Short–Time-Scale Evidence for Strong Langmuir Turbulence during hf Heating of the Ionosphere

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Results of short-pulse, low-duty-cycle hf-heating experiments are shown to agree with predictions of a model of correlated, localized cavitons which undergo cycles of nucleation, collapse, and burnout. Predicted "free-mode" spectral features associated with the radiation of Langmuir waves from collapsing cavitons are observed. Single-radar-pulse data provide evidence that temporal correlations between caviton events are present at early times following the onset of heating.

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Strongly enhanced plasma fluctuations are observed to be excited in the F-layer of the ionosphere under the irradiation of intense high-frequency (hf) waves.[1,2] This enhancement occurs at a range of heights between 200 and 300 km where the local plasma frequency, ω_p, matches approximately the hf or heater wave frequency, ω_0. There are compelling theoretical reasons to suggest that strong Langmuir turbulence effects involving collapsing cavitons are present in this excitation.[3] Previously, these fluctuations were believed to be excited through parametric instabilities[1,4] and their subsequent saturation had often been explained in terms of the weak turbulence (WT) theory.[5] The theory, however, failed in many ways to provide a consistent explanation of many phenomena observed.[6,7] For example, WT fails to predict the anomalously large Langmuir wave intensity observed with the radar probing only waves with wave vector k_T at an angle $\theta \simeq 50°$ with respect to the ambient geomagnetic field. The observed altitudes of the most intense wave activities were consistently higher than predicted for freely propagating plane Langmuir waves satisfying the linear wave dispersion relation. Also, WT is not valid at the nominal radiated hf power used in previous experiments which exceeded the strong turbulence threshold. As a result, more realistic modeling of the hf-heating process including strong turbulence effects was developed.[3] Recent results from such numerical simulations indicate that caviton nucleation,[8] collapse,[9,10] and burnout are the dominant turbulent processes. The cavitons excited by ionospheric heating are predicted to have spatial scales of 5–50 cm and lifetimes in the range of 50–100 μs. The predictions of this type of isothermal theory are applicable to the hf-heating experiments only if the time scale of the experiments is short enough to neglect thermal instabilities. In this Letter, we would like to present such experimental evidence which strongly suggests the important role of strong turbulence effects during controlled hf-heating experiments.

The experiments were performed in two separate campaigns (March 1987 and May 1988) at the Arecibo Observatory, Puerto Rico. Pulses of high-power, left-hand polarized (O-mode) electromagnetic wave, the heater wave, were radiated into the ionosphere. Typical effective radiated power (ERP) was between 40 and 60 MW and the wave frequency ($\omega_0/2\pi$) was between 3 and 9 MHz. To minimize the complications from thermal effects due to long-time heating that plagued many previous experiments, only low-duty-cycle, short-pulse experiments were performed. The typical heater pulse length was only 10 ms and the interpulse period (IPP) was 150 ms. Such short heater pulses were observed to be sufficient to excite strong turbulence effects as the typical collapse cycle lasts only 50–100 μs. The presence of intense Langmuir waves near the hf-wave reflection layer was detected by the incoherent scattering technique using the 430-MHz backscatter radar.[11]

The dynamics of strong Langmuir turbulence can be studied using Zakharov's model[3,8,9] that describes the coupling of high-frequency Langmuir waves with low-frequency ion density fluctuations driven by a pump field. Of particular interest is the nonlinear $\nabla \cdot (n\mathbf{E})$ term in the Zakharov equations which leads to the localization of Langmuir waves in density fluctuations or cavities n. Under the action of the ponderomotive force, these localized states then nucleate and collapse.[3] The turbulent plasma state is not sustained by parametric instabilities and successive cascading of plane Langmuir

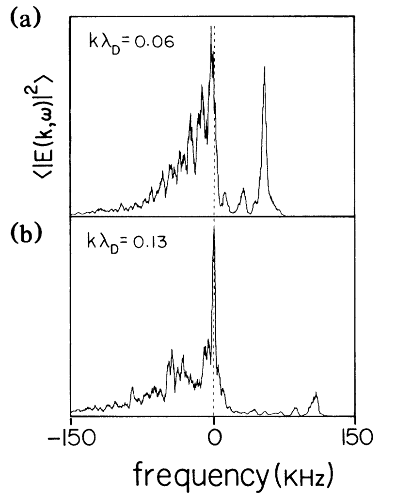

FIG. 1. $\langle |\mathbf{E}(\mathbf{k},\omega)|^2 \rangle$ from two-dimensional (2D) numerical simulations for two different values of $k\lambda_D$ with a heater intensity $E_0 \simeq 0.5$ V/m, $(\omega_0 - \omega_p)/\omega_p \simeq 1.7 \times 10^{-3}$ corresponding to the first heater Airy maximum, $\omega_c/\omega_p \simeq 0.3$, and $\theta = 45°$. The frequencies in the upshifted plasma line spectra are measured relative to $\omega_0/2\pi$.

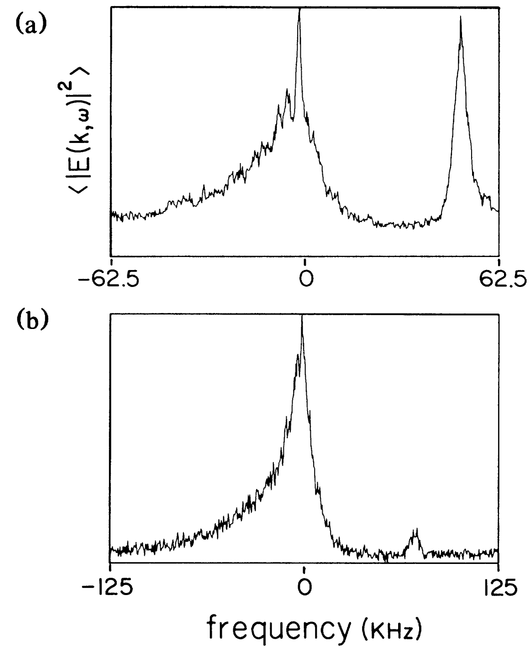

FIG. 2. $\langle |\mathbf{E}(\mathbf{k},\omega)|^2 \rangle$ from two separate experimental runs. hf-heating pulses 10 ms long, at 150 ms IPP, and with $\omega_0/2\pi = 7.3$ MHz were irradiated at an ERP of 60 MW. The radar pulse was delayed by (a) 0.5 ms and (b) 4 ms after the onset of the heater pulse, respectively. The frequencies are measured relative to $\omega_0/2\pi$.

waves as predicted by WT, but by nucleation and collapse of localized waves in density cavities remaining from previous collapse-burnout events.[3,12]

The dominance of nucleation and collapse in the strongly turbulent plasma state observed experimentally is supported by comparing with experiments the results of two-dimensional numerical simulations of the Zakharov equations generalized to include the weak ambient magnetic field.[3,12] The driving source due to the heater field and the dissipation term are the same as used in Ref. 3. Figures 1(a) and 1(b) show typical electric field power spectra, $\langle |\mathbf{E}(\mathbf{k},\omega)|^2 \rangle$, from the simulations. The spectra contain several distinct features: First, the spectra are broad and skewed towards lower-frequency spectral components with $\omega \lesssim \omega_0$, indicating the prominence of localized states. Second, this portion of the spectrum has a width determined by the collapse-cycle time. Third, a distinct "free-mode" peak appears at $\omega = \omega_f$, where $\omega_f^2 = \omega_p^2 + 3k^2 v_e^2 + \omega_c^2 \sin^2\theta$ is the dispersion relation for free Langmuir waves in a uniform geomagnetic field with electron gyrofrequency $\omega_c < \omega_p$. This peak is due to the dynamic nonlinear coupling between collapsing localized states and nonlocalized states that results in the radiation of nearly free Langmuir waves by collapsing cavitons.[12] Suprathermal electrons generated during the burnout of collapsing cavitons can radiate free Langmuir waves by Cherenkov emission. Calculations of the rates of energy dissipation and of nonlinear free-mode emission from single-collapse events lead to the conclusion that Cherenkov emission is a negligible source of free-mode excitation even if it is assumed that all the dissipated energy goes into suprathermal electrons.[12] Power spectra of experimental data show strikingly similar characteristics and typical spectra from two separate runs are shown in Figs. 2(a) and 2(b). The spectra shown are the result of 500-shot averages of 1.1-ms radar pulses delayed by 0.5 ms and 4 ms from the onset of the heating pulses. The skewed broad spectrum towards lower frequencies and the free-mode peak are clearly evident in each figure. The frequency offsets of the free mode from ω_0 are $\Delta\omega/2\pi = 52$ and 72 kHz, respectively. These values can easily be checked against the calculated frequency ω_f. Using $k = 2k_T$, $\omega_c/2\pi = 1.2$ MHz, and $\theta = 50°$, the observed frequency offsets correspond to electron temperature values of $T_e \sim 900$ and 1650 K, respectively, which are consistent with typical observed values of T_e. The observed difference in the frequency offsets for the two runs may be attributed to the increase in T_e during heating.

The relative peak strength of the free mode, $P_f(\omega \sim \omega_f)$, with respect to the peak strength of the spectral components near $\omega \lesssim \omega_0$, $P_0(\omega \lesssim \omega_0)$, depends sensitively on the heating time. For short heater periods of $\tau \lesssim 10$ ms, P_0 is small and the free mode is easily observable. In some instances, P_f and P_0 are observed to be comparable. This is illustrated in Figs. 1(a) and 2(a) where results from simulations and actual experiments are shown, respectively. As the heater period increases, including the case of continuous-wave (cw) heating, P_f

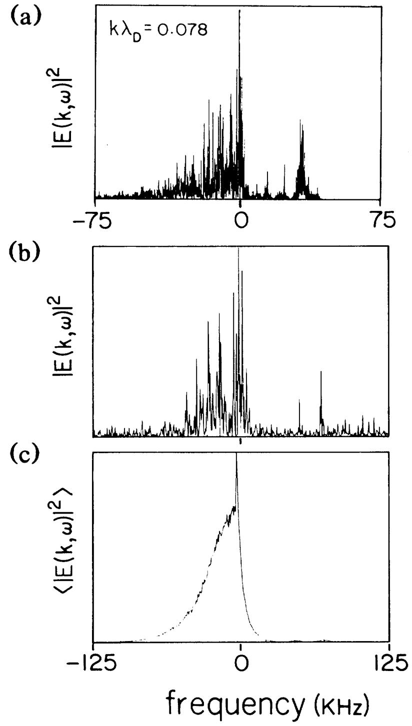

FIG. 3. (a) Single-shot spectrum, $|\mathbf{E}(\mathbf{k},\omega)|^2$, from 2D simulations. (b) $|\mathbf{E}(\mathbf{k},\omega)|^2$ from experiments. (c) 25-shot averaged spectrum $\langle|\mathbf{E}(\mathbf{k},\omega)|^2\rangle$. The data were obtained by irradiating hf-heating pulses (10 ms, 150 ms, 7.3 MHz, 40 MW) and with the radar pulse delayed by 8.9 ms after the onset of the heater pulse. The frequencies are measured relative to $\omega_0/2\pi$.

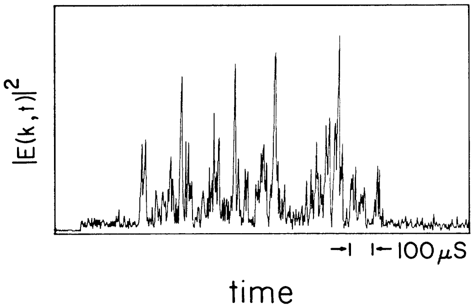

FIG. 4. (a) Real-time single-shot backscattered radar power signal, $|\mathbf{E}(\mathbf{k},t)|^2$, from experiments. The signal was obtained by irradiating hf-heating pulses (10 ms, 150 ms, 7.3 MHz, 60 MW) and with the radar pulse delayed by 8 ms after the onset of the heater pulse.

remains relatively constant while P_0 gains in strength rapidly and sharp spectral features develop near $\omega \lesssim \omega_0$. While the general behavior of the main spectrum P_0 was previously observed,[7,13] the present observations constitute the first unambiguous identification of the free-mode peak which is a phenomenon intimately connected with collapse and is not predicted by the WT cascade theory.

Further information regarding the dynamics of the strongly turbulent plasma can be obtained by analyzing individual single-shot fast-Fourier-transform spectra. Sample unaveraged single-shot spectra from both numerical simulations and actual experiments are shown in Figs. 3(a) and 3(b), respectively. The single-shot spectra display finer line structures that are not present in the averaged spectra. For comparison, a 25-shot averaged spectrum from experiments is also shown in Fig. 3(c).

Previous arguments which depend on the phase locking of the caviton fields to the heater field[3,12] lead to the conclusion that the observed power spectrum $|\mathbf{E}(\mathbf{k},\omega)|^2$ is proportional to $|\rho(\mathbf{k},\omega)|^2|\epsilon(\mathbf{k},\omega)|^2$, where $|\epsilon(\mathbf{k},\omega)|^2$ is the smooth Zakharov electric field envelope spectrum of a typical single-collapse event and $\rho(\mathbf{k},\omega) =\sum_i \exp[i(\omega t_i - \mathbf{k}\cdot\mathbf{x}_i)]$ is the transform of the caviton density summed over the N events at the space-time points $(\mathbf{x}_i,t_i)$ which occur in the radar detected volume during the 1.1-ms pulse. Here the frequencies ω are measured relative to ω_0. From simulation caviton densities and from backscattered power arguments, we estimate that $N \sim 10^7-10^8$.

From the perspective of the caviton model, the observed real-time backscattered power signal in a single radar pulse shown in Fig. 4 which has strong modulations on the caviton lifetime scale leads to the conclusion that many collapse events are coincident in time. This conclusion rests on our estimates for N and for the caviton lifetime. From this point of view each prominent peak in the time series is a resultant macrofluctuation of many coincident collapse events. The temporal width of the more prominent peaks, $\tau_m \sim 50-100$ μs, is consistent with caviton lifetimes observed in simulations. There are then only a small number, ~ 10, of macrofluctuations in the 1.1-ms time series. It is easy to see that if $|\rho(\mathbf{k},\omega)|^2$ is constructed from such a small number of temporal events, then its spectrum will consist of discrete lines. For example, the time series for the spectrum shown in Fig. 3(a) also consists of a small number (~ 40) of (mostly) *single*-collapse events.

The relative smoothness of the many-pulse, incoherently averaged spectra, such as Figs. 2 and 3(c), are the result of pulse-to-pulse fluctuations in the line spectra. If we assume that only the event times, t_i, change from pulse to pulse we can show[12] that the average structure factor, $\langle|\rho(\mathbf{k},\omega)|^2\rangle$, is nearly constant for $|\omega| > 2\pi\langle\delta\tau^2\rangle^{-1/2}$ and has a peak, perhaps with substructure, for $|\omega|$ less than this, where $\langle\delta\tau^2\rangle^{1/2}$ is a measure of rms fluctuation in times *between* events.

The theoretical understanding of the origin of these strong temporal correlations is incomplete at this time. These temporal correlations between cavitons observed here do not necessarily imply that the events are perfectly correlated spatially. We do know, however, that small increases in the electron density of about 1%–2% above the critical density of the heater can cause a dramatic increase in the temporal coherence at a single caviton site.[12] Such overdense domains with dimensions of 100 m or so may well exist in the heated volume. The increasing intensity and sharpness of the main spectrum P_0 with heating time, then, may be attributed to increasing space-time correlations between cavitons.[12]

These short-time-scale observations have allowed us, for the first time, to make detailed comparisons between the strong turbulence caviton theory and the actual plasma line dynamics. The agreement, both qualitative and quantitative, seems to be good enough to warrant further detailed studies based on this new theoretical paradigm.

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[1]J. A. Fejer, Rev. Geophys. Space Phys. **17**, 135 (1979), and references therein.

[2]A. V. Gurevich and V. V. Mugulin, J. Atmos. Terr. Phys. **44**, 1019 (1982).

[3]David Russell, D. F. DuBois, and Harvey A. Rose, Phys. Rev. Lett. **60**, 581 (1988); D. F. DuBois, Harvey A. Rose, and David Russell, Phys. Rev. Lett. **61**, 2209 (1988).

[4]A. Y. Wong and R. J. Taylor, Phys. Rev. Lett. **27**, 644 (1971).

[5]F. W. Perkins, C. Oberman, and E. J. Valeo, J. Geophys. Res. **79**, 1478 (1974); W. L. Kruer and E. J. Valeo, Phys. Fluids **16**, 675 (1973).

[6]W. Birkmayer, T. Hagfors, and W. Kofman, Phys. Rev. Lett. **57**, 1008 (1986).

[7]F. T. Djuth, C. A. Gonzales, and H. M. Ierkic, J. Geophys. Res. **91**, 12089 (1986).

[8]G. D. Doolen, D. F. DuBois, and Harvey A. Rose, Phys. Rev. Lett. **54**, 804 (1985).

[9]V. E. Zakharov, Zh. Eksp. Teor. Fiz. **62**, 1745 (1972) [Sov. Phys. JETP **35**, 908 (1972)].

[10]A. Y. Wong and P. Y. Cheung, Phys. Rev. Lett. **52**, 1222 (1984); P. Y. Cheung and A. Y. Wong, Phys. Rev. Lett. **55**, 1880 (1985).

[11]J. V. Evans, Proc. IEEE **57**, 496 (1969).

[12]D. F. DuBois, Harvey A. Rose, and David Russell, Los Alamos National Laboratory Report No. LA-UR-89-1419 (to be published).

[13]A. Y. Wong, G. J. Morales, D. Eggleston, J. Santoru, and R. Behnke, Phys. Rev. Lett. **47**, 1340 (1981).