Source characteristics and radiation mechanism of Jovian anomalous continuum

A. Morioka,[1] T. Yuasa,[1,2] Y. S. Miyoshi,[1,3] F. Tsuchiya,[1] and H. Misawa[1]

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[1] We investigate the characteristics of the Jovian anomalous continuum (JAC) in interplanetary space and in the magnetosheath, using Ulysses observations. Some new source characteristics of JAC were obtained in addition to those found by previous authors [e.g., *Kaiser*, 1998]. JAC tends to occur when the solar wind dynamic pressure decreases after a rapid increase. We confirm and show more concretely that the commencement of JAC has significant dependence on local time, i.e., its appearance is most likely when the System III longitude of the subsolar point is near 270°. The periodic appearance of JAC is not due to its intensity modulation but to its repeated individual excitation. JAC exhibited an abrupt amplitude change across the bow shock, possibly suggesting a mode conversion from quasi-electrostatic to electromagnetic waves at the bow shock. We also evaluate possible sources of JAC and hypothesize that its origin is Langmuir waves excited at the magnetopause by energetic particles such as quasiperiodic bursts ejected from the polar magnetosphere. The relation of magnetospheric disturbances to the generation of JAC is also discussed. *INDEX TERMS:* 2756 Magnetospheric Physics: Planetary magnetospheres (5443, 5737, 6030); 6220 Planetology: Solar System Objects: Jupiter; 7847 Space Plasma Physics: Radiation processes; *KEYWORDS:* Jovian magnetosphere, Jovian radio waves, Langmuir waves

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1. Introduction

[2] Giant planets emit various kinds of nonthermal radio emissions into interplanetary space. These emissions contain important information not only on the generation of natural radio waves in planetary plasmas but also on plasma environments and their dynamics in and around the magnetospheres.

[3] The low-frequency radio emission component from Jupiter, which is called Jovian continuum emission, was first reported by *Scarf et al.* [1979]. After that, many studies were carried out to investigate the emission mechanism and to explore the relation between wave generation and the magnetospheric environment, based on Voyager observations [*Gurnett et al.*, 1980; *Melrose*, 1981; *Moses et al.*, 1987; *Gurnett et al.*, 1983; *Kurth*, 1986; *Barbosa et al.*, 1990]. The Ulysses observations, which have been sending Jovian radio wave data since 1991, enabled a detailed study on the spectral characteristics of the Jovian continuum [*Kaiser et al.*, 1992]. *Kaiser* [1998] showed that the Jovian low-frequency radio waves detected in interplanetary space have two components. The first is the escaping Jovian continuum, which is generated in the Jovian magnetosphere through a mechanism presumably similar to that of the Earth's continuum [see *Kurth*, 1992, and references therein]. The second is the continuum component, which radiates from the planet's bow shock or magnetosheath region. This component is called an anomalous continuum following *Gurnett*'s [1975] nomenclature for the Earth's continuum. In this paper we call this component the Jovian anomalous continuum (JAC) to distinguish it from the Earth's anomalous continuum.

[4] The phenomenological features of JAC have been reported by *Kaiser et al.* [1992] and *Kaiser* [1998]. JAC is the same emission that *Kaiser* [1998] (and *Kaiser et al.* [2004]) called "reradiated" emission. JAC is characterized by a band of intense semicontinuous emission near 5–10 kHz, drifting toward lower frequencies. The higher-frequency component of these emissions is usually connected with a cluster of quasiperiodic emissions, which have a periodicity of about 15 or 40 min (QP-15 and QP-40 emissions [*MacDowall et al.*, 1993]) and occasionally broadband kilometric radiation (bKOM). The duration of JACs ranges from several to more than 10 hours. *Kaiser* [1998] pointed out that the sharp low-frequency edge of JAC corresponds to twice the expected plasma frequency, $2f_p$, in the solar wind at Jupiter and that the source region of the emission is near the bow shock based on the observation that the JAC's intensity peak is just inside the bow shock.

[5] The amplitude modulation of Jovian low-frequency radiation has been discussed since the observations by

[1]Planetary Plasma and Atmospheric Research Center, Tohoku University, Sendai, Japan.

[2]Now at Mitsubishi Space Software Co. Ltd., Amagasaki, Japan.

[3]Now at Solar-Terrestrial Environment Laboratory, Nagoya University, Toyokawa, Japan.

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Voyager. *Kurth and Gurnett* [1986] found that the continuum radiation observed in the Jovian magnetosphere had amplitude variations at the Jovian rotation period of 10 hours, and they suggested a clock-like modulation of energetic electrons as the origin of the radiation. Referring to this result, *Kaiser et al.* [1993] showed that the occurrence of JAC was more probable around 0°–90° of the subsolar longitude of System III.

[6] These extensive analyses revealed many unknown aspects of JAC and raised important issues regarding its origin. More important, it is of great interest how the very slow frequency drift of the emission occurs and continues for several hours, maintaining its intensity. In this paper we report reexaminations of some source characteristics of JAC and confirmation of the results presented in previous work using the released Ulysses database. We then discuss the origin of JAC.

2. Database

[7] We used the plasma wave data from the Unified Radio and Plasma Wave (URAP/RAR) Experiment [*Stone et al.*, 1992] and solar wind data from Solar Wind Observations Over the Poles of the Sun (SWOOPS) [*Bame et al.*, 1992], which are available from the Coordinated Heliospheric Observations (COHO) database. The plasma wave database contains electric field spectra in a frequency range from 1.25 to 940 kHz with a time resolution of 144 s. The solar wind data provided 3-min averaged bulk velocity and plasma density of the solar wind. We selected the period of analysis for the inbound path to be from 1 September 1991 to 8 February 1992, which corresponded to a spacecraft distance of 2700-10 Jovian radii (R_J) from Jupiter, and that for the outbound path to be from 9 February 1992 to 30 April 1992 (10–1000 R_J). Typical JAC events were selected during these observational periods. The total number of selected events was 84, where 56 events were detected during the inbound path and 28 were detected during the outbound path.

3. Occurrence Characteristics of JAC

3.1. Spectral Characteristics and Periodic Appearance

[8] The survey of the JAC observation by Ulysses revealed that JAC phenomena were only detected in interplanetary space and in the Jovian magnetosheath. Figure 1 shows typical dynamic spectra of JAC observed in interplanetary space during the inbound path from day 270 to 271, 1991. JAC is characterized by slowly decreasing frequency in a range from about 7 to 15 kHz and by its long duration. Figure 1 shows that three consecutive JAC phenomena were detected. At the beginning of each JAC, magnetospheric QP-15 and/or QP-40 radio bursts whose frequency extended up to 20 kHz or more overlapped into the JAC spectra, as reported by *Kaiser* [1998]. The duration of JAC was more than 10 hours in this case, which is longer than the planetary rotation. One of the curious features of JAC is its repeated appearance, as shown in Figure 1. About 40% of JAC events appeared with a series of more than three JACs. The repetition period for consecutive JACs was almost consistent with the rotational period of Jupiter, as was pointed out by *Kaiser et al.* [1993]. It should be noted that a newly appeared JAC overlaps with the tail of the previous JAC spectrum, as can be seen in Figure 1. This means that a series of JAC emissions is not an oscillatory modulation of the amplitude, but repeated radiation by individual excitation or a trigger with the period of the planetary rotation.

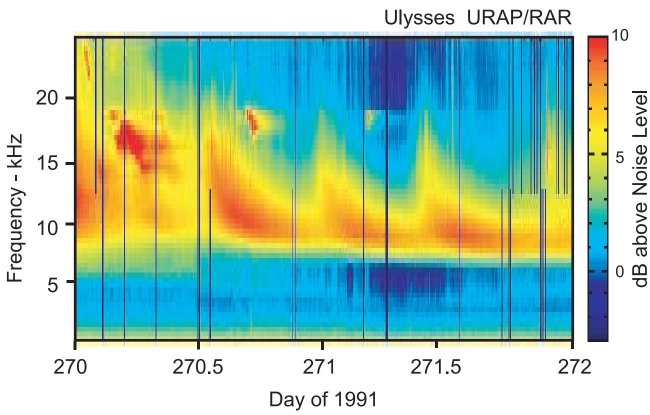

Figure 1. Two-day dynamic spectrum of URAP data observed on day 270–271, 1991. Three consecutive Jovian anomalous continuums (JACs) with about a 10-hour period were detected.

3.2. Amplitude Change Across Bow Shock

[9] Figure 2 shows dynamic spectrum and amplitude profiles at selected frequencies of the received signal during the period between 15 hours before and 5 hours after the Ulysses crossing of the Jovian bow shock on 2 February 1992. The upper right column is the plasma data quoted from *Phillips et al.* [1993] to refer to Jovian magnetospheric boundary regions. The Ulysses spacecraft first detected the JAC event at about 0640 UT on 2 February 1992 in interplanetary space. It is a general feature of JAC that the intensity gradually increases during the first 2 or 3 hours. The second JAC detection was about 10 hours later, at 1610 UT, when Ulysses was just in front of the bow shock. The amplitude of the second JAC was comparable with the first one, although strong QP radio bursts merged into it. Then, the spacecraft encountered the bow shock at 1733 UT [*Phillips et al.*, 1993]. It should be noted that JAC amplitude went up abruptly by 10 times or more during the crossing of the bow shock. The intensified JAC was observed until the spacecraft entered the magnetosphere. In the magnetosphere the dynamic spectrum showed that JAC was no longer detected but that strong trapped continuum radiation filled the magnetosphere. *Kaiser* [1998] reported on the intensity peak of the 7.25-kHz JAC component just inside the bow shock, and he suggested that the apparent source of JAC is near the bow shock. Here we note that Ulysses had been detecting the JAC across the bow shock and that the dramatic change in the JAC amplitude from weak to very strong was observed at the bow shock. This may imply a transition of the wave mode: JAC in the magnetosheath would be in a quasi-electrostatic mode with strong intensity and slow group velocity, and JAC in interplanetary space

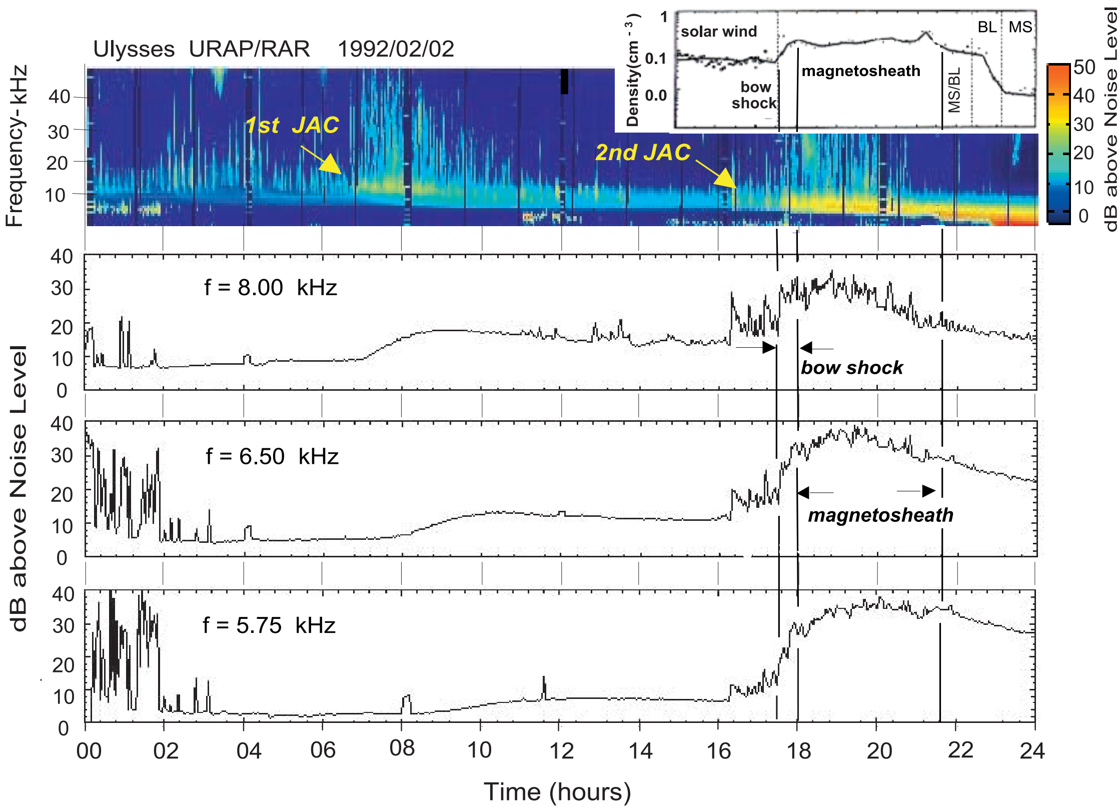

Figure 2. (top) Dynamic spectrum and (bottom three panels) amplitude profiles at frequencies of 8.00, 6.50, and 5.75 kHz of observed signals on 2 February 1992. Two JAC phenomena were detected at about 0640 and 1610 UT. The top right panel is plasma density data quoted from *Phillips et al.* [1993]. Spacecraft encountered Jovian bow shock at 1733 UT, when JAC intensity dramatically changed.

would be mode-converted radio waves from the quasi-electrostatic waves.

3.3. System III Dependence

[10] *Kaiser et al.* [1993] showed that the occurrence of JAC is more probable around 0°–90° of the subsolar longitude of System III and suggested the clock-like occurrence of JAC. In their analysis the subsolar longitude where JAC had a maximum intensity was taken as the longitude the emission occurred. We believe, however, that the subsolar longitude when JAC commenced is essential to investigating the relation between JAC occurrence and its alignment relative to the Sun. This is because the occurrence of JAC is not due to amplitude modulation but to individual excitation as mentioned in section 3.1. Thus we investigated subsolar longitude when JAC commenced for the period of both inbound and outbound path data. The results are plotted in Figure 3, together with the central meridian longitude of System III at Ulysses when JAC commenced. In Figure 3 the longitudinal scale is repeated twice. The top two panels indicate that JAC observed at different local times (inbound, ~10 hours; outbound, ~18 hours) had a shift in distribution. This means that JAC is not a radio emission fixed on Jupiter. The bottom panel in Figure 3 shows the subsolar longitude when JAC commenced during both inbound and outbound periods and clearly indicates that the most probable subsolar longitude of the emission was at about 270°. This means that JAC was favorably excited when the sector around the 270° System III longitude faced the Sun, that is, JAC commenced at a particular spin phase of the planetary rotation.

3.4. Relation to Solar Wind Variations

[11] The relation between solar wind dynamic pressure and the occurrence of JAC was investigated for inbound path data. The top and bottom panels in Figure 4 plot the number of daily occurrences of JAC and variations in solar wind dynamic pressure at Jupiter, respectively. Remote solar wind dynamic pressure at the Jovian magnetosphere was derived using the same process used by *Morioka and Tsuchiya* [1996], where solar wind plasma parameters at Jupiter were derived from an in situ spacecraft observation. There were many large-scale pressure increases accompanied by rather gradual decreases. Figure 4 shows that JAC was most likely excited when solar wind dynamic pressure was decreasing after being highly elevated. For example, an enhancement of the solar wind pressure was detected on day 298, and seven consecutive JAC events appeared during the phase of decreasing solar wind pressure. There were 15 major increases in the solar wind pressure during the period in Figure 4, and all these except for three accompanied trains of JAC. *Kaiser et al.* [1992] and *Kaiser* [1998]

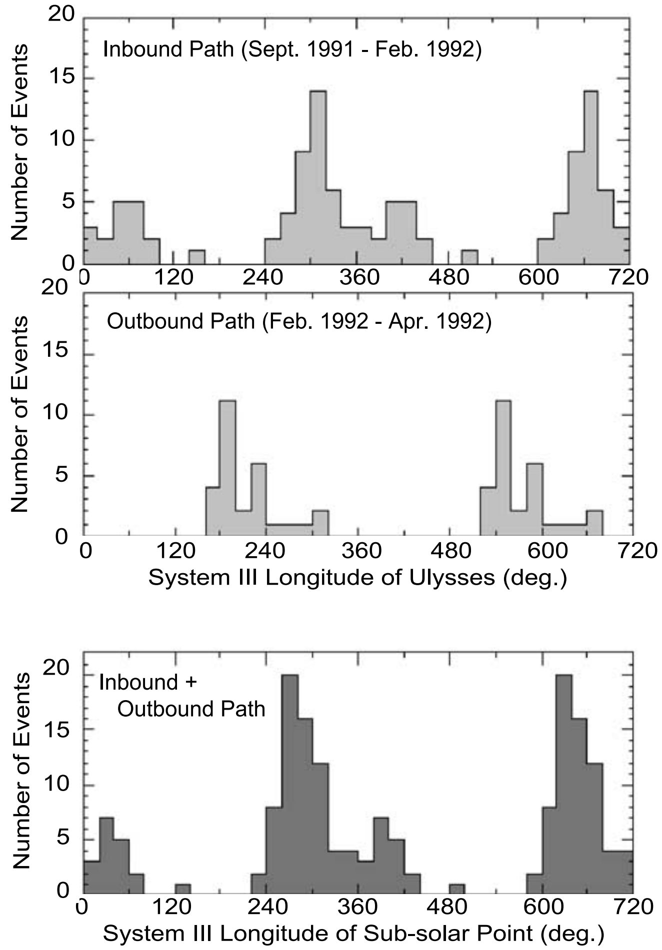

Figure 3. (Top and middle) Distributions of System III longitude of Ulysses during inbound and outbound path when JAC commencements were detected. (bottom) Distributions of System III longitude of Jovian subsolar point when JAC commencements were detected. The longitudinal scale is repeated twice. JAC commencement most probably occurs when System III longitude of 270° faced the Sun.

suggested that JAC's occurrence rate and frequency range respond to the solar wind ram pressure. The present analysis revealed detailed JAC behavior during solar wind variations.

4. Possible Emission Models and Their Evaluations

[12] The long life and slow decrease in frequency of JAC are its most outstanding characteristics. These features are the key to understanding the JAC generation mechanism. Frequency drift can be simply considered in two ways: (1) radiation from a slowly moving source region in the magnetosphere, such as a plasmoid, where the emission frequency at a local characteristic frequency decreases as the source moves, or (2) dispersion of waves propagating in strongly dispersive plasma. The former, however, can be ruled out because JAC is not detected in the magnetosphere. The latter may be possible if we consider the magnetosheath as a field of wave generation and/or propagation. Thus the following three processes can be considered: (1) dispersion of L-O mode waves during propagation in the magnetosheath, (2) excitation and propagation of *Z*-mode waves in the magnetosheath, and (3) excitation and propagation of Langmuir waves in the magnetosheath. These processes are evaluated next.

[13] The "dispersion of L-O mode waves" process was first proposed to interpret Jovian Type III bursts [*Kurth et al.*, 1989; *Desch*, 1994]. The broadband electromagnetic radio waves of the L-O mode such as QP radio bursts are radiated from the polar magnetosphere into space. The emitted radio waves experience group velocity delay as a function of the frequency during propagation in the dense plasma of the magnetosheath and can be observed with a falling tone spectrum in interplanetary space. However, this group velocity delay is insufficient in explaining the long JAC tail that sometimes lasts for more than 10 hours. Our calculation showed that L-O mode waves in the magnetosheath require a propagation path length of more than 20,000 R_J to attain the observed frequency drift in Figure 1. Such an extremely long propagation path in the Jovian magnetosphere is not relevant. Thus the long-lived JAC events can not be considered to be the dispersion of just one QP burst.

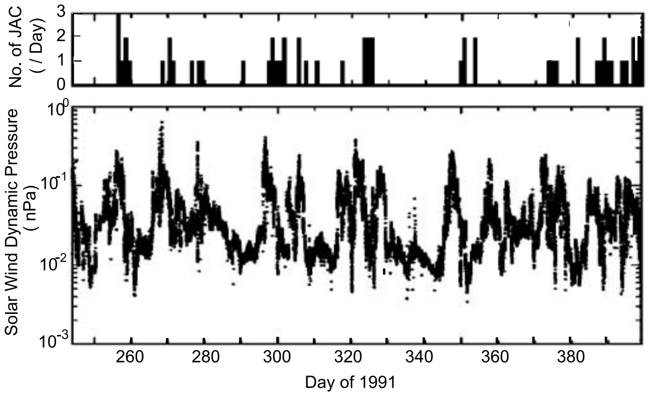

Figure 4. Relationship between (top) number of daily occurrences of JAC and (bottom) solar wind dynamic pressure at Jupiter. JACs tend to appear during a decreasing phase of solar wind dynamic pressure after a large increase.

[14] *Kaiser* [1998] applied L-O mode waves to a "re-radiated" emission, which is the same emission with JAC. His scenario is that the long-lived reradiation/JAC is the superposition of hundreds of dispersed QP radio bursts that appear to occur for a lengthy period of order of an hour or more. This may be a possible mechanism of JAC when the systematic frequency shift of the QP bursts during a planetary rotation is reasonably explained.

[15] In the "excitation and propagation of Z-mode waves" process, there is a possibility that Z-mode waves can produce the long-tail characteristics of the JAC spectrum during the propagation in the magnetosheath because a Z-mode wave has a low group velocity and experiences large dispersion in dense plasma. We examined this process assuming that energetic electron bursts from the magnetosphere would excite Z-mode waves through Landau resonance and that the excited waves would be converted to L-O mode waves at the bow shock after propagating in the magnetosheath. The estimated frequency drift curve, however, was different from that obtained from observations because the group velocity of Z-mode waves near the resonance frequency increases as the frequency decreases.

[16] The "excitation and propagation of Langmuir waves" process may be relevant because waves that can propagate more slowly with dispersive characteristics in the planetary plasma are Langmuir waves. Here we consider the excitation of Langmuir waves at the magnetopause and their propagation in the magnetosheath. If the Langmuir waves are stimulated at the magnetopause by energetic particles released from the Jovian magnetosphere, they penetrate into the magnetosheath and suffer a great deal of dispersion during propagation. The large group delay observed in the frequency-time diagram can possibly be reproduced with a reasonable propagation path length in the magnetosheath. One of the difficulties with this idea is a quite rare report on Langmuir waves in the magnetosheath [*Kaiser et al.*, 2004]. In the next section we discuss the possibility of Langmuir waves as the source of JAC.

5. Langmuir Wave Hypothesis for JAC Generation

[17] We hypothesize that JAC originates from Langmuir waves that are excited at the magnetopause and/or its boundary layer by electron beams released from the polar magnetosphere. Here we assume the broadband excitation of Langmuir waves, referring to the rather broader Langmuir waves observed near the Jovian bow shock [*Gurnett et al.*, 1981] and in the upstream region of the Earth in the solar wind plasma [*Etcheto and Faucheux*, 1984; *Lacombe et al.*, 1985; *Fuselier et al.*, 1985]. The excited Langmuir waves propagate parallel to the magnetic field in the magnetosheath because they have basically field aligned propagation. The orientation of the average magnetic field in the magnetosheath is almost parallel to the magnetopause, and a penetrating interplanetary magnetic field has a long span between the entrance into the magnetosheath and the exit into interplanetary space. Thus it takes a great deal of time for the Langmuir waves generated around the magnetopause to reach the bow shock. At the bow shock, where there is sharp discontinuity in the plasma density, Langmuir waves can be converted to electromagnetic waves through a linear or nonlinear conversion process, as has been discussed in the case of the solar Type II and III radio bursts and upstream f_p emissions [*Ginzburg and Zhelenzyakov*, 1958; *Gurnett and Anderson*, 1977; *Kellogg*, 1980; *Cairns and Melrose*, 1985; *Yin et al.*, 1998; *Kasaba et al.*, 2001]. A schematic illustration of the process is shown in Figure 5.

[18] The dispersion relation of Langmuir wave is given as

$$f^2 = f_p^2 + \frac{3}{2}\left(\frac{2k_BT}{m_e}\right)k^2, \tag{1}$$

where f and f_p are the Langmuir wave frequency and plasma frequency, and m_e, k_B, T, and k are the mass of the electron, the Boltzmann constant, electron temperature, and wave number, respectively. The relation between frequency f and travel time t is derived from the dispersion equation and group velocity of the Langmuir wave, as follows:

$$f = f_p\left(\frac{\frac{3}{2}\left(\frac{2k_BT}{m_e}\right)t^2}{\frac{3}{2}\left(\frac{2k_BT}{m_e}\right)t^2 - D^2}\right)^{\frac{1}{2}}, \tag{2}$$

where D is the ray path length.

[19] Setting f_p, T, and D as auxiliary variables, we did function fitting of equation (2) to the observed drift curve. Figure 6 shows two examples on day 298 of 1991 and day 9 of 1992. The drift curves indicated by the triangles in each panel correspond to the observed lower-frequency edges of JACs. The solid lines are the fitted functions. For day 298 of 1991, the observed lower-frequency edges of JAC fit a function with the auxiliary variables of $T = 1.0 \times 10^6$ K, f_p = 9.7 kHz, and D = 200 R_J well. This means that the slowly decreasing frequency drift of JAC may result from dispersion lag due to long distance propagation (200–300 R_J) of Langmuir waves in the magnetosheath. Another example is shown in the bottom panel of Figure 6 where plasma parameters of T = 0.7 $\times$ 10^6 K and f_p = 7.5 kHz and a propagation length of 250 R_J were obtained to reproduce the observed lower-frequency trace of JAC.

[20] The obtained plasma temperature T and plasma frequency f_p in the magnetosheath seem to be reasonable in the Jovian magnetosheath. The electron temperature in the magnetosheath was reported to be 0.5 $-$ 1.0 $\times$ 10^6 K

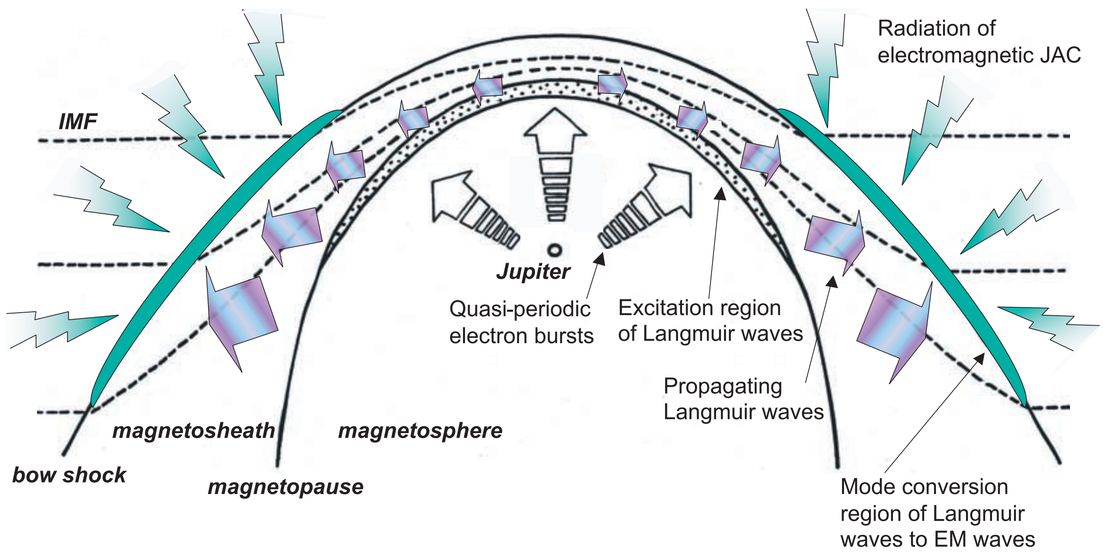

Figure 5. Illustration of scenario to generate JAC. Quasiperiodic particle bursts emitted from the polar magnetosphere hit the magnetopause and excite Langmuir waves. The excited Langmuir waves propagate in the magnetosheath along the magnetic field, and reach bow shock, suffering a great deal of group velocity dispersion. At the bow shock, part of the waves is converted to electromagnetic waves due to a sharp density gap and propagates into interplanetary space as long-lasting and frequency-drifting JACs.

from the Ulysses observation [*Phillips et al.*, 1993]. The obtained plasma frequency from 9.7 to 7.5 kHz corresponds to a plasma density of 1.1–0.7/cm^3, which is also consistent with the Ulysses observation. We assume Langmuir waves would have long distance propagation in the magnetosheath. An exact evaluation of the propagation path length D was difficult to determine because the penetrating interplanetary magnetic field into the magnetosheath could not be definitively traced. However, the approximate path could be estimated as shown in Figure 5 from past observations of the Earth's and Jupiter's magnetosheaths, and the estimated path length roughly ranged from 100 to 400 R_J.

6. Scenario for JAC Generation and Discussion

[21] On the basis of source characteristics of JAC and the Langmuir wave hypothesis, we propose a scenario for JAC generation as follows. The arrival of a large-scale pressure pulse structure in the solar wind causes a sudden compression and subsequent expansion of the Jovian magnetosphere. In the declining phase of large-scale solar wind pressure, the Jovian magnetosphere tends to become activated, and recurrent disturbances break out once per planetary rotation when the magnetic axis of Jupiter faces a certain local time direction. During the disturbance, quasi-periodic accelerations of energetic particles accompanied by QP15/40 radio bursts take place in the polar magnetosphere, and the particles are released toward interplanetary space. The released particles excite Langmuir waves at the magnetopause and/or the boundary layer in a broad frequency range above f_p. These excited Langmuir waves propagate in the magnetosheath plasma along the magnetosheath magnetic field, suffering large dispersion due to the high plasma density. When the waves reach the bow shock after a long distance propagation, part of them are converted to electromagnetic waves due to strong discontinuity in the plasma density. Thus characteristic Jovian emissions are observed in interplanetary space as long-lasting and frequency-shifting

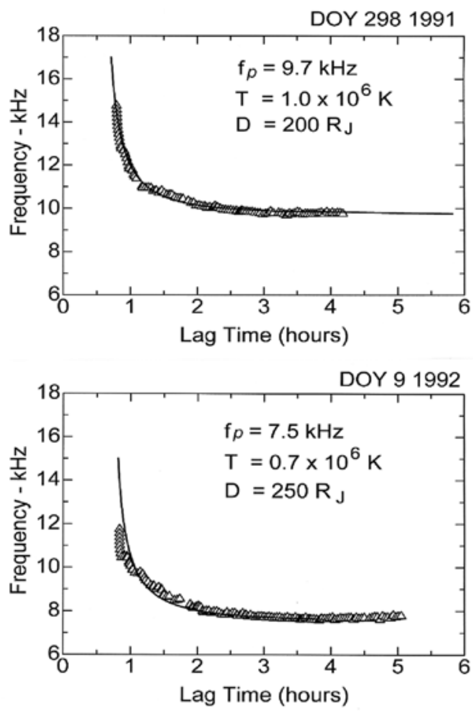

Figure 6. Lower-frequency traces of observed JACs (triangles) and fitted dispersion lags (solid lines). The derived plasma parameters are consistent with the in situ observation in the magnetosheath.

JAC. Next, we discuss some essential issues for the present scenario.

6.1. Solar Wind Disturbances

[22] Evidence that we found indicating JAC occurs when the solar wind pressure decreases after a rapid increase (Figure 4) is quite interesting because many reports can be found on the Jovian radio and auroral phenomena being positively related to solar wind variations, such as DAM [e.g., *Barrow et al.*, 1986], HOM [e.g., *Desch and Barrow*, 1984], bKOM [e.g., *Barrow et al.*, 1988; *Reiner et al.*, 2000], and auroral flares [*Waite et al.*, 2001]. *Reiner et al.* [2000] showed that the enhancement of bKOM and the triggering of nKOM are controlled by the sector structure of solar wind. *Southwood and Kivelson* [2001], on the other hand, theoretically predicted that the kinetic energy of the rotating magnetosphere is unloaded through an increased field-aligned current, preferably during magnetospheric expansion, and they claimed that Jovian magnetospheric activities are likely to be enhanced in conjunction with solar wind pressure decreases. Similar conclusions were also reached by *Cowley and Bunce* [2001]. The present occurrence characteristics of JAC may be connected with their theoretical prediction. *Morioka and Tsuchiya* [1996] and *Tsuchiya et al.* [1999] showed that an energetic electron release into interplanetary space from the Jovian magnetosphere takes place when solar wind dynamic pressure is decreasing. These pieces of evidence might also support the idea that the Jovian magnetosphere is active when the magnetosphere is expanded.

6.2. Recurrent Disturbances Once per Planetary Rotation

[23] A number of reports on the periodicity of magnetospheric disturbances have been presented by Galileo observations [*Woch et al.*, 1998; *Krupp et al.*, 1998; *Mauk et al.*, 1999; *Louarn et al.*, 1998, 2000], and the shortest period for the reported periodicity was about 3 days. Here we speculated on the existence of "recurrent disturbances" once per planetary rotation during the expansion phase of the magnetosphere. A recurrent disturbance implies the acceleration of energetic electrons and the emission of QP radio bursts, which break out once every 10 hours when a certain System III longitude faces a restricted local time. This disturbance may be related to the periodic release of energetic electrons [*Chenette et al.*, 1974] and modulation of magnetospheric continuum radiation [*Kurth and Gurnett*, 1986]. The many 10-hour variations of plasma and particles in and around the Jovian magnetosphere have been accounted for through three models: the clock model [*McKibben and Simpson*, 1974; *Chenette et al.*, 1974], the magnetic anomaly model [*Dessler and Hill*, 1975; *Vasyliunas and Dessler*, 1981], and the disc model [*Van Allen et al.*, 1974]. Among them, the magnetic anomaly model could be relevant to the present scenario because JAC occurrence is synchronized with the planetary spin phase as shown in Figure 3, and also JAC phenomena seem to be related to the interaction between the solar wind and magnetosphere. It is noteworthy that the preferred System III longitude of 270° obtained in this study is near the center of the so-called "active sector" [*Vasyliunas*, 1975; *Hill et al.*, 1983].

6.3. QP Radio Emission and Particle Release

[24] *MacDowall et al.* [1993] reported on detailed characteristics of quasiperiodic Jovian radio bursts (QP-15 and QP-40). QP-15 radio bursts appear in a frequency range from 1 to 50 kHz and are repeated in a group. *Kurth et al.* [1997] showed that the QP bursts correlated with intensifications of trapped continuum radiation inside the magnetosphere. The lower-frequency components of the QP radio bursts seem to merge into JAC spectra, as was shown by *Kaiser* [1998] and also shown in our Figure 1. Quasiperiodic relativistic electron bursts that are almost synchronized with low-frequency radio bursts were discovered by Ulysses during a flyby of Jupiter [*McKibben et al.*, 1993]. We suggest that a quasiperiodic acceleration accompanied by radio bursts takes place in the polar region predominantly at the time of the recurrent disturbances once per planetary rotation. The accelerated particles are assumed to be released toward interplanetary space and have been observed as periodic particle bursts in the magnetosheath [*Anagnostopoulos and Karanikola*, 2002].

6.4. Excitation and Propagation of Langmuir Waves

[25] We hypothesized that ejected quasiperiodic particle bursts from the polar magnetosphere hit the magnetopause, and excite Langmuir waves, which would be the same mechanism as that for the generation of solar Type II and III bursts [e.g., *Ginzburg and Zhelenzyakov*, 1958] or upstream Langmuir waves near the Earth's bow shock [e.g., *Kellogg*, 2003, and references therein]. Direct evidence that the JAC in the magnetosheath is a Langmuir wave mode could not be shown in the present analysis, but indirectly, the dramatic change in amplitude of JAC when Ulysses traversed the bow shock (Figure 2) implies that the waves in the magnetosheath are quasi-electrostatic mode such as Langmuir waves. Langmuir waves are generally considered to be narrowband emissions at the local plasma frequency, f_p, and slightly above f_p, at least in the Maxwellian plasma, because Landau damping becomes stronger as the wave frequency increases. Broadband electrostatic waves ($\Delta f/f > 0.3$) above and below f_p, however, have been observed in the Earth's electron-foreshock plasma [*Etcheto and Faucheux*, 1984; *Fuselier et al.*, 1985; *Lacombe et al.*, 1985]. *Cairns and Fung* [1988] tried to interpret broadband emissions in the Earth's electron foreshock and explained that broadband growth at $f > f_p$ is explained in terms of faster and warmer beams. *Etcheto and Faucheux* [1984] numerically showed that amplification of the waves was sufficient when the observed distribution function of solar wind was taken into consideration. In the present Langmuir wave hypothesis, we assumed that a process similar to the Earth's broadband Langmuir wave generation may be working in the Jovian magnetosheath, although theoretical interpretations of the broadband Langmuir waves have not been conclusive at this time.

[26] In situ Langmuir waves detected in interplanetary space are extremely bursty, as has been demonstrated in many studies. The present JAC in the magnetosheath, on the other hand, was not so bursty but had irregular amplitude variations (see Figure 2). This is a quite different point between the well-studied solar wind Langmuir waves and the hypothesized JAC in the magnetosheath.

6.5. Mode Conversion to Radio Waves

[27] After the long-distance propagation of Langmuir waves along the magnetosheath magnetic field which is draped around the magnetopause, the waves reach the bow shock, suffering a large degree of group velocity dispersion. At the bow shock, part of the waves would be converted to electromagnetic radio waves through a linear or nonlinear mode conversion process. The linear mode conversion processes of electron plasma waves to electromagnetic waves have been discussed focusing on inhomogeneous plasma around the Earth's foreshock region to explain the generation of electromagnetic f_p and $2f_p$ waves [*Yin et al.*, 1998; *Yin and Ashour-Abdalla*, 1999]. Here we assume that the steep and irregular plasma density wall at the Jovian bow shock acts as a sharp boundary, which is essential for linear mode conversion, although theoretical evaluation for the mode conversion process is necessary for Jovian Langmuir waves. The converted and transmitted radio waves propagate forward with respect to the boundary normal, whereas the reflected original waves go backward. Thus an electromagnetic JAC is observed in interplanetary space.

7. Summary

[28] In this paper we reported reexamination of the source characteristics of JAC, using the Ulysses data provided by NSSDC. We obtained new results in addition to previous works [e.g., *Kaiser*, 1998]: (1) JACs appear consecutively with about 10-hour periodicity when solar wind dynamic pressure declines after a rapid increase; (2) JAC's periodic appearance is not due to intensity modulation but to repeated individual excitation; and (3) the commencement of JAC has a significant dependence on local time. This suggests that JAC is excited when the Jovian magnetic axis has a preferred orientation with respect to the solar wind direction once per planetary rotation. We also showed (4) that JAC intensity changed dramatically at the bow shock, implying its mode transition from quasi-electrostatic in the magnetosheath to radio waves in the solar wind.

[29] We then evaluated possible emission models and proposed an alternate scenario with the previous model by *Kaiser* [1998]. In the proposed model, the origin of JAC is presumed to be Langmuir waves excited at the magnetopause by energetic particles from the polar magnetosphere. The particles are accelerated and released at the recurrent disturbances once per planetary rotation, which is activated during the period when the solar wind pressure is decreasing. The Langmuir waves propagating in the magnetosheath are converted to electromagnetic waves at the bow shock. Thus a long-lasting and frequency-drifting JAC can be observed in interplanetary space. The model described has some important issues: Langmuir waves have only rarely been observed in the Jovian magnetosheath and "recurrent disturbances" once per planetary rotation excite broadband Langmuir waves. However, the model would still be useful in exploring the mysterious JAC phenomena.

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H. Misawa, A. Morioka, and F. Tsuchiya, Planetary Plasma and Atmospheric Research Center, Tohoku University, Sendai 980-8578, Japan. (morioka@pparc.geophys.tohoku.ac.jp)

Y. S. Miyoshi, Solar-Terrestrial Environment Laboratory, Nagoya University, Toyokawa 442-8507, Japan.

T. Yuasa, Mitsubishi Space Software Co. Ltd., Fuji Techno-square, Amagasaki 661-0001, Japan.