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Formation of artificial ionospheric ducts

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[1] It is well known that strong electron heating by a powerful HF-facility can lead to the formation of electron and ion density perturbations that stretch along the magnetic field line. Those density perturbations can serve as ducts for ELF waves, both of natural and artificial origin. This paper presents the first experimental evidence of plasma modifications associated with ion outflows due to HF heating. The experiments were conducted using the HAARP heater during times that the DEMETER satellite flying at an altitude of approximately 670 km was close to the magnetic zenith of HAARP. The DEMETER satellite has provided in situ measurements of the ion temperature and composition. The experimental results are compared with the numerical model of inter-hemispheric artificial ducts, and it is found that they are in qualitative agreement.


1. Introduction

[2] It is well known that the presence of field aligned density striations plays a critical role in the propagation of whistler waves in the ionosphere [see, e.g., Streltsov et al., 2006]. These density structures serve as ducts for VLF/ELF waves as the density gradient perpendicular to the magnetic field leads to their total internal reflection. Such density structures have often been observed [Carpenter et al., 2002] to extend over distances covering entire magnetic field lines, trapping, channeling and reflecting whistler waves across conjugate regions. In fact, the presence of such ducts is often considered as a pre-requisite to the generation of Artificially Stimulated Emissions (ASE) such as have been extensively studied by using the Siple VLF transmitter [Helliswell, 1988], as well as more recently by the HAARP heater [Inan et al., 2004]. In the HAARP case the VLF waves were generated by modulating the auroral electrojet current at VLF frequencies [see, e.g., Papadopoulos et al., 2003, 2005; Ferraro et al., 1989; Barr and Stubbe, 1993].

[3] The possibility for artificially creating such trans-hemispheric ducts was first discussed by Perrine et al. [2006]. In this paper it was shown that long term (> 15 minutes) continuous HF-heating of the F-region by powerful ionospheric heaters such as HAARP generates a strong heat transport in the ionospheric and magnetospheric plasma, which is often called a “thermal wave”. This thermal wave propagates along the magnetic field line through the topside ionosphere and magnetosphere, driving ion outflows, displacing the ambient plasma and leading to the formation of density ducts that stretch along the magnetic field line to the conjugate point. We should mention that upward ion flows from the ionosphere such as the ones predicted by the model were detected by satellites [Shelley et al., 1976], as well as by the EISCAT incoherent radar [Wahlund et al., 1992]. They are ascribed to frictional ion heating by perpendicular electric fields in the ionosphere. Within our concept the frictional heating is replaced by artificial heating using the HAARP facility.

[4] It is the objective of this letter to present the first experimental evidence of plasma modifications associated with ion outflows due to HF heating. The experiments were conducted using the HAARP heater during times that the DEMETER satellite flying at an altitude of approximately 670 km was close to the magnetic zenith of HAARP, defined at the satellite altitude as the center of the magnetic tube intersecting the heated region in the ionosphere. The DEMETER satellite [Parrot, 2002] provided in situ measurements of the ion temperature and composition.

[5] The letter is organized as following: the next section briefly reviews the theoretical/computational model and its predictions. Section 3 describes the results of the joint HAARP/DEMETER heating experiments. The final section compares the experimental results with the model predictions and discusses their relevance.

2. Global Ionospheric Heating Model

[6] The theoretical/computational modeling is utilized by SAMI2 code which has been developed at the Naval Research Laboratory [Huba et al., 2000]. The code is an Eulerian grid-based code, which describes the ionosphere made up of 7 ion species. The equations of continuity and momentum are solved for the electrons and each ion species, with the temperature equation solved for the electrons and the species H+, He+, and O+. Electron density is determined on the basis of charge neutrality. The code includes E x B drift of the field lines (in altitude and longitude), a neutral atmosphere model, horizontal winds, photo-deposition into the ionosphere, ion chemistry models, and ion inertia. The inclusion of ion inertia is critical since allows for the study of sound wave propagation in the plasma. The SAMI2 model is inter-hemispheric and can thus simulate the plasma along entire magnetic dipole field...
Figure 1. Predicted changes in ion composition above the heated region during artificial heating. The vertical axis is the fraction of the total ion number density that is a single species, with traces (1) and (2) representing O⁺, and traces (3) and (4) representing H⁺ under both ambient and heated conditions, respectively. He⁺ which is weakly affected by the ionospheric heating, is shown by the trace (5). This plot represents the system after 15 minutes of HF-heating. Heating parameters for this data: \( q = 5000 \, \text{K/s,} \, z_0 = 380 \, \text{km}. \)

Figure 2. Changes in ion temperature above the heated region during artificial heating. Computed at the same conditions as in Figure 1.

3. Experiments

[11] A number of experimental tests were conducted following the completion of the HAARP heater in 2007. In all of the tests the transmitted power was 3.6 MW, O-mode and the beam was directed along the HAARP magnetic zenith. The modified ionosphere was sensed by two instruments on-board of Demeter, the ICE detector that measures the ionospheric electric field vectors, and the plasma analyzer that measures the ion temperature and composition (O⁺, H⁺, He⁺) [Berthelier et al., 2006a, 2006b]. We report below on cases corresponding to DEMETER-HAARP zenith closest approach less than 300 km. We identified five such cases during our experimental time. However, in two of those cases the F₂-layer critical frequency, \( f_0F₂ \), was much lower than the frequency available from the transmitter resulting in very weak absorption and no detectable effects.

[12] Table 1 describes the heater and ionospheric parameters for the remaining three cases. During the transmission and to accommodate a different experiment the transmitter was modulated by ULF frequency. The effect of the modulation was to reduce the effective constant wave power by a factor of approximately two.
In all of the above cases the on-site HAARP diagnostics indicated a smooth F-region layer, negligible D/E region absorption and absence of electrojet current. Figures 3 and 4 show key measurements made during two of the above DEMETER passes, 4/24/07 and 8/01/07. Figure 3 shows ion temperature and density profiles for the first case of Table 1. Both the ion temperature and O$^+$ density rise due to the HF-heating by about 60–70%. The rise of the temperature and density was detected over 3–4 minutes corresponding to 1,300 – 1,700 km distances. Reduction in the H$^+$ density correlated with the heating was also observed (not shown here) near the closest approach. The temperature peak occurs one minute earlier than the density. That corresponds to a lateral shift of approximately 480 km. Notice also a spatial asymmetry of the ion outflows directed towards the incoming satellite (see Figure 3). Notice the presence of a duct associated with the density gradient between 06:51:00 and 06:51:30 (marked by (1) in Figure 3), the presence of a cavity between 06:54:30 and 06:55:00 (marked by (3)), as well as a series of few percent short length ducts between 06:52:00 and 06:53:30 (marked by (2)). The latter correspond to magnetoionic waves at the 0.1 Hz modulation and are correlated with simultaneous detection of 0.1 Hz oscillations in both horizontal components of the electric field in the region of closest approach. They will be examined in a future publication.

Third case of Table 1 is similar to the second one (the figure is not presented). We detected increase in $T_i$ and O$^+$ density due to HF-heating ($\Delta T_i/T_i \approx 0.3, \Delta n_i/n_i \approx 2.5$), caused by the ion outflows. Reduction of the H$^+$ and He$^+$ was also observed. Similarly to the second case the natural ion precipitation occurred at the late stage of these observations as revealed by the DMSP F16 satellite, which led to the ion density perturbations.

4. Discussion

We presented the first experimental verification of strong ion outflows and formation of the ionospheric ducts by F-region ionospheric heating. Their generation requires
strong F-region heating which is known to be optimal in a quiet ionosphere with a distinct smooth $F_2$ region, and minimal D/E region absorption. The ion outflows and density structures are best detected by satellites passing within a few hundred kilometers to the HAARP magnetic field line.

[17] In the frequency range of 3–6 MHz the HF-heated region at 250–270 km is elliptical with the short axis 60–80 km and long axis 80–100 km. The abovementioned spread of the ion outflows by 1,300–1,700 km is partly due to $E \times B$ drifts. In fact, the electric field component perpendicular to the DEMETER orbit is 25–30 mV/m, corresponding to drift velocity directed along the DEMETER orbit in the range 0.4–0.5 km/s. Since the HF-heating by HAARP starts 10–15 minutes prior to the DEMETER over-fly the ion outflows spread by about 500 km, which is less than that observed, although some other phenomenon like winds could play a role.

[18] Furthermore the electric field component perpendicular to the DEMETER orbit is in E-W direction, resulting in southward ion drift, i.e. toward the satellite. It accounts for the presence of the spatial asymmetry toward the incoming satellite in Figure 3b.

[19] We should finally comment on the observed shift between the peaks of the perturbed ion temperature and the density of the oxygen ions (see Figure 3). We attribute this to the fact that two different transport mechanisms are involved, as seen in our model. First, the thermal wave caused by the electron heating transfer energy excess to ions. Later on the heating perturbs the electron density at the heating spot. This creates a temporary pressure imbalance which drives the density perturbations along the field line leading to ion outflows.

[20] Our computations reveal that at the heating rate such as produced by HAARP the expected ion temperature increase is approximately 70% at a distance 400 km above the heated spot along the field line, while the $O^+$ density rises by about 20%. This is in qualitative agreement with the observations. Notice, however, that the version of SAMI2 used here was appropriate to low and mid latitudes. A version of the code which describes high latitudes has been developed at NRL and we are planning to use it in quantitative comparisons with experiments.

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