CLUSTER observations of lower hybrid waves excited at high altitudes by electromagnetic whistler mode signals from the HAARP facility

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[1] We report new observations from the CLUSTER spacecraft of strong excitation of lower hybrid (LH) waves by electromagnetic (EM) whistler mode waves at altitudes ≥20,000 km outside the plasmasphere. Previous observations of this phenomenon occurred at altitudes ≤7000 km. The excitation mechanism appears to be linear mode coupling in the presence of small scale plasma density irregularities. These observations provide strong evidence that EM whistler mode waves are continuously transformed into LH waves as the whistler mode waves propagate at high altitudes beyond $L \sim 4$. This may explain the lack of lightning generated whistlers observed in this same region of space. *INDEX TERMS:* 0689 Electromagnetics: Wave propagation (4275); 0654 Electromagnetics: Plasmas; 2772 Magnetospheric Physics: Plasma waves and instabilities; 2778 Magnetospheric Physics: Ring current; 6984 Radio Science: Waves in plasma. **Citation:** Bell, T. F., U. S. Inan, M. Platino, J. S. Pickett, P. A. Kossey, and E. J. Kennedy (2004), CLUSTER observations of lower hybrid waves excited at high altitudes by electromagnetic whistler mode signals from the HAARP facility, *Geophys. Res. Lett.*, *31*, L06811, doi:10.1029/2003GL018855.

1. Introduction

[2] This paper reports recent observations on the CLUSTER spacecraft of LH waves excited by EM ELF/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; *Groves et al.*, 1988; *Bell et al.*, 1991a, 1991b, 1994] by reporting strong LH wave excitation at altitudes ≥20,000 km, much higher than previously explored. Our work shows that EM VLF whistler mode waves propagating in regions outside the plasmasphere are continuously transformed into LH waves in regions containing plasma density irregularities. This process may represent the major propagation loss for EM whistler mode waves in these regions, and may explain the lack of lightning generated whistlers observed there [*Platino et al.*, 2002]. The CLUSTER data strongly supports the idea that the LH waves are excited through linear mode coupling as the EM waves are scattered by small scale magnetic-field-aligned plasma density irregularities [*Bell and Ngo*, 1988, 1990]. The necessary conditions for excitation can be readily satisfied at the altitudes of interest. The excited LH waves represent a plasma wave population which can resonate with energetic ring current protons to produce pitch angle scattering on magnetic shells beyond $L \sim 4$. Thus linear mode coupling provides a new mechanism by which lightning generated whistler mode waves can affect the lifetimes of energetic ring current protons.

2. Observations

[3] The data reported here were acquired by the CLUSTER Wide-Band Plasma Wave Instrument [*Gurnett et al.*, 1997] during a recent campaign involving a high power HF heater at Gakona, Alaska, and the four CLUSTER spacecraft. The HF heater is operated by the High Frequency Active Auroral Research Program (HAARP) in Gakona. When the CLUSTER spacecraft are in the northern hemisphere on magnetic field lines whose foot print is within ~500 km of the HAARP facility, the HAARP HF heater modulates the auroral electrojet currents overhead at a series of fixed ELF/VLF frequencies. The modulated currents radiate EM waves which propagate through the ionosphere and enter the magnetosphere, where they are observed on CLUSTER at altitudes ≥20,000 km. Figure 1 shows a ray tracing simulation of typical propagation paths of the HAARP signals from the ground to the spacecraft location.

[4] Figure 2 is a frequency-time spectrogram of plasma wave data acquired on the CLUSTER 3 spacecraft on May 11, 2003, during the period 0637:52–0638:00 UT. This data is typical of that recorded during the period 0635–0645 UT. The data were acquired using an 88 m electric antenna. The spectrogram shows two sequences of ELF/VLF pulses generated by the HAARP HF heater. The pulses are of 0.5 s duration and produced sequentially at HAARP at the fixed frequencies: 1068, 1265, 1575, 2225, 2875, 3125, 3375, and 4375 Hz. The pulses are generated at each 0.5 s mark, and the complete sequence occupies a total time of 4 s. At the location of CLUSTER 3 at this time all pulses are observed with the exception of the pulses at 1068 Hz. The time delay from HAARP to CLUSTER 3 for each pulse is frequency dependent and lies in the range 100–200 ms. The ELF/VLF pulses produced by HAARP are fixed in frequency and possess an intrinsic bandwidth of ~2 Hz, as verified by ground observations at distances of 30–140 km from HAARP. However it can be seen that the received signals have an apparent bandwidth of 30–400 Hz, roughly centered around each nominal pulse frequency.

[5] Figure 3 shows a high resolution plot of spectral intensity vs frequency for the first ~1575 Hz pulse group shown in Figure 1. From the plot is clear that the relatively large bandwidth of the pulses in Figure 2 is due to the

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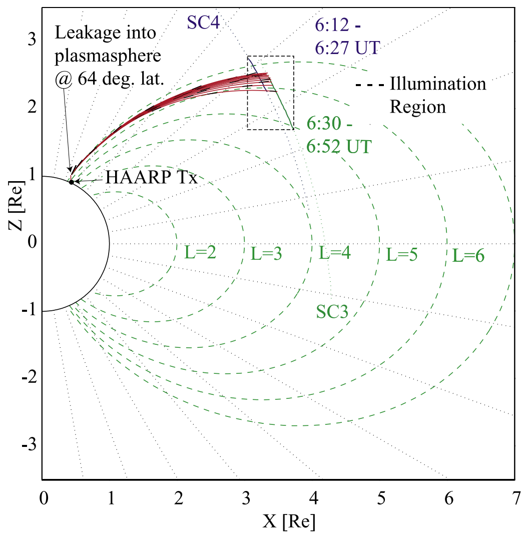

Figure 1. Raytracing simulation of the propagation path of HAARP-generated ELF/VLF signals from the ground up to the CLUSTER 3 and 4 spacecraft.

presence of a number of narrow intensity maxima of ~8 Hz bandwidth which are separated by ~25 Hz. The maximum of highest intensity is centered near 1575 Hz, the frequency of the HAARP input pulse. We refer to the waves which accompany the HAARP pulses as "sideband" waves, except for those which lie within the expected bandwidth of the HAARP pulse: 1575 ± 1 Hz. We refer to the narrow intensity maxima as sideband groups. Data from the Fluxgate Magnetometer instrument [*Balogh et al.*, 2001] indicates that the electric antenna lay in a plane which was nearly parallel to the Earth's magnetic field $\mathbf{B_o}$ but which was perpendicular to the local magnetic meridional plane. Thus twice per spin period (~4 s) the antenna was ~ parallel to $\mathbf{B_o}$, and twice, perpendicular to $\mathbf{B_o}$. In general the sideband waves are most intense and the largest number of sideband waves are detectable when $\theta \sim \pi/2$, where θ is the angle between $\mathbf{B_o}$ and the spacecraft electric antenna. The smallest number of sideband waves are detectable when $\theta \sim 0$, suggesting that the electric field $\mathbf{E}$ for these waves is approximately perpendicular to $\mathbf{B_o}$.

[6] In Figure 3 the sideband group of highest intensity is centered at 1569 Hz. We assume that this sideband group contains the input HAARP signal. Raytracing simulations as shown in Figure 1 suggest that the Doppler shift of the input 1575 Hz HAARP signal would be less than the nominal bandwidth of ~2 Hz for the 0.5 s signal. Taking the signal intensity per Hz at 1575 Hz from Figure 3 and multiplying by 2 Hz we estimate the intensity of the input HAARP signal to be $\sim 2\ \mu V^2/m^2$. This value can be contrasted with the total intensity of this sideband group which is $\sim 10^2\ \mu V^2/m^2$. Thus the input signal appears to have produced additional waves whose E field intensity exceeds that of the input signal by ~20 dB. However, this result does not necessarily imply any amplification process, since LH waves generally have very small magnetic fields, and thus carry relatively little wave energy.

[7] HAARP signals and associated sideband waves similar to those shown in Figure 2 were also observed in the same region of space by CLUSTER 4 about 15 minutes prior to the CLUSTER 3 observations. According to data from the WHISPER instruments [*Décréau et al.*, 1997] on both spacecraft, the plasma density distribution in the region was irregular over scales of ~100 km. This suggests that small scale (10–100 m) plasma density irregularities may also have been present.

3. Model

[8] The sideband waves in Figure 2 appear to be LH waves generated through linear mode coupling in the presence of small scale plasma density irregularities. To

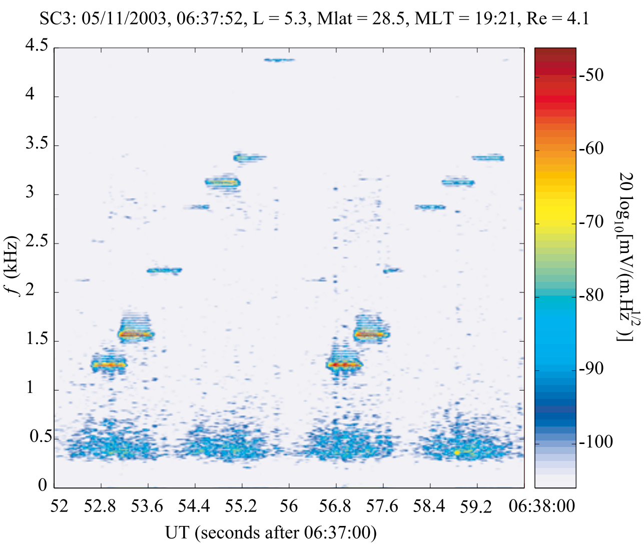

Figure 2. Frequency-time spectrogram of CLUSTER 3 plasma wave data showing HAARP-generated ELF/VLF fixed frequency pulses and associated sideband waves.

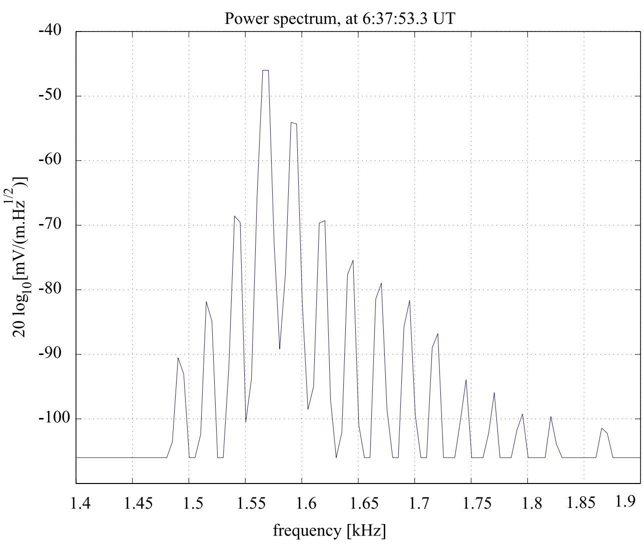

Figure 3. Spectral intensity of a 1575 Hz pulse and associated sideband waves at 0637:53.3 UT.

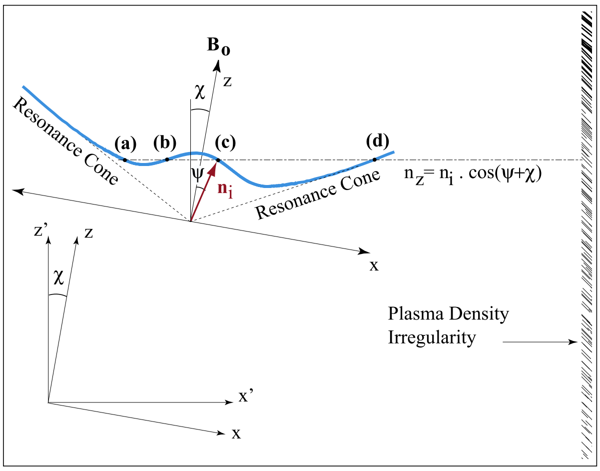

Figure 4. Refractive index surface for whistler mode wave encountering a planar plasma density irregularity.

test the hypothesis we compare model predictions with observations.

3.1. Antenna Response

[9] The CLUSTER spacecraft plasma wave electric field sensors consist of two orthogonal spherical electric antennas in the spin plane of the spacecraft. The spherical antennas have sphere-to-sphere separations of 88 m.

[10] The response of spherical electric antennas to LH waves has been investigated [*Temerin*, 1978; *Bell et al.*, 1991a, 1991b, 1994]. If $I_{LH}(\mathbf{k}, \omega_{\rm in})$ is defined as the spectral intensity of the electric field of the lower hybrid waves, it can be shown [*Temerin*, 1978; *Bell et al.*, 1991a] that the electric field intensity, $I_V(\omega)$, measured on a spherical electric antenna is related to $I_{LH}(\mathbf{k}, \omega_{in})$ through the integral equation:

$$I_V(\omega') = \frac{l^2}{2}\int R(\mathbf{k}) I_{LH}(\mathbf{k}, \omega_{in})\delta(\omega' - \mathbf{k}\cdot\mathbf{v_s})d\mathbf{k} \qquad (1)$$

where $\mathbf{k}$ is the wave vector, $R(\mathbf{k}) = \cos^2\beta[\sin 2\zeta/2\zeta]^2$, β is the angle between $\mathbf{k}$ and $\mathbf{l}$, $\mathbf{l}$ is a vector directed along the antenna with magnitude l, l is the antenna length, $\zeta = \mathbf{k}\cdot\mathbf{l}/4$, $\delta(x)$ is the Dirac delta function, $\omega' = \omega - \omega_{in}$, ω is the apparent frequency of the wave, ω_{in} is the actual frequency of the input signal, and $\mathbf{v_s}$ is the spacecraft velocity vector.

[11] If the sideband waves of Figure 2 are LH waves locally generated through linear mode coupling at the surface of a $\mathbf{B_o}$-aligned plasma density irregularity, their wave vectors $\mathbf{k}$ will be ~ perpendicular to this surface and to $\mathbf{B_o}$ [*Bell and Ngo*, 1990]. For simplicity we assume that the local irregularity surface is approximately parallel to the magnetic meridional plane. In this case when $\mathbf{l} \perp \mathbf{B_o}$ equation (1) becomes:

$$I_V(\omega') = \frac{l^2}{2}\left[\sin\left(\frac{\omega' l}{2v_{sx}}\right)/\left(\frac{\omega' l}{2v_{sx}}\right)\right]^2 I_{LH}\left(\frac{\omega'}{v_{sx}}, \omega_{in}\right) \qquad (2)$$

where v_{sx} is the component of the spacecraft velocity perpendicular to the magnetic meridional plane. It is clear from equation (2) that, aside from any null values inherent in $I_{LH}(\omega'/v_{sx}, \omega_{in})$, $I_v(\omega')$ will have a null value when $\omega' l/2v_{sx} = n\pi$, where $|n| = 1, 2, 3$, etc. The value of v_{sx} was 2.5 km/s at the time the pulses in Figure 2 were observed. Thus we find for the distribution of nulls: $f' = \omega'/2\pi = 28\ n$ Hz, which is similar to that seen in the LH wave spectrum shown in Figures 2 and 3. This type of antenna response gives the impression that the LH waves appear as distinct sideband wave groups when in fact the distribution of these waves can be quite smooth. For example, when a short electric antenna is used for detection, it is generally found that the excited LH wave spectrum varies smoothly with wavelength [*Bell et al.*, 1991a, 1991b, 1994].

3.2. Landau Damping

[12] We wish to estimate the expected Landau damping of the LH waves to determine if they are locally generated. The maximum Doppler shift of the LH waves excited by the 1.575 kHz HAARP pulses in Figure 2 is: $\mathbf{k_r}\cdot\mathbf{v_s}/2\pi \sim 250$ Hz, where $\mathbf{k_r}$ is the real part of $\mathbf{k}$ for the LH wave. Since v_s is ~4 km/s, the minimum magnitude of $\mathbf{k_r}$ is $k_r \sim 0.4$/m, corresponding to a wavelength of $\lambda \sim 16$ m. The local thermal protons, assumed to be at a temperature of 2000°K, have a gyroradius of $r_{gh} \sim 120$ m. Thus $\lambda \ll r_{gh}$ and we can consider the protons to be unmagnetized [*Stix*, 1992, chap. 15]. Furthermore for the HAARP pulses, $\omega^2 \ll \omega_{he}^2$, where ω_{he} is the electron gyrofrequency. In this case if the electron temperature parallel and perpendicular to $\mathbf{B_o}$ is the same, the well known quasi-electrostatic warm plasma dispersion relation [*Stix*, 1962, p. 225] can be written:

$$\eta\left(k_x^2 + k_z^2\right) + k_t^2\left[1 - \alpha e^{-\gamma} I_o(\gamma)\left(2S(\alpha) - i\sqrt{\pi}e^{-\alpha^2}\right)\right] = 0, \quad (3)$$

where k_z is the component of $\mathbf{k}$ along $\mathbf{B_o}$, k_x is the component of $\mathbf{k}$ perpendicular to $\mathbf{B_o}$, $k_t = \omega_{oe}/v_{tz}$, $\eta = 1 - \frac{\omega_{oi}^2}{\omega^2}$, ω is the angular frequency of the LH wave, ω_{oe} is the electron angular plasma frequency, ω_{oi} is the ion angular plasma frequency, $\gamma = \frac{1}{2}(k_x v_{t\perp}/\omega_{he})^2$, $v_{t\perp}$ is the rms thermal velocity of the electrons perpendicular to $\mathbf{B_o}$, v_{tz} is the rms thermal velocity of the electrons parallel to $\mathbf{B_o}$, $\alpha = \omega/\sqrt{2}k_z v_{tz}$, $I_o(y)$ is the hyperbolic Bessel function of zero order and argument y, and $S(y) = e^{-y^2}\int_0^y e^{t^2}dt$.

[13] In the linear mode coupling model [*Bell and Ngo*, 1990], the wave number of the LH waves excited by the input EM whistler mode waves depends on ω, $\omega_{oe,i}$, and $\omega_{he,i}$, as well as ψ_w, the wave normal angle of the input whistler mode wave with respect to $\mathbf{B_o}$, and χ, the angle at which the planar irregularity is inclined with respect to $\mathbf{B_o}$. The geometry of the system is illustrated in Figure 4, which shows the refractive index surface (blue) for an input EM whistler mode wave which encounters a planar plasma density irregularity. The irregularity is assumed to be parallel to the y' and z' axes and $\mathbf{B_o}$ lies in the x', z' plane. The component of the refractive index parallel to the surface of the irregularity is $n_{z'} = n_i(\psi)\cos(\psi + \chi)$, where $n_i(\psi)$ is the refractive index of the input wave. By Snell's law, $n_{z'}$ must be the same for the input wave and all reflected and transmitted waves. If we draw the level line: $n_{z'}$ = constant, we see from the refractive index surface that there are four possible solutions, (a), (b), (c), and (d). Solutions (c) and (b) represent the input EM wave and a reflected EM wave. Solutions (a) and (d) represent

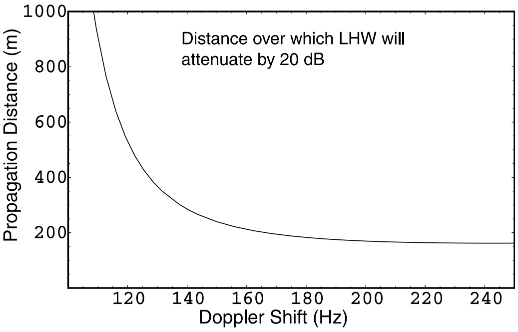

Figure 5. Distance over which lower hybrid waves will attenuate by 20 dB.

reflected and transmitted LH waves. Because of the tilt of the irregularity with respect to $\mathbf{B_o}$, one of the excited LH waves has a larger refractive index. This larger value is necessary in order to achieve Doppler shifts equal to those observed.

[14] For calculations, we transform into the coordinate system (x, y, z) in which the z axis is aligned along $\mathbf{B_o}$ and the y axis is parallel to the planar irregularity. The transformation of $n_{z'}$ into the (x, y, z) coordinate system yields:

$$k_{z'} = k_{inz'} = k_z \cos\chi - k_x \sin\chi \quad (4)$$

where $k_{z'} = \omega n_{z'}/c$, and k_z and k_x are the components shown in equation (3). With equation (4), we can eliminate the variable k_z from equation (3) and determine the effects of Landau damping on LH waves with a given value for k_{xr}, the real part of k_x. Since the angle χ in equation (4) is not known a priori, it will also be a variable. Since χ must be real, from equation (4) the imaginary parts of k_x and k_z must satisfy the relation: $k_{zi}\cos\chi = k_{xi}\sin\chi$. The solution of equation (3), with k_z eliminated using equation (4), proceeds by picking a value for χ (χ_o) and then solving equation (3) for $k_{xr} = k_{xro}$ with the Landau damping term set to zero. With the origin of the complex k_x space set at $k_{xr} - ik_{xi} = k_{xro}$ we scan the complex plane in the vicinity of the origin to find solutions to equation (3), i.e., those values of k_x for which both the real and imaginary parts of equation (3) were smaller than 10^{-3}. In most cases a single solution was obtained. When multiple solutions were found, the least damped mode was chosen. The value of $k_{inz'}$ in equation (4) was estimated through a raytracing simulation to be: $1.5 \cdot 10^{-4}$/m for the 1.575 kHz pulses.

[15] Figure 5 shows the results of the Landau damping calculations. The vertical axis shows the distance that a LH wave of 1.575 kHz frequency and wave number k_{xr} can propagate before being damped by 20 dB. The horizontal axis shows the maximum Doppler shift that would be measured on the moving spacecraft, assuming $\delta_D = k_{xr} v_{sx}$. LH waves with Doppler shifts of 150 Hz or more can propagate only a few hundred meters before being absorbed by the thermal electrons. This result suggests that the LH waves associated with the largest Doppler shifts in Figure 2 are locally generated.

4. Discussion

[16] The CLUSTER observations represent the first reported observations of the excitation of short wavelength LH waves at high altitudes ($\geq$20,000 km) outside the plasmasphere by fixed frequency EM whistler mode waves propagating in the presence of plasma density irregularities. It is reasonable to conclude that other EM whistler mode waves, such as lightning generated whistlers, will also excite LH waves in this region. In this case the mode coupling results in an effective damping of the input EM wave as the EM wave energy is continually transferred to the LH waves. This energy loss may be the main reason for the lack of lightning generated whistlers at high altitudes outside the plasmasphere [*Platino et al.*, 2002].

[17] The coupling of EM whistler mode wave energy into LH waves beyond $L = 4$ may play a role in the dynamics of ring current protons through pitch angle scattering during gyroresonance and Landau resonance interactions, where $\omega - k_{\parallel} v_{p\parallel} = n\omega_{hp}$, where ω is the LH wave frequency, $v_{p\parallel}$ is the proton velocity parallel to $\mathbf{B_o}$, ω_{hp} is the proton gyrofrequency, and $|n| = 0, 1, 2$, etc. In addition LH waves with wavelengths smaller than the gyroradius of the energetic protons can interact with these protons through the transverse Landau resonance, for which: $\omega \sim k_{\perp} v_{p\perp}$, where $v_{p\perp}$ is the proton velocity perpendicular to $\mathbf{B_o}$. For example, LH waves with $\omega \sim 3$ kHz and wavelengths between 300–2000 m would resonate with and cause pitch angle scattering of ring current protons of energy $\sim$1–20 keV. Further high altitude CLUSTER observations of LH wave excitation by EM whistler mode waves will provide a means of estimating how important this pitch angle scattering may be.

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