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DE-1 and COSMOS 1809 observations of lower hybrid waves excited by VLF whistler mode waves

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Abstract. Past work demonstrates that strong lower hybrid (LH) waves can be excited by electromagnetic whistler mode waves throughout large regions of the topside ionosphere and magnetosphere. The effects of the excited LH waves upon the suprathermal ion population in the topside ionosphere and magnetosphere depend upon the distribution of LH wave amplitude with wavelength λ. The present work reports plasma wave data from the DE-1 and COSMOS 1809 spacecraft which suggests that the excited LH wave spectrum has components for which $\lambda \leq 3.5$ m when excitation occurs at a frequency roughly equal to the local lower hybrid resonance frequency. This wavelength limit is a factor of ~ 3 below that reported in past work and suggests that the excited LH waves can interact with suprathermal H^+ ions with energy ≤ 6 eV. This finding supports recent work concerning the heating of suprathermal ions above thunderstorm cells.

1. Introduction

This paper reports recent observations on the Cosmos 1809 and DE-1 spacecraft of lower hybrid waves (LH) excited by electromagnetic (EM) VLF whistler mode waves. Our work extends earlier work [*Bell et al.*, 1983; *Titova et al.*, 1984; *Tanaka et al.*, 1987; *James and Bell*, 1987; *Bell and Ngo*, 1988; 1990; *Bell et al.*, 1991a,b] by reporting LH waves of shorter wave length than previously reported. This is an important factor since only short wavelength LH waves can effectively heat suprathermal ions [*Lysak et al.*, 1980; *Chang and Coppi*, 1981; *Koskinen*, 1985; *Retterer et al.*, 1986; *Bell et al.*, 1991a,b].

Although other explanations have been proposed [*Titova et al.*, 1984; *Groves et al.*, 1988; *Trakhtengerts and Hayakawa*, 1993], the data strongly suggests that the LH waves are excited by a passive linear mode coupling mechanism as the EM waves are scattered by small scale magnetic-field-aligned plasma density irregularities [*Bell and Ngo*, 1988, 1990]. The necessary excitation conditions [*Bell and Ngo*, 1990] can be readily satisfied both at midlatitude and high latitude at altitudes up to two Earth radii.

In addition, in the topside ionosphere directly over thunderstorm cells, the intense EM pulses from lightning discharges may excite intense LH waves with broadband intensities of $(100\frac{\text{mV}}{\text{m}})^2$ or more [*Bell et al*, 1993]. If λ for these LH waves extends down to $\sim$4 m, suprathermal H^+ ions with energy $\geq$6 eV can be heated by 20 to 40 eV as a result of a single lightning discharge [*Bell et al*, 1993].

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2. Observations

Figure 1 presents VLF wave electric field data from the Linear Wave Receiver (LWR) on the DE-1 spacecraft [*Shawhan et al.*, 1981], received on the 9 m electric dipole antenna aligned along the spacecraft spin axis, and roughly perpendicular to the magnetic meridional plane and to the spacecraft velocity vector $\vec{V}_s$. The data consists of two sequential f-t spectrograms covering the range 8.5$\leq f \leq$12.5 kHz. During this period, the LWR instrument was measuring EM pulses of $\sim$1 sec duration injected into the magnetosphere from the Omega (Ω) VLF transmitter in Australia (38.5°S, 147°E, geographic) which emits fixed frequency pulses at 10.2, 11.05, 11.333, 13.0 and 13.6 kHz in a standard format [*Bell and Ngo*, 1988].

At the time shown, the LWR instrument was acquiring data in the 10-16 kHz frequency range. Each spectrogram shows three 'direct' Ω pulses detected sequentially at 11.05, 10.2, and 11.333 kHz. The small measured time delay of these pulses, $\sim$ 100 msec, indicates that they propagated from their ionospheric entry point along a $\sim$1600 km path directly to the spacecraft. In the upper panel the position of each of the three direct Ω pulses is indicated by a bracket parallel to the time axis. For example the first pulse at 11.05 kHz arrives at the 0.7 second mark and has a bullet-like form with a total bandwidth $\Delta\omega$ of $\sim$ 1 kHz.

Following the direct pulse at 11.05 kHz is an 'echo' of the direct signal reflected from the conjugate hemisphere and arriving after a propagation delay of $\sim$1.7 sec. As a result of multiple reflection between hemispheres the echo signal endures for at least 2.5 seconds. In both panels the direct pulse at 11.05 kHz appears near 0.7 sec, the direct pulse at 10.2 kHz appears near 4.5 sec, and the direct pulse at 11.333 kHz appears near 7 sec.

In the lower panel only the direct pulse at 10.2 kHz is indicated by a bracket. For this pulse $\Delta\omega \sim 1$ Hz, while for the five other direct Ω pulses $\Delta\omega \geq 1$ kHz. The large $\Delta\omega$ for these five Ω pulses is due to the Doppler shift $\Delta\omega_D$ of the short wavelength LH waves excited by the input Ω pulses where,

$$\Delta\omega_D = \vec{k}_{LH} \cdot \vec{V}_s \tag{1}$$

where $\vec{V}_s$ is the spacecraft velocity and $\vec{k}_{LH}$ is the wave vector of the excited LH wave.

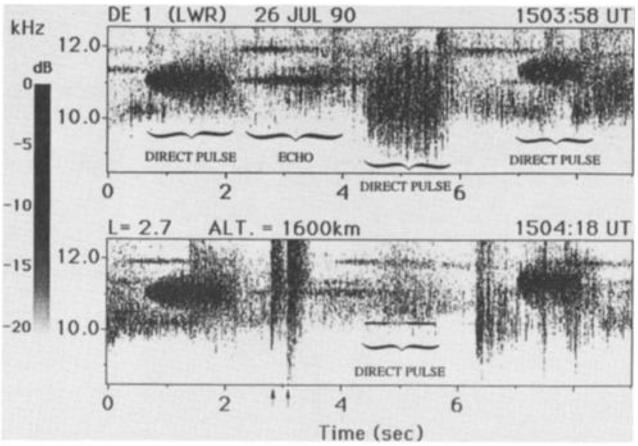

Figure 1. Spectrograms (8.5 to 12.5 kHz) of plasma wave data from the DE-1 spacecraft showing lower hybrid waves excited by electromagnetic whistler mode pulses from the Omega transmitter in Australia.

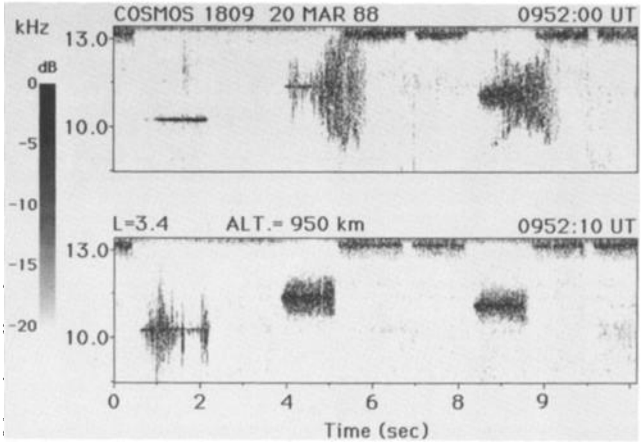

Figure 2. Spectrograms (9 to 13 kHz) of plasma wave data from the COSMOS 1809 spacecraft showing lower hybrid waves excited by electromagnetic whistler mode pulses from the Omega transmitter in North Dakota.

The six Ω pulses are located within, or near, the lower-hybrid-resonance noise band whose lower cut-off frequency near 10 kHz indicates the value of the local lower hybrid resonance frequency f_{LHR} [*Laaspere et al.*, 1971]. Due to locally changing plasma parameters f_{LHR} changes slowly with time. In the upper spectrogram $f \geq f_{LHR}$ for all three Ω pulses and each pulse is associated with intense LH waves of $\geq$ 1 kHz apparent bandwidth. In the lower spectrogram, the 10.2 kHz pulse lies below f_{LHR} and no LH waves are associated with this pulse. A remarkable feature of the 10.2 kHz pulse in the upper spectrogram in that $\Delta\omega$ is roughly twice that of the other two pulses. Furthermore the frequency of this pulse is very close to f_{LHR}.

The occurrence of enhanced $\Delta\omega$ when $f \sim f_{LHR}$ has been observed previously, but only with a relatively long electric dipole antenna (75 m) with very poor sensitivity to LH waves with $\lambda < 20$ m [*Bell et al.*, 1991*b*]. Thus to the best of our knowledge, the present paper reports the first observations with relatively short antennas of the LH wave spectrum excited by a fixed frequency EM pulse with $f \cong f_{LHR}$. In the case of Figure 1, because the receiver was in a bandpass mode with a lower cut-off at 10 kHz, the LH wave spectrum was attenuated in the receiver for $f < 10$ kHz. However, if we assume that the LH wave spectrum is symmetrically distributed about 10.2 kHz, (a behavior evident in the other pulses) we can use the observed spectrum for $f \geq 10.2$ kHz to reconstruct the entire pulse.

Figure 2 shows data acquired on the COSMOS 1809 spacecraft on 20 March 1988. At this time, observations were being made of ~1 sec. pulses from the Ω VLF transmitter in North Dakota (46°N, 98°W, geographic). The measured time delay of the pulses was ~ 100 msec, suggesting propagation directly to the spacecraft along a ~ 950 km path from the ground. The VLF receiver bandwidth was 0.1 to 22 kHz, with a dynamic range of 55 dB. The antenna was a double electric probe with two 15 cm diameter palladium coated spheres (with internal preamplifiers) separated by 2.5 m. The spacecraft was three axis stabilized in a nearly circular polar orbit at ~ 950 km altitude, with the double electric probe aligned perpendicular to the spacecraft velocity vector and roughly perpendicular to $\vec{B}_o(\pm 10°)$.

Each of the two spectrograms in Figure 2 shows three pulses (at 10.2, $11\frac{1}{3}$, and 11.05 kHz) as well as the Doppler shifted LH waves excited by these pulses (In addition, near 13 kHz are negatively Doppler shifted LH waves which were excited by Ω pulses at 13.1 kHz). Since no LH noise band was observed at this time, f_{LHR} could not be measured directly. However, f_{LHR} was calculated instead using local measurements of the plasma density, magnetic field, and ion composition. For the period shown in Figure 2, $f_{LHR} \cong 11$ kHz initially, and then slowly decreased with time as the spacecraft moved toward higher latitudes, reaching ~ 10 kHz at the end of the 20 second time period.

Thus the condition $f \cong f_{LHR}$ was satisfied for the 11.333 and 11.05 kHz pulses in the upper panel and the 10.2 kHz pulse in the second panel, consistent with the fact that $\Delta\omega$ for the LH waves is much larger for these pulses than, for example, for the 11.333 and 11.05 kHz pulses shown in the lower panel.

In both Figures 1 and 2, a number of pulses have a "bullet" or "chevron" shape in which the LH waves of largest $\Delta\omega_D$ exhibit the largest time delay [*Bell et al.*, 1983]. This temporal signature is believed to arise from a propagation effect in cases in which the LH wave excitation takes place at altitudes well below the observing point [*Bell et al.*, 1983; *Bell and Ngo*, 1990]. Thus there is reason to believe that most of the LH waves shown in Figures 1 and 2 were not locally generated but were excited over a range of altitudes below the spacecraft.

Figure 3a shows the average power spectral density (PSD), $I_V(\omega)$, of the antenna voltage induced by the LH waves excited by the 10.2 kHz pulse shown in the upper panel of Figure 1; Figure 3b shows $I_V(\omega)$ for the $11\frac{1}{3}$ kHz pulse shown in the upper panel of Figure 2, and Figure 3c shows $I_V(\omega)$ for the 10.2 kHz pulse in the lower panel of Figure 1. The PSD was calculated using a digital spectrum analyzer with a 4 Hz frequency resolution. Since Figure 3c concerns the 10.2 kHz pulse which did not excite LH waves (because $f < f_{LHR}$), a comparison with Figure 3a will indicate the apparent frequency range over which significant LH waves were excited by the 10.2 kHz pulse for which $f \cong f_{LHR}$. For $f > 10.2$ kHz, this comparison is complicated by the fact that both an echo signal at 11.05 kHz and a direct signal at 11.9 kHz excite LH waves which are received at the same time as the 10.2 kHz signal. Consequently there are peaks in the spectrum at 11.05 kHz and 11.9 kHz which represent excited LH waves not connected with the 10.2 kHz pulse, and the background noise level here cannot be readily

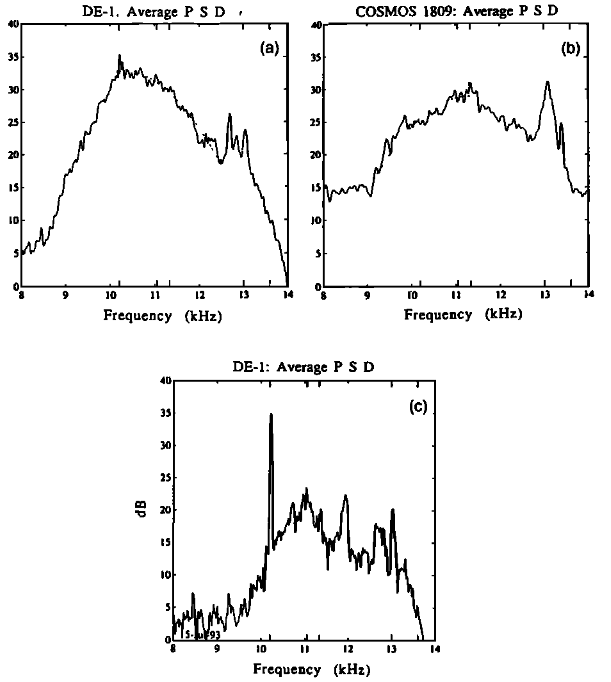

Figure 3. a) Power spectral density (PSD) of the antenna voltage signal induced by the 10.2 kHz pulse and associated lower hybrid waves shown in the upper panel of Figure 1. Marks on the frequency axis show the location of the input EM pulses at 10.2, 11.05, and $11\frac{1}{3}$ kHz; b) PSD of the signal induced by the $11\frac{1}{3}$ kHz pulse and associated lower hybrid waves shown in the upper panel of Figure 2. In each panel a Gaussian envelope (dashed lines) of minimum *rms* residual is fitted to the data; c) PSD of the signal induced by the 10.2 kHz pulse in the lower panel of Figure 1.

determined. However, making comparisons at frequencies between these peaks, we find that $I_v(\omega)$ exceeds the noise level by $\sim$ 15 dB at $f \sim 10.3$ kHz, by $\sim$ 7 dB at $f \sim 11.5$ kHz, and by $\sim$ 4 dB at $f \sim 12.2$ kHz. Thus we conclude that the LH wave intensity exceeds that of the noise level over the apparent frequency range: $\Delta f_D \leq 2$ kHz, where $\Delta f_D = |f - 10.2\text{ kHz}|$.

According to (1) the LH waves producing the largest values of Δf_D have: $\lambda_{LH} \cong \frac{1}{2} V_s \cos\beta \times 10^{-3}$ m, where β is the angle between $\vec{V}_s$ and $\vec{k}_{LH}$, and $\vec{V}_s$ is measured in units of m/sec. We can estimate an upper bound for the value of λ_{LH} consistent with the largest value of Δf_D by assuming that $\vec{k}_{LH}$ and $\vec{V}_s$ lie in the same plane (roughly the meridional plane) and that $\vec{k}_{LH}$ is closely perpendicular to $\vec{B}_o$. According to spacecraft ephemeris data for the period shown in Figure 1, $|V_s| \cong 9$ km/sec and $\beta \cong 43°$; thus $\lambda_{LH}^{UB} \cong 3.5$ m.

Figure 3b shows the $I_V(\omega)$ induced by the LH waves excited by the 11.333 kHz pulse shown in the upper panel of Figure 2. In this case the background noise level is $\sim$ 15 dB above the 0 dB reference level. For this case the LH wave intensity exceeds that of the noise level over the apparent frequency range: $|f - 11.333\text{kHz}| \leq 2$ kHz. Thus, the Doppler shift has a maximum value of $\Delta f_D \sim 2$ kHz. Again assuming for simplicity that $\vec{V}_s$ and $\vec{k}_{LH}$ lie in a meridional plane and that $\vec{k}_{LH} \perp \vec{B}_o$, we again find $\lambda_{LH}^{UB} \cong 3.5$ m. In contrast, the 11.333 and 11.05 kHz pulses shown in the lower panel of Figure 2 have $\Delta f_D \sim 600$ Hz and thus $\lambda_{LH}^{UB} \cong 12$ m here. Over the frequency range $|\Delta f_D| \leq 2$ kHz, the PSD shown in Figures 3a and 3b can be approximated by the curve $I_V(\omega) = I_o e^{-[\frac{f-f_o}{f_1}]^2}$, where I_o is a constant, and $f_1 = 1247$ Hz and $f_o = 10.2$ kHz for panel(a), and $f_1 = 1277$ Hz and $f_o = 11\frac{1}{3}$ kHz for panel(b).

In general if $I_{LH}(\vec{k}, \omega)$ is defined as the spectral intensity of the excited LH waves, it can be shown [*Temerin*, 1978; *Bell et al.*, 1991] that $I_V(\omega)$ is related to $I_{LH}(\vec{k}, \omega)$ through an integral equation:

$$I_V(\omega') = \frac{l^2}{2} \int R(\vec{k}) I_{LH}(\vec{k}, \omega_o) \delta(\omega' - \vec{k} \cdot \vec{V}_s) d\vec{k} \qquad (2)$$

where for the 9 m antenna on DE-1, $R_1(\vec{k}) = \frac{\cos^2\alpha}{4}(\sin\gamma/\gamma)^4$, and where for the 2.5 m antenna on COSMOS 1809, $R_2(\vec{k}) = \cos^2\alpha[\sin 2\gamma/2\gamma]^2$, where α is the angle between $\vec{k}$ and $\vec{l}$, $\gamma = \frac{1}{4}(\vec{k} \cdot \vec{l})$, $\vec{l}$ is directed along the antenna with magnitude equal to the antenna length, $\delta(\cdot)$ is the Dirac Delta function, $\omega' = \omega - \omega_o$, ω is the apparent frequency of the wave, and ω_o is the frequency of the input pulse. The expression for $R_1(\vec{k})$ is given in [*Gallagher,* 1985] and the expression for $R_2(\vec{k})$ is given in [*Temerin,* 1978]. Given that $I_V(\omega')$ is known and well behaved, the integral equation can be inverted to find I_{LH} [*James and Bell,* 1987].

To solve (2) to first order, the LH waves are assumed to be uniformly distributed around $\vec{B}_o$. Since in theory for $f \cong f_{LHR}$ the resonance cone half angle ψ_r is $\sim 90°$, we further simplify by setting $\psi_r = 90°$. The solution to (2) is then found to be:

$$I_{LH}(\vec{k}, \omega_{LHR}) \cong I_{LH_o}(k/k_o)^2 e^{-k^2/k_o^2} \qquad (3)$$

where I_{LH_o} is a constant and $k_o = 1.3$/m. $I_{LH}(\vec{k}, \omega)$ peaks at $k = k_o$, where $\lambda_o = 2\pi/k_o = 4.8$ m. The -10 dB points for $I_{LH}(\vec{k}, \omega_{LHR})$ occur at $k \cong 0.2k_o$ and $k \cong 2.2k_o$. Thus (3) predicts significant LH wave intensity over the wavelength range: 2.2 m$\leq \lambda_{LH} \leq 24$ m. However it should be noted that according to (2) the antenna voltage induced by LH waves with 3.5 m$\geq \lambda_{LH} \geq$2.2 m is at, or below, the noise level produced in the antenna by background plasma waves. Thus the existence of LH waves in this wavelength range may be open to question.

3. Discussion

Presumably the minimum value of λ_{LH} is determined by warm plasma effects near the altitude of the spacecraft since collisions between the plasma constituents are rare. It is of interest to compare the value $\lambda_{LH} = 3.5$ m with the local gyroradius ρ_p of thermal protons during the observations. Using ephemeris data on spacecraft position and assuming a centered dipole model of the Earth's magnetic field, the local proton gyrofrequency f_{HP} was found to be $f_{HP} \cong 400$ Hz for the DE-1 spacecraft and $f_{HP} \cong 500$ Hz for the COSMOS 1809 spacecraft. If we assume a thermal proton temperature of 1500° K, we find $\rho_p \cong 2$ m for the DE-1 case and $\rho_p \cong 1.6$ m for the COSMOS 1809 case. Thus in both cases the wavelengths of the excited LH waves may all have been larger than the local proton gyroradius.

Although the investigation of warm plasma effects is beyond the scope of the present paper, we note that *Kintner et al* [1992] have calculated $k_\perp^{LH}$ for various values of $k_\parallel^{LH}$ in the electrostatic approximation for applications to the auroral ionosphere near 1000 km altitude. For example Figure 2 of *Kintner et al* [1992] shows that for $f \cong f_{LHR}$ and $k_{\parallel}^{LH} \cong 6 \times 10^{-3}$ m^{-1}, the maximum value of $k_{\perp}^{LH}$ is $\cong 2\pi/\rho_p$. This suggests that the minimum value of λ_{LH} may be $\sim \rho_p$ for $f \cong f_{LHR}$, and lends support to the model (3) which predicts a significant LH wave intensity for $\lambda_{LH} \cong 2.2$ m.

To first order, the excited LH wave spectra shown in figures 1, 2, and 3 can interact with suprathermal ions through a transverse Landau resonance [*Lysak et al.*, 1980; *Chang and Coppi*, 1981] with:

$$v_{\perp} \cong \omega/k_{\perp} \cong f\lambda_{LH} \tag{4}$$

where $v_{\perp}$ is the ion velocity perpendicular to $\vec{B}_o$, and the last relation follows because $\vec{k}$ and $\vec{B}_o$ are nearly perpendicular over the frequency range shown in the Figures.

In general the amplitude of the excited LH waves is proportional to the amplitude of the whistler mode wave which excited them. Thus we can expect that in the case of lightning generated whistlers the excited LH waves would be most intense in the top side ionosphere almost directly over the lightning discharge which produces the whistler [*Bell et al.*, 1993].

From (4) we can calculate the minimum energy necessary for an ion to be heated by the LH waves shown in the Figures. Taking $f \cong f_{LHR} \cong 10$ kHz and $\lambda_{LH} \cong 3.5$ m we find $v_{\perp} \cong 35$ km/sec. A proton with this velocity would have an energy $\epsilon \cong 6$ eV. Since this value is approximately 30 times the mean thermal energy of 0.2 eV (assuming a Maxwellian distribution with T= 1500°K), it can be anticipated that only a very small fraction of the ions would possess the necessary energy for interaction with the LH waves. However, this situation would change markedly if the ion distribution has a non-Maxwellian high energy tail due to some additional heating mechanism. For example protons in the topside ionosphere over thunderstorm cells with $\epsilon \sim 1$ eV can be heated to ~ 6 eV through gyroresonance with proton whistlers [*Bell et al.*, 1993] and this process can form a high energy tail in which 6 eV protons are much more abundant.

It is worthy of note that the envelopes of the spectral intensity of the excited LH waves in Figure 3a and 3b are almost identical, i.e., $I(\omega) \propto e^{-[\frac{f-f_o}{f_1}]^2}$, where $f_1 \cong 1260$ Hz. This suggests that this distribution may be typical for $f \approx f_{LHR}$.

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