GEOPHYSICAL RESEARCH LETTERS, VOL. 36, L20102, doi:10.1029/2009GL039421, 2009

First observations of X-mode suppression of O-mode HF enhancements at 6300 Å

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Received 2 June 2009; revised 10 September 2009; accepted 15 September 2009; published 22 October 2009.

[1] We present observations of radio induced optical emissions from a HAARP experiment with simultaneous transmission in X and O-mode. The additional transmission of X-mode with a frequency 700 kHz higher than the O-mode, reduces the enhancement of the 6300 Å emission. This suggests that the wave-plasma process that energizes the electrons, which excites oxygen to the O(^1D) state, is closely connected to the excitation of upper-hybrid waves, whose onset and initial growth are reduced by additional X-mode pumping. **Citation:** Gustavsson, B., R. Newsome, T. B. Leyser, M. J. Kosch, L. Norin, M. McCarrick, T. Pedersen, and B. J. Watkins (2009), First observations of X-mode suppression of O-mode HF enhancements at 6300 Å, *Geophys. Res. Lett.*, *36*, L20102, doi:10.1029/2009GL039421.

1. Introduction

[2] A high-power O-mode HF radio-wave transmitted into the ionosphere perturbs the plasma in the region close to the reflection altitude, where the pump-frequency, f_0, equals the local plasma frequency, f_p. This perturbation can be observed in a number of ways: absorption is increased for radio waves with frequencies close to f_0 [*Gurevich et al.*, 1996; *Stocker et al.*, 1993]; the electron temperature is enhanced, from typical F-region temperatures of 1500 K to 2500 K during day-time [e.g., *Honary et al.*, 1993; *Robinson et al.*, 1996] and 3500 K during night-time experiments [*Gustavsson et al.*, 2001; *Rietveld et al.*, 2003]; large and small-scale density depletions are created [*Kelley et al.*, 1995] which causes artificial HF-radar back-scatter [*Bond et al.*, 1997]; in intricate wave-plasma interactions the perturbed plasma itself acts as a transmitter of electromagnetic emissions (SEE) at frequencies just below and above f_0 ($\approx \pm 100$ kHz) [see *Leyser*, 2001, and references therein]; some of the pump-wave energy leads to electron energization [*Carlson et al.*, 1982], which in turn enhances optical emissions in the strongest auroral emissions [e.g., *Bernhardt et al.*, 1989; *Gustavsson et al.*, 2005].

[3] Several of the ionospheric responses to the pump excitation are sensitive to f_0 near harmonics n of the electron gyro-frequency, f_e: stimulated electromagnetic emissions [*Leyser et al.*, 1989; *Stubbe and Kopka*, 1990], anomalous absorption of radio waves propagating through the pump–ionosphere interaction region [*Stocker et al.*, 1993], enhancements of the electron temperature, T_e, [*Honary et al.*, 1995], excitation of filamentary density irregularities [*Ponomarenko et al.*, 1999], and pump-induced emissions at 6300 Å from O(^{1}D), I_{6300}, [*Kosch et al.*, 2002].

[4] Previously it has been found that high latitude radio induced optical emissions are suppressed when the pump-frequency matches the double resonance condition [*Kosch et al.*, 2002; *Gustavsson et al.*, 2006] when f_0 equals the upper-hybrid (UH) frequency, f_{UH}, and a multiple of the electron gyro frequency, nf_e, at the same altitude. During such conditions UH turbulence is suppressed, which leads to reductions in enhancement of electron temperature [*Robinson et al.*, 1996], anomalous absorption of radio waves [*Honary et al.*, 1995; *Robinson*, 1989], as well as reduced back-scatter from artificial field aligned irregularities [*Honary et al.*, 1999; *Ponomarenko et al.*, 1999] and absence of certain features in SEE spectra [e.g., *Carozzi et al.*, 2002; *Leyser*, 2001, and references therein]. An important feature of UH turbulence is the excitation of small scale geomagnetic field-aligned density striations. The excitation of striations, with dimensions across the geomagnetic field of less than the ion gyro radius, has been studied theoretically as starting from infinitesimal density fluctuations, by the thermal parametric instability [*Grach and Trakhtengerts*, 1976; *Istomin and Leyser*, 1997] as well as from finite density perturbations involving the localization of UH oscillations inside the density depletions [*Vas'kov and Gurevich*, 1976; *Dysthe et al.*, 1982; *Gurevich et al.*, 1995; *Istomin and Leyser*, 1997].

[5] The initial growth of the UH related down-shifted maximum (DM) in the SEE spectrum is suppressed when an additional X-mode (right-hand circularly polarized) is transmitted at a frequency that gives the waves approximately similar reflection altitude [*Frolov et al.*, 1999]. This provides another means to investigate the processes that create radio induced optical emissions. With combined observations of SEE spectra, enhanced optical emissions and coherent radar back-scatter it will be possible to determine how density striations influence acceleration of ionospheric electrons.

[6] Here we present the first observations of X-mode reduction of O-mode induced emission at 6300 Å observed

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0094-8276/09/2009GL039421$05.00

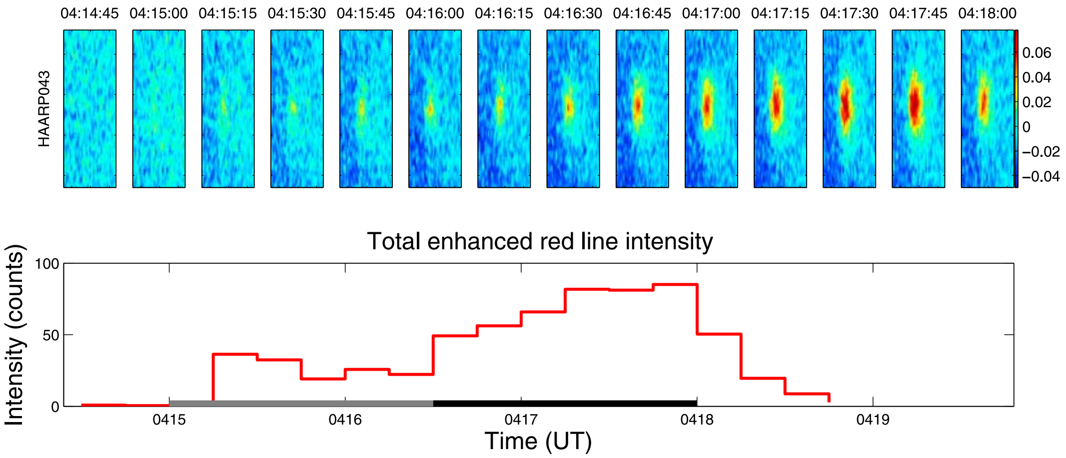

Figure 1. (top) Images of HF enhancements in 6300 Å for the 0415−0418 period. (bottom) Temporal variation of the total enhancement.

during a HAARP (62.39° N, 145.15° W) heating experiment on February 26, 2008. In combination with SEE measurements from Gakona located approximately 10 km away from the HAARP site, these observations show that there is a close connection between striations/UH-waves and electron acceleration.

2. Experiment and Observations

[7] From 0405 UT on February 27 2008 HAARP was operated in a 90 s on O-mode at 2.7 MHz and X-mode at 3.4 MHz, 90 s on O-mode only, 2 min off transmitting sequence, pointing in the magnetic zenith from 0400 to 0420 UT. During the experiment the array was split into two 6-by-15 arrays in North-South giving the beams similar shapes and transmitting approximately equal Effective radiated power, ERP, in X and O-mode. In this configuration the O-mode ERP at 2.7 MHz was $\approx$ 102 MW in a beam with -3 dB widths of 36° in N-S and 15.2° in E-W and the X-mode ERP at 3.4 MHz was $\approx$ 155 MW in a beam with -3 dB width of 29.8° in N-S and 12.1° in E-W.

[8] During the HF pulse from 0415 to 0418 UT on February 26th, it appears as if the enhancement in 6300 A was limited to a very narrow region and that the intensity was suppressed during the initial 90 s when there was additional X-mode transmission. From 0416:30 to 0418 UT the region with enhanced emissions at 6300 grows and the total intensity increases by a factor of 3.

[9] As can be seen in Figures 1 and 2 the growth of 6300 Å enhancement is suppressed by the additional X-mode transmission. In Figure 1 one can also see that the size of the region with enhanced 6300 Å emission is reduced by the X-mode transmission and not only the peak enhancement is suppressed as can be seen in Figure 2. Only after 30 s with O-mode transmission only, does the size of the region with enhanced emission reach a steady state.

[10] In addition to the optical measurements we made simultaneous observations of SEE, coherent radar backscatter and measurements of enhanced plasma-line echoes with the Modular UHF Ionospheric Radar (MUIR) incoherent scatter radar. Here we only discuss the SEE.

[11] Figure 3 displays a spectrogram of SEE for the three first pulses shown in Figure 1. The SEE consists of a slow narrow continuum (SNC) [*Leyser*, 2001] which is seen to be further down-shifted from f_0 than up-shifted. A spectral maximum can be seen at about $f_0 - 700$ Hz. The SEE spectrum resembles that observed in experiments at the High Power Auroral Stimulation (HIPAS) facility, Alaska, also obtained for a relatively low f_0 of 3.349 MHz [*Armstrong et al.*, 1990]. The spectral peak appears at a slightly smaller shift from f_0 than the well known down-shifted peak (DP) for f_0 at an electron gyro harmonic [*Stubbe and Kopka*, 1990] and the narrow continuum maximum (NCM) [*Thidé et al.*, 2005].

[12] As can be seen in Figure 3 the intensity of the entire SEE grows slowly during the O+X-mode transmission and rapidly reaches steady state during the period with O-mode transmission. Figure 4 shows the temporal evolution of the SNC peak intensity. The temporal resolution is 30 s. The

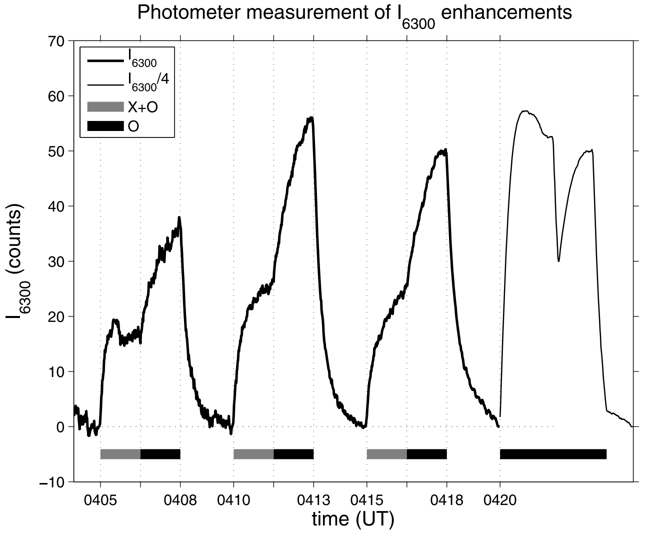

Figure 2. Photometer observations (averaged to a time resolution of 1 s) shows that the additional X-mode transmission suppresses the 6300 Å enhancements during the first 90 s of the HF-pump cycle. The low enhancements compared to the period after 04:20 UT is due to the lower ERP obtained by splitting the antenna array into two halves.

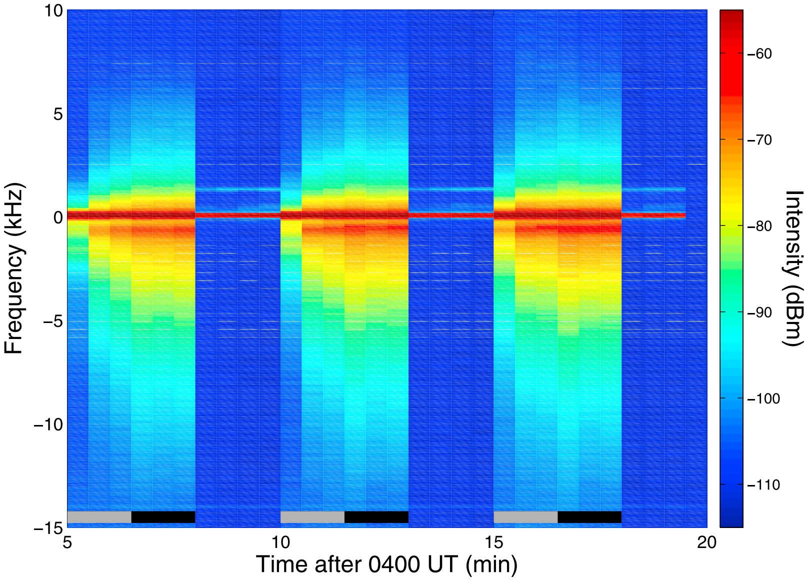

Figure 3. Spectrogram of the stimulated electromagnetic emissions at frequencies close to f_0 shows a slow growth during the first 90 s with O+X mode transmission, while the steady state is reached during the O-mode only period. The display shows spectra averaged over the first 10 s of each 30 s period.

SNC peak intensity grows from pulse to pulse, both during the initial O+X-mode transmission and at steady state. For transmission in O-mode only this feature rapidly, within less than a second, reaches its steady state. When comparing the 6300 Å enhancements in Figure 2 and the SNC peak in Figure 4 it is seen that the effect of the additional X-mode transmission is most pronounced during the first pulse, and reduces for the consecutive pulses. This we interpret as a preconditioning effect. This type of preconditioning has been seen in SEE from upper hybrid oscillations and associated with filamentary density striations, and attributed to pump-induced density irregularities that do not decay completely during pump-off which thus affects subsequent pumping [*Leyser*, 2001].

3. Discussion and Summary

[13] In this report we have presented observations of SEE and radio induced optical emissions showing suppression of the response from additional X-mode transmissions during a HAARP experiment with simultaneous transmission in X and O-mode. These results are in line with the findings of *Frolov et al.* [1999] that the additional transmission of X-mode, with a frequency 700 kHz higher than the O-mode, reduces the initial growth of UH related HF-pump effects. This shows that the wave-plasma process that accelerates the electrons, which excites oxygen to the O(^1D) state, is closely connected with the creation of upper-hybrid waves, that are suppressed by additional X-mode pumping.

[14] In addition to the observations presented here we tried to confirm our findings in observations from a preceding experiment. On 5 and 27 June 2003 a daytime experiment was performed using the EISCAT Heating facility to test whether the growth of O-mode pump-induced field-aligned plasma irregularities would be affected by simultaneous X-mode pumping at a frequency 700 kHz higher. The CUTLASS SuperDARN radar, which routinely observes backscatter from pump-induced striations over EISCAT, was used as the diagnostic (data not shown). Although in some pump cycles there is some evidence of reduced striation growth due to simultaneous X-mode pumping at the beginning of the experiment, the results are not conclusive. As is the case for the HAARP experiment, this may be due to pre-conditioning of the ionosphere, i.e., the 3-minute pump cycle used may have been too short to ensure a cold start.

[15] X-mode HF-waves do not excite Langmuir and UH waves, but cause T_e enhancements by Ohmic heating. The impact of the X-mode transmission on the O-mode induced UH turbulence is twofold. First the increased T_e leads to an increased Ohmic absorption of the O-mode wave, secondly

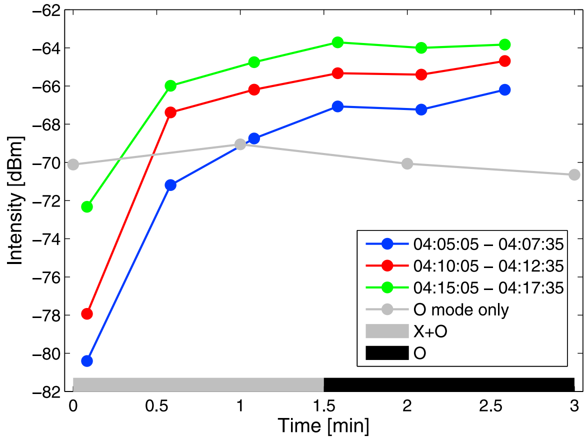

Figure 4. The SNC peak grow slowly during the 90 s with O+X mode transmission and reaches steady state during the O-mode only transmission. The grey curve, from another experiment, shows that for pulses starting with O-mode transmission only the SNC peak reaches steady state within a few 10 ms.

the E-field threshold for the thermal parametric instability depends on the electron temperature, both directly and indirectly through the T_e variation of the electron collision frequency, ν_e. Different theoretical models of the threshold differ with respect to the T_e dependence: $E_{th} \propto T_e^{1/2}\nu_e^{-1/2}$ [*Grach and Trakhtengerts*, 1976], $E_{th} \propto T_e^{3/4}\nu_e^{-1/2}$ [*Dysthe et al.*, 1983], $E_{th} \propto T_e^{1/2}\nu_e^{1/2}$ [*Lee and Kuo*, 1983], $E_{th} \propto T_e\nu_e^{1/2}$ [*Istomin and Leyser*, 1997]. If both electron-ion and electron-neutral collisions are taken into account all four predicted thresholds increase with increasing T_e. Thus, both the observations of suppressed emissions at 6300 Å presented here and the suppression of the initial growth of DM in the SEE spectra can be interpreted in terms of the electron temperature dependence of the excitation of UH oscillations. During X mode electron heating the nonlinear processes related to striations and driven by the O-mode pumping are suppressed. When the X mode heating ceases the ambient electron temperature decreases which results in stronger excitation by the O-mode pump.

[16] A significant difference between the experiment reported from here and the experiment of *Frolov et al.* [1999] is that here the transmitted ERP was on the order of 102 MW while in their experiment the O-mode ERP was 4–18 MW and the X-mode ERP was 20–100 MW. This raises the question of how the suppression effect depends on ERP, which should be answered by experiments with varying ERP - of both the O and X-mode transmissions. Likewise the indications of preconditioning reported here should be further investigated by using HF-off periods of varying length between HF-transmission. A final question that future experiments, is whether the enhancements in other optical emissions with higher excitation threshold, which rely on plasma resonances, is similarly suppressed, or if the suppression is mainly caused by reduction in electron heating.

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