Active Nonlinear Ultralow-Frequency Generation in the Ionosphere

S. Ganguly and W. Gordon
Department of Space & Astronomy, Rice University, Houston, Texas 77251
and
K. Papadopoulos[a]
Science Applications International Corporation, McLean, Virginia 22102
(Received 12 August 1985)

Experimental evidence for spontaneous excitation of ultralow-frequency (ULF) waves in the ionosphere through the use of high-frequency (HF) pumping is reported. The ULF waves were excited through beating of two HF pumps. The observed ULF power indicates conversion efficiency exceeding the one predicted by the Manley-Rowe relations consistent with theoretical expectations for stimulated excitation in the semicollisional regime. ULF wave excitation was also observed through the use of one amplitude-modulated HF pump, consistent with generation of ULF magnetic fields caused by the coupling of the heater-induced temperature gradient to ionospheric gradient.

PACS numbers: 94.20.Rr, 52.35.Mw, 52.40.Fd, 94.30.Qw

Nonlinear excitation of low-frequency waves by the interaction of two high-frequency (HF) waves or an amplitude-modulated HF wave has, in addition to its intrinsic scientific interest, many practical applications. It has been suggested recently[1-4] that extremely efficient down conversion from HF to ultralow frequency (ULF) can be achieved in the so-called semicollisional regime, defined as the region where the frequency ω_3 of the ULF wave is smaller than the electron-ion or electron neutral-collision frequency ν (i.e., $\nu >> \omega_3$). The proposed technique relies on nonlinear coupling of two HF waves, $(\omega_1, \mathbf{k}_1)$ and $(\omega_2, \mathbf{k}_2)$, satisfying the phase-matching conditions

$$\omega_1 - \omega_2 = \omega_3, \quad \mathbf{k}_1 - \mathbf{k}_2 = \mathbf{k}_3, \qquad (1)$$

where $(\omega_3, \mathbf{k}_3)$ are the frequency and wave number of the ULF wave. The process has a power threshold decreasing[2-4] with ω_3 and for $\omega_3 << \nu$ results in efficiency exceeding that expected on the basis of the Manley-Rowe relations.[5] More recently a second technique, relying on spontaneous magnetic field generation[6,7] by coupling the modulated hot-spot temperature gradient (∇T) created by the HF heater to the ambient ionospheric density gradient (∇n), was proposed. It should be noted that the above techniques do not rely on the presence of ambient ionospheric currents and are therefore fundamentally different from the observed extremely-low-frequency–very-low-frequency generation by current modulation.[8-10] In this Letter we report the experimental verification of these nonlinear processes.

The experiments were performed during the period 31 January–15 February 1985 using the Arecibo Observatory facilities. The HF transmitters were operated at 5.1 and 3.1 MHz at a power of 4×100 kW which was fed into an antenna of 22–25-dB gain. The receiving system was built around extremely low-noise portable induction coils,[11] with a flat response for magnetic fields in the frequency band 0.001–500 Hz. The receiving system was installed on the island of Mona, which is about 150 km west of the Puerto Rico station, and at Los Canos, located 7 km away from the heater.

Two types of experiments were performed. In the first one, the four HF transmitters were split into two pairs and the desired ULF frequency difference was introduced between each pair. The ULF frequencies generated were 3, 5, and 6.25 Hz. This ULF range was selected because it is nestled in a relatively low background region between the sub-ULF geomagnetic fluctuations below 1–2 Hz and the Schumann resonance near 8 Hz. Figure 1 shows an example of the data for HF operation at 5.1 MHz and 5.1 MHz + (5 or 3) Hz. The HF transmitters were operated at a difference of 5 Hz during 16:30–17:30 Atlantic Standard Time (AST). The frequency difference was changed to 3 Hz at 17:30 AST and then back to 5 Hz at 18:00 AST. These data are shown as power spectra over the frequency range 0–10 Hz in Fig. 1. The peaks correspond to absolute values of 150–350 $\mu\gamma/\mathrm{Hz}^{1/2}$ ($1\ \gamma = 10^{-5}$ G) and a signal-to-noise (S/N) ratio of about one. Note that there were no communications on Mona and the operators identified the 3- and 5-Hz signals without any prior knowledge except that the beat frequency would be between 0–10 Hz. All three components of the field were monitored. The signals received were polarized in the east-west direction, while there was no detectable signal in either the north-south or the vertical component of the magnetic field. The coherent nature of the signal can be used to improve the S/N ratio by use of a narrower filter. A significant finding was that the signal had considerable fading. The fading determined the narrowest filtering. With use of a 5-mH filter the S/N ratio increased in occasional bursts as much as fifty with signal strength of the order of 1 $\mathrm{m}\gamma/\mathrm{Hz}^{1/2}$. This is shown in Fig. 2 for the 3- and 5-Hz components.

In the second type of experiment (12 February 1985), all four transmitters were turned on and off at

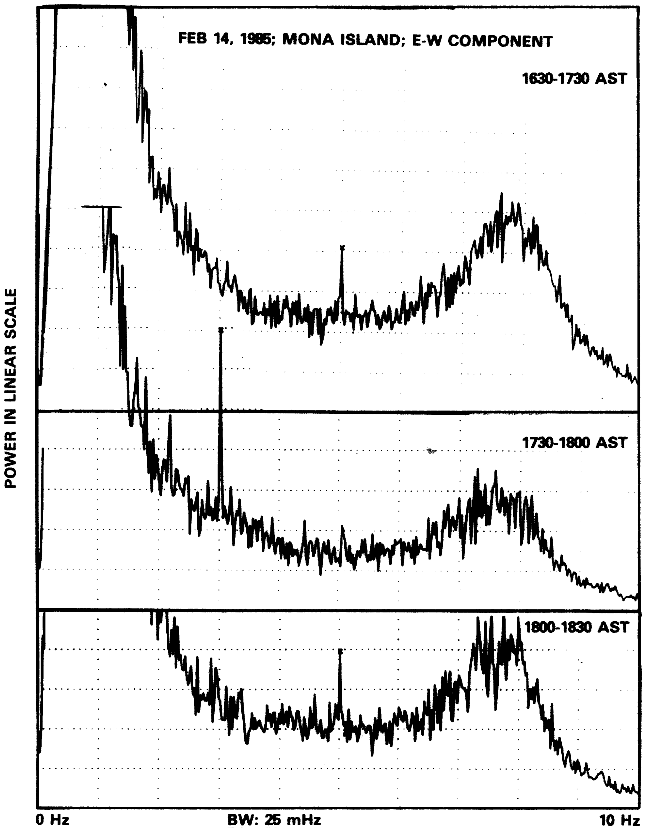

FIG. 1. Spectra of the received signal in the 0–10-Hz band (14 February 1985). Receiver was located at Mona Island. Data cover the period 16:30–18:30 AST. The HF transmitters were operated at 5.1 MHz and with a difference frequency Δf of 5 Hz during 16:30–17:30 AST, which was changed to 3 Hz during 17:30–18:00 AST and changed back to 5.0 Hz during 18:00–18:30 AST. The magnitude of the 5.0-Hz signal is about 160 $\mu\gamma$ $\mathrm{Hz}^{-1/2}$ and that of the 3.0-Hz signal is about 340 $\mu\gamma$ $\mathrm{Hz}^{-1/2}$.

equivalent ULF rates of 5.0 and 6.25 Hz. There was good coincidence of the transmitter operation and ULF detection. An example of such generation for a 5.0-Hz signal is shown in Fig. 3. The duration of this experiment was too short to compile any meaningful statistics.

The limited number of experimental results, as well as the absence of diagnostics of the modifications occurring in the ionosphere, preclude at present anything but the most crude comparison of the results with the theoretical predictions. In interpreting the experimental findings we should remark that the modifications occurred on the F region, where there are no significant ambient currents that can produce current modulation.[8–10] The first set of experiments utilized separate pump waves and therefore allowed for coherent three-wave interactions[4] to generate the low-frequency waves while satisfying Eqs. (1). For the beat excitation the theoretical analysis considered the

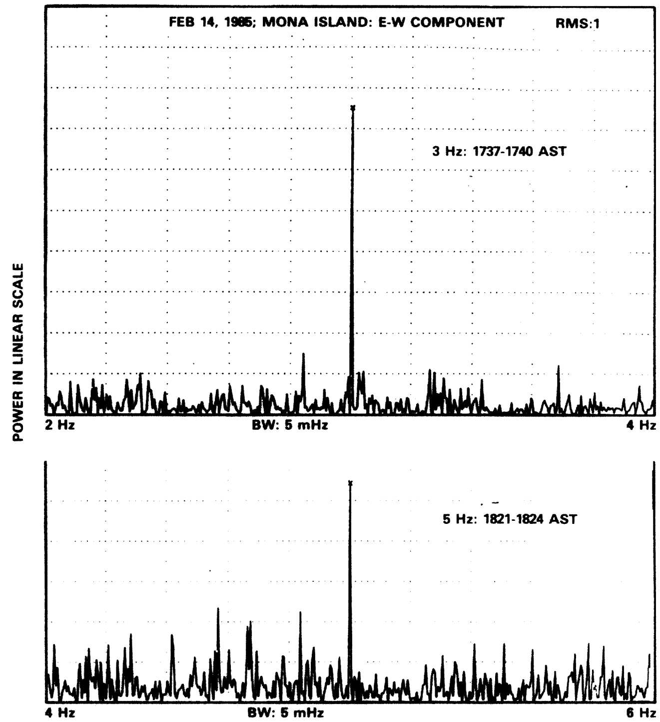

FIG. 2. Spectra for 14 February 1985, during 17:37–17:40 and 18:21–18:24 AST. The spectral bandwidth is 5 mHz. Note the large S/N ratios for both the 3- and 5-Hz signals.

geometry shown in Fig. 4. Such a geometry is justified since the interaction occurred near the critical layer where most of the power contained in the Arecibo HF-beam cone of 20°–30° was in the horizontal direction. The analysis utilizes extensively the theoretical results of Refs. 3 and 4, which predict stimulated beat-wave excitation leading to HF pump depletion for three interacting wave packets, when the electric field of the pump in the interaction region exceeds a thresh-

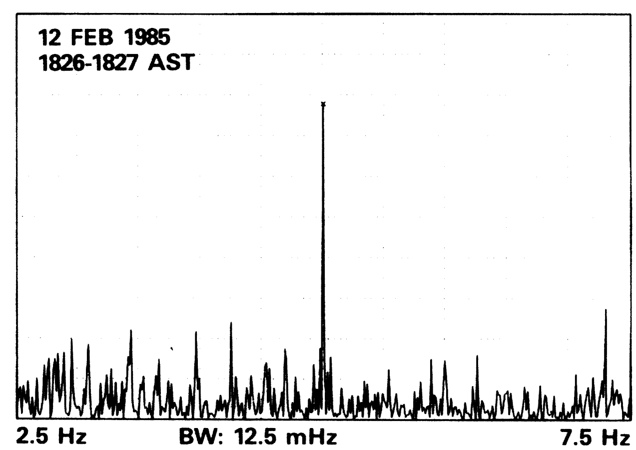

FIG. 3. ULF signal generated when the HF was turned on and off at 100-ms rate. The receiver was located at Los Canos.

old given by

$$E_{\rm thr}=4\times10^2\left(\frac{10\text{ km}}{L}\right)\left(\frac{\omega_1\Omega_e}{\omega_e^2}\right)\left(\frac{k_{2x}}{k_{3x}}\right)\frac{1}{|\Lambda|^{1/2}}\ \frac{\rm V}{\rm m}, \tag{2a}$$

where ω_e and Ω_e are the plasma and cyclotron frequency, L is the pump width, and $\Lambda=1+i\frac{4}{3}\nu/\omega_3$ where ν is the dominant electron collision frequency. The numerical solution of the conservation relations given by Eq. (1) for the waves under consideration[4] gives a typical value of $k_{2x}/k_{3x}\approx0.5$. Using this and for $\omega_3 << \nu$ we find

$$E_{\rm thr}=80\left(\frac{50\text{ km}}{L}\right)\left(\frac{\omega_1}{\omega_e}\right)\left(\frac{\Omega_e}{\omega_e}\right)\left(\frac{f_3}{\nu}\right)^{1/2}\ \frac{\rm V}{\rm m}. \tag{2b}$$

Using the resonance condition $\omega_e=\omega_1\sin\theta$, where θ is the incidence angle, taking the interaction region L of the order of the density gradient L_N (~ 50 km), and taking $\nu=500\ \text{sec}^{-1}$, we find $E_{\rm thr}\approx(2.5\sin\theta)^{-1}$ V/m; for θ of the order of the beam width ($\sim20°$–$25°$) we have $E_{\rm thr}$ of about 5 to 7 V/m. The effective pump electric field in the interaction can be approximately estimated from[12]

$$E_{\rm F}=2\times10^{-2}(P/200\text{ kW})^{1/2}[\sin\theta(f_1/\nu)(c/f_1L_N)^{1/2}]\ \text{V/m}, \tag{3}$$

where the factor in square brackets corresponds to the enhancement of the electric field component parallel to the density-gradient length (L_N) at the reflection region.[12] In estimating $E_{\rm F}$ only the power directed in the east-west direction with incidence angle larger than $\theta\approx20°$ was included. For F-region parameters $\nu\approx500\ \text{sec}^{-1}$ and $L_N\approx50$ km we find $E_{\rm F}\approx2.5$ V/m, which is of the order required by Eq. (2) for stimulated beat excitation. The field estimated with Eq. (3) is a very crude approximation. Under certain ionospheric conditions severe focusing and defocusing can occur. This could have resulted in the fading of the ULF signal.

An estimate of the ULF power generated can be found by an assumption that the wave is trapped by the relative maximum in the density of the F region which corresponds to a maximum of the dielectric constant for the excited helicon wave.[4] Taking the radius of the beam in the F region as $R\approx50$ km and the F-region peak at $h=300$ km, the power P_3 will be related to the observed field B_3 at $r=150$ km by

$$P_3=(B_3^2/8\pi)\,V_g(r/R)^2 2\pi Rh, \tag{4}$$

where V_g is the propagation velocity of the helicon wave given by

$$V_g=2c(\Omega_e/\omega_e)(\omega/\Omega_e)^{1/2}. \tag{5}$$

For the observed upper values of $B_3\approx1$–2 mγ and for $\Omega_e/\omega_e\approx\frac{1}{3}$ we find that the effective power $P_3\approx0.5$–0.7 W. In a nondissipative system the efficiency is limited to a maximum of ω_3/ω_1. Even taking as an effective interaction pump power 200 kW, the resulting efficiency is of the order of $(2\text{–}3)\times10^{-6}$ which is higher than the efficiency $\omega_3/\omega_1\lesssim10^{-6}$ on the basis of the Manley-Rowe relations.[5]

The absence of information concerning the precise coupling geometry and the direction of the density gradients makes difficult any quantitative comparison with observations relying on the flow pattern of the nonlinear currents. We can only comment on the implications of the dominance of the east-west magnetic component. First, the absence of a vertical field component implies that the nonlinear current flows horizontally in the ionosphere in a rather thin sheet. From Ref. 4 we note that $\mathbf{J}_3^{\rm nl}\approx\boldsymbol{\epsilon}^3\cdot\mathbf{k}_3$ where $\boldsymbol{\epsilon}^3$ is the low-frequency dielectric tensor. Since the dominant element of $\boldsymbol{\epsilon}^3$ is the off diagonal (ϵ_{xy}^3), the current flows on a plane perpendicular to $\mathbf{k}_3$ and for wave-packet interactions in the horizontal direction will produce no vertical field. The predominance of the east-west component over the north-south component is consistent with the interaction occurring predominantly in the north-south direction which is the direction of the magnetic meridian plane. Notice that in the F region, where the Pedersen conductivity is dominant, most of the currents are forced to flow in the north-south direction.

The concept tested on the second set of experiments was similar to the spontaneous magnetic field generation in laser-produced plasmas.[7] Namely, the coupling of a density gradient ∇n with a hot-plasma region produces a "battery" term proportional to $\nabla n\times\nabla T$, where T is the temperature of the hot region. This acts as a dynamo producing a magnetic field according to[6,7]

$$\partial B/\partial t=(c/en)(\nabla n\times\nabla T). \tag{6}$$

As discussed in Ref. 6 the magnitude of the low-frequency magnetic field produced by an oscillating temperature gradient is

$$B_3=100\left(\frac{1\text{ Hz}}{f_3}\right)\left(\frac{\tilde T}{1000\text{ K}}\right)\left(\frac{10\text{ km}}{L_N}\right)\left(\frac{10\text{ km}}{R}\right)\ \text{m}\gamma, \tag{7}$$

where $\tilde T$ is the oscillatory electron temperature due to the on-off HF heater operation. For our case $L_N\approx50$ km, $R\approx50$ km, $f_3=5$ Hz so that

$$B_3=0.8(\tilde T/1000\text{ K})\ \text{m}\gamma. \tag{8}$$

Thus, 1-mγ fields require $\tilde T=1000$ K. Such heating is

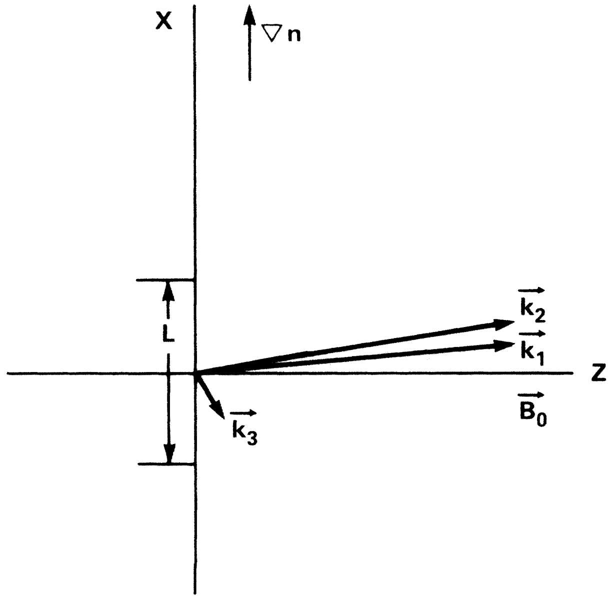

FIG. 4. Geometry of three-wave interaction in the ionosphere.

not inconsistent with that expected from the available HF power. Notice that Gordon and Carlson[13] observed *F*-region electron temperature increase by about 200 K for HF power 4 to 5 times less than ours. As noted in Ref. 6 we believe that this process is the cause of the micropulsations at 0.01 and 0.02 Hz with amplitude of 5–10 γ observed during on-off heating experiments by Stubbe and Kopa,[8] and Stubbe.[14] Before presenting our concluding remarks we should reemphasize that both types of ULF generation presented here are different from the low-frequency-wave excitation by modulation of the polar or equatorial electrojet.[8–10] The latter is basically a linear process which requires the presence of ambient ionospheric currents. The modulated electron heating modulates the local ionospheric conductivity tensor. In the presence of dc currents, an ac current is generated by conductivity modulation which radiates at the modulation frequency.

In this Letter we have presented the following: (i) the experimental evidence for the generation of ULF fields by stimulated beat-excitation processes. Observations indicate that the power levels attained during the experiment were in the vicinity of the thresholds expected in the semicollisional regime. An important finding for nonlinear physics is the verification of the prediction[2,4] that in this regime frequency down-conversion efficiencies exceeding the upper limits imposed by Manley-Rowe relations can be achieved; (ii) the experimental verification for generation of ULF waves by spontaneous magnetic field generation due to the coupling of hot-spot oscillatory temperature gradients with ambient ionospheric density gradients ($\nabla n \times \nabla T$). Before closing we should caution the reader that attributing the cause of ULF generation to two separate mechanisms is rather tentative. Namely, it is possible that both types of experiments could have been caused by the $\nabla n \times \nabla T$ process rather than the three-wave coupling, since an amplitude modulation at $\omega_3 = \omega_1 - \omega_2$ occurs also during the beat-excitation experiments. We, rather subjectively, believe that the quantitative agreement of the experiment with the threshold and efficiency as well as the unsteadiness of the oscillations is circumstantial evidence for the three-wave coupling. Further studies of the interaction will hopefully aid us in determining more convincingly the nature of the nonlinear interaction.

We gratefully acknowledge the cooperation of the Arecibo Observatory, H. F. Morrison and U. Conti for providing their equipment and expertise, J. Jost and S. T. Noble for participating in the experiment, A. Drobot for valuable discussions, and C. W. Roberson for timely help. This work was supported in part by the Office of Naval Research through Grants No. N00014-77-C-1234 and No. ONR N00014-84-C-0353.

[a]Permanent Address: University of Maryland, College Park, MD 20742.

[1]K. Papadopoulos, R. Sharma, and V. Tripathi, J. Geophys. Res. **87**, 1491 (1982).

[2]K. Papadopoulos, K. Ko, and V. Tripathi, Phys. Rev. Lett. **51**, 463 (1983).

[3]K. Papadopoulos, K. Ko, A. Rieman, and V. Tripathi, in *Active Experiments in Space: Proceedings of an International Symposium held at Altbach, Austria, 24–28 May 1983,* European Space Agency Report No. ESA-SP 195 (ESA, Paris, 1983), p. 11.

[4]K. Ko, C. R. Menyuk, A. Reiman, V. Tripathi, P. Palmadesso, and K. Papadopoulos, J. Geophys. Res. (to be published).

[5]R. Sagdeev and A. Galeev, Nonlinear Plasma Theory (Benjamin, New York, 1969), p. 24.

[6]K. Papadopoulos and C. L. Chang, Geophys. Res. Lett. **12**, 279 (1985).

[7]J. A. Stamper, K. Papadopoulos, R. N. Sudan, S. O. Dean, E. A. McLean, and J. M. Dawson, Phys. Rev. Lett. **26**, 1012 (1971).

[8]P. Stubbe and H. Kopka, J. Geophys. Res. **86**, 1606 (1981).

[9]P. Stubbe, H. Kopka, and R. L. Dowden, J. Geophys. Res. **86**, 9073 (1981).

[10]A. J. Ferraro, H. S. Lee, R. Allshouse, K. Carrol, A. A. Tomko, F. J. Kelly, and R. G. Joiner, J. Atmos. Terr. Phys. **44**, 1113 (1982).

[11]H. F. Morrison, W. Conti, V. F. Labson, E. Nichols, and N. E. Goldstein, "Field Tests of Noise in SQUID and Induction Coil Magnetometers," to be published.

[12]V. L. Ginzburg, *Propagation of Electromagnetic Waves in Plasmas* (Pergamon, New York, 1970), p. 263.

[13]W. E. Gordon and H. F. Carlson, Radio Sci. **9**, 1041 (1974).

[14]P. Stubbe, H. Kopka, M. Reiteld, and R. L. Dowden, J. Atmos. Terr. Phys. **44**, 1123 (1982).