Small-Scale Plasma-Density Depletions in Arecibo High-Frequency Modification Experiments

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Observations of Thomson scattering at uhf from Langmuir waves by a scheme involving the linear frequency modulation (chirping) of a uhf transmitter and the demodulation (dechirping) of the received signals show that a high-power hf wave used for ionospheric modification creates small-scale plasma depletions instantly. For a plasma frequency of 5.1 MHz, plasma frequency gradient of about 50 kHz/km, and power density input of 8×10^{-5} W/m^2, the depletion ranged from 3% to 55%. This provides direct evidence that the hf-induced modifications involve Langmuir waves trapped in density cavities.

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Modification of the ionospheric plasma by hf waves from transmitters on the ground has become an active experimental and theoretical research field.[1,2] Interesting plasma effects involving large-scale field-aligned striations, broad-band absorption, accelerated electrons, enhanced airglow, and parametric instabilities[3] have been observed, and have been explained with varying success. Suggestions have been made that the Langmuir waves excited in the parametric decay of the hf wave are confined to cavities.[4,5] Such confined Langmuir waves, cavitons or solitons, are predicted and observed in other contexts.[6,7] Direct observational evidence for their existence in ionospheric modification experiments has so far been lacking.

Figure 1(a) shows how the spectrum of a cw pulse

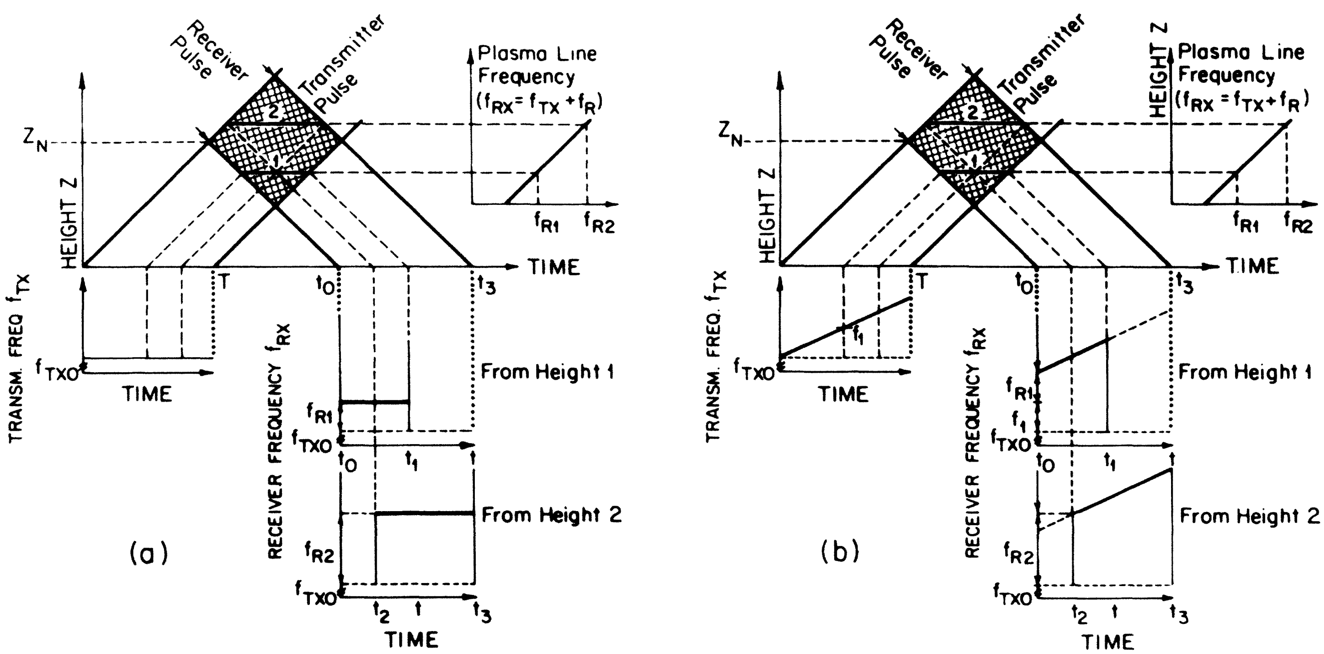

FIG. 1. Height-time diagrams: (a) cw, (b) with chirp.

of the uhf (430 MHz) Thomson-scatter diagnostic radar becomes broadened when scattered from a height range where the Langmuir frequency f_R varies with height z. Where $df_R/dz = 0$ the spectrum remains narrow and the detectability is optimum.

Figure 1(b) shows how the linear frequency modulation (chirping) of the transmitter and receiver local oscillators remove the effect of the linear part of the density gradient when the transmitter-receiver chirp is related to the rate of change of plasma line frequency with height by

$$df_{\mathrm{TX}}/dt = df_{\mathrm{RX}}/dt = c\, df_R/(2\, dz). \tag{1}$$

The scattered signal from height 1 is received from t_0 to t_2. The effective uhf transmitter starting frequency is $f_1 + f_{\mathrm{TX0}}$. From height 2 the scattered signal starts at time t_2. In this case the uhf transmitter chirp starts at f_{TX0}. For the correct chirp rate, after dechirping, the scattered signals from the two heights are at the same frequency and the original wide spectrum turns narrow with large improvement in signal-to-noise ratio. Similar advantages may be gained in laser diagnostics of laboratory plasmas. A nonlinear profile causes energy to appear in the dechirped spectrum at frequencies slightly different from those corresponding to the linear profile without altering these arguments, still allowing electron densities to be determined to one part in a thousand.[8]

The hf-modification (heating) experiments were carried out during three afternoons in January 1985. In all of them a hf-heater frequency of 5.1 MHz was used and the transmitter was cycled on for the first 15 s of each minute and off for the remainder. The power emitted by the hf-heater transmitter was either 200 or 300 kW. The vertically directed power flux at 200 km from the hf transmitter, on the assumption of free-space propagation, was 8×10^{-5} or 1.2×10^{-4} $\mathrm{W/m^2}$ at the center of the heater beam. The 430-MHz Thomson-scatter radar diagnostic system has peak transmitter power of 1.2 MW, pulse repetition rate 100 Hz, and integration time 1 s. The receiver alternated between upshifted and downshifted plasma lines each 1.35 s. The chirp rate and frequency offset were matched to the ionospheric profile within the range-gate window [see Eq. (1)]. Eight overlapping range gates were used in these experiments shifted by 16 μs or 2.4 km. The antenna beam was pointed in the direction of the heated region near zenith.

Unperturbed frequency spectra of the dechirped signal received by the Thomson radar are shown in Fig. 2(a). At other times these spectra are broadened by striations as shown in Fig. 2(b). There is no close correlation between the on-off cycle of the heater and the presence of these striations.

More interesting are observations made with the heater-induced plasma line present, shown in Fig. 2(c). The heater-induced plasma line is offset toward a lower frequency from the simultaneously observed natural, photoelectron-enhanced plasma line. The height of the heater-induced plasma line is determined as follows: In the frequency spectra the heater-enhanced plasma line is at a frequency of f_1 at the

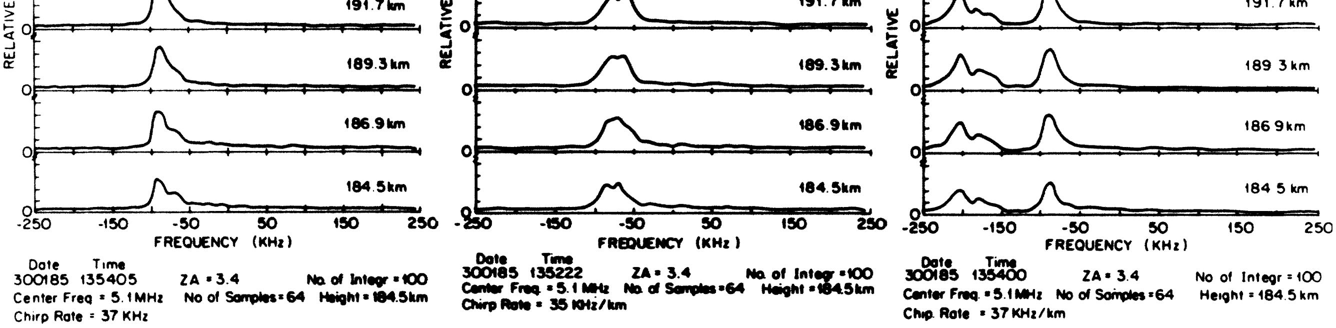

FIG. 2. Dechirped frequency spectra: (a) unperturbed, (b) broadened, and (c) with natural and heater-induced features both present.

lowest range gate. Previous experiments without chirp show that the dominant feature of the enhanced plasma line occurs at a Langmuir frequency f_R of about $f_{\rm hf}-f_{i\,\rm ac}$, where $f_{i\,\rm ac}$ is the ion acoustic frequency, and that the width of the plasma line is a few times the ion acoustic frequency. The chirp rate is known to be df/dz, set in the transmitter, and the height interval δz between the lowest height and that of the enhanced plasma line satisfies

$$\delta z\, df/dz=(f_{\rm hf}-f_{i\,\rm ac})-f_1.$$

In Fig. 2(c) $f_{\rm hf}=5100$ kHz, $f_1=4900$ kHz, and $df/dz=37$ kHz/km. With $f_{i\,\rm ac}=4$ kHz, determined from previous experiments, one obtains

$$\delta z=\{(5100-4)-4900\}/37=5.3 \text{ km}.$$

The height where the heater-induced enhancement occurs is at $z=184.5+5.3$ km $=189.8$ km. We have chosen the highest peak in the heater-induced spectral feature to determine f_1. This height deduced from the chirp is the same as obtained by interpolation of the power variation versus height as the receive window is moved [see Fig. 2(c)]. There is a spread in excess of what is usually observed in nonchirped pulsed plasma-line observations. This excess is evidence that the enhanced scattering occurs over a height range.

In our observations $f_1<f_2$ (the natural plasma line frequency in the lowest range gate) for the upshifted plasma line. The Langmuir oscillation frequency at the height of the heater-induced spectral feature is lower than the natural Langmuir frequency by $\delta f=f_2-f_1$. This means that there is a local depletion in electron density at the height of the heater-induced spectral feature. In Fig. 2(c) we find that $\delta f=110$ kHz. If the Langmuir frequency changes because of a decrease in electron density only, the reduction in electron density is 4.4%. If the electron temperature increases in the density depletions, the true reduction is larger [see Eq. (3)].

The heater-induced Langmuir oscillations at a frequency of 5100–4 kHz occur at a height greater by $110/37=2.97$ km than where the photoelectron-enhanced Langmuir oscillations of that same frequency occur. Muldrew and Showen[9] compared the height of return of the enhanced plasma line with the height of the natural one by turning the heater on and off. They concluded that the height of the heater-induced plasma line was higher than that of the natural one by several kilometers, as we observe.

The frequency difference of the heater-induced Langmuir oscillations and the photoelectron-enhanced oscillations, f, is equal to the frequency difference of the "cold" and the "warm" plasma oscillations:

$$\Delta f=-1.5 f_P (kD)^2, \tag{2}$$

where $f_p^2=(1/2\pi)^2 Ne^2/m\epsilon_0$ and $D^2=(v_{Th}/2\pi f_p)^2$ if an electron temperature T_e of 3000 K is assumed, typical of daytime conditions. The cavities hence develop close to the height where the heater frequency $f_{\rm hf}$ equals the plasma frequency f_p.

The heater feature of the spectrum appears instantly on the 1-s integration time scale used. On this time scale one cannot detect a gradual shift of the hf-induced plasma line frequency from that of the natural plasma expected in a gradual buildup of a plasma density depletion.

The hf-induced plasma line disappears as rapidly when the heater is turned off. Often the enhanced line disappears before the heater is turned off [see Fig. 2(a)], and for periods the enhancement may last only 3–5 s, shorter than the duration of the heater pulse. The enhanced line may reappear within the same heater pulse after having disappeared nearly completely. Such bifurcation may occur both in time and in frequency.

Integration of a number of spectra obtained during the heater-off periods to determine whether the depletions in plasma density are permanently present and only being excited more strongly during the heater-on periods gave negative results. Comparison of the spectra immediately following turnoff of the heater with those obtained prior to turnon shows no differences. The temporal behavior is shown in Fig. 3 as a sequence of spectra like those in Fig. 2 as an intensity plot. The power is indicated by shading, and time is

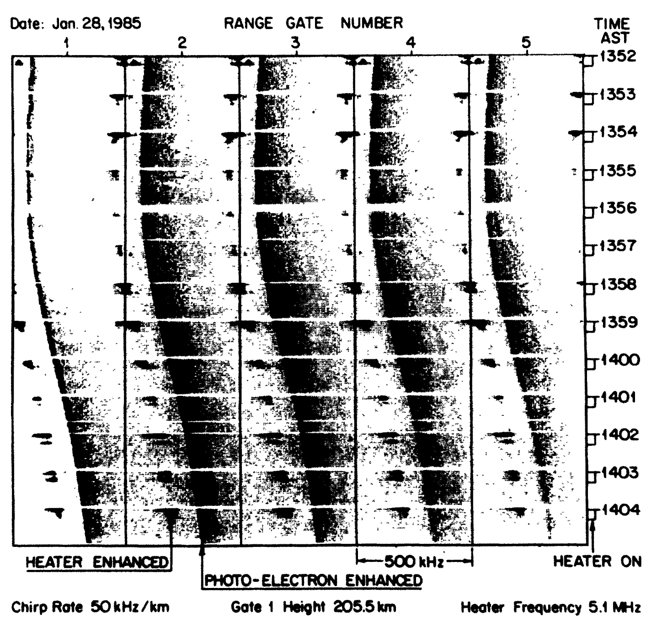

FIG. 3. Intensity plots of sequence of spectra such as shown in Fig. 2.

progressing from top to bottom, the heater-on period always occurring during the first 15 s of every minute. Several 500-kHz-wide spectra are shown along the horizontal axis. Each spectrum corresponds to a position of the range gate, and the change in range between adjacent gates is 2.4 km. The fuzzy line is the photoelectron-enhanced plasma line; the interrupted strong feature at the beginning of each minute is due to the heater. A close study of these data reveals all the phenomena mentioned above. The data suggest that the photoelectron-enhanced plasma line away from the heated region is slightly stronger during the heater-on period. This may be caused either by accelerated electrons from the modified region, or by interaction between the high-frequency wave and the Langmuir waves near the height where f_R is equal to $f_{\rm hf}$.

The Langmuir wave resonance is sensitive to temperature through the pressure correction term which contains the Debye length, Eq. (2):

$$f_R = f_P[1+1.5(kD)^2]. \tag{3}$$

The effect of the heating of the electron gas is to increase the resonance frequency, not decrease it, as observed.

Consider the possibility that the heater-induced plasma line occurs at the upper hybrid frequency, where

$$f_p^2 = f_{\rm hf}^2 - f_e^2. \tag{4}$$

f_e is the gyrofrequency. The frequency for a given height is higher, not lower as observed, and this possibility is ruled out.

Gurevich[10] has shown that the deposition of heat in a height interval in the ionosphere causes local heating and plasma depletion. The initial phase of this heating process is governed by ambipolar diffusion and by heat conduction. Assuming that all the power in the heater wave is deposited in an infinitely thin layer at 200 km altitude, we find that a plasma depletion develops gradually over a time of several seconds. The rapid turnon and turnoff suggest that a quasiequilibrium state is reached in much less than 1 s, and that it is impossible to reconcile the observed results with the computations. For the phenomena to occur as rapidly as they do, the spatial extent of the disturbed region(s) must be much less than what the classical computations lead us to believe.

Muldrew and Showen[9] explain their data by parametric instabilities developing inside low-density ducts between preexisting field-aligned striations. Our observations show that striations come and go, but the displaced heater-induced plasma line persists irrespective of the presence of striations. This argues against the striation and duct explanation.

Laboratory experiments and their interpretation in terms of solutions of Zakharov's equations have greater promise.[3–5,11] Tanikawa, Wong, and Eggleston[11] for instance, considered a situation reminscent of the experiment we have described. In their laboratory experiment the electric field is applied in the direction of the density gradient, but there is no magnetic field as in the ionosphere. With scaling of their Eqs. (4), the normalized parameters in our heating experiment are similar to their parameters, except our power is considerably higher. In the simulations shown in their Fig. 4, the plasma depletion is well developed at normalized time $\tau = 5.0$. In our experiment this scales to real time of 6 ms, and would explain the rapid time variation we observe. If we scale the extent of the depletion, we find that Tanikawa, Wong, and Eggleston predict an extent of about 10 units, which translates to 28 m in our case, and confirms that the spatial extent of the phenomenon must be small. The experiments and simulations of Tanikawa, Wong, and Eggleston are strictly one dimensional. We do not know whether to expect lateral homogeneity or inhomogeneity in the form of hot spots. The plasma depletions observed may be explained in terms of induced cavitons with trapped Langmuir waves, with an equilibrium between the ponderomotive forces of these waves and the plasma pressure, as described in considerable detail by Petviashvili[6] and Nezlin.[7] Our results provide the most direct evidence of caviton production and Langmuir wave trapping in Arecibo heating experiments so far.

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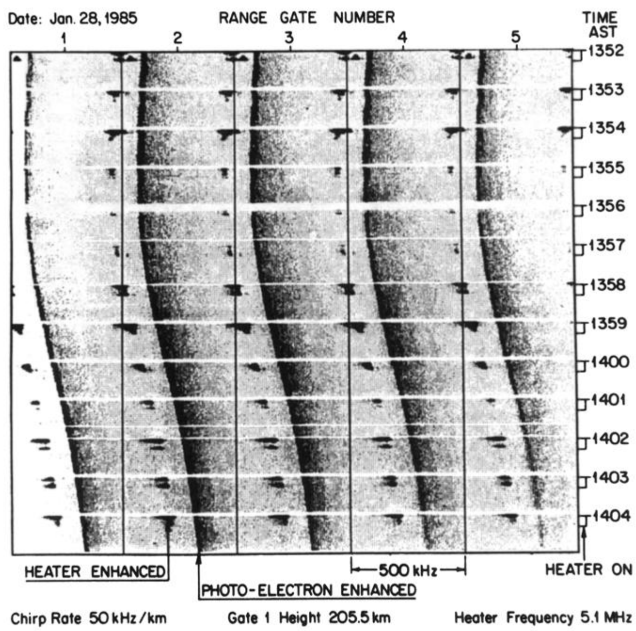

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