Cassini observation of Jovian anomalous continuum radiation

Sheng-Yi Ye,[1] D. A. Gurnett,[1] J. D. Menietti,[1] W. S. Kurth,[1] G. Fischer,[2] P. Schippers,[1] and G. B. Hospodarsky[1]

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[1] Jovian anomalous continuum is a narrowband electromagnetic radiation near 10 kHz that can escape from Jupiter's magnetosphere to interplanetary space. One possible source mechanism is the magnetosheath re-radiation of the Jovian low frequency radio emissions such as the quasiperiodic (QP) radio emissions, broadband kilometric radiation (bKOM) and non-thermal continuum. Jovian anomalous continuum was consistently observed by the Cassini Radio and Plasma Wave Science instrument from 2000 to 2004, right before the Saturn orbit insertion, which means the radiation can be detected as far as 8 AU away from Jupiter. An analysis of intensity versus radial distance shows that the Jovian anomalous continuum has a line source rather than a point source, consistent with the theory that the emission is radiated by the whole length of the magnetotail. The emissions are modulated at the system III period of Jupiter and are unpolarized. Since the lower cutoff frequency of the anomalous continuum is related to the plasma frequency in the magnetosheath of Jupiter, which is a function of solar wind density, the recurrent variations of the lower cutoff frequency can be used as a remote diagnostic of the solar wind condition at Jupiter. We propose that the frequency dispersion, a unique characteristic of the anomalous continuum, is likely a comprehensive effect of both the slow group velocity near the local plasma frequency and the refraction/scattering of the waves by density structures as they propagate in the magnetosheath.

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1. Introduction

[2] Jovian anomalous continuum is a very low frequency (3–30 kHz) radio emission of Jovian origin first observed by the Ulysses Unified Radio and Plasma Wave (URAP) experiment during the spacecraft's encounter with Jupiter in 1992 [*Stone et al.*, 1992; *Kaiser et al.*, 1992]. *Kaiser et al.* [1992] reported that the anomalous continuum can be observed by Ulysses from distances up to 2 AU from Jupiter, and their frequency range and intensity seem to respond to changes in solar wind ram pressure. It was also found that the anomalous continuum has a clock-like 10-hour periodic amplitude variation [*Kaiser et al.*, 1993]. The Jovian anomalous continuum should not be confused with the narrowband radio emission which was detected around 10 kHz by Voyager inside Jupiter's magnetosphere and revealed by the high resolution wideband receiver to consist of many closely-spaced narrowband emissions [*Gurnett et al.*, 1983].

[3] *Kaiser* [1998] showed that the most intense portion of the Jovian continuum emission appears to emanate from the planet's bow shock or magnetosheath region and the intense component is highly correlated with the Jovian "type III" [*Kurth et al.*, 1989] radio emissions, also called quasiperiodic (QP) bursts [*MacDowall et al.*, 1993]. *Kaiser* [1998] proposed that the intense continuum component may be the unresolved merging of the low-frequency portion of the QP bursts and occasionally the broadband kilometric emissions which have been scattered and dispersed in the magnetosheath. The magnetosheath acts to scatter and diffuse the emissions generated much closer to the planet. *Kaiser* [1998] also drew an analogy between the Jovian anomalous continuum and the terrestrial anomalous continuum, which is proposed to be generated by scattering and dispersion of terrestrial low-frequency (LF) bursts in the magnetosheath [*Kaiser et al.*, 1996; *Steinberg et al.*, 1988, 1990].

[4] *Menietti et al.* [2001] showed with Galileo high resolution data that the source of the low-frequency dispersion of QP bursts is not within the Jovian magnetosphere and suggested that the dispersion of the low-frequency portion of the QP bursts by the magnetosheath produces the anomalous continuum, in agreement with *Kaiser* [1998] and *Desch* [1994]. *Kaiser et al.* [2004] showed simultaneous observations of Jovian anomalous continuum by Cassini and Ulysses and confirmed that the emission is radiated into all directions and modulated by the rotation of the planet in a strobe light fashion. Observations of the Jovian anomalous continuum during the Cassini Jupiter flyby strongly suggest that the original magnetospheric emission is modified and

[1]Department of Physics and Astronomy, University of Iowa, Iowa City, Iowa, USA.
[2]Space Research Institute, Austrian Academy of Sciences, Graz, Austria.

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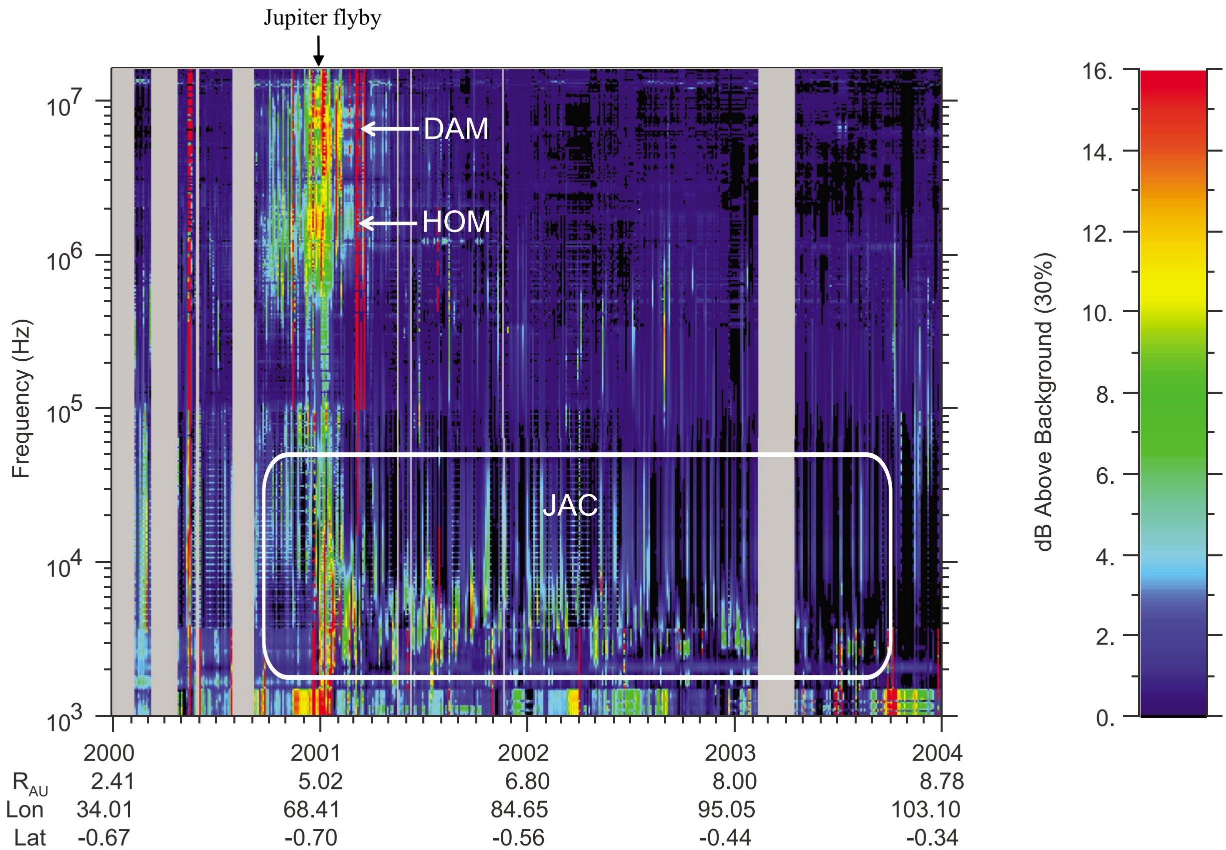

Figure 1. Wave electric field power spectrogram from Cassini RPWS for 2000–2004; the color shows the intensity of waves in dB above background level.

re-radiated by the magnetosheath so that the magnetosheath acts as a leaky waveguide of VLF emissions generated close to Jupiter. *Morioka et al.* [2004] pointed out that the Jovian anomalous continuum tends to appear when the solar wind dynamic pressure declines after a rapid increase and that the emission's dramatic intensity change at the bow shock indicates a transition from quasi-electrostatic emissions in the magnetosheath to radio waves in the solar wind.

[5] In this paper, we show the persistent observation of Jovian anomalous continuum radiation by Cassini between 2000 and 2004. In section 2, we describe the data set used. In section 3, we show the continuous observation of Jovian anomalous continuum by Cassini and provide evidence for the emission's Jovian origin. In section 4, we apply a Lomb-Scargle technique to analyze the periodicity of Jovian anomalous continuum. In section 5, we show the polarization characteristics of Jovian anomalous continuum and QP bursts. In section 6, we discuss the currently existing theories for the generation of Jovian anomalous continuum, and suggest the line source is consistent with dispersion due to refraction/scattering of O-mode emission propagating down the Jovian magnetosheath.

2. Data

[6] We used the radio wave data from the Radio and Plasma Wave Science (RPWS) instrument on board the Cassini spacecraft around the Jupiter flyby (30 December, 2000). For a description of the RPWS instrument, see *Gurnett et al.* [2004]. The Jovian anomalous continuum and QP bursts were mainly detected by band A (3.5–16 kHz) and B (16–71 kHz) of the RPWS High Frequency Receiver (HFR).

[7] The RPWS has three 10-meter long electric antenna elements, labeled E_u, E_v and E_w. Two of the three elements (E_u and E_v) are mounted on the spacecraft with an angle of 120° between them, and the third element (E_w) is mounted perpendicular to the plane formed by the first two elements. The monopoles E_u and E_v can also be operated as a dipole oriented along the x axis of the spacecraft and is called E_x. The HFR can be operated in either 2-antenna (dipole-monopole) mode or 3-antenna/direction finding (DF) mode. In the 2-antenna (dipole-monopole) mode, E_u and E_v are used as a dipole E_x and two auto correlations of E_x and E_w ($\langle V_x V_x^* \rangle$ and $\langle V_w V_w^* \rangle$), and the real and imaginary parts of the cross correlation between E_x and E_w are measured ($Re\langle V_x V_w^* \rangle$ and $Im\ \langle V_x V_w^* \rangle$). In the 3-antenna/direction finding (DF) mode, E_u and E_v are used as monopoles. In this case two consecutive sets of auto and cross correlations are measured between the E_u/E_v and E_w antennas. The auto and cross correlations between the antenna voltages are measured directly in flight for each frequency channel of the HFR, with the units of the measurements in V^2/Hz. Measurements from the three electric antennas using the HFR allow us to determine the direction of arrival, the Poynting flux (S) and the polarization of a radio wave using the analytical inversion methods provided by *Lecacheux* [2000] and *Cecconi and Zarka* [2005]. The polarization is usually

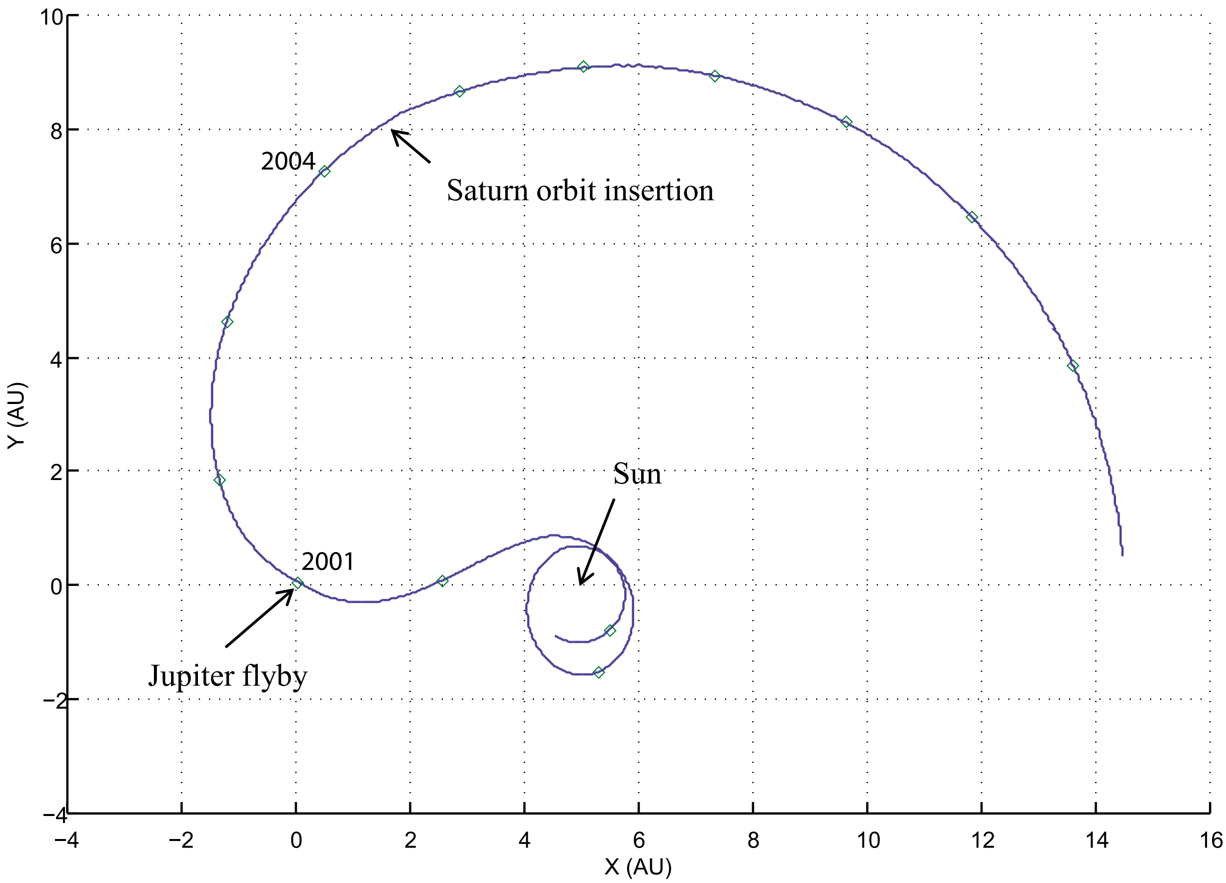

Figure 2. Trajectory of Cassini since the spacecraft's launch in 1997 in the Jupiter solar ecliptic frame. Each of the diamond marks in the plot indicates the beginning of a year.

described by the Stokes parameters Q, U, V, with Q and U denoting the degree of linear polarization and V the degree of circular polarization [*Kraus*, 1986]. For details of the direction-finding and polarization inversions, please refer to *Cecconi et al.* [2009], *Fischer et al.* [2009], and *Ye et al.* [2010a].

3. Observations

[8] The continuous operation of the Cassini RPWS instrument before, during and after the Jupiter flyby allows us to examine the Jovian anomalous continuum from different observation positions. Figure 1 shows a 4-year overview of Cassini RPWS observations from 2000 to 2004. The frequency range of the spectrogram is 1 kHz to 16 MHz. The color of each pixel on the spectrogram indicates the dB level of the signal above the background noise level. The Cassini flyby of Jupiter took place on Dec 30, 2000. The closest approach is marked by the arrow on top of the spectrogram in Figure 1. At frequencies above 500 kHz, intense Jovian hectometric radiation (HOM) and Jovian decametric radiation (DAM) were detected both before and after the Jupiter flyby. At frequencies between 3 and 30 kHz, Jovian anomalous continuum was persistently observed from 2000 to 2004.

[9] Figure 2 shows the trajectory of Cassini since the spacecraft's launch in 1997 in a Jupiter-centered coordinate system with the z axis perpendicular to the ecliptic plane and the positive x axis pointing to the sun. Each of the diamond marks in the plot indicates the position of Cassini at the beginning of a year. Between 2001 and 2004, Cassini was flying approximately perpendicular to Jupiter's magnetotail. Jovian anomalous continuum was observed by Cassini RPWS until shortly before Saturn orbit insertion, when Cassini was more than 8 AU from Jupiter. Figure 3 is a Cassini RPWS spectrogram showing the observation of Jovian anomalous continuum on DOY 165, 2004, when Cassini was ~170 R_S (Saturn radius = 60,268 km) away from Saturn and 17,510 R_J (Jupiter radius = 71,492 km) away from Jupiter. The Jovian anomalous continuum radiation, identified from the frequency, characteristic dispersion and modulation period (~10 hour), should not be confused with the Saturn narrowband emissions which are observed much closer to Saturn (< 70 R_S) and have different spectral shapes and modulation periods on the spectrograms [*Wang et al.*, 2010; *Ye et al.*, 2009, 2010b].

[10] Figure 4a shows the integrated wave power detected by the HFR between 3 and 30 kHz as a function of distance from Jupiter. Since in the interplanetary space there are few other emissions in this frequency range, the integrated power can be regarded as the power of Jovian anomalous continuum. It is clear that the power of the anomalous continuum varies approximately as $1/r$, where r is the radial distance from Jupiter (in units of R_J). For comparison, a red line representing $1/r^2$ dependence is also plotted. This confirms that the source of the anomalous continuum is Jupiter. The

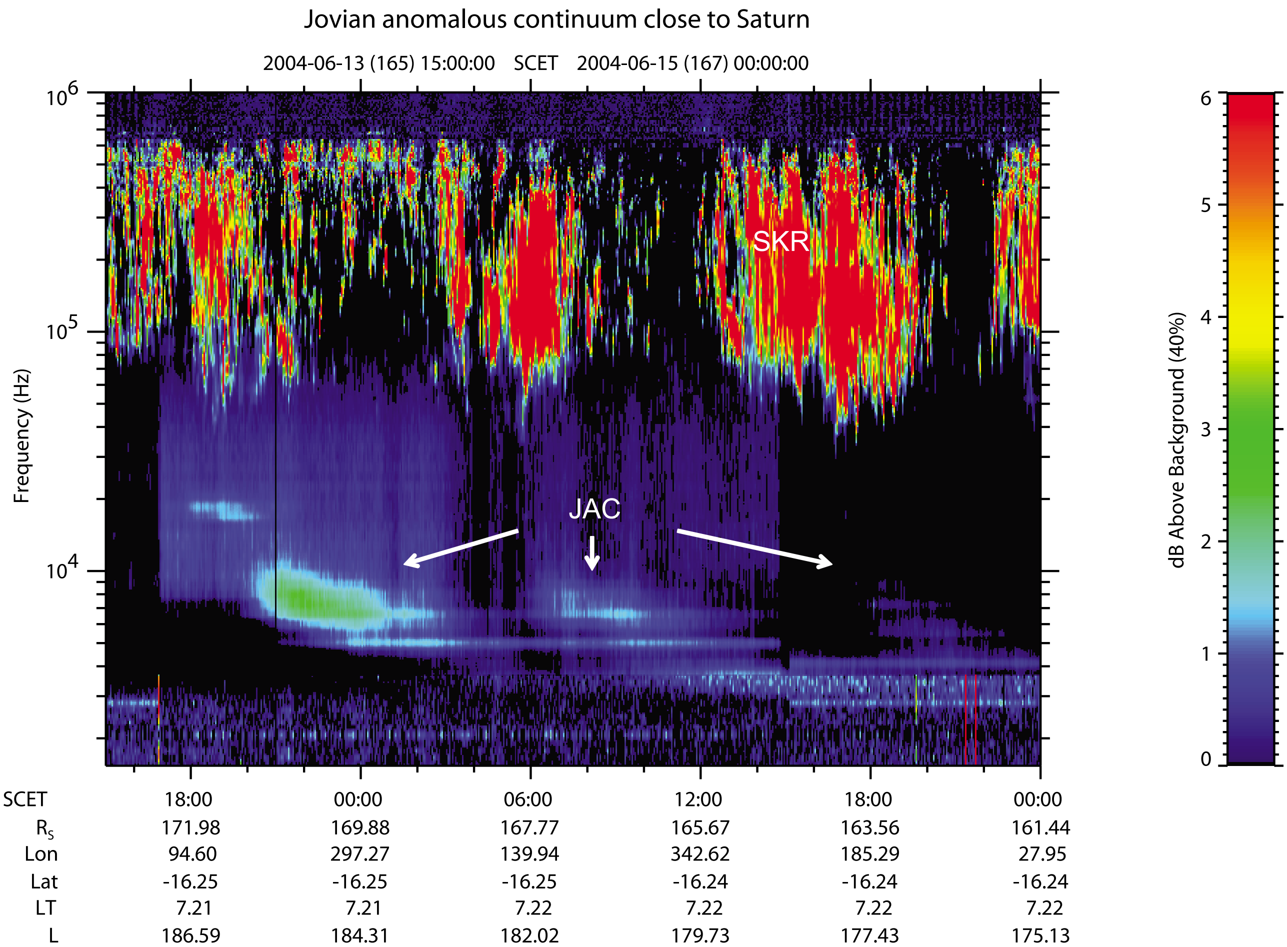

Figure 3. Cassini RPWS spectrogram showing the observation of Jovian anomalous continuum on DOY 165 and 166, 2004. Three Jovian anomalous continuum emissions separated by ~10 hours are visible on this spectrogram.

$1/r$ rather than $1/r^2$ dependence of wave power over the radial distance seems to indicate that the source is not a point source but rather a line source with a dimension comparable to the distance to the spacecraft. Figure 4b shows the integrated wave power detected by the HFR between 1 and 2 MHz as a function of distance from Jupiter. The wave power of HOM emission falls off as $1/r^2$ as the radial distance increases. This is expected because the source of HOM emission is restricted to the vicinity of Jupiter and can be treated as a point source to a remote observer.

4. Rotational Modulation

[11] We investigate the periodicity of Jovian anomalous continuum based on the Lomb-Scargle technique, which can be applied to a set of data points sampled over unequal periods of time. This technique is well suited for periodicity analyses of data with gaps [*Scargle*, 1982]. The wave power received by the HFR is integrated over the frequency range from 3 to 20 kHz and averaged every 10 minutes for the time period between 2000 and 2004. The integrated power is then normalized over the 10-hour Jovian rotation period average to eliminate the radial distance effect on the intensity modulation. To limit the spectrum analysis to a certain period, the normalized intensities are multiplied by a Hanning weighting function [*Priestly*, 1981], where the duration of the window has been chosen to be 240 days. The 240-day window also guarantees an accuracy better than 1% for the determined period of modulation. The weighted time series of the wave power is then fed into a routine developed according to the Lomb-Scargle period formula [*Scargle*, 1982]. This results in a power spectral function $P(\omega)$, where ω is the frequency of modulation. The 240-day window is then shifted 30 days to calculate another modulation power spectrum, and so on. This leads to a spectrogram of modulation power where the time resolution is one spectrum per 30 days.

[12] Figure 5a shows a spectrogram of modulation power for the Jovian anomalous continuum. The modulation power (unitless due to the normalization of wave power) is color coded in such a way that red (300) indicates strong modulation and blue (0) represents no modulation. It shows that the Jovian anomalous continuum was strongly modulated at the system III rotation rate of Jupiter (870°/day) [*Carr et al.*, 1958] between 2001 and 2004. This is consistent with the observation shown in Figure 1, where the emission was persistently observed by Cassini from 2000 to 2004. The modulation power drop-off in the middle of 2002 and after

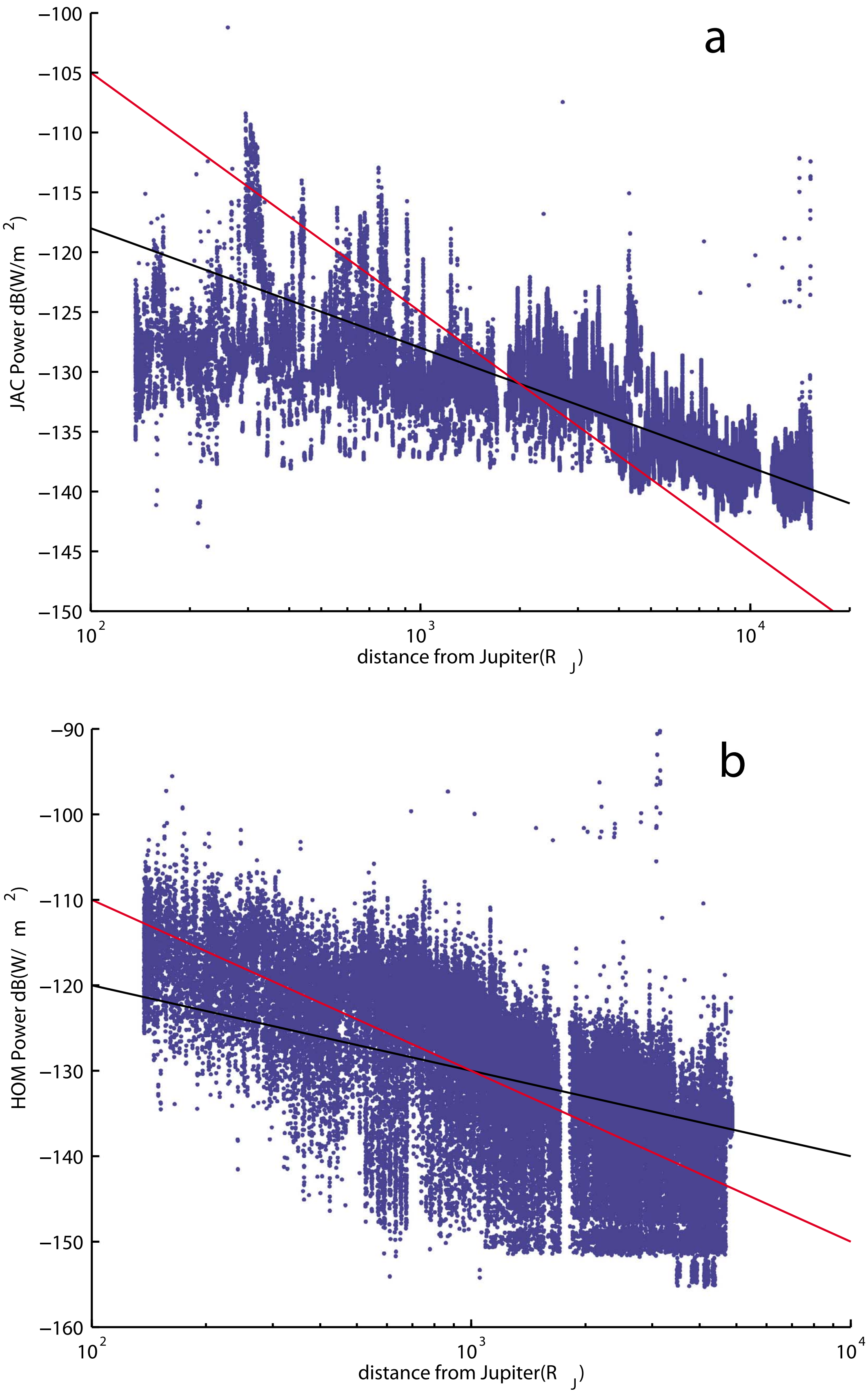

Figure 4. Integrated wave powers of (a) Jovian anomalous continuum (3–30 kHz) and (b) HOM (1–2 MHz) as a function of distance r to Jupiter. The black line illustrates a $1/r$ dependence and the red line a $1/r^2$ dependence.

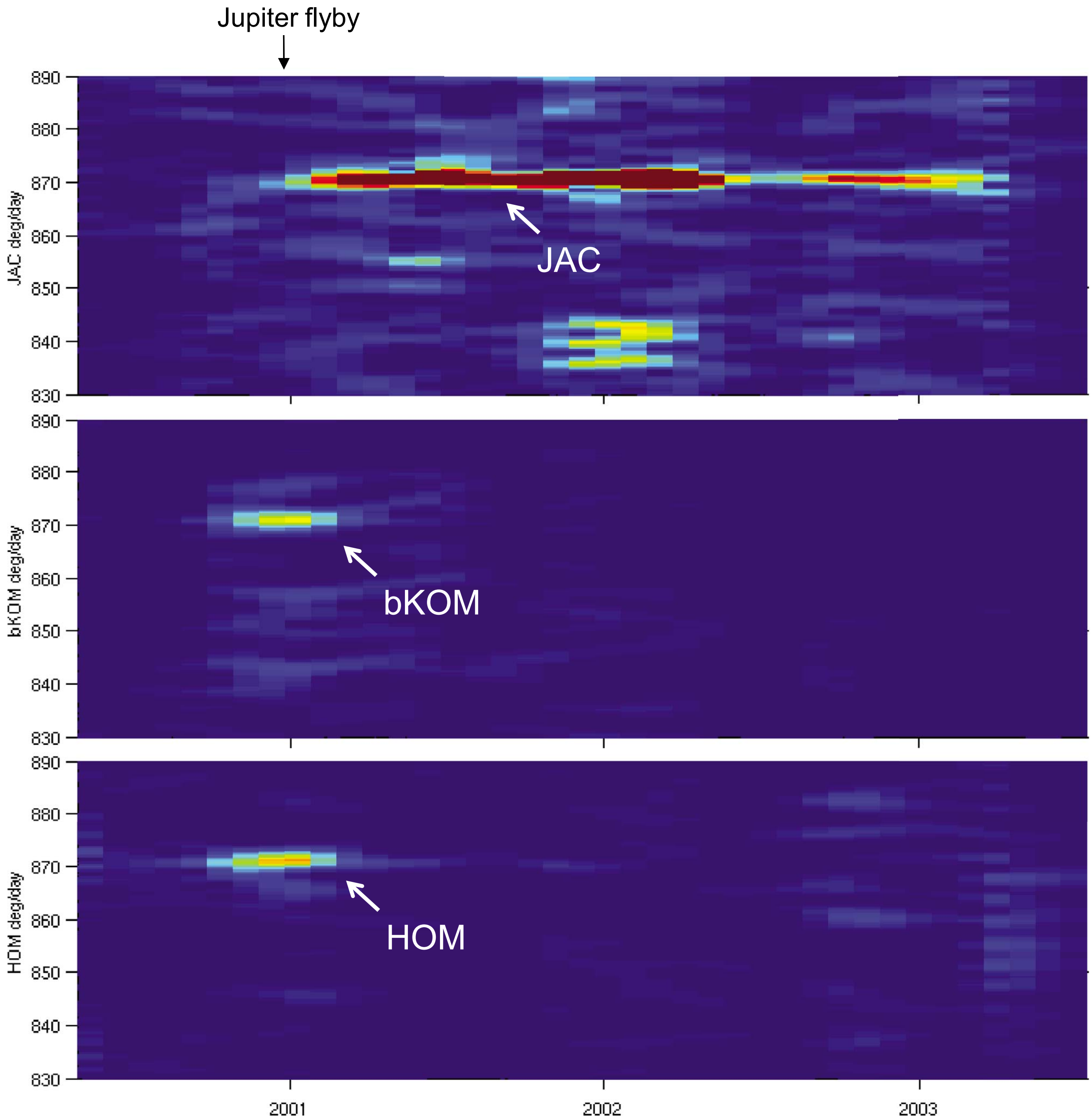

Figure 5. Spectrograms of modulation power for (top) Jovian anomalous continuum (3–20 kHz); (middle) Jovian bKOM (70–200 kHz); (bottom) Jovian HOM (600–3000 kHz).

the early months of 2003 is probably due to the sporadic occurrence of Jovian anomalous continuum in those periods, which might be an indication of either lack of solar activity or low emission intensity.

[13] Figure 5 shows the modulation spectrograms of Jovian broadband kilometric (bKOM) and hectometric radiations in the middle and bottom plots, respectively. These two spectrograms are generated based on the same method as Figure 5 (top), except that the frequency ranges of power integration are 70–200 kHz for bKOM and 600–3000 kHz for HOM. The same color scale (0–300) was used to show the modulation power of bKOM and HOM. The nKOM emissions also occur in the same frequency range of bKOM, but has a slightly slower modulation rate called system IV [*Kaiser and Desch*, 1980; *Dessler*, 1985]. Both bKOM and HOM are generated by the cyclotron maser instability on Jovian auroral field lines [*Ladreiter et al.*, 1995; *Zarka*, 1998]. When observed close to Jupiter, HOM and bKOM are much more intense than the Jovian anomalous continuum. However as the distance from Jupiter increases, these emissions appear as point sources, their intensity decreases much faster, $\sim 1/r^2$, compared to the anomalous continuum, which varies as $1/r$. So HOM and bKOM are only observable within a short period around the Jupiter flyby, as shown in

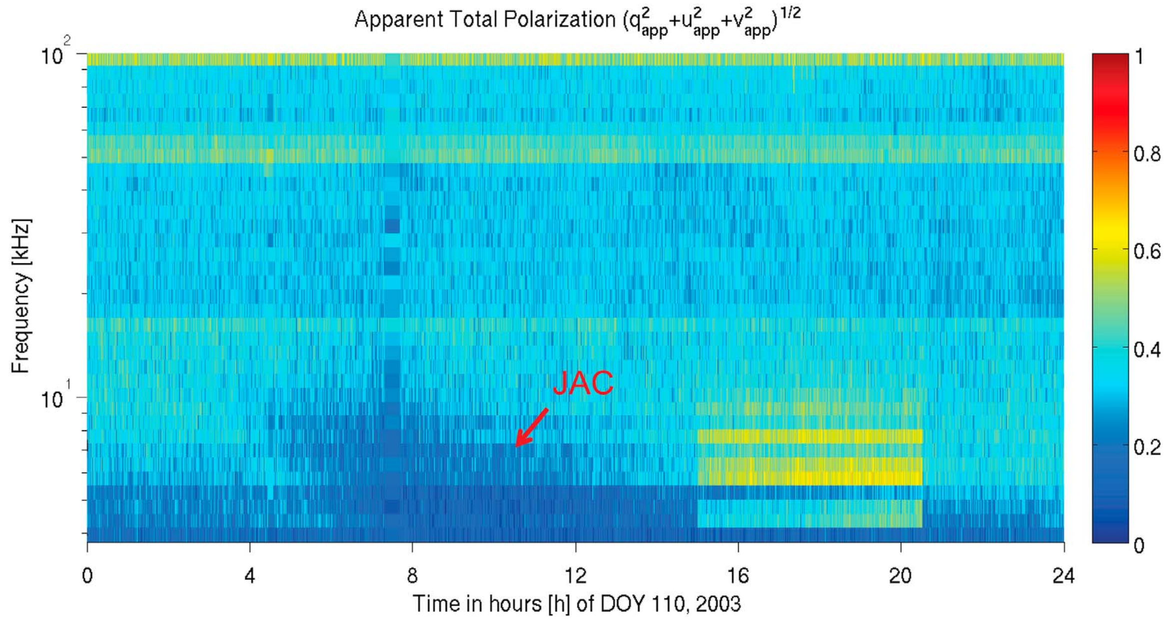

Figure 6. Apparent total polarization degree spectrogram for the Jovian anomalous continuum detected by Cassini RPWS on DOY 110, 2003.

Figure 1. This is also reflected in Figure 5 (middle and bottom), where the modulation power peak around 870°/day only lasted for a couple of months before and after the flyby.

5. Polarization

[14] The measurements on a pair of orthogonal antennas (either E_x, E_w or $E_{u/v}$, E_w) of the Cassini RPWS allow us to determine the apparent polarization of the Jovian anomalous continuum. The apparent polarization of a radio wave is given by the Stokes parameters defined in the antenna plane [*Fischer et al.*, 2009; *Ye et al.*, 2010a]. The calculation of apparent polarization assumes that the incoming wave vector is perpendicular to the antenna plane, which is convenient because the wave vector information is not always available. Although apparent polarization is different from the real polarization, which is given by the Stokes parameters defined in the wave plane rather than the antenna plane, it can provide valuable information about the sense of circular polarization and the total polarization degree.

[15] Figure 6 shows the apparent total polarization degree spectrogram for the Jovian anomalous continuum detected by Cassini RPWS on DOY 110, 2003, the same event presented in the study of *Kaiser et al.* [2004]. It shows that the total polarization degree of the emission below 10 kHz is near zero, which means that the anomalous continuum is unpolarized. The non zero total polarization degree of the background is due to the receiver noise, which is the same on both receivers which are connected to the two antennas. The algorithm for calculating the apparent polarization [*Fischer et al.*, 2009] takes into account the different lengths of the antennas. In the direction finding mode, where two monopoles are used, the effective lengths are the same and so the apparent linear polarization of the background goes to zero. In the dipole-monopole mode (Figure 6), where the dipole is used on one receiver and the monopole is used on the other, the noise is still the same on both receivers. Hence the different effective lengths used for monopole and dipole in the apparent polarization calculation introduces an artificial linear polarization of the background.

[16] Figure 7 shows the apparent degree of circular polarization spectrogram for the QP bursts detected by Cassini RPWS on DOY 357, 2000, before the Cassini Jupiter flyby. It shows that the group of bursty emissions in the frequency range of 10–40 kHz are highly circularly polarized. The circular polarization sense of the QP bursts is opposite to that of the high frequency Jovian decametric radiation (above 6 MHz), which is known to be emitted in the R-X mode. As these two emissions both originate from the polar region of Jupiter, we conclude that the QP bursts are emitted in the L-O mode. The polarization measurement of the QP bursts is also consistent with the theoretical prediction by *Kimura et al.* [2011], where linear wave growth calculations showed that relativistic electron beams can generate strong L-O mode waves.

6. Discussion

[17] So far, two scenarios have been proposed for the generation of Jovian anomalous continuum. *Kaiser et al.* [2004] proposed a leaky waveguide mechanism in which the low frequency part of the Jovian magnetospheric emissions, including QP bursts, continuum and bKOM, are modified, dispersed and re-radiated by the magnetosheath. *Morioka et al.* [2004] proposed Langmuir waves excited by the QP electron bursts in the magnetosheath as the source of Jovian anomalous continuum, although Langmuir waves have only rarely been observed in the Jovian magnetosheath. The latter authors argued that the slow propagation and dispersive characteristics of Langmuir waves could explain the long duration and slow decrease in frequency of Jovian

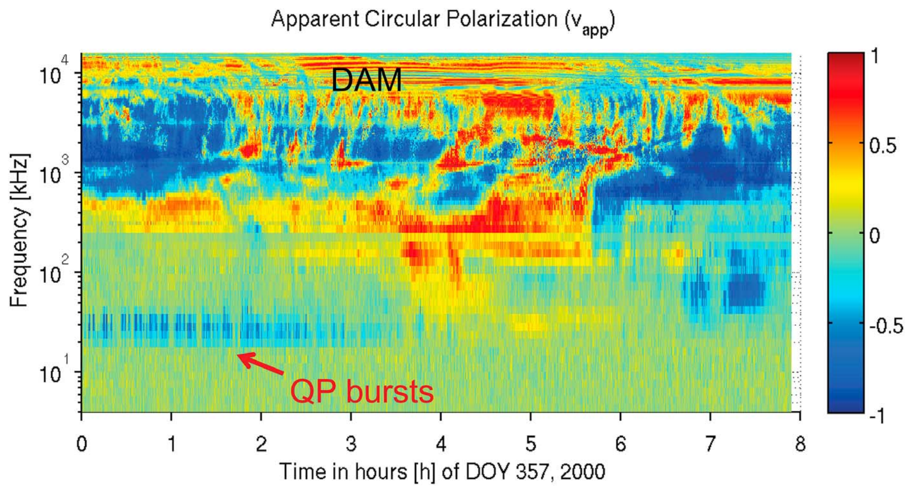

Figure 7. Apparent circular polarization degree spectrogram for the QP bursts (20–40 kHz) detected by Cassini RPWS from midnight to ~03:00 on DOY 357, 2000.

anomalous continuum. According to their estimation, a propagation length of more than 20,000 R_J is necessary for the observed frequency dispersion if L-O mode waves are the origin, and therefore they discount the possibility of L-O mode waves as the origin of the Jovian anomalous continuum.

[18] However, the calculation of the required propagation length by *Morioka et al.* [2004] is based on a fixed plasma frequency in the magnetosheath. In reality, the plasma frequency in the magnetosheath is a function of solar zenith angle and slowly decreases down the magnetotail. So any calculation of dispersion based on the L-O mode assumption must take into account the fact that different frequency waves escape to the solar wind via different sections of the magnetosheath. The low frequency waves are trapped in the magnetosphere until the plasma frequency in the magnetosheath is lower than the wave frequency, which could be a couple of AU down the magnetotail.

[19] As found by *Kurth et al.* [1982], the length of Jupiter's magnetotail is between 5000 and 9000 R_J (up to 4.5 AU). We model the plasma frequency of the Jovian magnetosheath as a function of distance down the magnetotail of Jupiter (Figure 8a):

$$f_p = \frac{5.2}{r+5.2} f_{psw} \left(1 + e^{-\frac{r^2}{2D^2}}\right) \tag{1}$$

where r is the distance down the Jovian magnetotail in AU; f_{psw} is the plasma frequency of solar wind at Jupiter, which is chosen to be 4 kHz; D = 0.1 AU is the scale length of the magnetosheath density profile near Jupiter. Equation (1) is a not so rigorous empirical model of the plasma frequency in the Jovian magnetosheath, based on our knowledge of the solar wind density at Jupiter and the common density profile of a magnetosheath. It is consistent with the Earth magnetosheath model by *Spreiter et al.* [1966], in which the plasma density decreases from 4 times the solar wind density at the nose of the magnetosheath to 1 in the magnetotail. Since Jupiter has such a long magnetotail that the surrounding solar wind density slowly decreases, the density in the magnetosheath will also decease as the distance down the tail increases. The group velocity of the L-O mode waves is given by

$$v_g = c\sqrt{1 - \frac{f_p^2}{f^2}} \tag{2}$$

where c is the speed of light in AU/hour; f is the wave frequency; f_p is the plasma frequency in the magnetosheath. If the wave frequency is lower than the plasma frequency in the sheath, it's trapped in the magnetosphere, so the group velocity is assumed to be the speed of light. The total time delay is given by

$$t = \int_0^r \frac{\mathrm{d}r}{v_g}. \tag{3}$$

[20] Figure 8b shows the delay time as a function of r for three different frequencies 3, 4 and 5 kHz. Figure 8c shows the differential time delay $\delta t = \frac{\mathrm{d}r}{v_g}$ as a function of r. It is shown that both the total delay time and the differential time delay significantly increases when the wave frequency is marginally higher than the local plasma frequency in the magnetosheath. This increase in the delay time is much larger for 3 kHz than for 4 or 5 kHz. The 3 kHz waves are trapped in the magnetosphere of Jupiter until several thousand R_J down the tail. There, the plasma density in the magnetosheath decreases much slower than in the vicinity of Jupiter, so the waves can maintain a low group velocity for a much longer distance. The dispersion of the leading edge of the Jovian anomalous continuum (a couple of hours) probably originates from the increasing scale length when the plasma density in the magnetosheath decreases down the magnetotail. It should be pointed out that the time delay for the lower frequency waves inside the magnetosphere is underestimated because straight line propagation is assumed. In reality, these waves bounce may back and forth inside the magnetosphere before they escape through the magnetosheath.

[21] The purpose of the model shown in Figure 8 is to illustrate (1) waves with different frequencies enter the

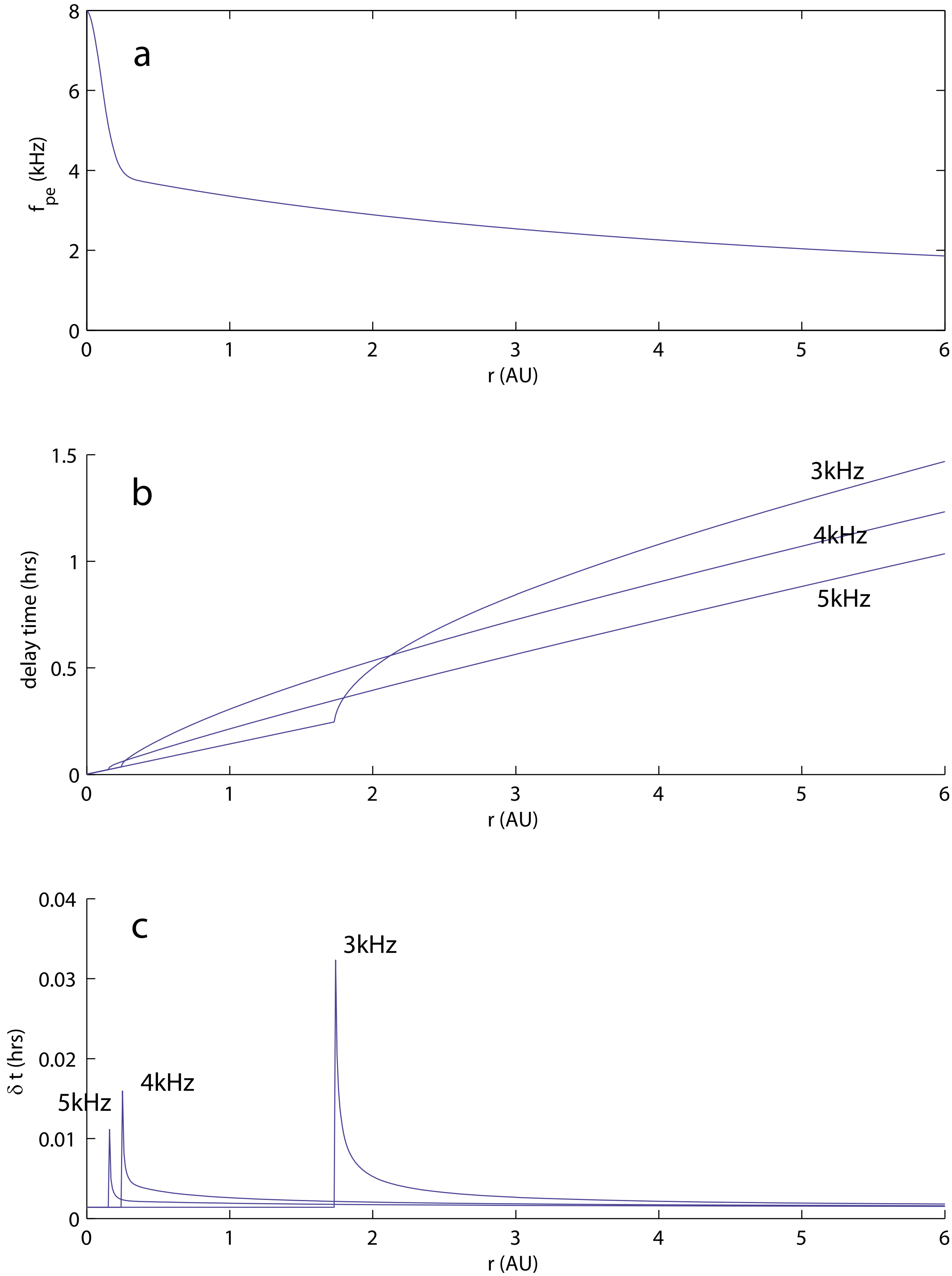

Figure 8. (a) Modeled plasma frequency versus distance down the magnetotail inside the Jovian magnetosheath. (b) Total propagation time delay for 3, 4 and 5 kHz waves. (c) Differential propagation time delay for 3, 4 and 5 kHz.

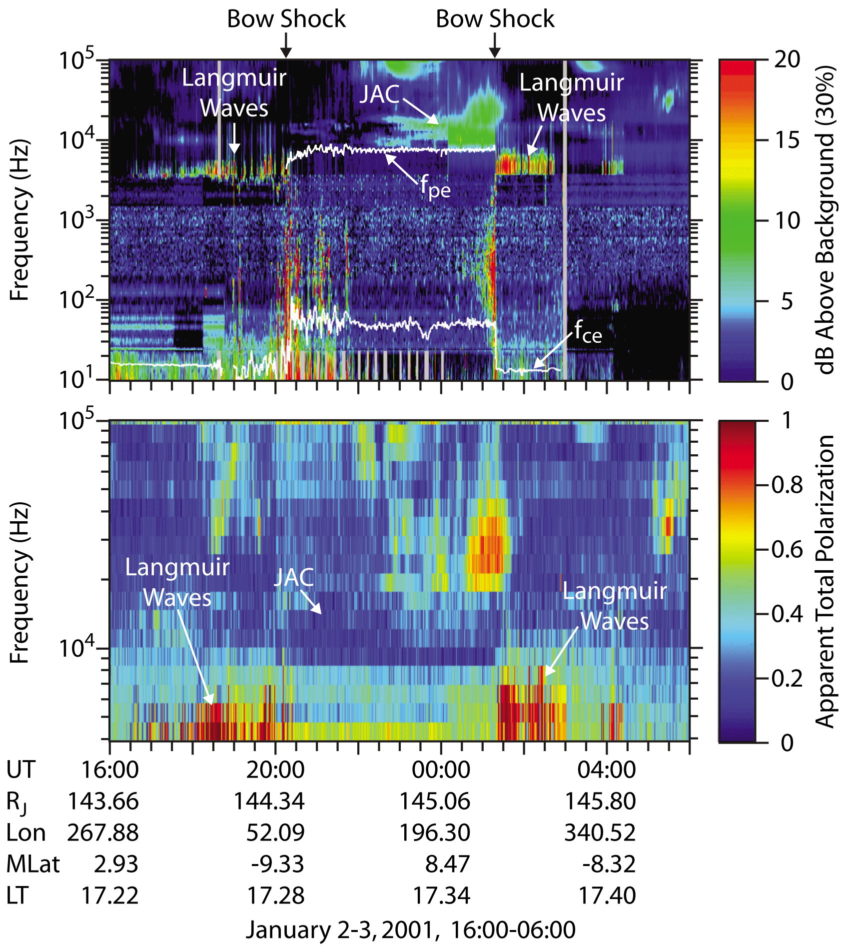

Figure 9. (top) Observation of the Jovian anomalous continuum inside the Jovian magnetosheath on DOY 002, 2001. (bottom) Apparent total polarization degree. Unpolarized electromagnetic Jovian anomalous continuum was observed inside the magnetosheath. Electrostatic Langmuir waves are excited just upstream of the bow shock. The emission at around 30 kHz with apparent total polarization ∼1 is bKOM.

magnetosheath and get delayed at different locations down the magnetotail; (2) the time delay for lower frequency waves is more significant than that for higher frequency waves. The dispersion calculated is not enough to explain the dispersion observed, because we assumed straight line propagation. In reality, the waves are scattered by density structures inside the magnetosheath, significantly increasing the length of the propagation path. This increase in the propagation path length was not taken into account in the simulation, therefore the time delay is underestimated.

[22] The long dispersive tail of the Jovian anomalous continuum originates from the refraction/scattering of the low frequency waves by density structures as they propagate within the magnetosheath. As shown by *Steinberg et al.* [2004], scattering plays a very important role in slowing down the rays in the magnetosheath, which can explain the dispersion of the terrestrial LF bursts. Their ray-tracing results show that scattering causes more time delay in the lower frequency waves than in the higher frequency waves. This is consistent with the observation of long tails in the low frequency part of both the Jovian anomalous continuum and the terrestrial LF bursts.

[23] The calculation of *Morioka et al.* [2004] indicates that all the Langmuir waves escape as the Jovian anomalous continuum after propagating 200–300 R_J in the magnetosheath. If this is true, the Jovian anomalous continuum would appear to remote observers as a point source, contrary to our finding that the Jovian anomalous continuum has a line source.

[24] Another difficulty of the Langmuir wave hypotheses is the lack of Langmuir waves observed in the magnetosheath. Instead, Cassini observed unpolarized Jovian anomalous continuum radiation inside the magnetosheath. This is contrary to the generation mechanism described by *Morioka et al.* [2004]. According to the Langmuir wave hypotheses, the Jovian anomalous continuum is mode converted from quasi-electrostatic Langmuir waves at the bow shock. Therefore the electromagnetic radiation should not be observed in the magnetosheath. The following in-situ Cassini RPWS observations show that this is not the case.

[25] Figures 9 and 10 show Cassini RPWS observations of the Jovian anomalous continuum inside the magnetosheath of Jupiter on DOY 002 and DOY 016 of 2001 respectively. The magnetosheath is identified by the abrupt increase in the local electron cyclotron and plasma frequencies (white

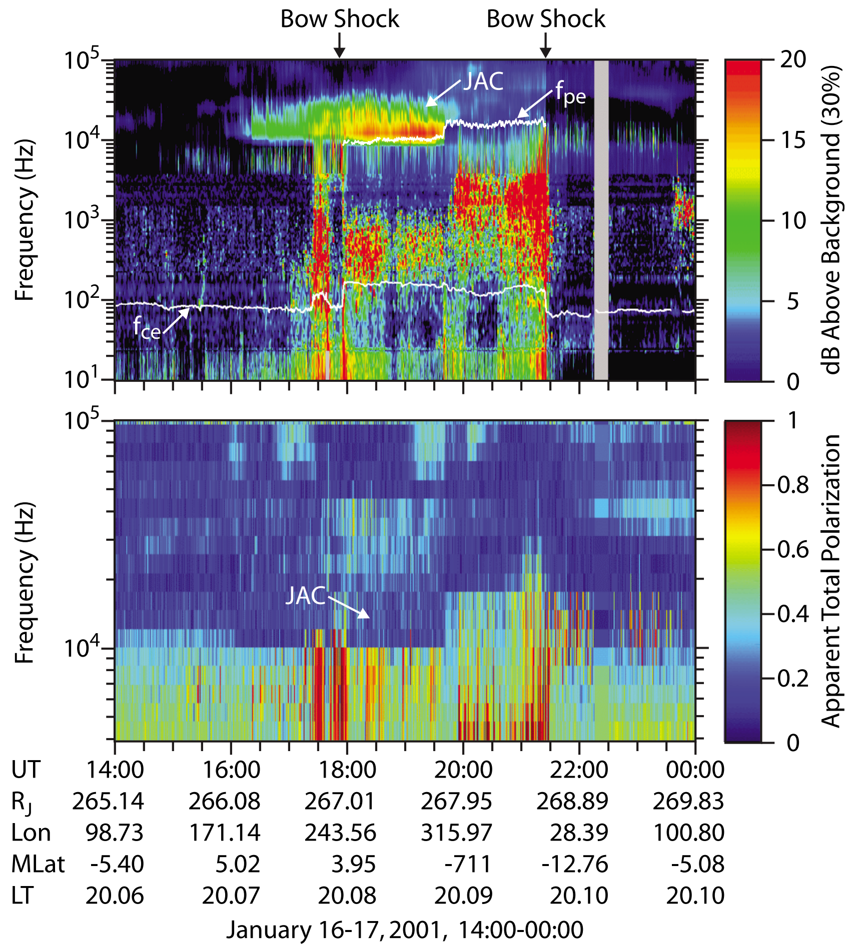

Figure 10. (top) Observation of the Jovian anomalous continuum inside the Jovian magnetosheath on DOY 016, 2001. (bottom) Apparent total polarization degree. Unpolarized electromagnetic Jovian anomalous continuum was observed inside the magnetosheath. Note the lower cutoff frequency of the Jovian anomalous continuum inside the magnetosheath matches the plasma frequency calculated from the CAPS/ELS density measurement.

curves in the upper panels of both figures) calculated from Cassini magnetometer (MAG) and Cassini plasma spectrometer/electron spectrometer (CAPS/ELS) measurements respectively. The intense broadband bursty emissions are signatures of bow shock crossing [*Kurth et al.*, 2001]. Langmuir waves are excited at local plasma frequency just upstream of the bow shock. In both cases, the Jovian anomalous continuum observed inside the magnetosheath appear to be unpolarized, as shown by the near zero apparent total polarization degrees in the lower panels of Figures 9 and 10. In contrast, the total polarization degrees of the Langmuir waves are close to 1, consistent with the high linear polarization degree of electrostatic waves. Note that the lower cutoff frequency of the Jovian anomalous continuum inside the magnetosheath matches well with the plasma frequency calculated from the electron density measurements by CAPS/ELS, which is consistent with the L-O mode propagation.

[26] In Figure 9, the Jovian anomalous continuum emission can be observed inside the sheath region, and there seems to be a cutoff at the bow shock. The Langmuir waves in Figure 9 show that the electron plasma frequency f_{pe} in the Solar wind is roughly 5 kHz, but could be even more in some regions due to electron density fluctuations close to the bow shock. This is only slightly smaller than the frequency of the Jovian anomalous continuum (~10 kHz). The nondetection of the Jovian anomalous continuum in the solar wind in Figure 9 could be a geometric effect. For example, if the angle of incidence α of the Jovian anomalous continuum with respect to the normal to the bow shock is larger than 60°, they cannot get out of the magnetosheath since the cutoff frequency is given by $f_{pe}/\cos(\alpha)$.

[27] As shown by the polarization measurements of Cassini RPWS, the higher frequency escaping QP bursts are usually circularly polarized L-O mode, whereas the low frequency anomalous continuum emissions are found to be essentially unpolarized (Figures 6 and 7). This is similar to the case of Saturn narrowband emissions, where the 5 kHz emission is found to be highly circularly polarized when detected at high latitudes but is unpolarized at low latitudes outside the plasma torus [*Ye et al.*, 2009]. The depolarization of low latitude Saturn narrowband emission could be due to the multiple reflections of the Z-mode waves between the

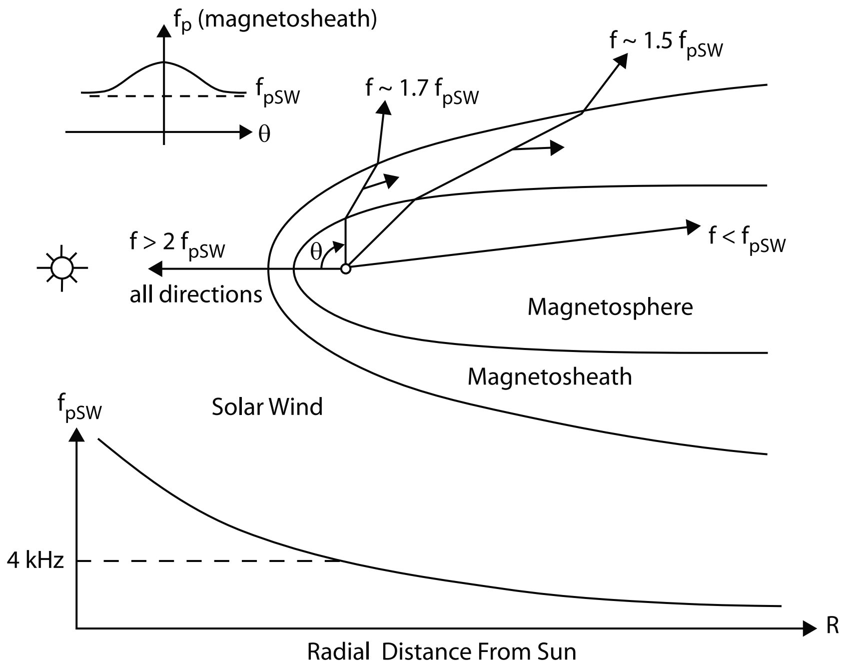

Figure 11. Magnetosheath guiding and re-radiation of low frequency Jovian radio emissions as the generation mechanism of Jovian anomalous continuum (based on *Kaiser et al.* [2004, Figure 4]).

f_{UH} and $f_{L=0}$ surfaces before mode conversion to the L-O mode and escaping as discussed by *Ye et al.* [2010a].

[28] Figure 11 illustrates the leaky waveguide hypothesis for the emission mechanism of Jovian anomalous continuum. The QP bursts are first generated near Jupiter as L-O mode broadband bursty waves without dispersion [*Menietti et al.*, 2001; *Hospodarsky et al.*, 2004]. The bKOM is emitted from the auroral field lines by cyclotron maser instability [*Ladreiter et al.*, 1995]. The non-thermal continuum is generated on the boundary of the plasma torus through mode conversion of electrostatic upper hybrid waves [*Gurnett et al.*, 1983]. For these waves to escape the Jovian magnetosphere, the wave frequency needs to be higher than the plasma frequency in the magnetosheath. The plasma frequency in the magnetosheath is a function of the solar zenith angle. According to the shock theory, the maximum attainable density compression ratio at a shock is 4 [*Gurnett and Bhattacharjee*, 2005]. Therefore at the nose of the sheath, the plasma frequency is nearly two times the solar wind plasma frequency. As the solar zenith angle increases, the plasma frequency of the sheath gradually decreases to the solar wind plasma frequency. So waves with a frequency higher than two times the solar wind plasma frequency can escape from the magnetosphere in all directions, while waves with a frequency lower than the solar wind plasma frequency are trapped in the magnetosphere. Waves with a frequency between one and two times the solar wind plasma frequency can escape to the interplanetary space at a certain solar zenith angle and beyond. Inside the magnetosheath the low frequency part of the anomalous continuum is significantly slowed down causing the large dispersion.

[29] This picture also explains why only higher frequency QP bursts and Jovian anomalous continuum was observed before the Jupiter flyby, because the lower frequency emissions cannot escape from the nose region so its energy is channeled/beamed down the magnetotail by the magnetosheath. The solar wind plasma density at Jupiter is typically around 4 kHz. As the distance from the Sun increases, the solar wind plasma frequency decreases as a function of $1/R$, where R is the radial distance from the Sun. So, the lower frequency emissions that are originally trapped in the magnetosphere can escape into the solar wind further down the magnetotail. This also contributes to the dispersion because the lower frequency waves are trapped longer in the magnetosphere before escaping to the solar wind. The leaky waveguide hypothesis is also more consistent with the $1/r$ dependence of the Jovian anomalous continuum power, in that the emission is radiated along the whole length of the magnetotail of Jupiter, which is more than 5000 R_J (2.5 AU) long [*Kurth et al.*, 1982].

[30] Simultaneous detections of Jovian anomalous continuum by two spacecraft separated by a large local time difference indicates that the generation of these emissions is triggered periodically like a clock [*Kaiser et al.*, 2004]. *Hospodarsky et al.* [2004] compared the observations of QP bursts by Galileo and Cassini during the Cassini Jupiter flyby and concluded that the QP bursts are also triggered periodically like a clock. *Morioka et al.* [2006] compared the occurrence characteristics between the Jovian anomalous continuum observed by Ulysses and QP bursts groups observed by Galileo and found that both phenomena share the same occurrence peak at around λ_{III} = 260°–320°. This finding supports the model that both the QP bursts and Jovian anomalous continuum are generated by the recurrent quasiperiodic particle accelerations [*McKibben et al.*, 1993], which are caused by magnetospheric disturbances when Jupiter has a certain rotation phase with respect to the solar wind direction. We propose that the anomalous continuum radiation is a result of trapping and re-radiation of QP

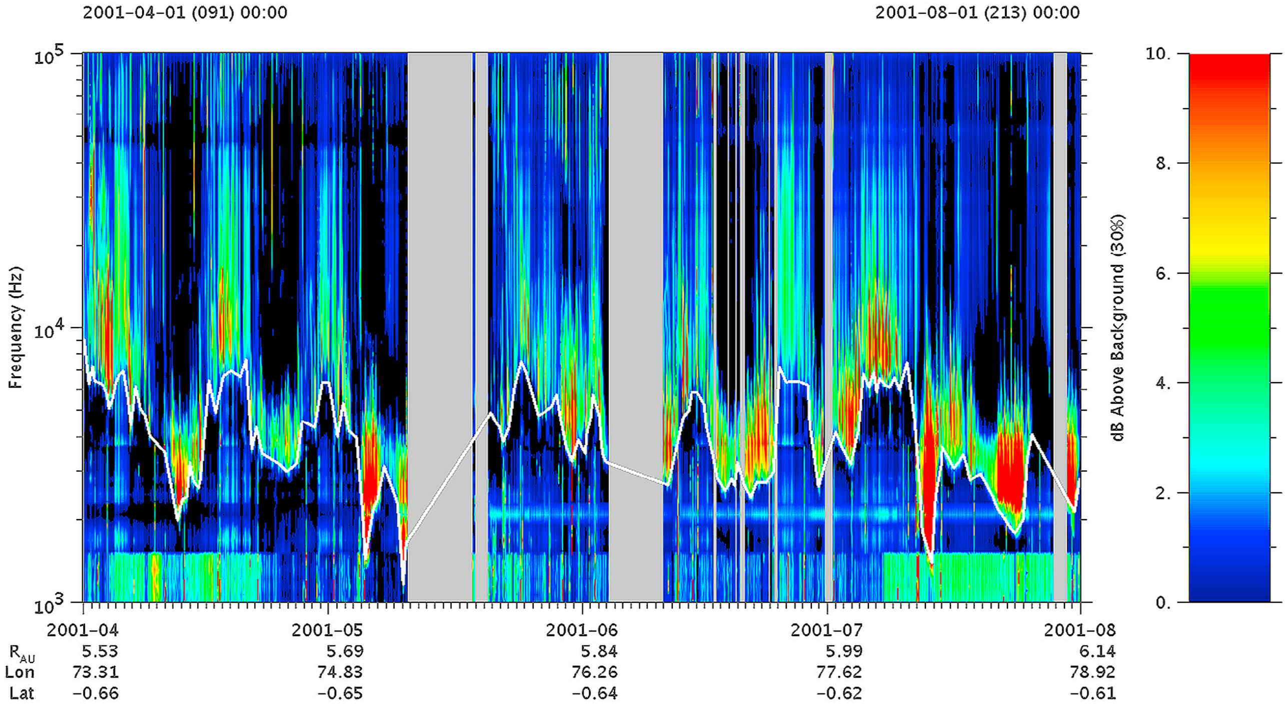

Figure 12. Solar wind control of the Jovian anomalous continuum over 4 months. The variation of the lower cutoff frequency (traced by the white curve) has a period of roughly 12–14 days.

bursts and other low-frequency Jovian emissions by the magnetosheath.

[31] Figure 12 shows that the Jovian anomalous continuum oscillates up and down in frequency in response to a periodic change in solar wind conditions, which determines the plasma frequency in the magnetosheath which then determines what frequencies may escape. As shown in the 4-monthlong spectrogram, the modulation period of the frequency of Jovian anomalous continuum is roughly 12–14 days, which is about one half of the solar rotation cycle.

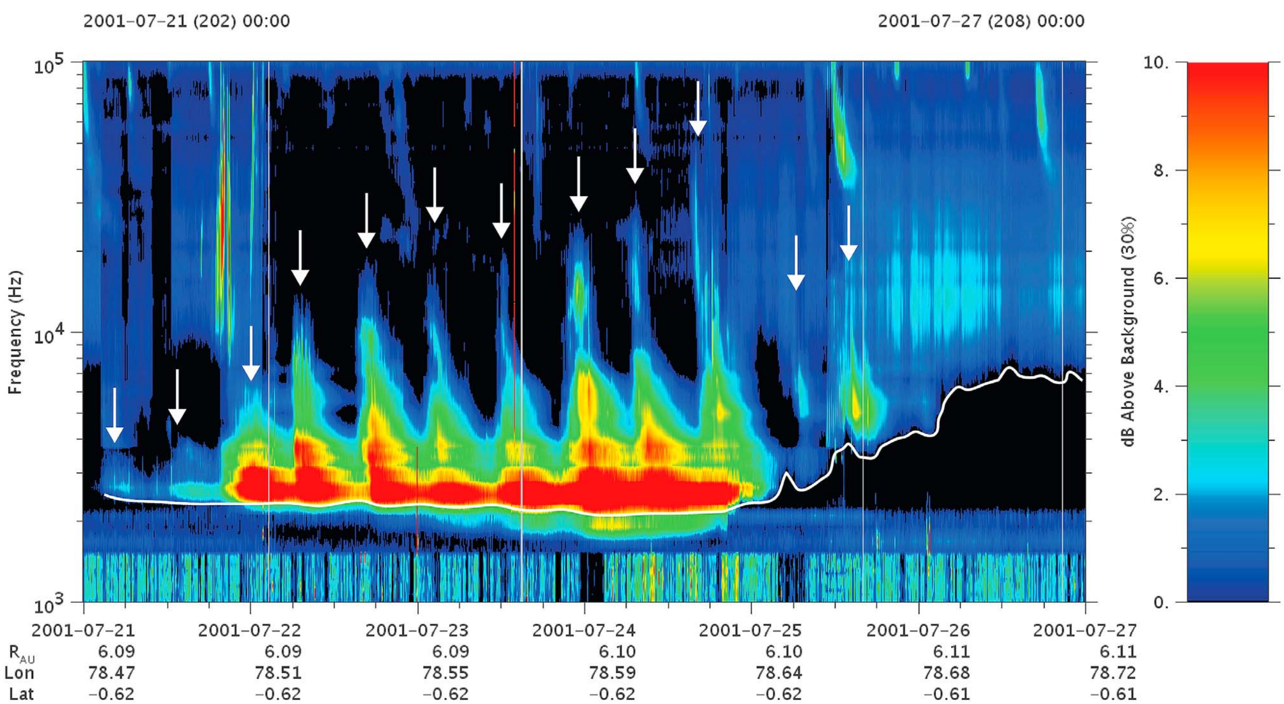

Figure 13. Solar wind control of the Jovian anomalous continuum over 6 days in July 2001. The high frequency limit of the Jovian anomalous continuum increased while the lower cutoff frequency did not increase until 4 days later.

A comparison of the frequency variation of Jovian anomalous continuum with a modeled solar wind condition at Jupiter would confirm this, which will be the subject of a future study.

[32] The solar wind control of the Jovian anomalous continuum is largely dependent on how the emission is generated. As proposed in this paper, the emission is caused by re-radiation of the Jovian magnetospheric emissions, including QP bursts, bKOM and continuum. The QP bursts and bKOM are triggered when a certain Jovian longitude faces the Sun. The variable solar wind condition may also play a role in changing the intensity and frequency extent of these emissions. The density profile of the Jovian magnetosheath, which is a function of the solar wind condition, determines what frequencies of JAC can be observed by a remote spacecraft like Cassini, as only the frequencies that are close to the plasma frequency of the magnetosheath can be trapped and dispersed by the magnetosheath waveguide. When the solar wind condition changes abruptly at Jupiter, the density in the day side magnetosheath will increase first and the density in the tail will remain unchanged, which will cause a step in the density profile of the magnetosheath. This step will slowly move down the magnetotail at the speed of the solar wind. Note that the electromagnetic waves will propagate down the magnetotail much faster (several hours compared to several days for the solar wind). So we propose that the high frequency limit of the JAC will be increased when high density solar wind arrives at Jupiter, whereas the low frequency limit will remain unchanged for several days until the solar wind enhancement propagates through the whole length of the magnetotail. This is exactly what is observed by Cassini as shown in Figure 13, where the increase in the high frequency extent of Jovian anomalous continuum is followed by an increase in the low frequency cutoff several days later.

7. Summary

[33] We have shown that the Jovian anomalous continuum near 10 kHz was detected by Cassini RPWS from DOY 202, 2000 to DOY 165, 2004, when the distance between Jupiter and Cassini was more than 8 AU (see Figure 2). Wave power versus radial distance analyses revealed a $1/r$ dependence which is consistent with an elongated apparent source rather than a point source. The rotational modulation analyses show that Jovian anomalous continuum is modulated at the system III period of Jupiter. Strong modulation of Jovian anomalous continuum was detected between 2001 and 2004, consistent with the continuous observation during that period (see Figure 1). In contrast, the higher frequency emissions such as Jovian DAM, HOM and bKOM, although more prominent when Cassini was still close to Jupiter, disappeared on both the wave power spectrogram and the modulation power spectrogram because, as point sources, they fall off as $1/r^2$. The persistent observation of Jovian anomalous continuum by Cassini RPWS suggests that the Jovian magnetosheath acts like a leaky waveguide, which channels the wave energy down the magnetotail of Jupiter before the wave escapes to the solar wind. The polarization characteristics of Jovian anomalous continuum are also consistent with the leaky waveguide model, where the magnetosheath depolarizes the L-O mode waves through refraction/scattering and reflections. The frequency of the Jovian anomalous continuum is determined by the plasma frequency in the magnetosheath of Jupiter, which is then related to the solar wind plasma density. So the observation of the Jovian anomalous continuum can be used as a remote diagnostic of the solar wind condition at Jupiter.

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G. Fischer, Space Research Institute, Austrian Academy of Sciences, Schmiedlstrasse 6, A-8042 Graz, Austria. (georg.fischer@oeaw.ac.at)

D. A. Gurnett, G. B. Hospodarsky, W. S. Kurth, J. D. Menietti, P. Schippers, and S.-Y. Ye, Department of Physics and Astronomy, University of Iowa, 203 Van Allen Hall, Iowa City, IA 52242, USA. (donald-gurnett@uiowa.edu; george-hospodarsky@uiowa.edu; william-kurth@uiowa.edu; john-menietti@uiowa.edu; patricia-schippers@uiowa.edu; shengyi-ye@uiowa.edu)