Katoh, Y., Tsuchiya, F., Miyoshi, Y., Morioka, A., Misawa, H., Ujiie, R., Kurth, W. S., Tomas, A. T., Krupp, N. (2011): Whistler mode chorus enhancements in association with energetic electron signatures in the Jovian magnetosphere. - Journal of Geophysical Research, 116, A02215

DOI: 10.1029/2010JA016183

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 116, A02215, doi:10.1029/2010JA016183, 2011

Whistler mode chorus enhancements in association with energetic electron signatures in the Jovian magnetosphere

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Received 6 October 2010; revised 10 January 2011; accepted 14 January 2011; published 22 February 2011.

[1] By conducting a statistical survey of both wave and particle observations of the Galileo spacecraft, we reveal a close relationship between enhancements of whistler mode chorus and development of energetic electron anisotropies in the Jovian inner magnetosphere. We studied the spatial distribution of intense chorus emissions in the Jovian magnetosphere and identified 104 chorus enhancements by analyzing plasma wave data in the frequency range from 5.6 Hz to 20 kHz obtained from the entire Galileo mission in the inner Jovian magnetosphere during the time period from December 1995 to September 2003. Enhanced chorus emissions with integrated wave power over 10^{-9} V^2/m^2 were observed around the magnetic equator in the radial distance range from 6 to 13 R_J. A survey of energetic particle data in the energy range of 29–42 keV reveals that all of the identified chorus events were observed in the region of pancake pitch angle distributions of energetic electrons. The ratio of the electron plasma frequency to the electron cyclotron frequency in this region is estimated to be in the range from 1 to 10 using empirical plasma and magnetic field models. This range is suitable for efficient whistler mode wave generation. The present study shows the complete survey of the correspondence between intense chorus and flux enhancement of energetic electrons having statistically significant pancake pitch angle distributions in the Jovian magnetosphere.

Citation: Katoh, Y., F. Tsuchiya, Y. Miyoshi, A. Morioka, H. Misawa, R. Ujiie, W. S. Kurth, A. T. Tomás, and N. Krupp (2011), Whistler mode chorus enhancements in association with energetic electron signatures in the Jovian magnetosphere, *J. Geophys. Res.*, *116*, A02215, doi:10.1029/2010JA016183.

1. Introduction

[2] Whistler mode chorus is commonly observed in planetary magnetospheres: Earth [*Tsurutani and Smith*, 1974; *Santolík et al.*, 2006], Jupiter [*Scarf et al.*, 1979], Saturn [*Gurnett et al.*, 1981; *Hospodarsky et al.*, 2008], and Uranus [*Gurnett et al.*, 1986]. Chorus emissions at these planets seem to have similar characteristics. Although the detailed physics of the generation of planetary chorus emissions has not been clarified yet, observational and theoretical studies suggest that chorus emissions are generated by energetic electrons with energies of tens of keV and with anisotropic velocity distributions. Progress in simulation studies has revealed the importance of a nonlinear resonant interaction in the generation process, which takes place in the region close to the magnetic equator [*Katoh and Omura*, 2007; *Omura et al.*, 2008, 2009].

[3] The fundamental characteristics of whistler mode chorus in the Jovian magnetosphere have been studied using Voyager 1 observations [*Coroniti et al.*, 1980, 1984; *Inan et al.*, 1983; *Kurth*, 1992; *Kurth et al.*, 2001]. These investigations revealed that Jovian chorus emissions are observed in the region from 7.5 to 9 R_J, between the Io plasma torus and the low-density middle magnetosphere (1 R_J = 71,492 km: equatorial radius of Jupiter). It has also been discussed that the diffuse aurora could be explained by the precipitation of energetic electrons due to pitch angle scattering by whistler mode waves including chorus and hiss emissions in the middle magnetosphere ($10 < R_J < 30$) [*Scarf et al.*, 1979; *Coroniti et al.*, 1980; *Thorne and Tsurutani*, 1979; *Inan*, 1986; *Tomás et al.*, 2004a; *Bhattacharya et al.*, 2005]. *Xiao et al.* [2003] studied the linear growth rate of whistler mode waves under the presence of an anisotropic velocity distribution of energetic electrons observed by Galileo during an interchange event in the Io torus, based on a relativistic formulation presented by *Xiao et al.* [1998]. *Bolton et al.* [1997] discussed whistler mode emissions in the Io torus

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0148-0227/11/2010JA016183

simultaneously observed with flux increases of electrons of tens of keV and suggested enhanced whistler mode emissions are an indicator of regions of inward interchange motion in the Io torus. Recently, *Menietti et al.* [2008] conducted a detailed survey of Jovian chorus using the Galileo observations and showed that chorus emissions with frequency-integrated power levels of 10^{-8} V^2/m^2 are observed commonly in the approximate radial range from 6 to 10 R_J. Although there are many studies about characteristics and distributions of Jovian chorus emissions by different spacecraft, there remain unsolved problems in both the generation process and energy source of Jovian chorus emissions.

[4] In this study, we investigate the spatial distribution of whistler mode chorus and its relationship to the energetic electrons in the Jovian magnetosphere based on the observations made by the Galileo spacecraft. The result of the present study updates the spatial distribution of Jovian chorus emissions which provides important information to investigate the generation process. We also show a close relationship between chorus enhancement and energetic electron anisotropies in the Jovian magnetosphere.

2. Observations of Whistler Mode Waves

[5] We used data from the Plasma Wave Science investigation (PWS) [*Gurnett et al.*, 1992] on the Galileo spacecraft, obtained from the NASA Planetary Data System (PDS), to analyze chorus emissions in the Jovian magnetosphere. The PWS detected plasma waves in the frequency range from 5.60 Hz to 5.65 MHz with 158 logarithmically spaced frequency channels and with a time resolution of 18.677 s. We analyzed plasma wave data obtained during the entire Galileo mission in the inner Jovian magnetosphere from December 1995 to September 2003. We selected the data observed in the range of the radial distance from 5 to 30 R_J and surveyed whistler mode emissions. The analyzed frequency range is from 5.6 Hz to 20 kHz, covering from f_{LHR} to f_{ce} at Galileo's position, where $f_{\rm LHR}$ is the lower-hybrid resonance frequency given by $\sqrt{f_{ce}f_{ci}}$ for the case of $(f_{ce}/f_{pe})^2 \ll 1$, f_{ce} is the local electron cyclotron frequency, and f_{ci} is the proton cyclotron frequency. In calculating the *in situ* electron and proton cyclotron frequencies, we used local magnetic field intensities observed by the magnetometer (MAG) [*Kivelson et al.*, 1992] on the Galileo spacecraft. During the period when MAG data were not available, we estimated the local magnetic field intensities using magnetic field models. In this study, we used both the VIP4 spherical harmonic model [*Connerney et al.*, 1998] and the external field model proposed by *Khurana* [1997] in modeling the Jovian magnetic field. We note that the modeled magnetic field intensities are in good agreement with the MAG observations in the inner magnetosphere.

[6] Figures 1a and 1b show the frequency-time spectra of wave electric and magnetic field components observed by the PWS, with a typical example of whistler mode emissions in the Jovian magnetosphere. Four solid curves in Figures 1a and 1b denote f_{ce}, 0.5 f_{ce}, 0.1 f_{ce} and $f_{\rm LHR}$. Enhanced emissions in the frequency range from $f_{\rm LHR}$ up to f_{ce} that can be seen in both electric and magnetic field components are identified as whistler mode emissions. By referring to the characteristic features of wave spectra reported by previous studies about the Jovian whistler mode waves [e.g., *Coroniti et al.*, 1980], we can categorize these whistler mode waves as chorus or hiss emissions. In the region very close to the magnetic equator, chorus emissions are divided into upper band and lower band chorus by a narrow frequency gap around 0.5 f_{ce}. In the present study we define the frequency ranges from $f_{\rm LHR}$ to 0.1 f_{ce} as the hiss band and from 0.1 to 0.5 f_{ce} as the chorus band, for the convenience of data processing. We found that the lower band chorus emissions decrease in frequency from 0.5 f_{ce} to ~ 0.1 f_{ce} as the Galileo spacecraft moves away from the magnetic equator. Figures 1c and 1d show variations in the integrated wave power of the chorus band and the hiss band, respectively, during the time period of Figure 1. While chorus emissions are usually highly structured in both frequency and time in the frequency-time diagram, hiss emissions have a smoother spectrum that varies slowly in time compared to the chorus emissions.

[7] We surveyed enhanced chorus emissions that appeared distinctly in the frequency-time spectra and identified 104 chorus enhancements during the observation periods of the Galileo spacecraft. A similar survey of Jovian chorus has been performed by *Menietti et al.* [2008] using the Galileo PWS data. They showed the radial profile of wave power integrated over the frequency range from 400 Hz to 8 kHz and revealed that chorus are observed from 6 to 17 R_J, while faint emissions in this frequency range are included in their analysis. In the present study, we identified whistler mode emissions observed around the magnetic equator in the chorus band with the frequency-integrated power level over 10^{-9} V^2/m^2 as distinct chorus enhancements. We confirmed that the radial profile of the integrated wave power of identified chorus is consistent with *Menietti et al.* [2008], and the peak of the integrated power ~ 3×10^{-8} V^2/m^2 is found near 9 R_J. We analyzed the statistical distribution of chorus using the data set of chorus enhancements. The red short lines in Figure 2a show the spatial distribution of 104 chorus enhancements projected on the $X - Y$ plane of the Jovicentric Solar Ecliptic (JSE) system in units of R_J. The occurrence probability is shown in Figure 2b. It should be noted that distinct Jovian chorus emissions are observed in the radial distance range from 6 to 13 R_J, and some high-probability regions (>0.5) can be found in the region from 6 to 10 R_J. The local time dependence shown in Figure 2 is unclear because the Galileo spacecraft had considerably biased orbital coverage, as shown in the inset of Figure 2a.

3. Discussions

[8] Planetary whistler mode chorus is widely known to be generated in the region close to the magnetic equator [e.g., *Tsurutani and Smith*, 1974; *Inan et al.*, 1983]. We estimated the ratio of the electron plasma frequency f_{pe} to f_{ce} in the Jovian magnetosphere to determine the background conditions of the generation region. This estimate is important in determining the cyclotron resonance condition between energetic electrons and whistler mode waves. Figure 3 shows the obtained meridional distribution of f_{pe}/f_{ce}, where f_{pe} was computed from the cold plasma distribution model proposed by *Divine and Garrett* [1983]. The model shows that f_{pe}/f_{ce} becomes less than 10 around the equatorial region within 12 R_J. This range of f_{pe}/f_{ce} is similar to that of the terrestrial inner magnetosphere (outside of the plasmapause) during geomagnetic storms, which is a favorable condition

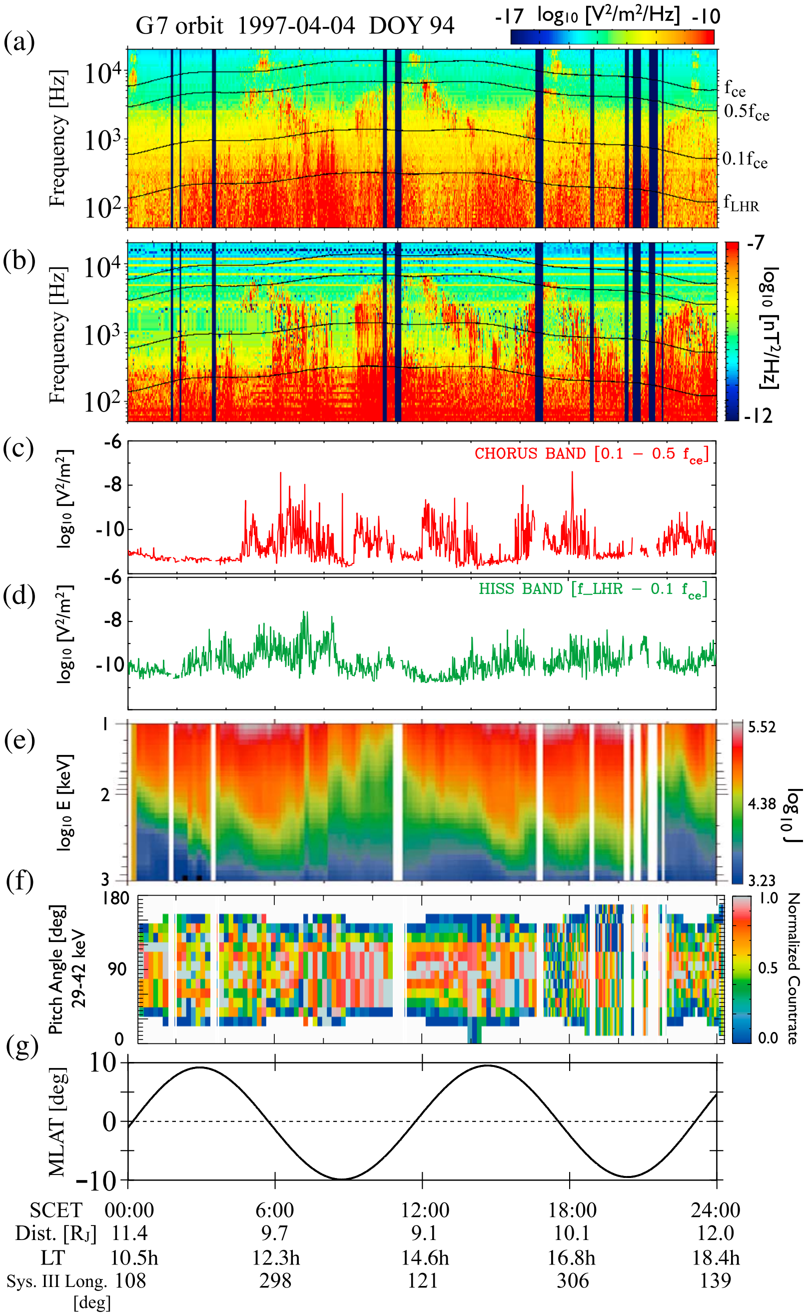

Figure 1. Frequency-time spectrogram of (a) wave electric and (b) magnetic field components observed by PWS during day of year 94, 1997. The four solid curves denote the local electron cyclotron frequency f_{ce}, 0.5 f_{ce}, 0.1 f_{ce}, and f_{LHR}. Variations in integrated wave power within (c) the chorus band and (d) the hiss band. (e) Energy-time spectrogram of energetic electrons observed by EPD. Note that the vertical axis showing the electron energy is inverted and that the color is coded according to $\log_{10}$ of the particle intensity $(\mathrm{cm}^2 \cdot \mathrm{s} \cdot \mathrm{sr} \cdot \mathrm{keV})^{-1}$. (f) Pitch angle distribution of energetic electrons in the energy range from 29 to 42 keV. (g) Magnetic latitude of Galileo during the observations.

for efficient wave-particle interactions between energetic electrons transported from the plasma sheet and whistler mode waves [*Meredith et al.*, 2003; *Miyoshi et al.*, 2003; *Jordanova et al.*, 2010]. Therefore, we can expect chorus emissions to be generated associated with the enhancement of energetic electrons in the equatorial region of the Jovian inner magnetosphere.

[9] It is interesting to note that the background plasma is important not only in generating chorus but in energizing relativistic electrons through the cyclotron resonant interaction, as has been discussed regarding the Earth's inner magnetosphere [*Meredith et al.*, 2003; *Miyoshi et al.*, 2003; *Horne et al.*, 2005; *Summers et al.*, 2007; *Katoh et al.*, 2008]. *Summers and Omura* [2007] have demonstrated that Jovian chorus can energize seed electrons having energies of several

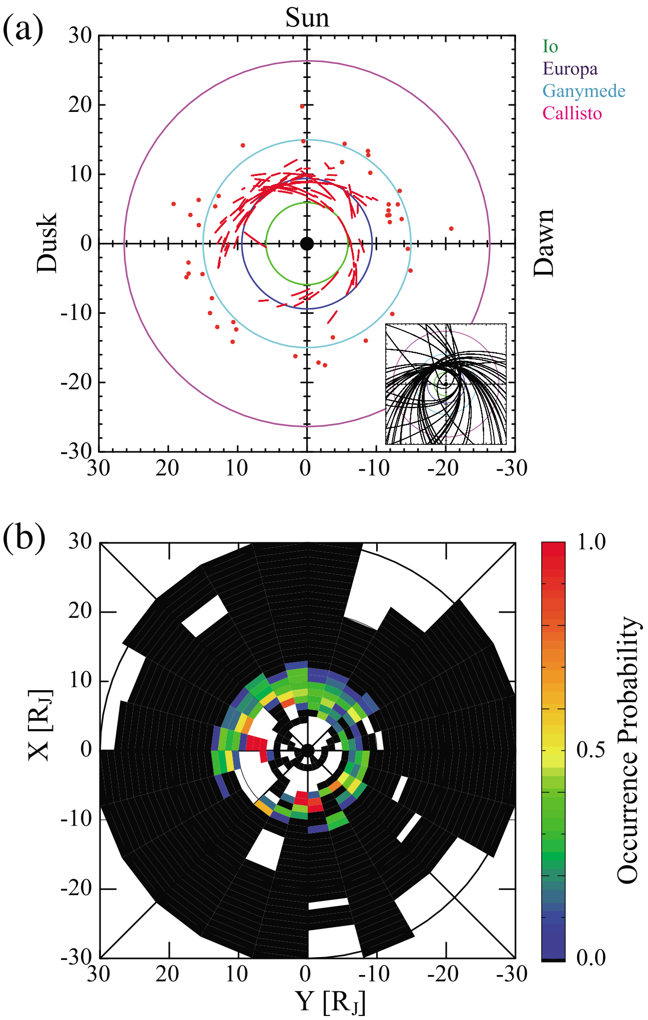

Figure 2. (a) Spatial distribution of chorus projected on the $X - Y$ plane of JSE coordinate system in R_J units. The inset shows the orbital coverage of the Galileo spacecraft. Each red-colored solid line corresponds to the time period of a chorus enhancement. Red dots show locations of pitch angle distribution boundaries. Four circles represent the orbit of Io (green), Europa (blue), Ganymede (cyan), and Callisto (magenta). (b) Occurrence probability of chorus emissions. White indicates no observations. The size of each bin is 1 R_J in radius and 1 h in local time.

hundred keV to relativistic energies of tens of MeV, and *Horne et al.* [2008] have also suggested the possibility of gyroresonant acceleration of relativistic electrons in the Jovian magnetosphere. *Summers et al.* [2009] assumed that whistler mode waves generated at Jupiter's magnetic equator acquire a specified gain over a convective growth length, and compared the theoretical limit on the trapped flux with energetic electron fluxes measured by the Energetic Particle Detector (EPD) [*Williams et al.*, 1992] on board the Galileo spacecraft.

[10] For terrestrial chorus emissions, the source of free energy for generating chorus is widely accepted to be anisotropic electrons with energies of the order of tens keV in the equatorial region. Because these energetic electrons are supplied from the nightside plasma sheet by the injection and/or enhanced convection during substorms and subsequently drift through dawn to the dayside, the intensity of the terrestrial chorus emissions has clear dependences on both substorm activity and local time [*Tsurutani and Smith*, 1974; *Tsurutani et al.*, 1979; *Meredith et al.*, 2001; *Miyoshi et al.*, 2007]. In the Earth's magnetosphere, the anisotropic velocity distribution, $T_\perp > T_\parallel$, is naturally formed during the inward transport of energetic electrons as the first two adiabatic invariants are conserved. Here, $T_\perp$ and $T_\parallel$ are temperatures for perpendicular and parallel to the background magnetic field, respectively. Previous studies regarding the Jovian magnetosphere reported that energetic particles are intermittently injected into the inner magnetosphere [*Mauk et al.*, 1997]. In particular, *Mauk et al.* [1999] conducted a statistical analysis and revealed that the most probable radial distance of injection events is between 10 and 12 R_J. The radial range of injection events suggests a close relationship

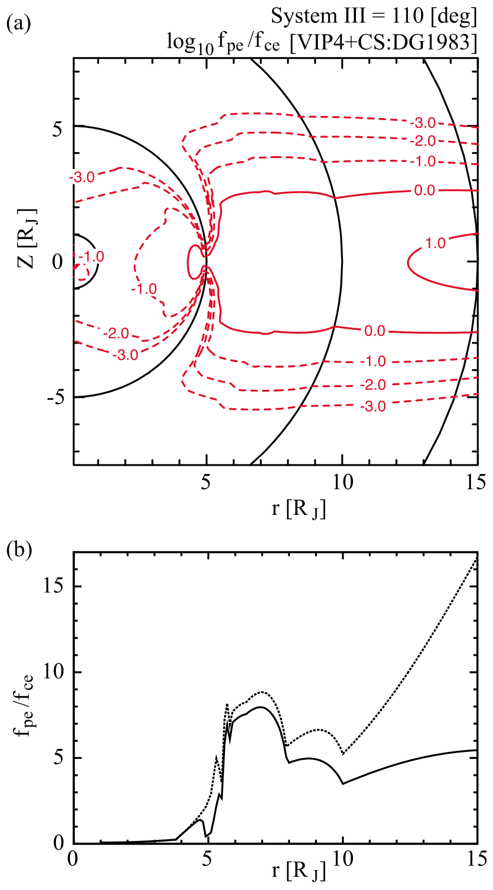

Figure 3. (a) Model estimation of the spatial distribution of the ratio of f_{pe} to f_{ce} on the meridional plane at 110° System III (1965) longitude in Jovian inner magnetosphere. The vertical axis is the distance Z from the rotational equatorial plane, and the horizontal axis is the distance r from the rotational axis normalized by R_J. The red-colored contour lines represent the distribution of $\log_{10}$ of f_{pe}/f_{ce}, while the dashed lines represent negative values. The solid semicircles show the radial distances 1, 5, 10, and 15 R_J. (b) Radial profile of f_{pe}/f_{ce} at the magnetic equator. The solid line shows the profile averaged over all System III longitude, and the dashed line represents the profile at 110°.

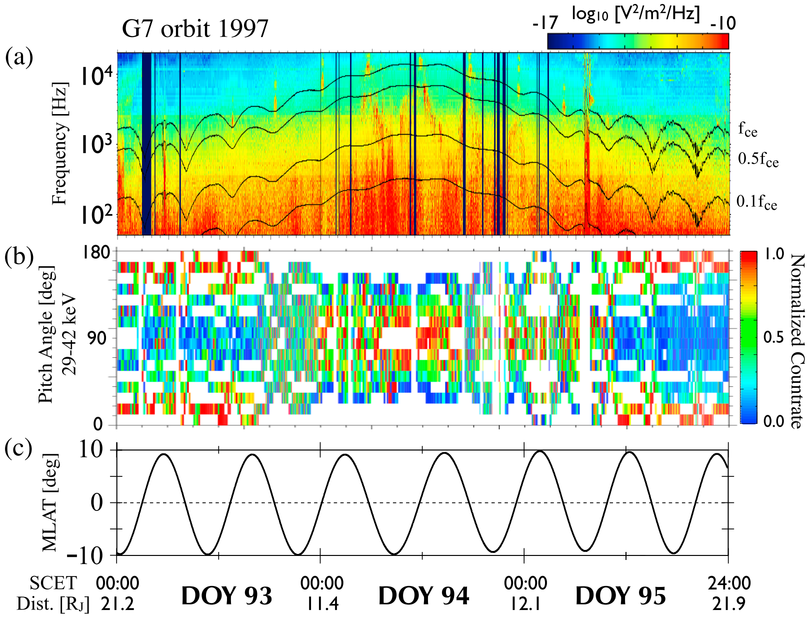

Figure 4. (a) Frequency-time spectra of the wave electric field component observed by PWS during days 93 to 95 of year 1997. The four solid curves denote the local electron cyclotron frequency f_{ce}, 0.5 f_{ce}, 0.1 f_{ce}, and f_{LHR}.(b) Pitch angle distribution of energetic electrons in the energy range from 29 to 42 keV observed by EPD. (c) Magnetic latitude of Galileo during observations.

between the energetic electron injection and the presence of whistler mode waves. Furthermore, in the Jovian magnetosphere the inward transport of energetic electrons could be driven by the interchange motion of Iogenic cold plasma [e.g., *Bolton et al.*, 1997; *Thorne et al.*, 1997], which provide conditions favorable to the generation of whistler mode waves.

[11] Based on these considerations, we show an example of the close relationship between the enhancement of whistler mode waves and the anisotropic velocity distribution of energetic electrons observed by EPD on board the Galileo spacecraft. Figure 4a is the frequency spectra of the wave electric field component during days of year 93 to 95 in 1997 where chorus emissions are enhanced only during day 94, the event shown in Figure 1. Figure 4b shows the pitch angle distribution of the energetic electrons in the energy range of 29 to 42 keV and we found that the chorus activity was closely correlated with the presence of the pancake distribution (peak fluxes near 90 degrees) almost throughout day 94. This pancake distribution is further evident in Figure 1f. The association between chorus emissions and pancake pitch angle distributions in the Io torus has also been discussed by *Xiao et al.* [2003]. The energy-time spectrogram of energetic electrons (Figure 1e) shows that injection events are observed during the time period of Figure 1. The cyclotron resonance condition is given by $\omega - kV_R = \Omega_e/\gamma$, where V_R is the resonance velocity, $\Omega_e = 2\pi f_{ce}$ is the gyrofrequency of electrons, γ denotes the Lorentz factor, and k and ω are the wave number and the wave frequency, respectively. Based on typical parameters observed near the orbit of Europa [*Kurth et al.*, 2001], we assumed that f_{pe} is 100 kHz, f_{ce} is 12 kHz, and f_{pe}/f_{ce} is 8. We then estimated that an electron having a kinetic energy of 35 keV can resonate with parallel propagating whistler mode waves with a frequency of 0.2 and 0.5 f_{ce} at pitch angles of 58 and 81 degrees, respectively.

[12] *Tomás et al.* [2004b] reported the existence of a pancake pitch angle distribution of energetic electrons in the energy range of 29 to 42 keV and 304 to 527 keV in the inner Jovian magnetosphere. Following *Tomás et al.* [2004b], we statistically analyzed the EPD data to clarify the correspondence between the enhancement of chorus and the presence of pancake distributions of energetic electrons. We used a function of $\sin^N \alpha$ to fit the pitch angle distribution of energetic electrons in the energy range of 29 to 42 keV averaged over 1 h time intervals, where α denotes pitch angle and N is a coefficient representing the pancake (positive N) or bidirectional (negative N) pitch angle distribution [*Morioka et al.*, 2001]. We estimated values of N at each time interval and identified the location of the pitch angle distribution boundary at which the sign of N changes. The red dots in Figure 2a show the locations of the pitch angle distribution boundaries identified in the present study. The pancake distributions are found inside of the boundary with the bidirectional distributions located outside of the boundary. Although the locations of the boundary identified in the present study are basically consistent with the previous studies, they are not exactly the same as presented by *Tomás et al.* [2004b]. This is because of the different criteria used in identifying the boundary. Besides, in Figure 2a, ambiguous events showing gradual transitions of the coefficient N are included as well as the distinct boundaries, while Tomás et al. focused on precise locations of the distinct boundaries in order to study the relation between the boundaries and the structures in the Jovian aurora. By comparing the locations of chorus enhancements and boundaries shown in Figure 2a, we found that all chorus enhancements are observed in the region of pancake pitch angle distributions of energetic electrons.

[13] We further studied the correspondence between chorus enhancements and energetic electron signatures by conducting

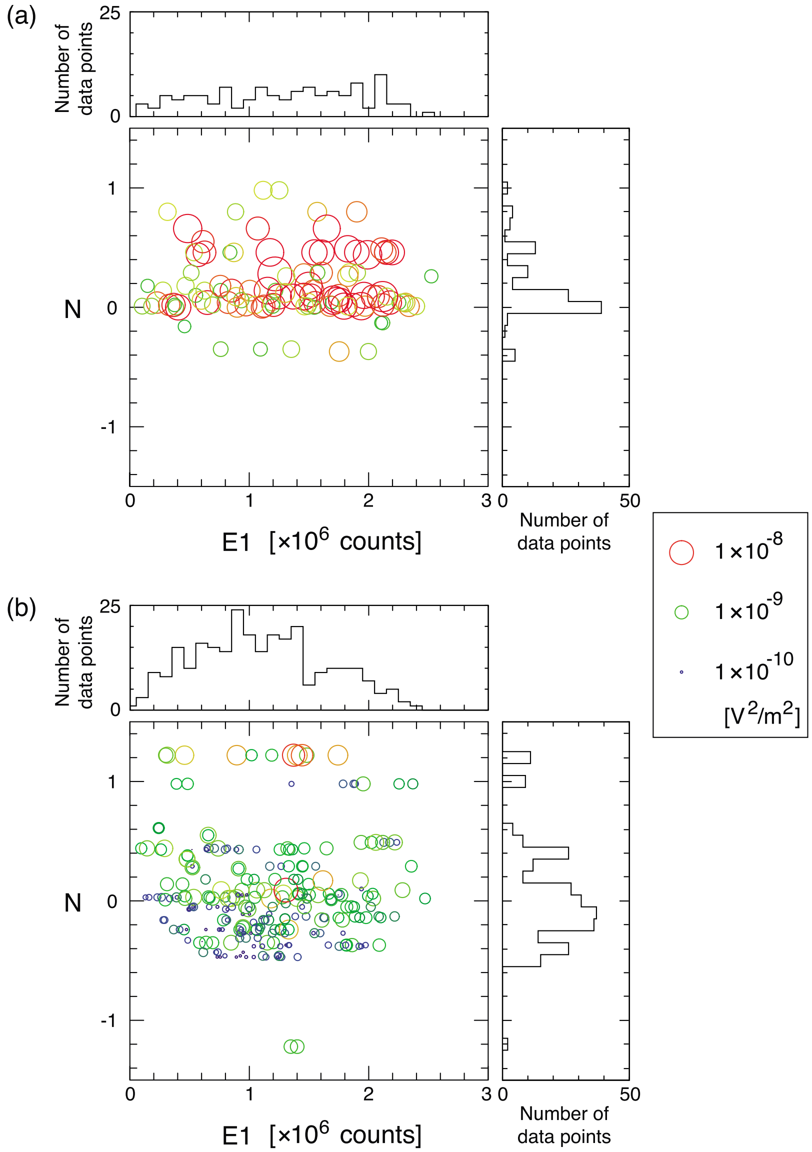

Figure 5. Statistics of the integrated amplitude of waves in the chorus band, count rate and fitting result of the pitch angle distribution of energetic electrons of E1 channel during (a) the chorus events and (b) period without distinct chorus emissions. The integrated wave amplitude is indicated by both radius and color of circles as shown by the legend. Each data point corresponds to the averaged value of 1 h time interval within the magnetic latitude ±5 degrees.

a statistical survey of both PWS and EPD data. Since chorus are generated in the region very close to the magnetic equator, we analyzed the integrated amplitude of waves in the chorus band, count rate and anisotropy coefficient N of energetic electrons of the EPD E1 channel within the magnetic latitude range of ±5 degrees. We calculated the averaged values in 1 h time intervals and sorted the results, comparing the periods with/without distinct chorus emissions.

[14] Figure 5 shows the results of the statistics; correspondence among 1 h averaged values of the integrated wave amplitude, count rate and N during the time periods with (Figure 5a) or without (Figure 5b) distinct chorus emissions. Figure 5a reveals that the intense chorus is generated in association with pancake pitch angle distributions of energetic electrons. On the other hand, Figure 5b shows that the values of N are shifted to $N \leq 0$ compared with Figure 5a. We note that a few events with large wave amplitude ($>10^{-8}$ V^2/m^2) shown in Figure 5b correspond to broadband whistler mode emissions instead of discrete structures. Although the count rates of the energetic electrons during the chorus events are widely distributed, the distributions tend to have slightly larger count rates than those shown in Figure 5b. We quantified the differences of the distributions shown in Figure 5 by statistical tests and confirmed their significance. Based on the results of the statistical test, we conclude that the distinct chorus in the Jovian magnetosphere are observed during time periods of enhanced flux of energetic electrons of several tens of keV having pancake pitch angle distributions.

[15] As shown in Figure 1b, emissions in the hiss band are broadband and show no obvious latitudinal variation, but

they are intermittently enhanced. The wave activity in the hiss band is correlated with the flux enhancements in energetic electrons of hundreds of keV as can be seen in Figures 1d and 1e, and the cyclotron resonance is possible between hiss and electrons of hundreds of keV. *Meredith et al.* [2004] revealed the dependence of plasmaspheric hiss activity on substorms in the Earth's magnetosphere, suggesting the possibility that the energy source for the hiss emissions is related to the injected energetic electrons during substorms in a manner similar to the chorus emissions. A similar discussion might be applied to the hiss in the Jovian magnetosphere. On the other hand, another idea of a possible generation process of plasmaspheric hiss has been proposed [*Bortnik et al.*, 2008]; chorus waves outside the plasmapause can propagate into the plasmasphere due to multiple reflections of their raypath. Based on this new idea, *Wang et al.* [2008] conducted ray-tracing analyses of whistler mode waves in the Jovian inner magnetosphere and proposed that the origin of a band of low-frequency whistler mode waves can be explained by reflections and inward propagations of chorus emissions generated in the outer region of the magnetosphere. For further discussions of the correspondence between the wave activity in the hiss band and chorus band with the flux enhancement of energetic electrons, quantitative evaluations are necessary, such as a survey of linear growth rates of whistler mode waves in the Jovian inner magnetosphere as has been performed by *Xiao et al.* [2003] for an interchange event in the Io torus.

4. Summary

[16] In this paper we conducted the statistical survey of both wave and particle observations of the Galileo spacecraft, and we identified a close relationship between the enhancements of whistler mode chorus and the development of energetic electron anisotropies in the Jovian inner magnetosphere. We studied the plasma wave data observed by the PWS in the frequency range from 5.6 Hz to 20 kHz in the range of the radial distance from 5 to 30 R_J. By analyzing the spatial distribution of whistler mode chorus, we revealed that the intense chorus emissions with the frequency-integrated power level over 10^{-9} V^2/m^2 were observed in the radial distance from 6 to 13 R_J and that high occurrence probability (>0.5) is obtained in the region from 6 to 10 R_J. Next we studied the pitch angle distributions of energetic electrons using the EPD data and showed that all of distinct chorus identified in the present study were observed in the region of pancake pitch angle distributions. We also showed that the estimated ratio of f_{pe} to f_{ce} in the region where chorus emissions are observed is less than 10 which is suitable for efficient whistler mode wave generation. In addition, we showed the complete survey of the statistically significant correspondence between intense chorus and flux enhancements of energetic electrons having pancake pitch angle distributions in the Jovian magnetosphere. These results of the present study clarified that both intense chorus emissions and anisotropic energetic electrons are ubiquitous in the Jovian inner magnetosphere. A further quantitative analysis is necessary to reveal the correspondence between whistler mode wave-particle interactions and inward transport processes supplying anisotropic energetic electrons into the magnetosphere.

[17] **Acknowledgments.** We thank J. D. Menietti for discussion of the integrated wave power. We acknowledge the use of PWS data (D. A. Gurnett, P.I.), MAG data (M. G. Kivelson, P.I.) and EPD data (D. J. Williams, P.I.) in this research. The data used in this study were provided through the Planetary Plasma Interactions Node of the Planetary Data System located at the Institute of Geophysics and Planetary Physics at the University of California, Los Angeles. This work was supported by the Global COE program "Global Education and Research Center for Earth and Planetary Dynamics" of Tohoku University and by grant-in-aid 22684025 of the Ministry of Education, Science, Sports and Culture of Japan and was conducted as a collaborative research project with the Solar-Terrestrial Environment Laboratory of Nagoya University. The research at the University of Iowa is supported by NASA through grant NNG05GG98G. We thank H. Nozawa for his technical assistance and suggestions on the use of the Galileo data.

[18] Masaki Fujimoto thanks the reviewers for their assistance in evaluating this paper.

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