Enhanced whistler-mode emissions: Signatures of interchange motion in the Io torus

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Abstract.
During the Galileo inbound pass through the Io torus the plasma wave instrument detected intervals of enhanced whistler-mode emissions. Over two of these intervals in the inner torus ($L < 6.5$), for which energetic particle data is also available, the flux and pitch angle anisotropy of resonant electrons exhibited a simultaneous enhancement consistent with inward adiabatic transport from a source region in the outer torus. The enhanced electromagnetic emissions are interpreted as a modulation of cyclotron whistler-mode instability above the normal marginally stable state of the plasma. This suggests that the enhanced emissions are a sensitive indicator of rapid inward transport associated with interchange motions in the Io torus.

1. Introduction

On December 7, 1995, the Galileo spacecraft passed through the Io torus collecting high resolution fields and particles data from approximately $7.7R_J$ to $5.4R_J$. During this period the Plasma Wave Subsystem (PWS) detected intervals of enhanced emissions above a relatively constant background of whistler-mode noise. The enhanced emissions were previously reported as whistler mode radiation (Gurnett et al. 1996). Similar signals were observed during the Voyager 1 pass through the Io torus and were generally interpreted as whistler-mode emissions associated with anisotropic trapped energetic electrons (Scarf et al. 1979, Thorne and Tsurutani 1979). Free energy associated with natural anisotropic loss cone distributions of electrons which satisfy the resonant condition are a potential source of whistler-mode emission.

A coordinated analysis (Thorne et al. 1997) of one of these intervals, at 17:34 UT, when the spacecraft was $\approx 6R_J$ from Jupiter, identified pronounced enhancements in the plasma wave emissions, sharp changes in the pitch angle distribution and phase space density of the energetic particles and a small abrupt increase in the magnetic field. These signatures were identified as evidence of rapid inward interchange transport.

Due to the hazardous radiation environment present near Jupiter the energetic particle experiment (EPD) observed with special instrument modes during most of the inbound torus pass and complete distributions of the energetic particles are only available inside of approximately $6.5R_J$. We present a coordinated study of two intervals when both the PWS and EPD instruments were operative. Emphasis is placed on the parameters associated with the expected resonant interaction between the energetic electrons and enhanced whistler-mode emissions. We discuss the interpretation of the plasma wave events as part of the coordinated evidence for rapid transport and interchange motions in the Io torus. In accompanying papers Kivelson et al. (1997) present the magnetometer observations of this and other similar anomalous events throughout the inbound torus pass and Thorne et al. (1997) present details of the 17:34 UT event and discuss these signatures in the context of the rapid inward transport mechanism.

2. Observations

The initial inbound passage of Galileo through the Jovian system provided the opportunity to obtain measurements through the Io torus outside of Io's orbit. A 2.5 hour recording inbound provided measurements at longitudes $210° < \lambda_{III} < 270°$ near the magnetic equator ($\lambda_m \sim 3° - 8°$). A relatively constant background of emission below 500 Hz is observed in both the electric and magnetic field measurements. Sev-
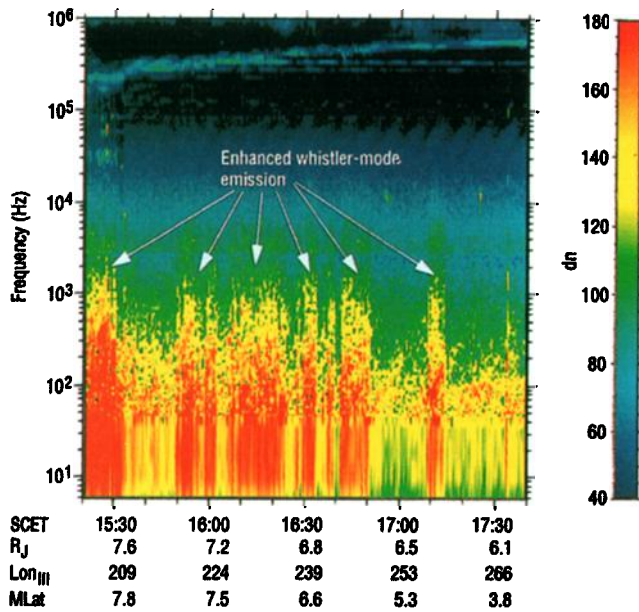
Figure 1. Frequency time spectrogram of the electric field intensities measured by the Galileo Plasma Wave Subsystem during the inbound Io torus pass. Intervals of enhanced whistler-mode emissions from a few Hz to a few kHz are present throughout the torus. Upper hybrid emission which is a measure of electron density is seen to increase slowly across the top of the figure.

sociated with the constant background of whistler-mode emissions evident in both Figures 1 and 2.

During the first interval of enhanced whistler-mode emissions (17:09 - 17:14) in Figure 2 most EPD channels indicate an increase in phase space density. The electron channels all demonstrate an increase in anisotropy with a notable greater flux increase in the lower energy channels. The second interval of enhanced whistler-mode emissions occurs at 17:34 and lasts only 10 seconds. This interval is characterized by a broadband electromagnetic signal from a few Hz to approximately 4 kHz with intermittent emission from $4kHz - 20kHz$ and a pronounced narrowband signal at $95kHz$ as shown in Figure 2. The event is further characterized by the absence of the strong upper hybrid emission line at ~ 550 kHz. During this event the energetic particle data indicate an abrupt change in the count rate of energetic ions and electrons with the most significant increase in the direction perpendicular to the field. The increase for the highest energy ions is larger than for low energy ions and electrons although all particles exhibit changes except the high energy electrons ($E > 300$ keV). The magnetometer observes an abrupt (< 1 s) increase in the magnetic field of order $1-2\%$ with almost no change in direction. The magnetic field returns to the pre-event level less then 10 seconds later in the same abrupt man-

eral intervals of enhanced emissions from a few Hz to a few kHz in the electric field and magnetic field are observed by the PWS as shown in Figure 1. Both the enhanced emissions and the background emission are interpreted as whistler-mode emissions due to presence of the magnetic component between the proton cyclotron frequency (10-30 Hz) and the electron cyclotron frequency (20-60 kHz). No other mode is possible in this frequency range (Gurnett et al. 1996). All intervals of enhanced emissions demonstrate similar characteristics although the duration of the intervals range from 10 seconds to 15 minutes with most intervals being 5-10 minutes long.

Figure 2 illustrates the two intervals when energetic particle data are available. The frequency time spectrogram from the electric antenna is shown along with the corresponding count rates in selected energy channels from the energetic particle detector (EPD). An increase in the amplitude of the electromagnetic emissions occurs from 17:09-17:14 UT and at 17:34 UT. The extension of the frequency range of the enhanced emissions is evident with the peak frequency reaching slightly over $4kHz$ with intermittent weaker emission observed to $20kHz$. In comparison, the background whistler-mode emissions extends to only about $300 - 500Hz$. Two of the EPD electron channels are shown in the lower part of Figure 2. The two channels correspond to: $93keV - 188keV$ (F0) and $1.5MeV - 10.5MeV$ (B1). Prior to and after the event the high energy electrons exhibit a normal loss cone distribution which can be as-
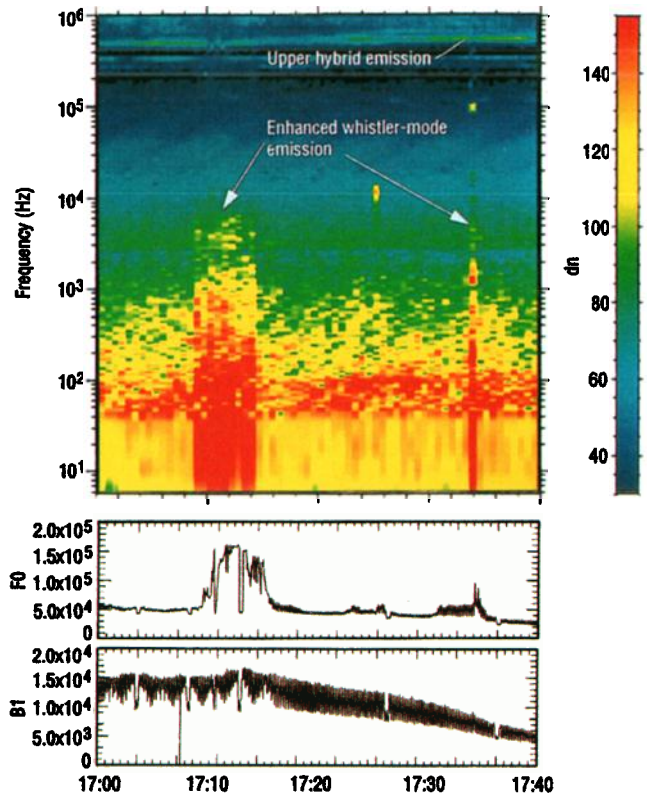

Figure 2. Observations from the Plasma Wave Subsystem (upper panel) and Energetic Particle Detector (lower panels) showing two intervals of enhanced whistler-mode emission (17:09 - 17:14 UT and near 17:34 UT). The particle channels shown indicate electron count rates for energies of $93keV - 188keV$ (F0) and $1.5MeV - 10.5MeV$ (B1).

ner. The magnetometer signature was further characterized by the absence of ion cyclotron waves which are present in the surrounding data (Kivelson et al. 1997).

3. Cyclotron Resonance with Whistler-Mode Waves

First order cyclotron resonance between whistler-mode waves and relativistic electrons occurs when $1 - n_* \beta = Y/\gamma$ where $n_* = \eta_\| \cos \alpha$, $\eta_\|$ is the parallel component of the wave refractive index, $\beta = v/c$, $\gamma = (1 - \beta^2)^{-1/2}$, and $Y = \Omega_-/\omega$ is the ratio between the gyrofrequency and the wave frequency. We consider electrons moving opposite to the wave $\pi/2 > \alpha > \pi$ and $n_* < 0$. The enhanced broadband emission shown in Figure 1 starts below the proton cyclotron frequency, $\Omega_+ \sim 26$ Hz, and thus estimates of the refractive index must consider affects from protons. For field aligned waves with $\omega \ll \Omega_-$

$$n_\| \approx [\frac{\Omega_-}{\omega}]^{1/2} \frac{1}{(1 + \Omega_+/\omega)^{1/2}} \frac{\omega_p}{\Omega_-} \qquad (1)$$

To estimate the minimum energy required for resonant interaction we consider electrons moving almost parallel to the field or $\alpha \approx \pi$. During the 17:34 UT event $\omega_p \approx 570$ kHz, $\Omega_- = 48$ kHz, $\Omega_+ = 26$ Hz, and equation (1) yields resonant electron energies of $5MeV > E > 80keV$ for waves between $10Hz < \omega < 1000Hz$, respectively. For electrons with $\alpha < \pi$ the required resonant energy would be larger. This result suggests we consider the particle signatures of electrons with $E > 80$ keV to investigate interactions with 1 kHz waves. Electrons of substantially greater energy would be needed to interact with the bulk of the emission at $\omega < 400$Hz. During the 17:09 - 17:14 UT interval the resonant energies as a function of wave frequency would be slightly less.

4. Discussion

The coordinated data sets shown in Figure 2 indicates the correlation between the enhanced whistler-mode emissions and the behavior the energetic electrons during two intervals of enhanced emissions. Details of the EPD data are provided by Thorne et al. (1997) in a report on the distributions of energetic particles for the 17:34 event at $6.03R_J$. The EPD data show pronounced increases in the flux levels primarily in the direction perpendicular to the field. They report the highest increases for high energy ions with more modest increases for low energy ions and electrons. The higher energy electrons ($E > 300$ keV) show the least change before, during, and after the event. Our analysis of the cyclotron resonance energy suggests that the relatively constant loss cone distribution of the high energy electrons is responsible for the background emission below 500 Hz throughout the torus.

The 17:34 UT event allows a complete analysis of the physics of the enhanced whistler-mode emissions due to the availability of coordinated observations from both the magnetometer and energetic particles. During this 10 second interval the characteristic changes observed in the magnetic field, high energy particles, and electromagnetic emissions are an indication of an abrupt change in the plasma conditions. Thorne et al. (1997) suggests the events are related to a flux tube originating from a source region in the outer torus which has been transported inward with little or no change to the phase space density of the energetic particles.

If the event is associated with an inwardly transported structure the time for electrons to gradient drift across the interchange structure can be estimated as $\tau_D = \Delta x/v_{gc}$ where Δx is the size of the structure and v_{gc} is the gradient drift speed. Near L=6 $v_{gc} \approx 4km/s$ for high energy electrons with $\gamma = 4$. A structure of $\Delta x \approx 10^3 km$ (Thorne et al. 1997) gives $\tau_D \approx 250s$. The distance that electrons are transported inward can be estimated by considering $\Delta R = V_R \tau_D$. For $V_R = 10^2 km/s$ (Thorne et al. 1997) we find $\Delta R \sim 0.35R_J$ implying the 1.5 MeV electrons measured during the 17:34 event (channel B1 in Figure 2) have been transported in from $\approx 6.35R_J$.

Assuming μ and J are conserved an estimate of the expected increase in electron anisotropy during the transport can be obtained. The differential flux $j = p^2 f$ with $p^2_\perp \sim B \sim 1/L^3$ and $p_\| \sim 1/L$. Assuming that f is conserved (Thorne et al. 1997) energetic, $E_c > 1.5MeV$, electrons will experience an increase in $j_\perp$ of 17% and an increase in $j_\|$ of 10% during the transport from $6.35R_J$ to $6.03R_J$. This suggests that high energy electrons will generally experience a modest increase in flux and anisotropy associated with the inward radial transport. Lower energy electrons will drift slower and may thus originate from a source region further out in the torus. Spending more time in the structure they will experience a larger relative increase in both anisotropy and flux. We estimate electrons of $E \approx 100keV$ will experience an increase in $j_\perp \approx 240\%$ and $j_\| \approx 180\%$ assuming a inward radial transport of approximately $2R_J$. This is approximately what is observed by EPD (Figure 2). The increase in electron anisotropy A^- during the event will modify both the wave growth rate $\gamma \sim \eta_{res}(A^- - A_c)$ and the maximum frequency of the emission $\omega_{max}/\Omega_- \sim A^-/(1 + A^-)$ (Kennel and Petschek, 1966). Inward transport should thus result in a preferential enhancement in the growth rate of high frequency whistler-mode emissions consistent with the PWS data shown in Figures 1 and 2.

In order for the electrons to maintain the anistropy gained from the inward transport the scattering due to resonant interaction must be small $D_{\alpha\alpha}\tau_D \ll 1$ where the pitch angle diffusion coefficient $D_{\alpha\alpha} \sim (B_w/B_0)^2 \epsilon\Omega_-/\gamma$. For the 17:34 UT event, $B_0 = 1700nT$ suggesting $B_w \sim 0.7nT$ would be required for significant scattering. Since the observed whistler-mode emission amplitude is $\approx 10^{-3}nT$ at 1 kHz we do not expect resonant interaction with the waves to change the anisotropy of the electrons significantly during transport.

The similarities between the other intervals of enhanced whistler- mode emissions shown in Figure 1 suggest each of these intervals represent regions of interchange motion. The overall compactness of the 17:34 UT event may imply uniqueness related to the proximity to Io. The longer duration of some intervals may suggest slower transport speeds or larger scale size structures. Two of the anomalous magnetic field events reported by Kivelson et al. (1997) are correlated with drops in the upper hybrid emission (16:46 UT and 17:10 UT) which suggests density drops on timescales of a few seconds. This is consistent with the 17:34 UT event and may provide clues to the typical scale size of the interchange structures. If the intervals of enhanced whistler-mode emissions are actually many small intervals close together, the sampling rate of the PWS sweep frequency receiver would be insufficient to separate individual events. We expect further detailed analysis of these events and a comparison with data from the Plasma Analyzer (PLS) will be required to more fully understand the transport of plasma in the Io torus and interchange motion.

5. Summary

The enhanced emission intervals observed by PWS show a strong correlation to changes in the energetic electrons measured by the EPD during times when both data are available. Estimates of the resonant energy for electrons to interact with the whistler-mode waves suggests electrons with $E > 80keV$ would interact with waves of $\omega \approx 1kHz$ and higher energy electrons would interact with lower frequency emissions. The increase in resonant electron anisotropy and flux associated with the enhanced PWS emission is consistent inward radial transport. The higher frequency extent of the enhanced emissions compared to the background emission is also consistent with the energy dependent effects of inward radial transport. Based on the analysis of the intervals when both PWS and EPD data are available we suggest the enhanced whistler-mode emissions are an indicator of regions of inward interchange motion in the Io torus.

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