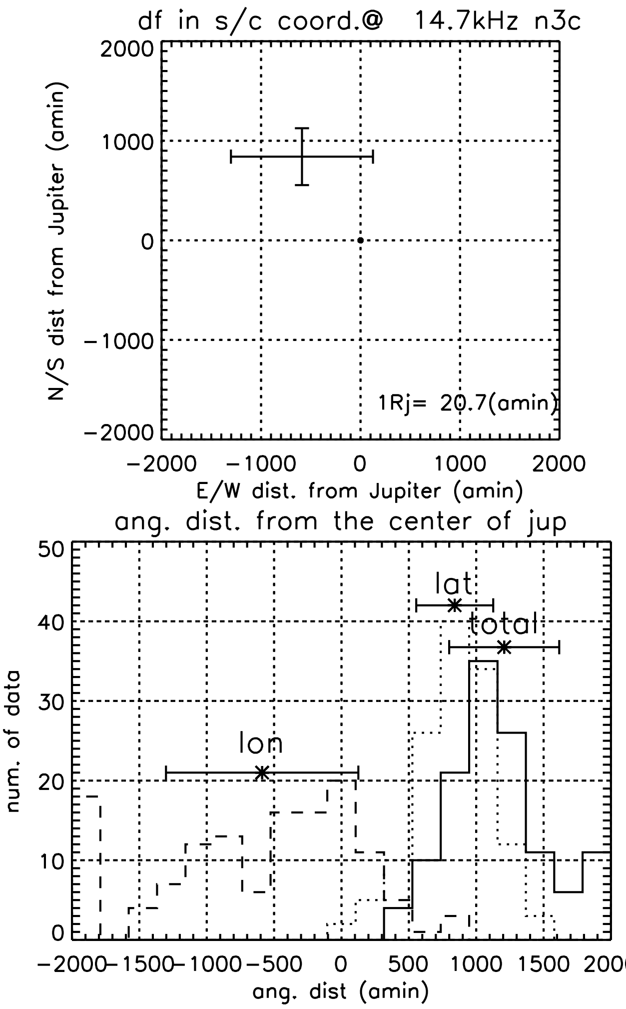

Figure 12. DoA measurements of QP bursts at 14.7 kHz on 23 Dec. 2000, under the assumption *Q*, *U* = 0 (100 % circularly polarized emission), with the same format as Figure 9.

occurrence at low and high latitudes are almost in antiphase. As source regions at low and high latitudes were suggested to lie at different altitudes (emission of $f \leq f_c$ at high altitudes and of $f \sim f_p$ at low altitudes [*Kimura et al.*, 2011b], we may infer that source regions at high and low altitudes are activated at different rotational phases, and that electron acceleration regions consequently have different altitudes at different rotational phases.

[52] However, this does not explain how electron acceleration and thus QP radio bursts emission depend on the rotational phase. Electron acceleration mechanisms, based on cusp reconnection [*Bunce et al.*, 2004] or Alfvénic acceleration [*Kimura et al.*, 2011a], should include this rotational modulation as an observational constraint. A possible candidates is a corotating current system, that could drive QP particle accelerations followed by radio bursts and UV and X-ray aurora when the system rotates through a specific LT sector. A suggested source for QP radio bursts is the field line connected to the outer and/or external regions of the Jovian magnetosphere [*MacDowall et al.*, 1993; *Kimura et al.*, 2008, 2010]. The phase of QP burst occurrence in SSL should thus map to particular point of the outer and/or external regions of the magnetosphere. We note that strong plasma subcorotation in the source region seems ruled out by the recurrence of QP bursts at the rotational period. This suggests a QP burst source in outer/external magnetospheric regions where subcorotation is not significant.

6. Summary

[53] We have studied the polarization properties and directions of arrival of quasiperiodic (QP) bursts from the Radio and Plasma Wave Science investigation data recorded at low latitudes during 6 months around the closest approach to Jupiter. We found that:

[54] 1. Positive Stokes parameter V is 30 % more frequent than negative V, and it occurred in association with negative Q and U values. This suggests that QP bursts observed at low latitudes are partially left-handed polarized (circular or elliptical) waves.

[55] 2. Occurrence of QP bursts observed by Cassini is dependent on the sub-solar longitude, similar to those

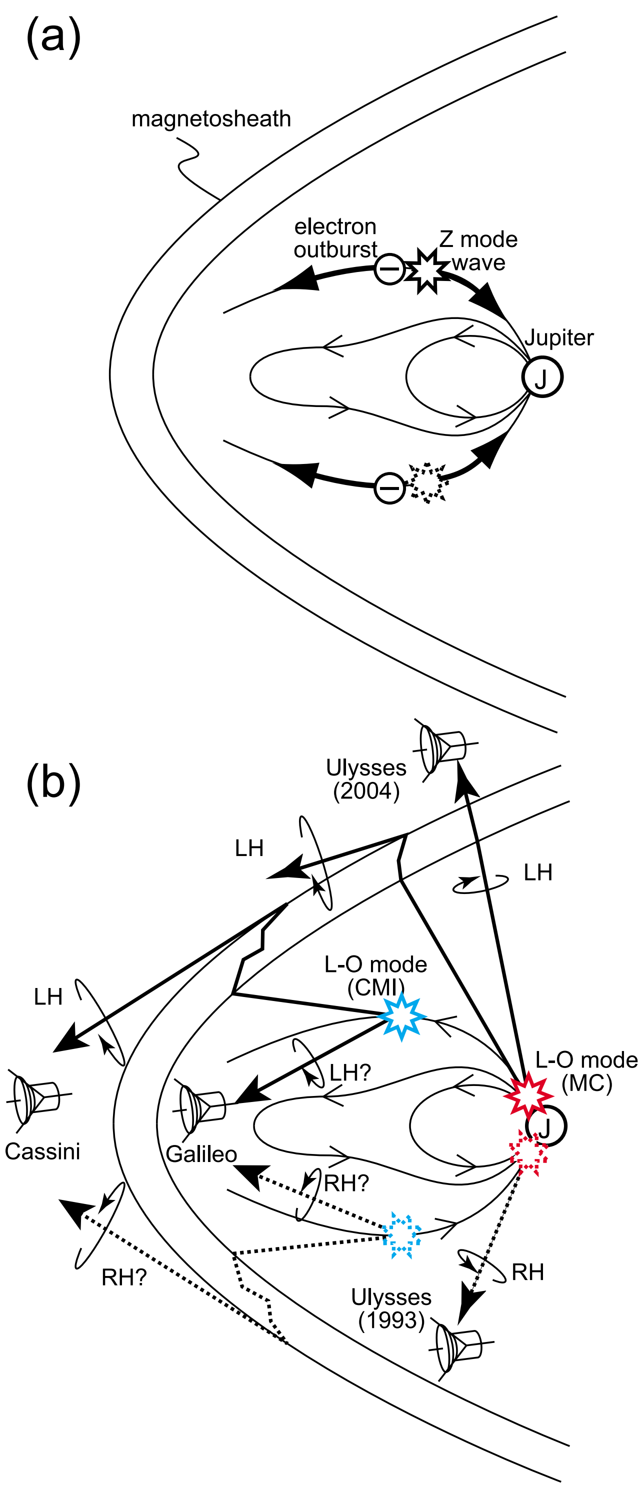

Figure 13. A possible picture of QP bursts generation and propagation as suggested by the present study. (a) Initial phase, just after QP relativistic particle accelerations in the polar region. Electron outbursts are accelerated in the anti-Jupiter directions, generating Z-mode waves in the downgoing direction (toward the polar ionosphere), and accompanied by periodic heavy ion and electron precipitations responsible for QP radio bursts, and X-ray and UV auroral emissions. (b) Excitation of radio waves by the relativistic electron outburst and their propagation into the magnetosphere and through the magnetosheath. L-O mode waves are excited directly via the CMI (light blue region) by the electron outbursts propagate toward low latitudes. Downgoing Z-mode waves are converted at the top of the polar ionosphere (red region noted MC) to L-O mode waves propagating toward high latitudes. Low frequency waves are refracted and scattered in the high latitude magnetosheath, and can escape toward equatorial regions. Cassini, Galileo, and Ulysses in its inbound phase in 1992, could detect these low frequency waves as LH circular waves. High frequency waves from the MC source propagate through the magnetosheath without refraction. Ulysses in its outbound phase in 1992 and its distant encounter in 2004 could detect these waves at high latitudes. Polarization senses denoted with "?" means that they have not yet been confirmed by observations. Dotted raypaths in the southern hemisphere symbolize the weaker intensity inferred for southern sources.

observed by Galileo. Maximum occurrence corresponds to $260° \leq SSL \leq 480°$.

[56] 3. Apparent direction of arrival of two groups of intense QP bursts are confirmed to be from within an altitude at about 50 R_J north of Jupiter, significantly more distant than the altitudes at which $f \sim f_p$ or $f \sim f_c$ (both below $\sim$10 R_J).

[57] From these results, we proposed the following interpretations and suggestions:

[58] 4. The observed left-handed polarized waves are left-handed ordinary mode waves from the northern polar source region.

[59] 5. The waves are strongly refracted in the magnetosheath so that the apparent direction of arrival does not match the actual location of the source.

[60] 6. QP relativistic electron outbursts may have more energetic and unstable velocity distributions in the northern polar region than in the southern polar region.

[61] 7. QP radio bursts and associated QP accelerations of relativistic particles may result from a "recurrent disturbance" excited at the planetary rotation period.

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