GEOPHYSICAL RESEARCH LETTERS, VOL. 22, NO. 16, PAGES 2099-2102, AUGUST 15, 1995

VLF wave localization in the low-altitude auroral region

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Abstract. Localized packets of electrostatic whistler emissions near the lower hybrid frequency have been observed in the low-attitude auroral region by sounding rockets and the Freja satellite. We present a model for wave localization that requires two ion species, O^+ and H^+, whereby the minority H^+ ions control the localization process. The theoretical basis is that the plasma dispersion is dramatically affected by small changes in the H^+ density and that the observed emissions would selectively heat H^+. We show observational support for the proposed model.

Introduction

Observations by sounding rockets and the Freja satellite in the low-altitude auroral region have uncovered localized packets of electrostatic whistler emissions near the lower hybrid frequency [*LaBelle et al.*, 1986] that have been correlated with small-scale density depletions [*Kintner et al.*, 1992; *Vago et al.*, 1992; *Eriksson et al.*, 1994]. The packets appear as filamentary structures along the magnetic field (**B**) with the scale length across **B** ranging from 20 m to 100 m. The amplitude of the emissions ranges from ~20 mV/m to >500 mV/m in the frequency range of ~1 kHz to ~20 kHz. *Vago et al.*, [1992] presented rocket observations that associate the wave events with enhanced ion fluxes (H^+ and O^+) perpendicular to **B** in the energy range of ~2 eV. The Freja satellite observations show no obvious correlation between wave events and more energetic (>10 eV) ion heating [*Eriksson et al.*, 1994; *Andre et al.*, 1994].

The simultaneous observation of localized packets of enhanced wave emissions and density depletions is suggestive of lower hybrid wave collapse from ponderomotive force of large-amplitude waves [*Musher and Sturman*, 1975, *Morales and Lee*, 1975]. While ongoing research indicates it is possible that ponderomotive collapse explains the recent low-altitude observations [*Shapiro et al.*, 1993, *Chang et al.*, 1993, *Seyler*, 1994], it is not conclusive. There have been alternative suggestions, one of which is that kinetic ion effects combined with the magnetic mirror force acceleration [*Singh*, 1994] causes a localized density depletion which traps the lower hybrid waves.

In this letter, we propose a localization model that calls for a two ion species plasma with O^+ the majority and H^+ the minority. The presence of a few per cent H^+ alters the dispersion relation near the lower hybrid frequency significantly. The resulting dispersion relation is far more sensitive to H^+ density perturbations than to O^+ density perturbations. The two ion dispersion relation also is such that waves generated by low-energy auroral electrons have a perpendicular phase velocity near the H^+ thermal velocity [*Ergun et al.*, 1993] that causes H^+ ions to be preferentially heated.

Under the proposed model, a small H^+ density perturbation traps and refracts lower hybrid waves which, in turn, selectively heat H^+ ions. The heated ions experience an increased magnetic mirror force which causes a further depletion of the H^+ density, maintaining the instability. The localization model predicts a transverse (to **B**) scale size of tens of meters and a parallel scale size of ~100 km, in agreement with the observed scale sizes [*Kintner et al.*, 1992]. It is predicted that the H^+ density perturbations endure for tens of seconds.

There is strong observational support that H^+ plays an important role in wave localization. Almost all observed localization events were in an O^+ plasma with a few per cent H^+, which is a typical plasma in the low-altitude auroral zone. There were observed downshifts in the lower hybrid frequency that were much greater than can be explained by the observed density depletions if the depletions contained H^+ and O^+ in proportion to their ambient abundances. We show that the changes in the lower hybrid frequency can be explained by a small quasi-neutral depletion in the H^+ density.

Localization Model

Before presenting a physical model, we examine wave refraction near the lower hybrid frequency and the quasi-static, quasi-neutral plasma response to increased mirror force from ion heating.

The response of the high-frequency electric field ($\mathbf{E}^h = \tilde{\mathbf{E}}^h e^{i(k\cdot x-\omega t)} + c.c.$) to a low-frequency density perturbation [*Ergun et al.*, 1991] can be generalized for a multi-component plasma as:

$$i(\partial/\partial t+\mathbf{v}_g\cdot\partial/\partial\mathbf{x})\tilde{\mathbf{E}}^h+\mathbf{D}{:}\partial^2/\partial\mathbf{x}^2\tilde{\mathbf{E}}^h=\sum_s\frac{\partial\epsilon/\partial n_s}{\partial\epsilon/\partial\omega}\delta n_s\tilde{\mathbf{E}}^h \tag{1}$$

where ω and k are the wave frequency and the wave vector, $\tilde{\mathbf{E}}^h$ is the slowly evolving amplitude of the high-frequency electric field, $\mathbf{D}$ is the dispersion tensor $(-1/2(\partial^2\epsilon/\partial\mathbf{k}^2)/(\partial\epsilon/\partial\omega))$, $\mathbf{v}_g$ is the group velocity, ϵ is the high-frequency dielectric function, n_s represents the density of the species, and δn_s is the low-frequency perturbation. The evolution of the wave envelope is controlled by dispersion and the sensitivity of the dielectric function to a density perturbation.

The electrostatic dielectric function for an O^+ and H^+ plasma near the lower hybrid frequency under typical auroral conditions can be approximated as:

Paper number 95GL02004
0094-8534/95/95GL-02004$03.00

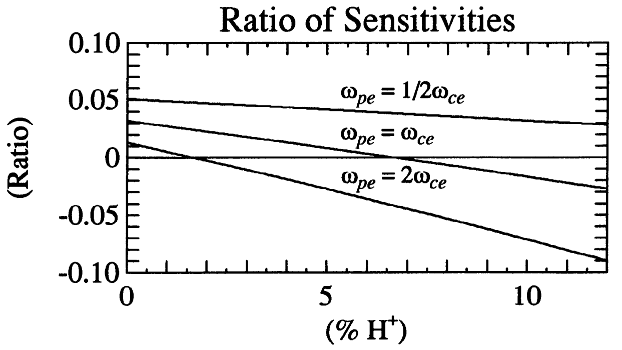

Figure 1. Plots of $(d\epsilon/dn_O)/(d\epsilon/dn_H)$. A negative ratio occurs when $d\epsilon/dn_O$ changes sign in which case a density depletion in O^+ will not serve to trap lower hybrid waves.

$$\epsilon \approx 1-(\frac{\omega_{pH}^2}{\omega^2}+\frac{\omega_{pe}^2}{\omega^2})\frac{k_\|^2}{k^2}-(\frac{\omega_{pH}^2}{\omega^2-\omega_{cH}^2}-\frac{\omega_{pe}^2}{\omega_{ce}^2})\frac{k_\perp^2}{k^2}-\frac{\omega_{pO}^2}{\omega^2} \tag{2}$$

where $k_\|$ and $k_\perp$ are the parallel and perpendicular wave number, ω_{pe} and ω_{ce} are the electron plasma and cyclotron frequencies, ω_{pO} is the O^+ plasma frequency, and ω_{pH} and ω_{cH} are the H^+ plasma and cyclotron frequencies. We have neglected thermal terms.

In a plasma where n_H/n_e is a few per cent:

$$\left|\frac{d\epsilon}{dn_H}\right| \gg \left|\frac{d\epsilon}{dn_O}\right|, \text{ where } \frac{d\epsilon}{dn_H}=\frac{\partial\epsilon}{\partial n_H}+\frac{\partial\epsilon}{\partial n_e}, \tag{3}$$

$$\text{and } \frac{d\epsilon}{dn_O}=\frac{\partial\epsilon}{\partial n_O}+\frac{\partial\epsilon}{\partial n_e}$$

We assume a quasi-neutral plasma whereby the electron density (n_e) is the sum of the O^+ (n_O) and H^+ (n_H) densities. Figure 1 plots $(d\epsilon/dn_O)/(d\epsilon/dn_H)$ for $\omega_{pe}=1/2\omega_{ce}$, $\omega_{pe}=\omega_{ce}$, and $\omega_{pe}=2\omega_{ce}$. If $\omega_{pe}=\omega_{ce}$, and $n_H/n_e \approx 6\%$, the dispersion is insensitive to a quasi-neutral change in the O^+ density ($d\epsilon/dn_O=0$) because the electron and O^+ contributions are opposite. Furthermore, as n_H/n_e increases to greater than 6%, $d\epsilon/dn_O$ changes sign in which case a density depletion in O^+ will not serve to trap lower hybrid waves. If $\omega_{pe} \gg \omega_{ce}$, the sign of $d\epsilon/dn_O$ changes at very small values of n_H/n_e, while if $\omega_{pe} \ll \omega_{ce}$, the ratio of the sensitivities $(d\epsilon/dn_O)/(d\epsilon/dn_H)$ is the inverse mass ratio of the two species. The electrostatic dispersion near the lower hybrid frequency is far more sensitive to a quasi-neutral H^+ density perturbation than to a O^+ density perturbation, or to a density perturbation of both O^+ and H^+ in proportion to the ambient abundances. Equations 1, 2 and 3 strongly suggest that H^+ dominates the localization process.

A density perturbation can arise from ponderomotive force or from ion kinetic effects [*Singh*, 1994]. We will concentrate on ion kinetic effects for two reasons. There is experimental evidence of H^+ bulk heating [*Arnoldy et al.*, 1992] and very clear theoretical evidence that H^+ is preferentially heated by electrostatic waves near the lower hybrid frequency [*Chang and Coppi*, 1981; *Retterer et al.*, 1986; *Ergun et al.*, 1993]. Ponderomotive collapse may be very interesting in a two ion species plasma since the H^+ ponderomotive force is much higher than the contribution from O^+ due to the difference in mass. A study of two ion species collapse which includes ion ponderomotive force is needed.

The quasi-static, quasi-neutral H^+ density response parallel to **B** can be derived using the plasma fluid equations assuming the pressure terms dominate over the momentum terms for all species. We arrive at an approximation:

$$\frac{dn_H}{dz}=\frac{\Delta T_{\perp H}}{T_e+T_{\|H}}\frac{\partial B}{\partial z}\frac{n_H}{B} \tag{4}$$

where $T_{\|H}$ is the parallel H^+ temperature, T_e is the electron temperature, $\Delta T_{\perp H}$ is the change in the perpendicular H^+ temperature, and z is along **B**.

The scale size of the wave localization along **B** can be estimated from Equation 4. The observed H^+ heating in the localization events indicates perpendicular temperatures ~2 eV [*Arnoldy et al.*, 1992] and typical ionospheric parameters have $T_{\|H}, T_e \approx 0.2$ eV. A scale size of ~100 km parallel to **B** is required to have a density perturbation of $\delta n_H/n_H \approx 30\%$ (or $\delta n_H/n_e \approx 2\%$ if $n_H/n_e = 6\%$). Equation 4 does not account for transverse response.

In the proposed localization model, preferential heating of H^+ ions by lower hybrid waves combined with mirror force acceleration causes a local density depletion in H^+ on the order of a few per cent ($\delta n_H/n_e$). Figure 2 shows the contours of constant ω_{lh} of what may be a typical case of a 2% density depletion ($\delta n_H/n_e$) with a scale width of 40 m and a scale height of 100 km [*Kintner et al.*, 1992]. We imposed an exponentially falling background density with a scale height of 100 km and a magnetic field falling as $(1/z)^3$. The plasma

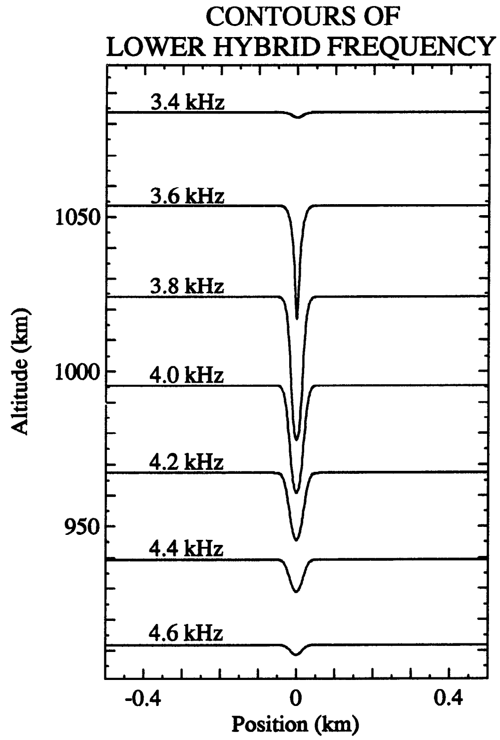

Figure 2. Contours of constant lower hybrid frequency. A -2% ($\delta n_H/n_e$) Gaussian H^+ density perturbation with a 40 m width and a 100 km scale height was superimposed on a decreasing density profile and a magnetic field falling in altitude. The lower hybrid frequency contours form funnel shaped depressions that would trap incident electrostatic whistler waves.

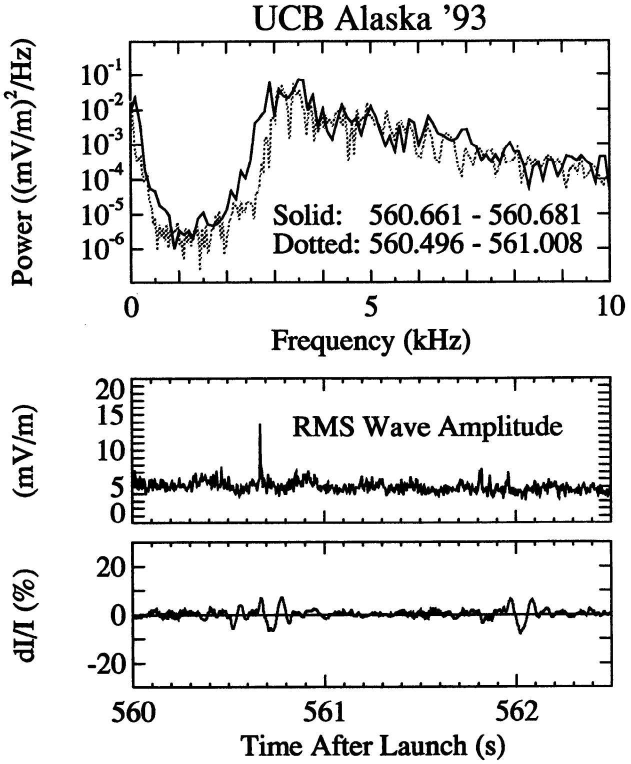

Figure 3. (a) The wave-frequency spectrum of a localized wave event (solid line) and the ambient spectrum (dotted line). There is a down shift in the lower hybrid frequency of ~250 Hz during the localization event. (b) The RMS amplitude of emissions in the 500 Hz to 16 kHz band as a function of time. The localization event is at 560.67 s. (c) The perturbation in the current to the Langmuir probe ($\delta I/I$). The perturbations at ~560.7s and 562 s are spin periodic perturbations from probe shadowing.

consisted of 6% H^+ and 94% O^+. Waves just above the local lower hybrid frequency, produced by the precipitating auroral electrons [*Maggs*, 1976] or by field-aligned electron bursts [*Ergun et al.*, 1993] propagating earthward nearly parallel to the magnetic field would enter the funnel-shaped region and become trapped in the H^+ density depletion, maintaining the instability. The suggested localization process is not a resonant process whereby waves become trapped as the density cavity forms, but instead endures over time scales of tens of seconds.

Wave refraction plays an important role. The small H^+ density perturbation mimics a very large density gradient of both O^+ and H^+ in proportion to the background abundances. The H^+ density perturbation refracts the incident whistler emissions, which causes scattering of the longer wave length emissions [*Bell and Ngo*, 1990] resulting in a wave number (**k**) spectrum that contains a short wavelength component which efficiently heats the H^+ ions.

Under the proposed model, the process that controls the perpendicular scale size is pump depletion from O^+ heating. If the transverse scale size decreases to a few times the O^+ gyroradius ($\rho_O \approx 6$ m), finite Larmar radius effects would increase the efficiency in O^+ heating [*Reitzel and Morales*, 1994]. A quasi-neutral perturbation in O^+ density does not alter the lower hybrid dispersion significantly and therefore contributes little to wave trapping or refraction, so O^+ heating results only in depleted wave power which stabilizes the instability. Observations consistently show a 20 m to 100 m transverse width regardless of wave amplitude and spectral shape, supporting such a mechanism.

The proposed localization model calls for bulk heating of the minority species (H^+) to ~2 eV in a filamentary structure approximately 50 m wide extending ~100 km along the magnetic field. The energy for the H^+ heating ($n_H/n_e \approx 6\%, n_e = 5 \times 10^3 \mathrm{cm}^{-3}$) requires ~10 s of incident wave emissions ($E = 100$ mV/m, group velocity $v_g = 2 \times 10^3$km/s) at 100% efficiency. This ties in well with the travel time of thermal H^+ ion along the filamentary structure (~10 s). The focusing effect of the funnel shaped-shaped lower hybrid contours (Figure 2) would offset the need for 100% heating efficiency.

Observational Support

All of the observed localized events, to the authors' knowledge, occurred in an O^+ plasma with a few per cent H^+, a typical plasma on the low-altitude auroral zone. The strongest observational support, however, comes from examining the frequency spectra of the localized wave emissions.

Figure 3a compares the frequency spectra of the enhanced, localized wave emissions (solid line) and the ambient emissions (dotted line). The RMS power over a several second interval is shown in Figure 3b. The enhanced wave power near the lower hybrid frequency is indicative of wave trapping. There is a down shift of ~250 Hz in the lower hybrid cut off. Such down shifts were also seen by the TOPAZ 3 sounding rocket [*Vago et al.*, 1992] and by the Freja satellite [*R. Boström*, private communication]. The 250 Hz downshift in the lower hybrid plasma frequency would require either a ~1.8% H^+ ($\delta n_H/n_e$) density depletion or ~21% quasi-neutral density depletion of O^+ and H^+ in proportion to the ambient abundances. The observed electron current to a Langmuir probe (Figure 3c) does not support the latter. The observed perturbation in electron current after the event is a spin periodic perturbation from probe shadowing, recurring at ~562 s. We are able to determine that the plasma contained ~5% H^+ by comparing the Langmuir wave frequency to the lower hybrid cut-off. The plasma density (n_e) was ~ 2.2×10^3 cm^{-3}.

Figure 4 shows a different type of localized (solid line) and ambient (dotted line) spectra. There is no

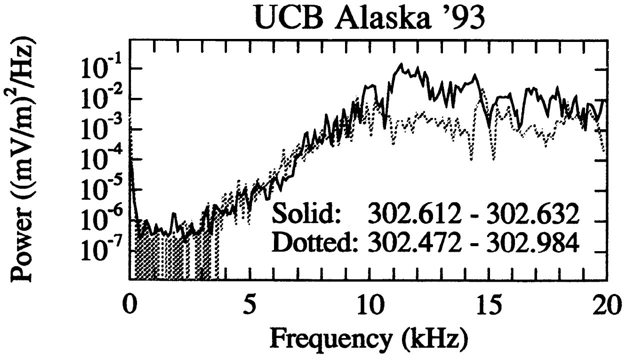

Figure 4. The wave-frequency spectra of a localized wave event (solid line) and the ambient spectrum (dotted line). There is very little power near the lower hybrid frequency (~4 kHz). The ambient waves were electromagnetic (long wave length) while the localized emissions had a short wave length component.

evidence of wave trapping of emissions near the lower hybrid frequency. Wavelength analysis, however, indicates the ambient waves were nearly electromagnetic (long wavelength) whereas the localized emissions had a short wavelength component. The observed electron current to a Langmuir probe indicates density turbulence of a few per cent. This event supports the hypothesis that wave refraction at an H^+ density gradient plays an important role in the process. It would be extremely difficult to explain the event in Figure 4 as a signature of ponderomotive collapse.

The observations reported here and by the Freja satellite indicate much lower-amplitude density depletions (0% to $\sim$ 5%) than the tens of per cent depletions that were reported by the TOPAZ 3 sounding rocket [*Vago et al.*, 1992]. A study of nonlinear effects of spacecraft Langmuir probe instruments shows that deriving electron density from Langmuir probe current is unreliable when large-amplitude waves were present [*Ergun et al.*, 1994]. The proposed model, therefore, may be consistent with the reported TOPAZ 3 data.

Conclusions

We propose a localization mechanism for electrostatic whistler emissions near the lower hybrid frequency that is applicable in the low-altitude auroral region. The localization process is dominated by H^+ ions. We expect an H^+ density depletion of a few per cent that extends several O^+ gyroradii transverse to $\mathbf{B}$ and many tens of kilometers along $\mathbf{B}$. Incident electrostatic whistler waves near the lower hybrid frequency can be focused and trapped in the density structure while longer wavelength electrostatic and electromagnetic waves undergo severe refraction from the H^+ density gradients. The H^+ ions are selectively heated by the trapped and refracted waves. The resulting increase in magnetic mirror force causes a quasi-static, quasi-neutral H^+ density perturbation maintaining the H^+ density structure.

The proposed model properly predicts the perpendicular and parallel (to $\mathbf{B}$) sizes of the observed structures [*Kintner et al.*, 1992], and is consistent with the observed bulk heating of H^+ and tail heating of O^+ [*Arnoldy et al.*, 1992]. The perpendicular width is controlled by pump depletion due to O^+ heating while the $\sim$100 km extent along $\mathbf{B}$ is required for the magnetic mirror force to generate the quasi-static density depletion. Energy conservation also requires time scales of tens of seconds to achieve the observed bulk heating in H^+. The downward shifts in lower hybrid frequency that were occasionally observed by several sounding rockets coupled with the few per cent variations in plasma density provides strong observational support that H^+ density perturbations play a role in the localization process.

Further work is needed to examine the role of H^+ in creating the observed wave localization events. Although ponderomotive collapse can not be ruled out, localization from ion kinetic effects is attractive because it can explain the large variation in wave amplitude and spectral shapes that are observed. A ray tracing analysis is needed to verify that wave trapping and refraction near H^+ density gradients can lead to enhanced H^+ heating. A fully kinetic simulation of the above process also may be possible.

Acknowledgments. The authors thank D.L. Newman, K.A. Lynch, and R. Boström for informative discussions. This research was supported by NASA grant NAG6-10.

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(received April 24, 1995; accepted May 23, 1995.)