

DE-1 OBSERVATIONS OF LOWER HYBRID WAVES EXCITED BY VLF WHISTLER MODE WAVES

T.F. Bell, U.S. Inan, V.S. Sonwalkar, and R.A. Helliwell

Space, Telecommunications and Radioscience Laboratory, Stanford University Stanford, CA 94305

Abstract. Recent satellite data show high amplitude lower hybrid (LH) waves excited by electromagnetic (EM) whistler mode waves throughout magnetospheric regions where small scale magnetic-field-aligned plasma density irregularities exist. One important consequence in the auroral acceleration region is the heating of suprathermal ions by the excited LH waves. To evaluate such heating it is necessary to know the wavelength (λ) range of the waves, information not previously available since most past observations were made with long ($l \geq 75$; l =antenna length) electric dipole antennas which have very poor response for $\lambda < l$. New observations using the short 9 m electric dipole antenna on the DE-1 spacecraft show that LH waves with $\lambda \leq 10$ m are excited by EM input waves from ground-based VLF transmitters. Sequential observations on the short (9 m) and long (200 m) dipole antennas show that the long antenna generally has no measurable response to LH waves with $\lambda \leq 26$ m. Since most previous correlative observations of LH waves and ion conics in the low altitude auroral acceleration region have involved long electric antennas, it is suggested that the intensity of the LH waves in this region may have been seriously underestimated.

1. Introduction

One of several commonly accepted mechanisms for the creation of ion conics in the auroral regions is heating by lower hybrid (LH) waves, although the origin of these waves remains unclear [Lysak *et al.*, 1980; Chang and Coppi, 1981; Koskinen, 1985; Retterer *et al.*, 1986]. While it has been proposed that LH waves arise from either a drift instability or a beam driven instability [Chang and Coppi, 1981; Koskinen, 1985], the resulting wavelengths may not be small enough to effectively heat the ions [Retterer *et al.*, 1986]. An additional source of LH waves is their excitation throughout large regions of the ionosphere and magnetosphere by ordinary electromagnetic (EM) VLF whistler-mode waves, both of natural and man-made origin. [Bell *et al.*, 1983; Titova *et al.*, 1984; Tanaka *et al.*, 1984, 1987; Inan and Bell, 1985; James and Bell, 1987; Bell and Ngo, 1988; 1990]. Since the LH wave amplitude can at times exceed that of the input EM waves by as much as 30 dB [Bell *et al.*, 1983; Bell and Ngo, 1990], this phenomenon can play an important part in wave-particle interactions in the ionosphere and magnetosphere.

Although other explanations have been proposed [Titova *et al.*, 1984; Groves *et al.*, 1988], we believe the LH waves are excited by passive linear mode coupling as the EM waves are scattered by small scale magnetic-field-aligned plasma density irregularities [Bell and Ngo, 1988, 1990]. In this model, the LH waves are quasi-electrostatic whistler-mode waves with

wave vector \vec{k}_{LH} on the resonance cone, inclined a few degrees from perpendicular to the earth's magnetic field, \vec{B}_0 .

In the linear mode conversion model, for planar irregularities, high amplitude LH waves are excited whenever $f_{LHR} \leq f \ll f_{He}$, and:

$$\lambda N^{-1} \frac{dN}{ds} \geq 1 \quad (1)$$

where f and λ are respectively the frequency and wavelength of the EM whistler mode wave, f_{LHR} is the lower hybrid resonance frequency, f_{He} is the electron gyrofrequency, N is the thermal plasma density and s is the direction perpendicular to both \vec{B}_0 and the planar irregularities. When (1) holds, the WKB approximation fails for the EM wave and strong mode coupling occurs with the LH waves.

Within the plasmasphere (1) is readily satisfied for small scale magnetic-field-aligned irregularities. For example, a 5% density fluctuation occurring over a distance of 50 m gives $N^{-1} dN/ds \sim 10^{-3} \text{m}^{-1}$, whereas typical values for the whistler mode wavelength are $\lambda \sim 1 - 3$ km. It can also be readily satisfied in the auroral regions where large gradients in N are known to commonly coexist with a significant background spectrum of EM whistler mode waves [Jorgensen, 1968; Laaspere, 1971; Gurnett and Frank, 1972] acting as the input energy source for exciting the LH waves.

Wavelength spectrum measurements of LH waves are needed to test the excitation mechanisms proposed for these waves and to calculate their effects upon the suprathermal ion population. The present paper reports new data from the Linear Wave Receiver on the DE-1 satellite [Shawhan *et al.*, 1981] showing for the first time the wide range of λ for the LH waves excited by EM whistler mode waves. These observations use both the long (200 m) and short (9 m) dipole antennas, as well as the magnetic loop antenna and were carried out in January, 1989, and July, 1990. The source of input EM waves were the Omega transmitters in North Dakota (46°N, 98°W, geographic) and Australia (38.5°S, 147°E) which transmit fixed frequency pulses of roughly 1 s duration at 10.2, 11.05, 11.333, 13.0 (Australia only), 13.1 (North Dakota only) and 13.6 kHz [Bell *et al.*, 1983; Bell and Ngo, 1988].

As demonstrated previously [Bell *et al.*, 1983; James and Bell, 1987; Bell and Ngo, 1988; 1990] the apparent frequency bandwidth of LH waves excited by fixed frequency EM signals is produced by the Doppler shift of the LH waves according to the well known relation:

$$\Delta\omega_D = \vec{k}_{LH} \cdot \vec{V}_s \quad (2)$$

where \vec{V}_s is the spacecraft velocity. In this model, the shortest wavelengths will be produced when $\omega \sim \omega_{LHR}$, since k_{LH} is then largest. On DE-1 this condition was achieved in January 1989 and July 1990. We focus on data from one day during each period, January 2, 1989, and July 20, 1990.

2. Observations

Figure 1 shows a magnetic meridional projection of the DE-1 satellite orbit on January 2, 1989, and July 20, 1990. Excited LH waves were observed at altitudes as low as 900 km, and λ values at least as small as 10 m were measured. On January 2, 1989, LH waves excited by Omega transmitter pulses were observed continuously over an 18 minute period as DE-1 moved from the outer edge of the inner radiation belt toward higher latitudes. At higher altitudes (>3000 km) observations with both the short (E_x) and long (E_z) electric antennas were similar to those reported on the ISEE-1 satellite [Bell and Ngo, 1988]. However at lower altitudes significant differences were observed in the data acquired using the E_x and E_z antennas, as shown in Figure 2. The spectra shown were obtained in a toggle mode in which data from the E_x antenna, the magnetic antenna, and the E_z were sampled sequentially for 30 s each. The difference in response of the two electric antennas is discussed in the Appendix.

The upper and lower panels respectively show data from the two antennas obtained within 70 s. Pulses of ~ 1 s duration from the Omega transmitter in North Dakota are present at 10.2 kHz, 11.05 kHz and 11.333 kHz. For instance, in the upper panel, direct pulses appear near 1 s at 11.05 kHz, near 4.5 s at 10.2 kHz and 7 s at 11.333 kHz. These pulses have propagated from the ground along a ~ 2000 km path directly to the spacecraft. Following the direct pulses are echoes of the direct signals reflected from the conjugate hemisphere with a delay of ~ 2 s. In the lower panel direct pulses appear near 5 s at 10.2 kHz, near 8 s at 11.333 kHz, and near 1 s at 11.05 kHz. In both panels the apparent bandwidth ($\Delta\omega_A$) of the direct pulses is larger than 100 Hz, ~ 100 times the 1 Hz bandwidth of the transmitted pulses. This effect is due to the Doppler shift of the short wavelength LH waves excited by the transmitter pulses [Bell et al., 1983, Bell and Ngo, 1988]. Note that $\Delta\omega_A$ for the 10.2 kHz pulse observed with the E_x antenna is roughly twice that of the 10.2 kHz pulse observed with the E_z antenna.

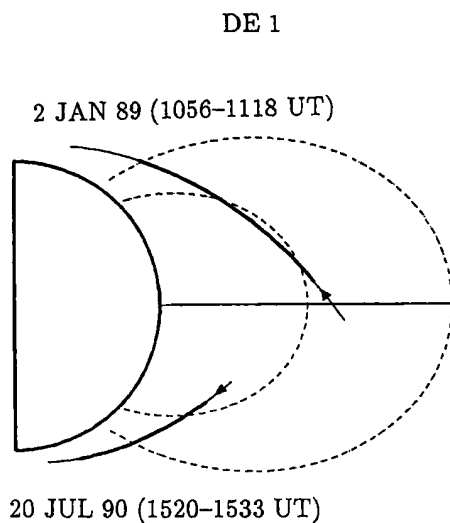


Fig. 1. Magnetic meridional plane projections of DE-1 satellite orbits on 2 January 1989, and 30 July, 1990. Heavier lined portions of the orbits indicate locations where lower hybrid waves were excited by electromagnetic whistler mode waves.

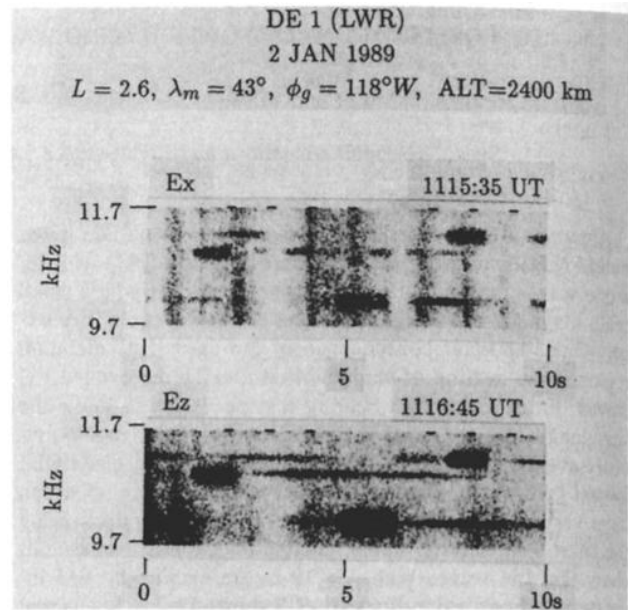


Fig. 2. Observations of lower hybrid waves excited by signals from the Omega (ND) transmitter. The top and bottom panels respectively show reception by the E_x and E_z antennas. The E_x antenna consists of two 100 m wires deployed in the spin plane. The E_z antenna consists of two 4 m tubes deployed along spin axis.

The distribution of power with apparent frequency for the two 10.2 kHz pulses is shown in Figure 3. The left hand panel shows the dynamic power spectral density (DPSD) as observed on the E_x antenna while the right hand panel shows the DPSD observed on the E_z antenna. These measurements concern different pulses and are not simultaneous. The DPSD was sampled every 50 ms using a digital spectrum analyzer with 4 Hz frequency resolution. The average antenna voltage induced by the wave spectrum shown was $V \sim 2$ mV for the E_x antenna and ~ 0.5 mV for the E_z antenna.

In the E_x data the LH amplitude exceeds the noise level over the apparent frequency range, $\Delta f = |f - f_0| \leq 400$ Hz, where $f_0 = 10.2$ kHz. According to (2) the LH waves producing the largest value of Δf have:

$$\lambda_{LH} = \frac{V_s \cos \beta}{400} \text{ m} \quad (3)$$

where β is the angle between \vec{V}_s and \vec{k}_{LH} and V_s is measured in units of m/sec. The largest value of λ_{LH} can be estimated by noting that observations [Bell et al., 1983; James and Bell, 1987] indicate that \vec{k} is located on the whistler-mode resonance cone [Stix, 1962], which theoretically was \sim perpendicular to \vec{B}_0 . Since the angle between \vec{V}_s and \vec{B}_0 was $\sim 40^\circ$ at 1116 UT according to spacecraft ephemeris data, then $\beta \geq 50^\circ$ at this time. Assuming $\beta = 50^\circ$ and using $V_s = 8$ km/sec we find: $\lambda_{LH} \leq 13$ m. In the E_x antenna data the maximum value of Δf is ~ 200 Hz, consistent with $\lambda_{LH} \sim 26$ m. Thus the E_x antenna does not detect the waves with $\lambda < 26$ m which are readily detectable on the short antenna.

Averaging the five DPSD plots of Figure 3b, the result can be approximated with the curve $P_{SE} = P_0 e^{-[\Delta f/f_0]^2}$, where

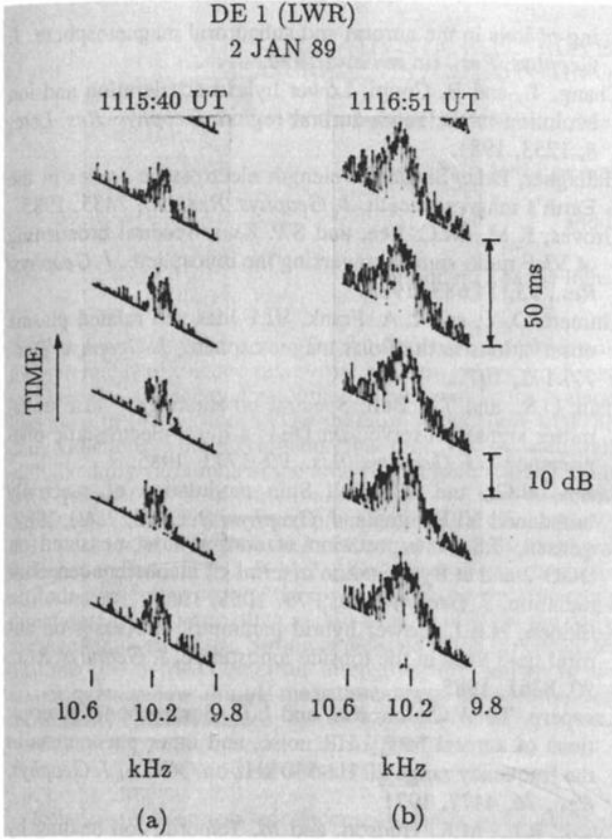


Fig. 3. Dynamic power spectral density of lower hybrid waves excited by two transmitter pulses shown in Figure 2. Panel (a): E_x long antenna data ; (b): E_x short antenna data.

P_{SE} is the LH intensity on the E_x antenna, $P_0 = 0.25$ (mV)², and $f_1 = 175$ Hz. In general if $P_{LH}(\vec{k}, \omega)$ is defined as the power spectral density of the excited LH waves it can be shown [Temerin, 1978] that the LH wave power measured on the E_x antenna has the form:

$$P_{SE}(\omega') = \frac{l^2}{8} \int R(\vec{k}) P_{LH}(\vec{k}, \omega_0) \delta(\omega' - \vec{k} \cdot \vec{V}_e) d\vec{k} \quad (4)$$

where $\delta(\cdot)$ is the Dirac Delta function, $\omega' = \omega - \omega_0$, ω is the apparent frequency of the wave, ω_0 is the frequency of the input pulse, l is the antenna length, and where $R(\vec{k})$ is given in (A.1) of the Appendix (Equation (4) is obtained from the equation directly preceding (A.1) of Temerin, 1978, with the dipole antenna response replacing the double sphere antenna response). Given that $P_{SE}(\omega')$ is known and well behaved, the integral equation can be inverted to find P_{LH} [James and Bell, 1987].

To solve (4) the LH waves are assumed to be uniformly distributed around \vec{B}_0 . Since in theory the resonance cone half angle ψ_r was $\sim 89^\circ$, we further simplify by setting $\psi_r = 90^\circ$. The solution to (4) is then found to be:

$$P_{LH}(k, \omega_0) = 0.3(k/k_0)^2 e^{-k^2/k_0^2} (\text{mV})^2 \quad (5)$$

where $k_0 = 0.22$ m⁻¹. $P_{LH}(k, \omega)$ peaks at $k = k_0$, where $\lambda = 2\pi/k_0 = 28$ m, and the 10 dB points occur at $k = 0.2k_0$ and

$k \sim 2.2k_0$, i.e., at $\lambda = 140$ and 13 m. (Note that the $\lambda = 13$ m cut off was obtained by different means following (3).) Thus substantial LH energy is contained at $\lambda < 28$ m, a range for which the E_x antenna has a very poor response.

To relate P_{LH} to the electric field intensity E_i of the input EM wave, which was obscured by the LH waves, the magnetic field of the input wave was measured, and raytracing techniques used to calculate E_i locally from Maxwells' equations. At 1116:20 UT measurements from the magnetic antenna gave $B_i \sim 0.7$ pT and a calculated value of $E_i \sim 20$ mV/m. Assuming this value also applied at the time shown in Figures 2 and 3, we can rewrite (5): $P_{LH}(k, \omega) = 7.5 \times 10^2 E_i^2 (k/k_0)^2 e^{-k^2/k_0^2} \text{m}^2$. Integrating over all \vec{k} we find: $E_{LH}^2 = 136 E_i^2$. Thus the LH intensity is ~ 20 dB larger than that of the input wave. This ratio is typical of that commonly observed during LH wave excitation by EM whistler mode waves [Bell et al., 1983; Bell and Ngo, 1988].

On July 20, 1990, LH waves excited by Omega Australia transmitter pulses were observed continuously on the E_x antenna over a 13 minute period as the satellite moved from the southern edge of the inner radiation belt into the southern auroral zone. The maximum observable Doppler shift in the LH waves was $\sim \pm 600$ Hz, with $\beta \sim 50^\circ$, and $V_s = 9$ km/sec. Thus from (3) we obtain $\lambda_{LH} \leq 10$ m. From DPSD measurements similar to those of Figure 3 (not shown) it is found that the data can be approximated with the curve $P_{SE} = P_0 e^{-(\Delta f/f_1)^2}$, where $f_1 = 280$ Hz. Assuming as before that \vec{k} is isotropically distributed about \vec{B}_0 , the inversion of (4) gives a solution with the same form as (5), but with $k_0 = 0.3$ m⁻¹. Thus $P_{LH}(k, \omega)$ peaks at $\lambda_{LH} \sim 20$ m. During the periods of LH wave excitation by transmitter pulses, it was also observed that natural EM waves, such as lightning generated whistlers, were also exciting LH waves along their path to the spacecraft [Bell and Ngo, 1988].

3. Discussion

E_x antenna data on DE-1 show that EM VLF whistler mode waves can excite LH waves with $\lambda \leq 10$ m. This result confirms earlier ISIS-2 spacecraft measurements made with a 75 m electric antenna in which LH waves with $10 \leq \lambda \leq 30$ m, were observed only when the antenna orientation resulted in the maximum response to these waves, as discussed in the appendix [Bell et al., 1983]. Because of the ISIS-2 receiver Automatic-Gain-Control, it was not possible to measure the amplitude of these short wavelength waves. Thus the present observations are the first to determine the amplitude of excited LH waves with $\lambda \leq 30$ m and the relative intensity of these waves compared to the input pulse. These short wavelength LH waves are important because they are the most efficient in heating suprathermal ions in the auroral acceleration region [Lysak, et al., 1980; Chang and Coppi, 1981].

We note that the bulk of recent satellite data (for example on the DE-1 and ISEE-1 spacecraft) on the electric field of ELF/VLF plasma waves in the magnetosphere has been obtained using long electric antennas of ~ 200 m in length. As shown above and in the appendix, these long antennas discriminate heavily against short wave length ($\lambda \leq 26$ m) LH waves by as much as 50 dB, making these waves virtually invisible to the detectors. Thus, it is very likely that the intensity of LH waves in the low altitude auroral acceleration region has been significantly underestimated in past

experiments. Clearly, future observations of LH waves in this region should be carried out using short electric antennas in order to evaluate properly the role of LH waves in the heating of ions and production of ion conics.

4. Appendix

According to a model of antenna response by Gallagher [1985], the response R of the long antenna on DE-1 to a LH wave of wave vector \vec{k} has the form:

$$R = \cos^2 \alpha \left(\frac{\sin^4 \gamma}{\gamma^4} \right) \quad (A.1)$$

where α is the angle between \vec{k} and \vec{l} , $\gamma = \frac{(\vec{k} \cdot \vec{l})}{kl}$ and \vec{l} is directed along the antenna with magnitude l equal to the antenna length (This result follows from (8) of Gallagher [1985] with $L_1=0$, since the antenna is not insulated, and $L_2=l$).

In the limit of long wavelengths, $\gamma \ll 1$, and $R \sim \cos^2 \alpha$. In the short wavelength limit, $kl \gg 1$, and if $\alpha \sim 0$, then $R_0 \sim (kl/4)^{-4}$. On the other hand, R has an absolute maximum value when $\alpha = \cos^{-1}[(kl)^{-1}]$: $R_m \sim (kl/4)^{-2}$, a value occurring when the projection of \vec{l} along the wave electric field vector $\sim \lambda/2$.

As an example assume that the LH wave has $\lambda=20$ m and $l=200$ m. In this case $R_0 \sim 10^{-5} \cos^2 \alpha$ and $R_m \sim 4 \times 10^{-3} \cos^2 \alpha$. Thus the long antenna discriminates against short wavelength waves by as much as 50 dB. On the other hand, for the short dipole antenna when $\lambda \sim 20$ m, $R \sim \cos^2 \alpha$.

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T. F. Bell, U. S. Inan, V. S. Sonwalkar, and R. A. Helliwell, Space, Telecommunications And Radioscience Laboratory, Department of Electrical Engineering/SEL, Stanford University, Stanford, CA 94305.

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