

WHISTLER-MODE CHORUS AND MORNINGSIDE AURORAE

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Abstract. Quasi-electrostatic ELF/VLF chorus emissions immediately above the equatorial half-gyrofrequency, observed to propagate with wave normal angle (ψ) within 0.4 – 1.2° of the resonance cone (ψ_r) [Muto *et al.*, 1987], are shown to efficiently resonate with 0.1 – 10 keV electrons. These waves may thus be important in driving the relatively low energy (<10 keV) component of pulsating aurorae and the morningside diffuse aurorae (~ 1 keV).

1. Introduction

Whistler-mode chorus emissions are the most intense natural plasma waves in the outer magnetosphere. Data from the high altitude OGO-3,5 satellites were used to extensively study the occurrence patterns and normalized frequency of ELF (10–1500 Hz) [Tsurutani and Smith, 1974], and ELF/VLF (300 Hz–12.5 kHz) [Burtis and Helliwell, 1976] chorus, with emissions occurring primarily in two distinct bands, just above and somewhat below half the equatorial gyrofrequency (f_{Heq}) (i.e., 0.5 – $0.6f_{Heq}$ and $\sim 0.35 \pm 0.1f_{Heq}$) [Burtis and Helliwell, 1976]. OGO 5 search coil magnetometer data (limited to <1 kHz) indicated that chorus most commonly occurred at intermediate angles (average $\psi \simeq 9$ – 12°) and that in all cases $\psi < 50^\circ$ [Goldstein and Tsurutani, 1984 and references therein]. OGO 3 receivers covered a higher frequency range (0.3–12.5 kHz) but used single sensors (electric or magnetic) so that no directional measurements were possible [Burtis and Helliwell, 1976]. Using wave distribution function analysis with data from the GOES 1 and 2 satellites, Hayakawa *et al.* [1984] found that chorus emissions in the lower band have relatively low ψ ($5^\circ < \psi < 45^\circ$), but that the higher frequency band is highly oblique with $\psi \simeq \psi_r$. Lefeuvre and Helliwell [1985] observed a two-peaked angular distribution for chorus, one with $\psi \simeq 10$ – 40° , and the other with $\psi \simeq 50$ – 60° , in a case for which $\psi_r = 66^\circ$. Further analysis of the GOES 2 data showed that the half-gyrofrequency chorus (i.e., $f \simeq 0.5$ – $0.6f_{Heq}$) is likely to be generated near the geomagnetic equator at ψ such that $|\psi_r - \psi| = 0.4$ – 1.2° , the quasi-electrostatic nature of these emissions being consistent with the measured cB/E ratio [Hayakawa *et al.*, 1984].

The energy spectrum of the morningside aurorae, and particularly the pulsating aurorae, extends from hundreds of eV to ~ 50 keV, with the component below ~ 2 keV exhibiting relatively weak temporal modulation, being possibly caused by atmospheric backscatter [Evans *et al.*, 1987]. The primary

component of pulsating aurora rises sharply from 1 – 2 keV and peaks at 10 – 20 keV. Many observed features of auroral bursts at >15 – 20 keV (e.g., occurrence rates, local time distribution, pulsating or semi regular character, absolute flux levels) were found to be consistent with gyroresonant interaction with chorus having wave amplitudes of 1 – 100 pT [Swift, 1981; Davidson, 1990 and references therein]. However, since the minimum gyroresonant energy at $5 < L < 7$ for typical chorus frequencies, and for $\psi = 0^\circ$, is >20 keV, the relatively low energy (1 – 10 keV) component of the pulsating aurora and the ~ 1 keV diffuse auroral background could not be understood in a similar context [Davidson, 1990]. Interactions with electrostatic electron cyclotron harmonic (ECH) waves was suggested as an alternate mechanism for precipitation of ~ 1 keV auroral electrons. However, observational evidence is not yet fully developed and one recent study based on SCATHA satellite data concluded that the observed intensities of ECH waves were insufficient [Fennell *et al.*, 1991]. Further, SCATHA particle distributions often do not have enough anisotropy or particle density to support the generation of such waves by plasma instabilities.

Up to now, chorus-induced auroral precipitation has only been considered for parallel propagation (i.e., $\psi \simeq 0^\circ$) and for chorus waves at frequencies 0.25 – $0.35f_{Heq}$ [Swift, 1981; Davidson, 1990 and references therein]. Chorus was implicitly assumed to be generated by the loss-cone instability, i.e., same electron population that is precipitated by chorus. We consider here the general cases of both the upper and lower frequency bands of chorus as well as propagation with $\psi \neq 0^\circ$. We also recognize that the emissions may be generated by electrons at higher pitch angles and limit our attention to evaluating the effect of the waves on the electrons near the loss cone. We only consider first order gyroresonant interactions since, for the parameters considered in this paper, Landau resonant pitch angle scattering is found to be 10 – 100 times smaller. Our results indicate that highly oblique ($|\psi_r - \psi| \simeq 1$ – 2°) chorus waves in both frequency bands can efficiently resonate with 0.1 – 10 keV electrons. Since the so-called half-gyrofrequency chorus ($f \simeq 0.5$ – $0.6f_{Heq}$) is observed to propagate with $\psi \simeq \psi_r$, [Muto *et al.*, 1987, and references therein] these waves may be responsible for the precipitation of the relatively low energy component (1 – 10 keV) of the pulsating auroral forms as well as the morningside diffuse aurora (~ 1 keV).

2. Resonant Energies and Pitch Angle Scattering

The nonrelativistic first order gyroresonant energy E_R for electrons is $E_R \simeq (1/2)m[c(\omega_H - \omega)/(\omega\mu \cos \psi \cos \alpha)]^2$, where c is the speed of light, ω_H and ω are the electron gyrofrequency and wave frequency, m is the electron mass, α

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is the pitch angle, and μ is the refractive index. The refractive index μ is dependent on ψ , ω , ω_H and the local electron density N_e and is given by the cold plasma formulation, as long as the wave is not Landau damped, i.e., $c(\mu \cos \psi)^{-1} \gg v_{th}$ [Sazhin and Sazhina, 1985], a condition readily satisfied for the parameters considered here. We consider only ψ up to ψ_o , for which the wave parallel phase velocity $(c(\mu \cos \psi_o)^{-1})$ is equal to thermal velocity of 100 eV electrons; so that Landau damping is safely neglected.

In the outer magnetosphere on L -shells of interest here ($5 < L < 7$) and for a morningside (~ 0700 MLT) plasmatrough, N_e at the equator typically decreases from $\sim 7 \text{ cm}^{-3}$ at $L=5$ to $\sim 2 \text{ cm}^{-3}$ at $L=7$, while during nighttime (~ 0200 MLT) the trough densities typically decrease from $\sim 5 \text{ cm}^{-3}$ at $L=5$ to $\sim 1.5 \text{ cm}^{-3}$ at $L=7$ [Carpenter and Anderson, 1991]. In our analysis, we consider two different density models as shown in Figure 1. Model I is representative of an early stage in the recovery of the trough from depletion during substorms [Carpenter and Anderson, 1991], where as Model II is an ad hoc reduction in density compared to Model I, to reflect lowest N_e levels occasionally observed in the pre-midnight sector at synchronous orbit [Higel and Wu, 1984] and in the immediate aftermath of substorms [Carpenter and Anderson, 1991]. N_e as given by Model II was used in previous considerations of the role of chorus in producing the morningside aurora [Swift, 1981; Davidson, 1990].

Figure 2a and 2b respectively show $E_R(\psi)$ for $L=5, 6$, and 7 for the lower band chorus ($\Omega=f/f_{H_{eq}}=0.35$) for Models I and II and for $\psi < \psi_o$, where as noted above, $c(\mu \cos \psi_o)^{-1}$ corresponds to the velocity of 100 eV electrons. For Model II (Figure 2b), $E_R > 10 \text{ keV}$ for all L except for $|\psi_r - \psi| < 0.5^\circ$. For Model I, $E_R > 10 \text{ keV}$ for $L=5$ and 6 and for $|\psi - \psi_r| > \sim 3^\circ$ and $> 2 \text{ keV}$ except for $|\psi_r - \psi_o| < 1^\circ$. For $L=7$, $E_R \leq 5 \text{ keV}$ for $|\psi - \psi_r| > \sim 3^\circ$ and $> 2 \text{ keV}$ for $|\psi_r - \psi| < 2^\circ$. The E_R for $\psi=0^\circ$ in Figure 2 confirm the earlier findings [Swift, 1981; Davidson, 1986 and references therein] that gyroresonance with parallel propagating chorus is limited to $E_R > 10 \text{ keV}$. While lower E_R is possible at high ψ , the lower band chorus ($\Omega \simeq 0.35$) is observed to propagate mostly at relatively low ψ [Hayakawa et al., 1984] and is thus not likely to be associated with the precipitation of $\sim 1 \text{ keV}$ electrons.

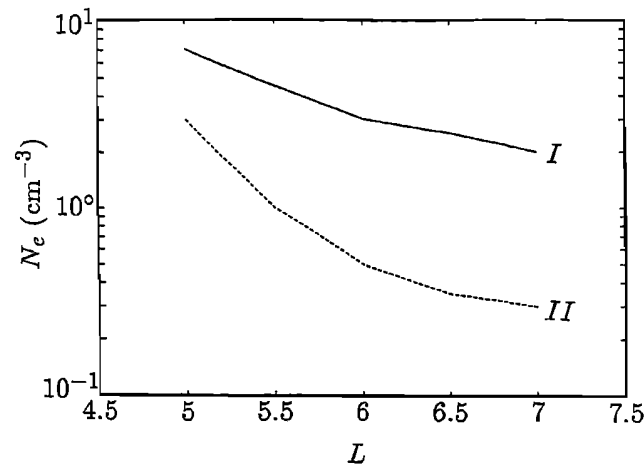


Fig. 1. Two different electron density (N_e) models used in numerical calculations.

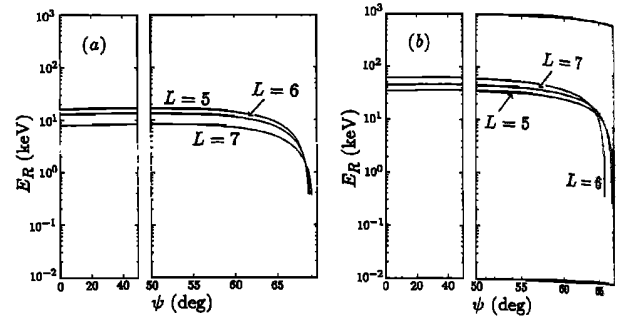


Fig. 2. $E_R(\psi)$ for $\Omega=0.35$ and for $L=5, 6$, and 7. (a) for Model I. (b) for Model II.

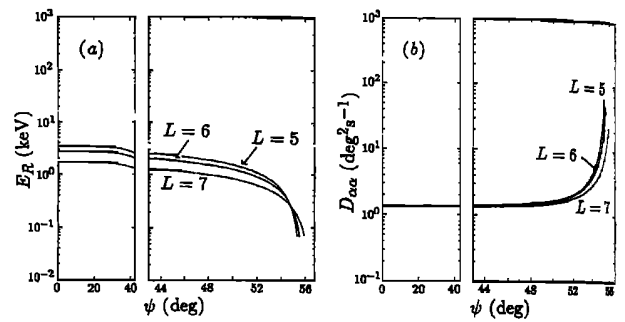


Fig. 3. (a) $E_R(\psi)$ for Model I, $\Omega=0.55$, and $L=5, 6$, and 7. (b) $D_{\alpha\alpha}(\psi)$ for the same.

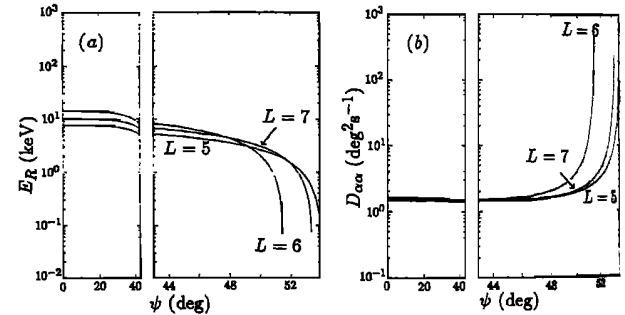


Fig. 4. (a) $E_R(\psi)$ for Model II, $\Omega=0.55$, and $L=5, 6$, and 7. (b) $D_{\alpha\alpha}(\psi)$ for the same.

Figure 3a and 4a respectively show $E_R(\psi)$ for $L=5, 6$, and 7 for the upper band chorus ($\Omega=0.55$) (i.e., half-gyrofrequency chorus) for Models I and II and again for $\psi < \psi_o$. For Model I, E_R for $\psi=0^\circ$ is lower than those in Figure 2 but still $> 2 \text{ keV}$ for $L=5$ and 6 and $> 1.8 \text{ keV}$ for $L=7$. Thus, gyroresonance with $\sim 1 \text{ keV}$ electrons does not seem possible for parallel propagation for the upper band chorus. However, we note from Figure 3a that $E_R \simeq 1 \text{ keV}$ or lower over a relatively large range of ψ . For $L=5$ and 6, $E_R \leq 1 \text{ keV}$ for $|\psi - \psi_r| \leq 2^\circ$, whereas for $L=7$, $E_R \leq 1 \text{ keV}$ for $|\psi - \psi_r| \leq 8^\circ$. Since the reported measurements of ψ for the upper band chorus indicate $|\psi_r - \psi| \simeq 0.4 - 1.2^\circ$ [Muto et al., 1987], the half-gyrofrequency chorus can interact in the first order gyroresonance mode with $\sim 1 \text{ keV}$ (or lower) electrons.

Figure 4a shows that E_R for Model II are higher than those in Figure 3a and that the dependence on ψ for $\psi \simeq \psi_r$ are different for each L . (We note here that E_R does

not simply scale with N_e , since the dependence on N_e of both μ and ψ_r are not simple; for a single-ion cold plasma $\psi_r = \cos^{-1}\{(\omega/\omega_H)[1 + (\omega_H^2 - \omega^2)/\omega_p^2]^{1/2}\}$, where ω_p is the angular plasma frequency. For parallel propagation ($\psi \simeq 0^\circ$), $E_R \simeq 10$ keV, so that the half-gyrofrequency chorus components at angles $\psi \simeq 0^\circ$ can contribute to the higher energy auroral precipitation that have previously been attributed to primarily the lower band chorus. In terms of the ~ 1 keV electrons, we find from Figure 4a that for $L=5$ and 7, $E_R \leq 1$ keV for $|\psi - \psi_r| \leq 1^\circ$, whereas for $L=6$, $E_R \leq 1$ keV only for $|\psi - \psi_r| \leq 0.2^\circ$. While the range of ψ for which $E_R \leq 1$ keV in this case is lower than that for Model I, interactions with half-gyrofrequency chorus would still be an important source of precipitation, in view of the measured ψ [Muto et al., 1987]. Furthermore, the magnitude of scattering coefficients for these highly oblique waves is relatively high, as discussed below.

The pitch angle scattering coefficients (i.e., $D_{\alpha\alpha}$) for given values of ω , ω_H , N_e , α , ψ , and for a normalized value of the wave Poynting Flux (assumed to be constant as a function of ψ) are evaluated using a formulation recently put forth by Inan and Bell [1991]. The $D_{\alpha\alpha}$ given in Figures 3b and 4b are for a particle pitch angle of $\alpha=5^\circ$ (near loss-cone), a wave bandwidth of 100 Hz and for a Poynting Flux equal to that for a $\psi=0^\circ$ wave with magnetic field intensity at the equator of $B_w=1$ pT. Figure 3b and 4b respectively show $D_{\alpha\alpha}$ (in units of $\text{deg}^2\text{s}^{-1}$) vs ψ for $\Omega=0.55$ (i.e., upper band, or half-gyrofrequency chorus), for Models I and II, at $L=5, 6$, and 7, and again for $\psi < \psi_o$.

From Figure 3b, we note that the $D_{\alpha\alpha}$ remain relatively constant with ψ until $|\psi - \psi_r| \leq 5^\circ$ and increase relatively rapidly with further increases in ψ . For $|\psi - \psi_r| \leq 1^\circ$, $D_{\alpha\alpha}$ are larger by a factor of 5-50 with respect to that for $\psi=0^\circ$. These enhanced pitch angle diffusion coefficients near $\psi \simeq \psi_r$ are in part due to the higher values of the wave electric field resulting from the assumption of constant Poynting Flux as a function of ψ and in part due to the fact that the group velocity for these quasi-electrostatic waves is low, resulting in longer interaction times [Inan and Bell, 1991]. The important result from Figure 3b is that the pitch angle scattering of the ≤ 1 keV electrons due to the highly oblique half-gyrofrequency chorus waves is expected to be relatively high.

We arrive at a similar conclusion for the case of density Model II shown in Figure 4. While, as discussed above, the range of ψ for which $E_R \leq 1$ keV was found to be narrower for this case, $D_{\alpha\alpha}$ rapidly increases with ψ for angles close to ψ_r , reaching to up to 10-100 times larger scattering as compared to the $\psi=0^\circ$ case.

The absolute values of $D_{\alpha\alpha}$ given in Figures 3b and 4b are also high, lying in the range of 1-100 $\text{deg}^2\text{s}^{-1}$. For comparison, we note that for the lower band chorus ($\Omega \simeq 0.35$) and for parallel propagation ($\psi=0^\circ$) $D_{\alpha\alpha} \simeq 0.5 \text{ deg}^2\text{s}^{-1}$ for the same wave Poynting Flux. With $D_{\alpha\alpha}=1-100 \text{ deg}^2\text{s}^{-1}$, the average scattering (i.e., $\langle \Delta\alpha \rangle$) for a 1 keV electron, during a single traverse through a typically ~ 1000 km equatorial interaction region [Inan et al., 1983] at $L=5$, would be $\sim 0.2-2^\circ$. It thus appears that scattering by these upper band chorus waves is at the level of strong diffusion (i.e., $\Delta\alpha \simeq \alpha$) and we can expect significant precipitation fluxes and filling of the loss cone.

Previous work on the association of chorus with the morningside aurorae [e.g., Davidson, 1990] considered only the lower band chorus with $\Omega \simeq 0.25-0.35$, due probably to historical reasons, since the earlier work on chorus [e.g., Tsu-

rutani and Smith, 1974] was limited to frequencies of < 1500 Hz. VLF data from OGO-3 indicated that the 'average' magnetospheric chorus near the equatorial plane consisted of both the upper and lower bands but that in general, while the lower band consisted of discrete elements clearly spaced in time, the upper band was more diffuse in character, consisting of a succession of closely spaced elements [Burtis and Helliwell, 1976]. The wave magnetic field amplitudes for chorus were reported to be in the 1-100 pT range [Burtis and Helliwell, 1975], with peak amplitudes of the lower band emissions being a factor of 2-10 larger than those of the upper band. In terms of pitch angle scattering of electrons, the lower peak intensities (and thus lower $D_{\alpha\alpha}$) of the upper band chorus would tend to be compensated by their more diffuse and continuous-like character, also consistent with the fact that the 1-10 keV fluxes in the morningside aurorae are not strongly modulated [Evans et al., 1987]. We also note that for magnetic measurements of quasi-electrostatic waves (i.e., the upper band), the commonly adopted assumption [Burtis and Helliwell, 1975] of $\psi = 0^\circ$ would underestimate the wave power density. For example, for the cases shown in Figures 3 and 4 (normalized to constant Poynting Flux), B_w for $\psi=0^\circ$ is ~ 5 times larger than for $\psi \simeq \psi_o$.

3. Summary and Discussion

In summary, we find that the half-gyrofrequency chorus emissions, omnipresent in the outer magnetosphere in the morning local time sector and at normalized frequencies of $\Omega \simeq 0.55 \pm 0.5$, and generally propagating at highly oblique angles with respect to the earth's magnetic field, can efficiently scatter electrons with energy ~ 1 keV or lower. Thus, the characteristics of these waves appear sufficient for them to contribute to the formation of the low energy (1-10 keV) component of pulsating auroral forms as well as the morningside diffuse aurora consisting of ~ 1 keV electrons. Our findings in this regard appear to resolve a major obstacle faced by previous authors in their studies of the association between ELF/VLF chorus and morningside aurorae. It appears that important limitations of earlier studies were the fact that they considered only the lower band chorus, and the fact that chorus waves were assumed to be propagating parallel to the magnetic field lines.

Our results indicate that the traditional picture of morningside pulsating and diffuse aurorae should be modified to take account of the new results on scattering by upper band chorus. Originally it was thought that pulsating aurorae consisted of a single component due to interactions with ELF/VLF chorus. However, Evans et al. [1987] demonstrated that there must be, in addition to the primary component, a secondary component at energies below 1-2 keV, due to backscatter from the atmosphere. What we now suggest is that there may actually be three distinct components: (i) an energetic component ($\sim 10-50$ keV) that is produced by strongly modulated interactions with lower-band chorus, (ii) an intermediate component ($\sim 1-10$ keV) that is produced by weakly modulated interactions with obliquely propagating upper-band chorus, and (iii) a steady low energy component (< 1 keV) that results from production of secondary electrons backscattered from the atmosphere. This picture is consistent with other observations [McEwen et al., 1981] as well as the work of Evans et al. [1987] which imply that the modulation of the precipitating fluxes decreases rapidly below 10 keV.

The new picture of pulsating auroral precipitation clears up perplexing problems that were faced in previous investigations of its association with chorus [Davidson, 1990]. In addition it provides a simple mechanism for the production of diffuse aurorae in the regions apart from the bright pulsating patches. Since the two chorus bands are commonly observed together [Burtis and Helliwell, 1976], when wave-particle interactions lead to the production of chorus, we can expect the presence of obliquely propagating upper-band emissions as observed [Muto et al., 1987] both near the source and distant regions populated via propagation. Based on our results, we infer that the extensive morningside outer magnetospheric regions where chorus is observed can be dominated by ~ 1 keV precipitation caused by upper-band interactions leading to the morningside diffuse aurorae.

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