Ionospheric Ducts and Plasma Waves Induced by HF Heater over Gakona

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Abstract

Ionospheric HF heating experiments were conducted at Gakona, Alaska to investigate (1) ionospheric ducts (viz., large plasma sheets acting as parallel-plate waveguides) and (2) cascading spectra of Langmuir wave turbulence, excited by large- and short-scale plasma instabilities, respectively. The first subject is inspired by our earlier Arecibo experiments [Lee et al., 1998] whereby sheet-like ionospheric ducts were generated by HF heater waves and detected by Arecibo radar. The second one is aimed at testing our theory of [Kuo and Lee, 2005] that addresses how the cascade of Langmuir waves can distribute spatially via the resonant and non-resonant decay processes.

1. Motivations

During 2005-2007 we have conducted experiments at Gakona, Alaska to investigate field-aligned large-scale ionospheric plasma irregularities (i.e., ionospheric ducts) and spatial distribution of Langmuir waves generated by the HAARP HF heater. It is expected that sheet-like ionospheric density irregularities can be excited above Gakona within minutes by vertically injected O-mode and X-mode heater waves. This expectation is based on our theory of thermal filamentation instabilities [1] and the detection of large plasma sheets in our 1997 Arecibo experiments [2]. In brief, sheet-like plasma irregularities were generated by O-mode heater waves within the meridional planes. When these plasma sheets experienced E x B drifts, they were detected by incoherent scatter radar (ISR) and seen as slanted stripes in the range-time-intensity (RTI) plots (see Figures 3 and 5 of [2]). These sheet-like structures can act as parallel-plate waveguides (viz., ionospheric ducts) to effectively guide whistler waves to propagate from the ionosphere into the magnetosphere. It was demonstrated that 28.5 kHz whistler waves launched by the Naval transmitter (code-named NAU at Aguadilla, Puerto Rico) could be guided by these waveguide structures to propagate from Arecibo, Puerto Rico to reach Trelew, Argentina near the magnetic conjugate point [3-5].

In contrast, Langmuir waves are important short-scale plasma waves parametrically excited by HF heater waves less than a second. The recent work of Kuo and Lee [6] presents a theory to describe how Langmuir waves excited by O-mode heater waves via parametric decay instability (PDI) or oscillating two-stream instability (OTSI) can distribute spatially in ionospheric plasmas. It predicts two possible processes generating spectra of Langmuir waves via resonant and non-resonant cascading mechanisms. The non-resonant mechanism occurs at the same height where the PDI or OTSI is excited, to generate cascading Langmuir waves under the eigen-frequency mismatch condition. In the resonant process, the PDI or OTSI-excited Langmuir wave will propagate to a lower altitude as a pump wave to excite Langmuir cascades via a parametric instability. The tradeoff is that the Langmuir pump wave experiences propagation attenuation before cascading occurs. The instability thresholds under the frequency mismatch in the former process are found to be significantly greater than those under the propagation loss in the latter. Because of the lower instability thresholds, Kuo and Lee's theory predicts the following for experiments to verify. The resonant cascade process would be the dominating mechanism, which produces cascading spectra of Langmuir waves in several patches at different altitudes during the O-mode overdense heating of ionospheric plasmas. Because Langmuir waves are excited in a time scale much shorter than that for ionospheric ducts, we discuss the cascading spectra of Langmuir waves first.

2. Spatial Distribution of HF Wave-excited Langmuir Waves

The set of data presented in Figure 1 was acquired by HAARP MUIR radar in our March 18, 2006 experiments at 3:14:58 UT. In the experiments we transmitted O-mode heater wave along magnetic at 4.3 MHz CW, when the local peak plasma frequency was 4.5 MHz. The MUIR antenna was directed along the magnetic zenith, transmitting coded-long pulses of 998-µs length with 10-ms IPP and 1-µs baud length, thus yielding 150 m range resolution. MUIR detected three cascade lines, as displayed in Figure 1. The intensity is in SNR (dB) relative to the average noise level. The changes in altitude were measured as 174 m from the first to the second peak and 225 m from the second to the third peak, corresponding to ionospheric plasma inhomogeneity scale lengths of 41.9 km and 54.2 km, respectively.

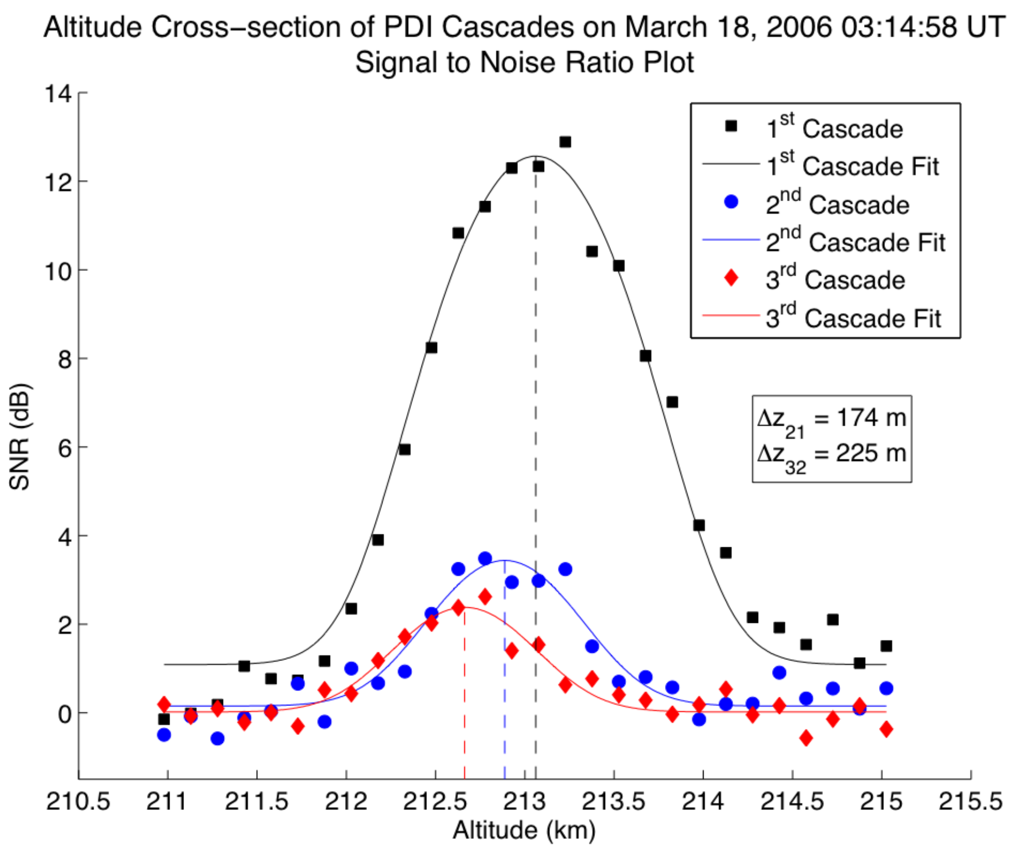

Figure 1. Altitude cross-sections of MUIR data from March 18, 2006 at 3:14:58 UT.

These observations were cross-checked with the predictions from the resonant and non-resonant decay theory of Kuo and Lee. The electric field amplitude of the injected wave is ~1.2 V/m. The calculated wave field damping factor for scale lengths 41.9 km and 54.2 km are 2.95 and 4.05, respectively. Using these wave field damping factors, the pump wave amplitude falls below the threshold of 0.075 V/m after undertaking three cascades. This agrees well with our observations with MUIR. When checked with the non-resonant cascade thresholds, only 2 cascades are expected proving that the non-resonant cascade is not possible in this experiment. In addition, the frequency difference between two adjacent plasma lines ranges from 7.7 to 8.8 kHz which is about twice the local ion acoustic wave frequency, reflecting the spectral characteristics of resonant cascade Langmuir waves. Consistent results were also obtained for our August 2007 campaign.

3. Ionospheric Ducts Created by Thermal Filamentation Instabilities

The ionospheric plasma environment at Gakona, Alaska is quite different from that at Arecibo, Puerto Rico. The magnetic dip angles are 75.4º at Gakona and 45º at Arecibo, respectively. Because of the large magnetic dip angle, the E x B drifts of ionospheric plasma structures will move nearly horizontally at Gakona for eastward or westward quasi-DC electric field (E). Thus, it would be rather difficult to see the slanted stripes in the ISR-generated range-time-intensity (RTI) plots. However, using ionosonde, we are able to investigate other characteristic features of the thermal filamentation instability-induced ionospheric duct at Gakona. As illustrated in Figure 2, ionosonde signals had no problem to be totally reflected and appear in ionograms in the presence of O-mode generated plasma sheets, which are parallel to the meridional plane.

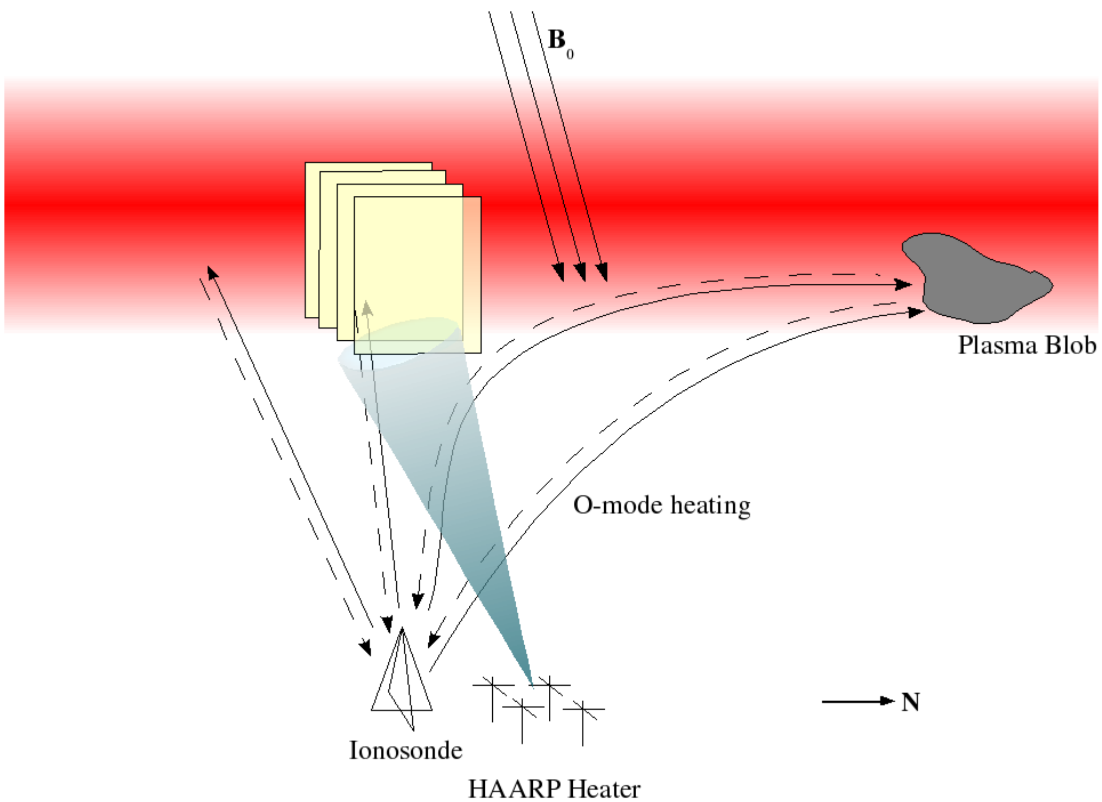

Figure 2. Large plasma sheets are generated by O-mode heater waves within the meridional plane.

In contrast, because X-mode heater waves induce orthogonal plasma sheets, ionosonde signals transmitted near the zenith will be guided to propagate away, as delineated in Figure 3. They, thus, cannot be reflected to appear in the ionograms. However, when plasma blobs are present, the ionosonde signals transmitted at a large angle may still be bounced back from the remote plasma blobs, as observed in our August 21, 2005 experiments. The prominent effect of Bragg scattering of ionosonde signals by heater-induced medium-scale ionospheric irregularities was confirmed by skymaps. A correlation of skymap signal intensity with heater operation was clearly found.

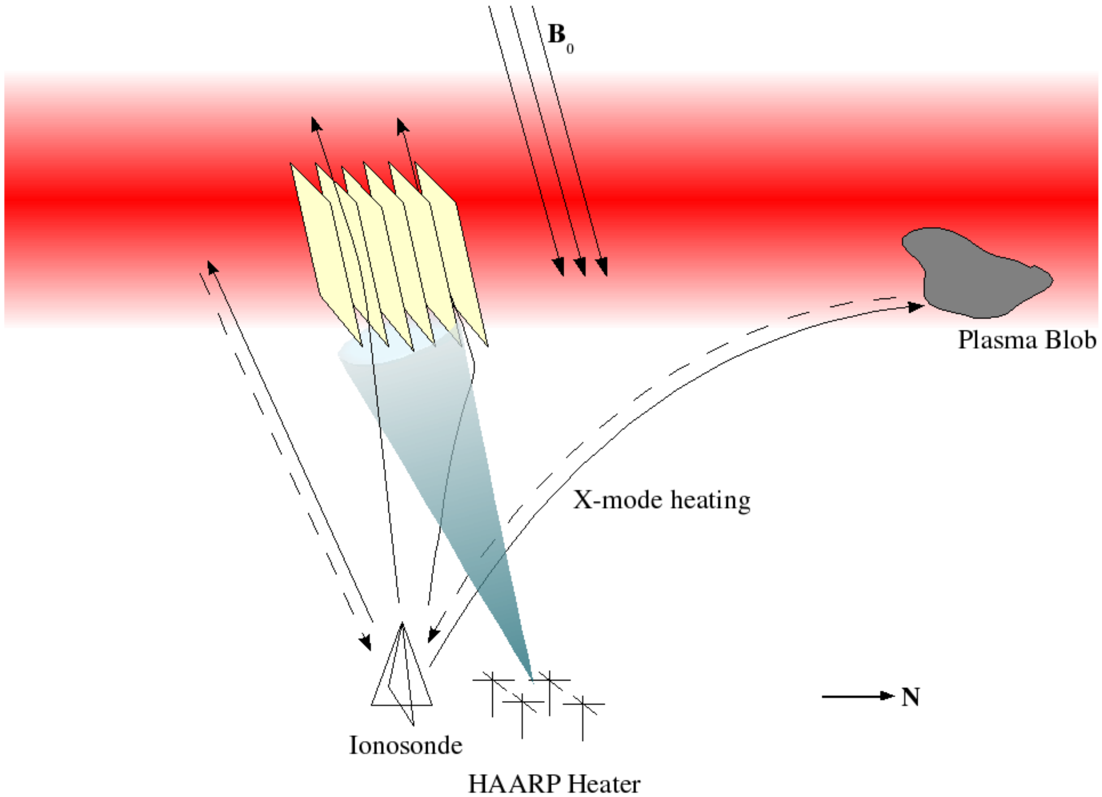

Figure 3. Large plasma sheets generated by X-mode heater waves are orthogonal to the meridional plane. Ionosonde signals transmitted near the zenith will be guided by these plasma sheets to propagate away. Those ionosonde signals transmitted at large angles from the zenith can still be reflected by remote plasma blobs and recorded in ionograms**.**

References

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