GEOPHYSICAL RESEARCH LETTERS, VOL. 30, NO. 14, 1749, doi:10.1029/2003GL017123, 2003

Whistler-mode excitation and electron scattering during an interchange event near Io

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Received 13 February 2003; revised 16 April 2003; accepted 16 June 2003; published 24 July 2003.

[1] The enhanced growth rate of whistler-mode waves has been evaluated during an extended interchange event in the Io torus that occurred between 1709–1715 UT, on December 7, 1995. The energetic electron population observed by the Galileo EPD instrument is modeled using a bi-loss-cone distribution function (composed of a highly anisotropic component and a quasi-isotropic component). During the injection event, the path integrated gain increases by more than a factor of ten over a broad frequency range near a few tenths of the electron gyrofrequency, consistent with the observed enhancement in Galileo PWS emissions. The enhanced PWS emissions are mainly associated with an increase in the flux of cyclotron resonant electrons below 55 keV. Scattering of electrons by the enhanced whistler-modes causes the pitch-angle distribution of resonant electrons to evolve from a normal "pancake" distribution in the unperturbed torus to a quasi-isotropic distribution during the interchange event. This change provides an enhanced flux of electrons with mirror points close to Jupiter, which could be important for understanding the enhancement of Jovian auroral emissions in association with electron injection events. *INDEX TERMS:* 2772 Magnetospheric Physics: Plasma waves and instabilities; 2720 Magnetospheric Physics: Energetic particles, trapped; 2756 Magnetospheric Physics: Planetary magnetospheres (5443, 5737, 6030); 7867 Space Plasma Physics: Wave/particle interactions. **Citation:** Xiao, F., R. M. Thorne, D. A. Gurnett, and D. J. Williams, Whistler-mode excitation and electron scattering during an interchange event near Io, *Geophys. Res. Lett.*, *30*(14), 1749, doi:10.1029/2003GL017123, 2003.

1. Introduction

[2] Centrifugally driven interchange instability occurs in the Io plasma torus in response to mass loading associated with volcanic activity on Io [*Hill et al.*, 1981; *Siscoe and Summers*, 1981; *Southwood and Kivelson*, 1987; and *Pontius and Hill*, 1989]. The interchange motions, which carry Iogenic thermal plasma outward, also bring mass depleted flux tubes (containing energetic particles) inward. This inward transport provides an important mechanism for maintaining the energetic particle population in the inner Jovian magnetosphere against various loss processes. The first conclusive evidence for inward interchange motions near Io was discovered during the Galileo insertion orbit, near 1734 UT on December 7, 1995, as reported in a series of papers by *Bolton et al.* [1997]; *Kivelson et al.* [1997]; and *Thorne et al.* [1997]. In the present study, we analyze a more complex interchange event, which occurred between 1709–1715 UT on December 7, 1995 as Galileo moved inward (near 6.3 R_J) toward Io. Over this extended interval, there was a pronounced change in both the flux and pitch-angle anisotropy of energetic ions and electrons observed with the energetic particle detector (EPD) instrument [*Williams et al.*, 1992]. These changes were associated with enhanced whistler-mode emissions observed by the plasma wave subsystem (PWS) instrument [*Bolton et al.*, 1997]. In addition, short duration step-like increases in the magnetic field occurred [*Kivelson et al.*, 1997], which were interpreted as evidence for an abrupt decrease in plasma density. These correlated signatures are similar to those seen near 1734 UT [*Thorne et al.*, 1997] and are interpreted as evidence for rapid inward interchange motion in the torus. Here we report on a detailed analysis of enhanced whistler-mode wave instability associated with changes in the electron distribution during the complex interchange event between 1709–1715 UT. We demonstrate that the enhanced waves are directly associated with changes in the measured electron population. We also show that the enhanced waves induce pitch-angle scattering, which tends to produce a quasi-isotropic electron distribution during the peak of the event.

2. Coordinated Observations

[3] Particle and field signatures during the extended event between 1709–1715 are very complex and suggest that it may be composed of several distinct injection events. The PWS enhancements are strongly correlated with an abrupt increase in the flux of cyclotron resonant (15–100 keV) electrons (Figure 1). An abrupt increase in electron flux begins near 1709 UT, associated with the onset of enhanced PWS wave emission. Higher energy electrons exhibit an increase at a slightly later time. This dispersed signature is consistent with the gradient drift of freshly injected electrons, which are carried past Galileo by the corotational flow [*Mauk et al.*, 1997]. At the onset of the event, abrupt changes in the electron flux occur over a

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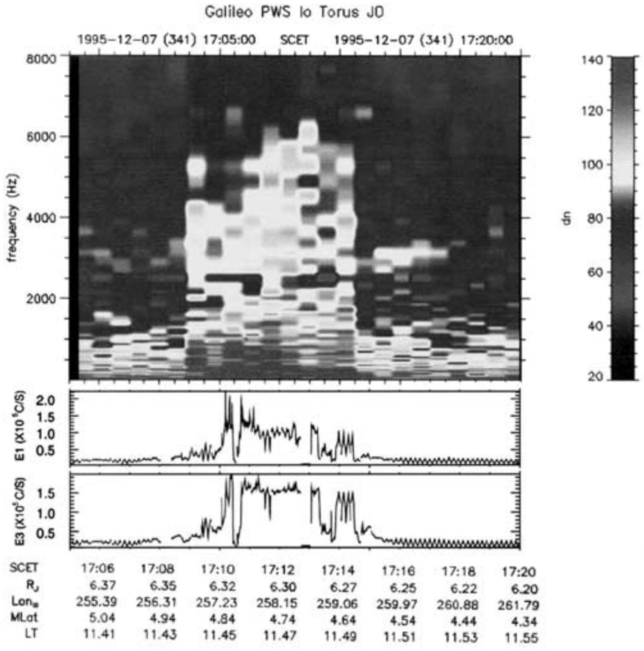

Figure 1. A comparison between PWS whistler-mode emissions (upper panel) and variations in the count rate of 29–42 keV (E1) and 55–93 keV (E3) electrons (lower panels) measured on Galileo during a 15 minute period (17:05–17:20 UT) on December 7, 1995. The electron gyrofrequency is approximately 41 kHz.

single spin cycle (<19*s*), as evidenced by the non-gyrotropic pitch-angle distributions observed between 17:09:24 and 17:09:43 (Figure 2). As the injection event intensifies, lower energy electrons initially exhibit a strong enhancement at pitch-angles near $\alpha = 90°$. The increase in the flux and pitch-angle anisotropy of lower energy electrons can provide the source of free energy for the excitation of whistler-mode waves during this injection event. Lower energy (E0-F1) electron fluxes are typically enhanced by a factor of 5–10 at the center of the injection event (between 17:11:24 and 17:11:43). Flux enhancements at higher energy are progressively smaller, becoming insignificant above 1 MeV. The pitch-angle distribution for electrons in the energy range between 30–800 keV (E1-F3 channels) also becomes relatively isotropic, in contrast to the “pancake” distributions before and after the event. This is interpreted as evidence for rapid scattering by the strongly enhanced PWS waves within the injection event. A separate injection event occurs between 17:14:04 and 17:14:23, as shown by sharply peak pitch-angle distribution near $\alpha = 90°$. After 17:16:00, electron flux returns to the normal distribution formed within the quiet-time torus and the intensities of whistler-mode emission become notably weaker.

3. Modeling and Evaluation of Wave Growth

[4] During rapid interchange inward transport, it is reasonable to assume that the electron first and second invariants μ and J are initially conserved. As the interchange event carries the flux tube inward, the energetic particle phase space density f is also conserved to first order. For a dipole magnetic field, the electron differential flux $j = m^2p^2f$ is therefore enhanced, since $p_\perp \sim B^{1/2} \sim L^{-3/2}$ and $p_\| \sim L^{-1}$. Here, m is the mass of electron, $p = \gamma v$ is the relativistic momentum per unit mass with components $p_\| = \gamma v_\|$ and $p_\perp = \gamma v_\perp$, respectively, parallel and perpendicular to the ambient magnetic field, and $\gamma = (1 - v^2/c^2)^{-1/2}$. Under strictly adiabatic transport, the electron pitch-angle anisotropy should also increase. In contrast to this expectation, the anisotropy is in fact reduced in the center of the event (Figure 2). We interpret this as evidence of rapid pitch-angle scattering due to resonance with the enhanced whistler-mode waves.

[5] Based on the results of *Xiao et al.* [1998], the linear wave growth rate ω_i of whistler-mode waves in a relativistic plasma can be expressed in a simple form analogous to the non-relativistic formula in *Kennel and Petschek* [1966],

$$\omega_i = \frac{\pi\omega_{pe}^2\tilde{\eta}_{rel}}{\left[2\omega_r + \omega_{pe}^2|\Omega_e|/(\omega_r - |\Omega_e|)^2\right]}\{A_{rel} - A_c\} \qquad (1)$$

where ω_r is wave frequency, Ω_e electron gyrofrequency and ω_{pe} is plasma frequency. The relativistic pitch-angle anisotropy of the resonant particles

$$A_{rel} = \frac{\frac{k}{(\omega_r - |\Omega_e|)}\int_0^\infty dp_\perp \Delta_R \frac{p_\perp^2}{\gamma_R}\left[p_\perp \frac{\partial f_h}{\partial p_\|} - p_\| \frac{\partial f_h}{\partial p_\perp}\right]_{p_R}}{\int_0^\infty dp_\perp \Delta_R p_\perp^2 \left[\frac{\partial f_h}{\partial p\perp}\right]_{p_R}} \qquad (2)$$

and $A_c = w_r/(|\Omega_e| - w_r)$ is the minimum resonant anisotropy required for instability.

$$\tilde{\eta}_{rel} = \pi\nu_{hot}\frac{(\omega_r - |\Omega_e|)}{k}\int_0^\infty dp_\perp \Delta_R p_\perp^2 \left[\frac{\partial f_h}{\partial p_\perp}\right]_{p_R} \qquad (3)$$

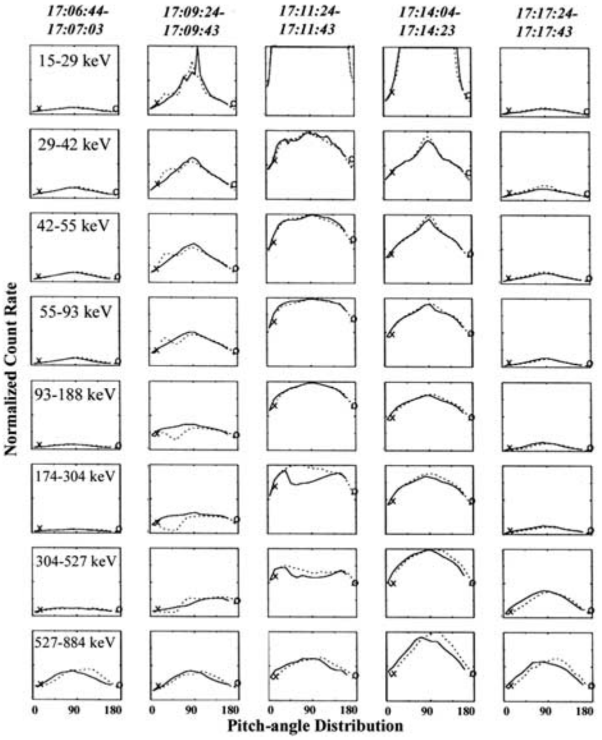

Figure 2. Electron pitch-angle distribution at different time intervals during the event. The numbers above each box indicate the time of each observation.

Table 1. Parameter Fits to the Electron Distribution

Time	a_1	a_2	q_1	q_2	s	$p_0^2/2m$
Pre-event 6:44–7:03	0.25	0.75	4	0.3	2.8	18 kev
	0.25	0.75	4	0.3	1.62	68 kev
	0.25	0.75	4	0.3	1.51	288 kev
Event onset 9:24–9:43	0.15	0.85	20	0.8	2.38	19 kev
	0.15	0.85	20	0.8	1.63	70 kev
	0.15	0.85	20	0.8	1.52	290 kev
Center of event 11:24–11:43	0.04	0.96	18	0.3	2.5	20 kev
	0.04	0.96	18	0.3	1.62	69 kev
	0.04	0.96	18	0.3	1.51	289 kev
End of event 14:05–14:23	0.25	0.75	30	0.4	2.2	21 kev
	0.25	0.75	30	0.4	1.61	69 kev
	0.25	0.75	30	0.4	1.52	286 kev

is the fraction of the relativistic particle distribution near resonance, and ν_{hot} is the density ratio between the hot and cold electron populations [*Xiao et al.*, 1998]. Here k is the wave number and

$$\Delta_R = \left[1 - \omega_r p_R / c^2 k \gamma_R\right]^{-1}. \tag{4}$$

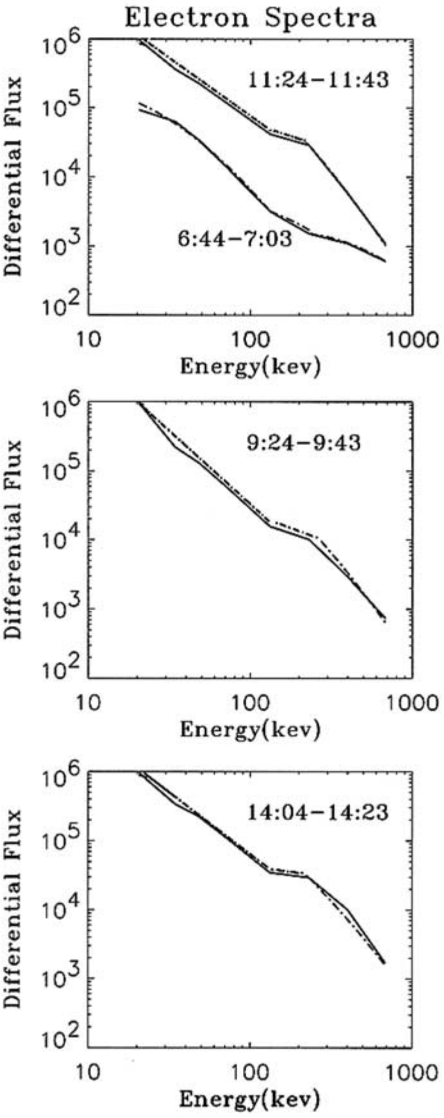

Figure 3. Comparison between model fits (dot-dash) and observed (solid) EPD energy spectra at specified times.

The resonant kinetic energy $E_k = (\gamma_R - 1)mc^2$ can be obtained from the resonant relativistic factor,

$$\gamma_R = \frac{-1 + \left(\frac{ck}{\omega_r}\right)\left[\left\{\left(\frac{ck}{\omega_r}\right)^2 - 1\right\}\left(1 + \frac{p_\perp^2}{c^2}\right)\frac{\omega_r^2}{|\Omega_e^2|} + 1\right]^{1/2}}{\left\{(ck/\omega_r)^2 - 1\right\}(\omega_r/|\Omega_e|)} \tag{5}$$

and the resonant value of the electron-parallel momentum is

$$p_R = (\gamma_R \omega_r - |\Omega_e|)/k. \tag{6}$$

The path integrated gain G can be obtained from the integral $G = \int (\omega_i/v_g)ds$ taken along the wave ray path where v_g is the wave group velocity. Here we adopt an approximate estimate for $G \approx 2\ R_J\, \omega_i/v_g$, based on the assumption of an unstable path length 2 R_J through the torus.

[6] To evaluate the change in wave growth and path integrated gain, a bi-modal distribution is used to model the EPD data at different times during the event:

$$f_h(p_\parallel, p_\perp) = a_1 f^{q_1}(p_\parallel, p_\perp) + a_2 f^{q_2}(p_\parallel, p_\perp). \tag{7}$$

Each component, with variable weighting functions a_1 and a_2, is expressed as:

$$f^q(p_\parallel, p_\perp) = N \frac{2\Gamma((q+3)/2)\Gamma(s+1)}{\pi^2 p_0^3 \Gamma((q+2)/2)\Gamma\left(s - \frac{1}{2}\right)} \cdot \frac{\sin^q \alpha}{\left(1 + p^2/p_0^2\right)^{s+1}} \tag{8}$$

where N is the number density of each energetic electron population, Γ is the gamma function, and s (>3/2) is the energy spectral index. The indices q_1 and q_2 represent the pitch-angle anisotropy of each component and the total anisotropy $A = a_1 q_1/2 + a_2 q_2/2$ [e.g., *Xiao et al.*, 1998]. The parameters a_1, a_2 (with $a_1 + a_2 = 1$), q_1, q_2, s and p_0 are chosen to provide the best fit to the observed energy spectrum and pitch-angle distribution at different times during the event (Table 1). Figure 3 shows a comparison between model fits (dot-dash) and the observed energy spectra (solid) at different times during the event. Corre-

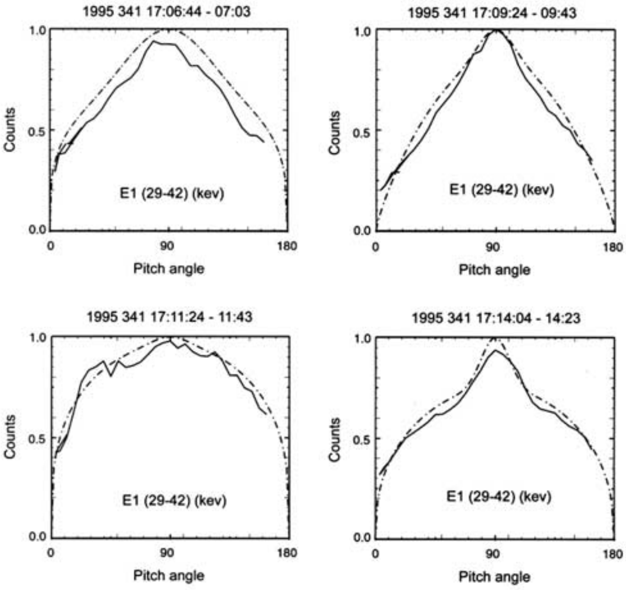

Figure 4. Comparison between model fits (dot-dash) and observed (solid) pitch-angle distributions of 29–42 keV at specified times.

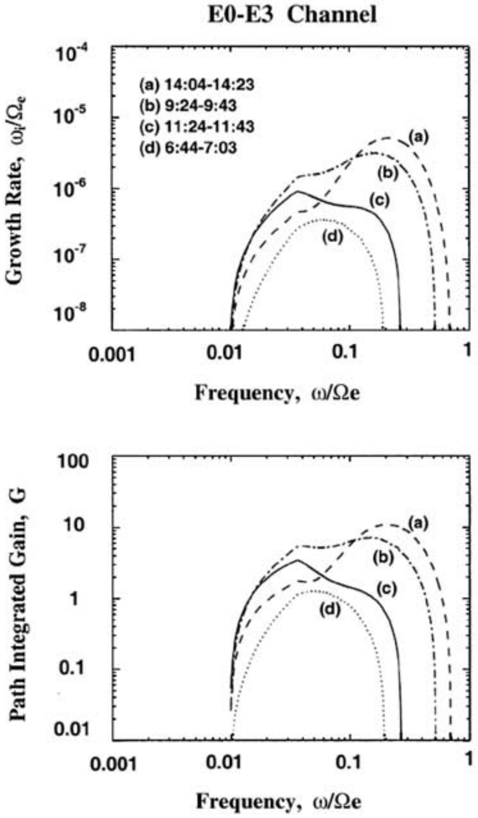

Figure 5. Computed wave growth rate (upper) and path integrated gain (lower) at different times during the event.

sponding fits to the pitch-angle distribution for 29–42 kev electrons are shown in Figure 4. The following constants are adopted to calculate wave growth during the event: $\omega_{pe} = 3.09 \times 10^6$ rads/s [*Gurnett et al.*, 1996] and B = 1480 nT and $\Omega_e = 2.6 \times 10^5$ rads/s [*Kivelson et al.*, 1997].

[7] Calculations of the wave growth rate at different times before and during the event are shown in the top panel of Figure 5. The corresponding path integrated gain (lower panel) indicates a dramatic increase during the event compared to quiet conditions (curve (d)). In the center of the event, the path integrated gain can exceed 10 e-foldings over a broad frequency range $(0.03–0.4)\Omega_e$. Strong wave growth should occur and this will lead to rapid pitch-angle scattering [e.g., *Kennel and Petschek*, 1966]. This pitch-angle scattering is probably responsible for the quasi-isotropic distributions observed in the center of the interchange event near 17:11:30 UT. The peak wave growth occurs near a frequency comparable to one-tenth of gyrofrequency, which is consistent with the enhanced emissions of whistler-mode waves detected by the PWS instrument (Figure 1).

4. Conclusion

[8] Data from EPD and PWS instruments have been used to study wave excitation during an extended interchange event between 1709–1715 UT, as Galileo passed through the inner Io torus. The theoretical model of *Xiao et al.* [1998] has been applied to calculate wave growth and integrated path gain of whistler-mode waves due to cyclotron resonance with observed energetic electrons. We demonstrate that wave growth is dramatically enhanced during the electron injection event. As long as the enhanced electron pitch-angle anisotropy is maintained by rapid interchange motion [e.g., *Thorne et al.*, 1997], the waves will grow rapidly (with a few seconds). The enhanced waves will cause rapid resonant electron pitch-angle scattering, which will eventually lead to a reduction of anisotropy comparable to the level associated with wave marginal stability. This probably accounts for the quasi-isotropic pitch-angle distribution observed near the center of the event. Enhanced whistler-mode emissions, which have been observed over multiple intervals during the Galileo passage [e.g., *Bolton et al.*, 1997] through the Io torus, are probably a reliable indicator of electron injection events. Enhanced whistler-mode emissions may therefore be useful as an indirect identification of interchange driven injection, especially during periods when the EPD data is unavailable. Electron injection events have also been directly linked to enhanced auroral emission [*Mauk et al.*, 2002]. It is tempting to suggest that the auroral enhancements may be caused by an increase in pitch-angle scattering associated with enhanced whistler-mode waves generated during the electron injections, but this remains to be demonstrated.

[9] **Acknowledgments.** This work is supported in part by NASA grants NAG5-11216, NAG5-97271 (task 6) and NAG5-9074 and by JPL contract 958779.

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