GEOPHYSICAL RESEARCH LETTERS, VOL. 29, NO. 11, 1510, 10.1029/2002GL014934, 2002

Modification of the electron density profile near the upper hybrid layer during radio wave heating of the ionosphere

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Received 17 February 2002; revised 10 April 2002; accepted 18 April 2002; published 6 June 2002.

[1] High frequency (HF) radio waves can modify the electron density profile of the ionosphere in the upper hybrid resonance region (UHR). The spatial and temporal development of this modification was investigated using a multi-frequency Doppler diagnostic system at the TROMSØ facility [*Lobachevsky et al.*, 1992]. We present the results of the simulations of the density profile modification near the upper hybrid resonance height for the parameters relevant to the experiment and show that the spatio-temporal development of the density modification is quantitatively modelled by the mode conversion and the radio wave heating. *INDEX TERMS:* 2439 Ionosphere: Ionospheric irregularities, 2471 Ionosphere: Plasma waves and instabilities, 2487 Ionosphere: Wave propagation (6934) 2467 Ionosphere: Plasma temperature and density

1. Introduction

[2] The thermal self-focusing instability (SFI) is an important mechanism for inducing irregularities in the ionosphere irradiated by high-powered HF radio waves. This was first demonstrated in the work of *Litvak* [1970] and *Perkins and Valeo* [1974]. These investigations were for an underdense plasma in which the high frequency heater wave amplitude grew convectively in narrow filaments as it propagated in the inhomogeneous plasma. *Cragin et al.* [1977] and *Gurevich* [1978] later developed linear theories of the self-focusing instability in the vicinity of the critical surface in an inhomogeneous ionospheric plasma and they found that the SFI is an absolute instability, which grows in time at all locations. Both these types of investigations studied the self-focusing instability of the original electromagnetic heater wave. In an inhomogeneous gyrotropic plasma, the heater wave can be converted into an electrostatic upper-hybrid wave by direct mode conversion or by parametric processes. Linear instability analysis of SFI of the electrostatic wave was then developed by *Vaskov and Gurevich* [1977], *Das and Fejer* [1979]. More recently *Gurevich et al.* [1996] have provided a nonlinear theory for the structure and characteristic size of stationary small scale thermal filament formed by highly localized heating in the vicinity of the upper hybrid resonance layer.

[3] The first detailed numerical modeling of thermal self-focusing of the electromagnetic heater wave was carried out by *Bernhardt and Duncan* [1987]. They performed 2D numerical simulations of the self-focusing instability in the underdense plasma. *Blaunstein* [1996, 1997] has investigated the temporal evolution of the plasma density modification induced by the heating of the ionosphere by specifying a localized heating profile which mimics the excitation of an electrostatic wave between the upper-hybrid and reflection heights. The heating wave is prescribed and does not evolve in time. More recently 2D codes to study the nonlinear thermal SFI of the electromagnetic heater wave in the vicinity of the critical surface of the ionosphere have been developed [*Guzdar et al.*, 1998; *Gondarenko et al.*, 1999]. These studies addressed the full nonlinear self-consistent development of the absolute SFI instability starting at the critical surface and developing filamentary structures along the field-line. The modification of the density also affects the wave propagation and consequently the electron heating. The development of the SFI was described by a set of nonlinear equations coupling the radio wave propagation with the density and temperature equations for the heated electrons [*Gondarenko et al.*, 1999]. However these investigations were limited to wave propagation along the magnetic field lines and hence did not include any mode-conversion processes near the UHR layer. In this letter we present results of the first two-dimensional numerical simulations of the heating and modification of the density profile, and self-consistent changes in the full-wave propagation in an inhomogeneous magnetized plasma. The focus of the simulations presented here is to provide an understanding of the observations showing the density modification at the UHR layer of an *O*-mode pump wave.

2. Mode Conversion of an Ordinary *O*-Mode

[4] We have developed a 2D wave propagation code in a magnetized plasma, where an ordinary *O*-mode, launched at the lower boundary of the computational domain, is propagated vertically in a stratified plasma, in which the magnetic field is at an arbitrary angle with the vertical axis. Direct

0094-8276/02/2002GL014934

conversion of the ordinary mode allows for Budden tunneling of the *O*-mode to create the second branch of the extraordinary *X*-mode, which in the ionospheric context is referred to as the *Z*-mode [*Mjølhus and Flå*, 1984; *Mjølhus*, 1990]. The extraordinary mode (or *Z*-mode) can propagate to its higher cut-off altitude and be reflected there. The downward propagating *X*-mode can then be mode-converted into an electrostatic mode. The localized mode-converted wave then leads to strong heating of the electrons, which in turn modifies the local plasma density dominantly by transport processes. The simulations are self-consistent in the sense that the positions of the various critical layers, alluded to above, change with time as the heating modifies the plasma density.

3. Numerical Results

[5] We compare results of our simulations with the experiments carried out during the 17 October-4 November 1988 heating campaign in the Tromsø facility to study the dynamics of the density profile near the reflection height. Radio waves at 7.953 MHz with a power of 56 MW and 280 MW were launched. With the use of a Doppler diagnostic instrument, probe waves at eight frequencies slightly below the pump frequency were launched seven and a half seconds before the turn on of the high power heater wave. The spatial resolution in height due to this multiple-frequency diagnostic was 0.1 km and the temporal resolution was 1 s. The details of the diagnostic technique can be found in [*Lobachevsky et al.*, 1992].

[6] To model the observations in the work of [*Lobachevsky et al.*, 1992], shown in their Figures 3-5, we have used our 2D code with the equations for density and temperature perturbations similar to those given in *Gondarenko et al.* [1999]. The magnetic field in our simulations is inclined at a finite angle with respect to the z axis (it is 12° for Tromsø facility). Thus in our wave model, all three components of the electric field are finite and are evolved in time. The transport coefficients for the electron thermal conduction and the density ambipolar diffusion were obtained from *Gurevich* [1978] and *Blaunstein* [1996]. The parallel thermal conductivity $K_{\|} = 2 \cdot 10^{11} \cdot [(T/T_0)^{5/2}/n]$ cm^2/s and ambipolar diffusion coefficient $D_{\|} = 6 \cdot 10^9 \cdot (T/T_0)$ cm^2/s, where T is the electron temperature at an instant of time while T_0 is the initial electron temperature. These simulations were performed for a heater with intensity $I = 0.028$ and 0.142 mW/m^2 and a heater frequency of 7.953 MHz. In the absence of wave absorption the wave intensity would be $I = 0.07$ mW/m^2 for the effective radiative power (ERP) $P =$ 56 MW at $z_0 = 250$ km and $I = 0.357$ mW/m^2 for $P = 280$ MW. However, we have assumed a 14 *db* reduction in the intensity due to the absorption of the heater wave in the E-region of the ionosphere and a 10 *db* enhancement due to Airy swelling due to the propagation in an inhomogeneous plasma. Our simulations were performed in a computational box 1.53 km wide and 4.9 km high, centered around the upper-hybrid layer.

[7] In Figure 1 we plot the changes in the height Δz (in km) as a function of frequency f (in MHz) calculated with our code. $\Delta z = (\Delta n/n_0)L$, where n_0 is the density at the given height and L is the scale length of the density inhomogeneity. In the absence of any density perturbations for the chosen initial linear density profile, Δz would be zero over the entire range of frequencies. For this low power case, the changes in Δz computed using our 2D code are displayed at t = 0.02, 0.15, 0.5, 1.66, 3.33 and 6.65 s, respectively, after the heater turn on. Note that in order to make direct comparison with the experimental results, we have to average changes in the height over the horizontal direction. The first interesting feature seen in our simulations, which is in agreement with the observations (in Figure 3 of *Lobachevsky et al.* [1992]), is that the maximum change in the density as measured by Δz occurs at the location for which the density is such that the frequency matches the upper hybrid frequency 7.829 MHz, i. e. $\omega_p = \sqrt{\omega_0^2 - \omega_{ce}^2}$. Here ω_0 is the heater frequency, ω_p is the local plasma frequency and ω_{ce} is the electron cyclotron frequency. The increase in Δz indicates that the density at the upper hybrid layer in the unperturbed ionosphere has decreased. The decrease in the density is caused by the strong heating at the layer which leads to an expulsion of the plasma from that height.

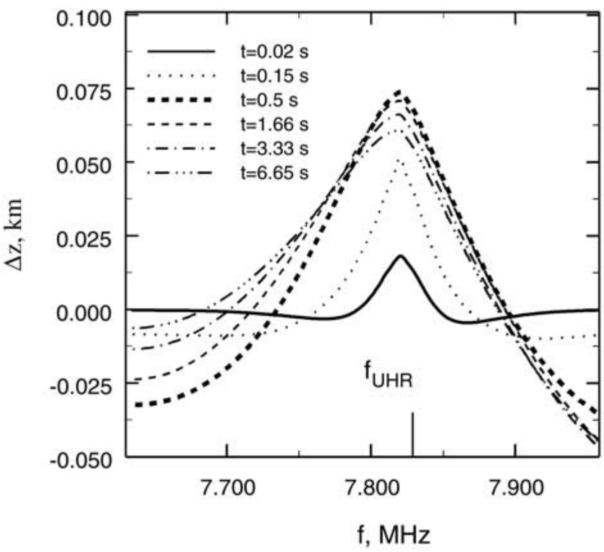

Figure 1. Variations of the plasma frequency profile for P = 56 MW at t = 0.02 s (solid), 0.15 s (dotted), 0.5 s (double-dashed), 1.66 s (dashed), 3.33 s (dashed-dotted) and 6.65 s (dashed-three-dotted).

[8] Many theoretical investigations [*Das and Fejer*, 1979; *Mjølhus and Flå*, 1984; *Gurevich et al.*, 1996, 1999] have conjectured that the region between the upper-hybrid layer and the reflection height is the region of strongest influence of the heater wave, since it is believed that the heater wave can undergo either mode conversion or parametric decay into a large amplitude upper hybrid wave and a low frequency cyclotron wave or lower-hybrid wave. The large amplitude upper-hybrid wave would then heat the local plasma. The observations as well as our simulations indicate that the mode conversion process may be the dominant process leading to the heating and subsequent density modification at the upper hybrid frequency.

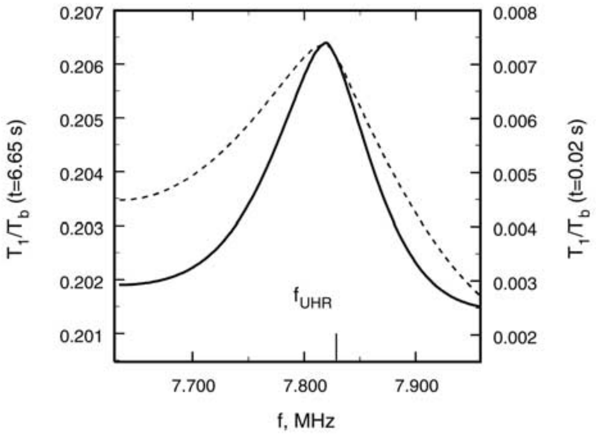

Figure 2. Perturbed temperature profiles at t = 0.02 s (solid line), and 6.65 s (dashed line).

[9] The next characteristic feature that one sees in the observations in Figure 3 of *Lobachevsky et al.* [1992] as well as in our simulations (Figure 1), is that at early time, near the location of the UHR frequency, the local density decreases, but on either side of the resonance layer the density increases (where Δz becomes negative).

[10] This behavior can be understood as follows. The dominant process that controls the dynamics of the electron density is transport. The localized heating at UHR layer and the parallel thermal conduction creates a Gaussian perturbed temperature. The temperature perturbation T_1 normalized to the background ion temperature T_b, shown in Figure 2 (solid line) at t = 0.02 s, clearly demonstrates this. Then the particle flux, associated with this temperature, causes a density perturbation with a spatial structure that resembles the observed density modification. However Figure 1 shows that on a much longer time scale, of about five seconds, the spreading of the density becomes asymmetric about the UHR height with more density depletion occurring below the UHR layer than above it. Figure 2 (dashed line) shows the same asymmetry in the perturbed temperature at later time t = 6.65 s. The heating in the underdense plasma, where the heater wave exists (the electromagnetic component), causes the temperature asymmetry. This additional heating further depletes the density in this region thereby creating the observed asymmetry in the density profile.

[11] In Figure 3 we consider the higher power case with intensity five times larger than that presented in Figure 1. Displayed are the changes in the height as a function of the frequency for t = 0.02, 0.05, 0.1, 0.2, 1.4 and 2.2 s, respectively. What is evident for the higher power case is that the change in the density is almost symmetric near the upper hybrid resonance height on the time scale of about two seconds. This is again consistent with the observed change in height presented in Figure 5 of *Lobachevsky et al.* [1992]. However we find that for the same transport coefficients as that used for the earlier low power case, the level of depletion is a factor of two larger than that observed. The underdense heating has not have enough time to change the local temperature-dependent transport coefficient enough to produce the observed asymmetry for the lower power case. Note that the magnitude of the change in the height is strongly affected by the choice of the transport coefficients so if one would use a higher value for the thermal conductivity coefficient, one should expect the smaller change in the amplitude of the height. Thus the preconditioning of the ionosphere can influence the heating and the subsequent evolution of the density in the vicinity of the upper hybrid layer.

[12] As one can observe in the Figures 1 and 3, the depth of Δz deviation increased with increasing pump power, that is consistent with the theory of *Vaskov and Gurevich* [1977]. However on the other hand, the experimental data in the Figures 3 and 5 of *Lobachevsky et al.* [1992] show that the level of density depletion is almost independent of the pump intensity. There can be various reasons for this discrepancy. First, it appears that the original perturbation in the ionosphere was different in the two experiments. Therefore the ionosphere could have been preconditioned by the earlier heating event so as to modify the transport coefficients. Also it could be that the absorption in the lower ionosphere changed over 20 minutes between the two experiments due to the fact that the high latitude ionosphere is so variable. Thus based on these uncertainties the comparison between the observations and simulations can at best be to the level of noting that the location of maximum change is the same (upper hybrid layer), and the magnitude and time scale for the evolution of the density depletions are very similar.

[13] In conclusion, the results of our simulations demonstrate that in the present formulation, which involves a coupled system of equations for the full-wave propagation in an inhomogeneous magnetized plasma with self-consistent evolution of the density and temperature equations, we can model the evolution of the density variations in the

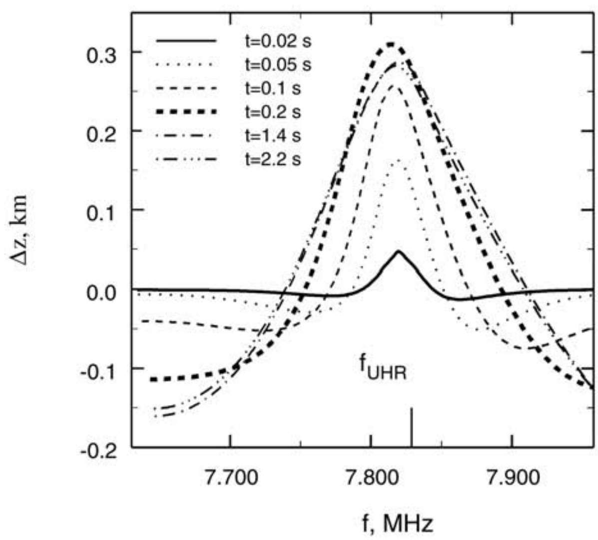

Figure 3. Variations of the plasma frequency profile for P = 280 MW at t = 0.02 s (solid), 0.05 s (dotted), 0.1 s (dashed), 0.2 s (double-dashed), 1.4 s (dashed-dotted), and 2.2 s (dashed-three-dotted).

upper hybrid resonance regions, which is in reasonably good agreement with the observed data.

[14] **Acknowledgments.** This work was supported by NRL under the Grant Number NOO17399C2002.

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