Theoretical studies of fast stochastic electron heating near the upper hybrid layer

A. Najmi, 1 B. Eliasson, 2 X. Shao, 1 G. Milikh, 1 and K. Papadopoulos 1

1 Departments of Physics and Astronomy, University of Maryland, College Park, MD, USA

2 SUPA, Department of Physics, University of Strathclyde, Glasgow, Scotland, UK

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Abstract

It is well-known that heating of the ionosphere by high-frequency (HF), ordinary (O) mode electromagnetic waves, can excite magnetic field aligned density striations (FAS) in the ionospheric plasma. Furthermore, the O-mode pump wave can excite upper hybrid and lower hybrid turbulence in the striations. We have used Vlasov simulations in one spatial and two velocity dimensions to study the effects of ionospheric heating when the pump frequency is in the vicinity of the upper hybrid resonance, employing parameters consistent with high-latitude ionospheric heaters such as HAARP. We have found that by seeding the plasma with a meter-sized FAS with a 10% density depletion, and applying a spatially uniform HF dipole pump electric field representing the O-mode, the pump wave gives rise to upper hybrid and lower hybrid turbulence, as well as to large amplitude electron Bernstein waves. The latter leads to stochastic, collisionless, bulk electron heating when the amplitude of the electron Bernstein waves exceeds a threshold value for stochasticity. This leads to a rapid increase of the electron temperature by several thousands of Kelvin within the striation.
I. INTRODUCTION

For more than forty years, large amplitude HF radio waves have been used to generate and study ionospheric turbulence near the turning point of electromagnetic waves. These experiments have given rise to a large variety of phenomena such as: artificial optical emissions, stimulated electromagnetic emissions, density perturbations, triggered ELF and ULF waves, and field-aligned striations (FAS). FAS were first produced during O-mode HF heating of the ionospheres F-region at the Platteville HF heater Rao and Thome [1974] and they were found to scatter various electromagnetic signals. EISCAT experiments have also produced FAS. Rietveld et al. [2003] presented observations of 20% electron depletions inside FAS near their interaction height, while Blagoveschenskaya et al. [2011] were able to excite meter-scale FAS using both O-mode and X-mode HF waves.

Below the turning point of the O-mode wave, upper hybrid and lower hybrid turbulence take place and FAS are formed on the timescales of a few seconds [Frolov et al. 1997]. After FAS have been formed, O-mode electromagnetic waves are mode converted to upper hybrid waves leading to an enhancement of the upper hybrid and lower hybrid turbulence, and to anomalous absorption of the electromagnetic wave. This gives rise to efficient heating of electrons. Experiments performed by Rietveld et al. [2003] at the EISCAT heater in Tromsø directly measured electron temperature using incoherent scatter radars (ISR). They found an increase in electron temperature by up to 3000K, while the ion temperature was enhanced by only about 100K.

Near the turning point of the O-mode wave, where the wave frequency equals the electron plasma frequency, strong Langmuir turbulence is generated due to the interaction between large amplitude Langmuir waves and ion acoustic waves. The resonant wave-particle interactions can lead to the acceleration of high energy tails of the plasmas electrons through caviton plasma oscillations. Hot electrons moving faster than the phase speed of the plasma oscillations are accelerated, while cooler electrons merely oscillate. After the HAARP facility was upgraded to produce ERPs up to 5 GW, Pedersen et al. [2009] almost immediately observed descending artificial ionospheric layers (DAILs). The mechanism of the layer formation is believed to be the ionization of the neutral gases by suprathermal electrons accelerated by
TABLE I: Summary of physical parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>(n_0)</td>
<td>(1.27 \times 10^{11} \text{ m}^{-3})</td>
<td>(\omega_{pe})</td>
<td>(20.09 \times 10^6 \text{ s}^{-1} = 3.197 \text{ MHz})</td>
</tr>
<tr>
<td>(B_0)</td>
<td>(5.17 \times 10^{-5} \text{T})</td>
<td>(\omega_{ce})</td>
<td>(9.092 \times 10^6 \text{ s}^{-1} = 1.447 \text{ MHz})</td>
</tr>
<tr>
<td>(E_0)</td>
<td>(2.0 \text{ V/m})</td>
<td>(\omega_0)</td>
<td>(21.59 \times 10^6 \text{ s}^{-1} = 3.436 \text{ MHz})</td>
</tr>
<tr>
<td>(T_{e0})</td>
<td>(1500 \text{ K})</td>
<td>(v_{Te0})</td>
<td>(1.508 \times 10^5 \text{ m/s})</td>
</tr>
<tr>
<td>(T_{i0})</td>
<td>(1000 \text{ K})</td>
<td>(\omega_{LH})</td>
<td>(1.95 \times 10^5 \text{ s}^{-1} = 31 \text{ kHz})</td>
</tr>
</tbody>
</table>

The purpose of this paper is to explore heating mechanisms near the upper hybrid layer using simulations relevant to ionospheric heating experiments. We will discuss the possibilities for bulk heating of electrons by upper hybrid waves and electron Bernstein waves produced by parametric decay instabilities near the upper hybrid resonance.

II. SIMULATION

The Vlasov equation describes the evolution of the distribution function \(f_\alpha\) of charged particles of species \(\alpha\) in position and velocity space. The O-mode pump wave is represented by an external oscillating, dipole electric field \(\vec{E}_{ext} = \hat{x} E_0 \sin(\omega_0 t)\) directed along the x-axis at frequency \(\omega_0 = 21.59 \times 10^6 \text{ s}^{-1}\) and with a constant amplitude \(E_0\) in space. As an initial condition, we seed a Gaussian density striation and choose the pump frequency such that \(\omega_0\) equals the local upper hybrid frequency \(\omega_{UH} = \sqrt{\omega_{pe}^2 + \omega_{ce}^2}\) at the half-maximum of the striation. We take the electrostatic approximation and use a Fourier method [Eliasson 2010] to solve the Vlasov equation in position and velocity space. This results in a spatial grid of 1.5cm and an average time-step of 7ns. Our simulation parameters are summarized in table I.
III. RESULTS

Our simulation included a number of diagnostics: the ion density and electron temperature are derived from moments of the distribution functions, while wave modes may be examined from the simulation electric fields. We observed significant correlations, including a shared characteristic turn-on time of 0.05 ms.

Plots of the ion density, both evolution in time and snapshots in time, are shown in figure 1. After the turn-on time of 0.05 ms, the ion density shows a standing wave pattern oscillating in time with frequency close to the lower hybrid frequency. In each case, we can see five depletion zones forming before the turn-on time, while at slightly later times many smaller scale structures also develop.

Similar plots showing both the time evolution and snapshots in time of the electron temperature are shown in figure 2. The electron temperature is characterized by the same turn-on time of 0.05 ms as seen in the ion density. The most efficient heating occurs near the center of the striation while electrons outside of the central cavity are heated slowly. After the initial turn-on time, the electrons in the striation are heated rapidly to $T_e \approx 3000K$ over the next 0.05 ms, after which they heat more slowly to $T_e \approx 4500K$ over the remaining 0.20 ms.

Inside the striation, a variety of high and low frequency waves are excited by the external pump wave. The absolute value of the electric field is shown in figure 3a while the power spectrum in $\omega - k$ is shown in figure 3b. The pump wave is seen just below $f = 3.5$ MHz at $k = 0$. The immediately neighboring non-zero wavenumbers are upper hybrid waves,
and the spectral components that extend out to higher wavenumbers are branches of the electron Bernstein waves. Similarly, the arched features near $k = 50 \text{ m}^{-1}$ and $f = 2.0 \text{ MHz}$ are continuations of the electron Bernstein wave dispersion curve. The branch of the Bernstein waves associated with the upper hybrid frequency has a resonance at the second cyclotron resonance, $\omega = 2\omega_{ce} = 2.9 \text{ MHz}$, while the arched branches are associated with the first cyclotron resonance $\omega = \omega_{ce} = 1.45 \text{ MHz}$ at large wavenumbers. Components of the third Bernstein wave are visible for frequencies near $f = 4.5 \text{ MHz}$. The last important feature is the lower hybrid waves, visible for $-100 \leq k \leq 100 \text{ m}^{-1}$ and near $f = 30 \text{ kHz}$. 
FIG. 4: Upper hybrid wave decays to, 4a, two electron Bernstein waves, 4b, an electron Bernstein wave and a lower hybrid wave. In each figure, the lower hybrid dispersion curve is indicated for reference. In 4a, the difference between the $1\omega_{ce}$ and $2\omega_{ce}$ Bernstein wave dispersion curves are also plotted, and in 4b, the upper hybrid dispersion curve and the difference between the upper hybrid and $2\omega_{ce}$ Bernstein wave dispersion curves are also plotted.

IV. DISCUSSION

The rich $\omega-k$ spectra seen in figure 3b can be explained by parametric decay instabilities, and large amplitude electron Bernstein waves can explain the bulk heating. Pump waves mode converted to upper hybrid waves can decay through three wave processes to daughter upper hybrid waves and lower hybrid waves. By employing frequency and wavenumber matching, and using the upper hybrid dispersion relation, it can be shown that daughter upper hybrid and lower hybrid waves produced in this process condense to small wavenumbers. To explain the Bernstein waves in the simulation, we first solve the Bernstein wave dispersion relation numerically. Since the lower branch is about half the pump frequency and the upper branch is close to the pump and upper hybrid frequency, we can consider the decay of a pump to two Bernstein waves of the lower branch, or to one Bernstein wave of the upper branch and a lower hybrid wave. These processes are outlined in figures 4a and 4b. The latter process provides a mechanism for producing large wavenumber waves near...
both the upper hybrid and lower hybrid frequency while avoiding the condensation to small wavenumber that is produced by a simple decay of upper hybrid waves to upper hybrids and lower hybrids.

The acceleration of charged particles by electric field gradients perpendicular to a stationary magnetic field can lead to stochastic motion and rapid heating. Previous work by [Balikhin et al. 1993] and [Stasiewicz et al. 2000] has shown that for the stochastic heating of electrons and ions by nonlinear electrostatic waves, if a condition on the amplitude of the electric field gradients given by

\[ |A| = \left| \frac{m}{qB_0^2} \frac{\partial E_x}{\partial x} \right| \gtrsim 1. \quad (1) \]

is fulfilled, particle orbits that are initially close in phase space will diverge exponentially in time leading to rapid heating. Following this idea, we have plotted \( A \) in figure 5a, focusing on the region in the striation, near the characteristic turn-on time. We find \( |A| > 1 \) and by examining the \( \omega - k \) spectrum in figure 5b near this time, we see that the primary contributions to \( A \) during the fast heating come from waves near the upper hybrid frequency at a broad spectrum of wave numbers. Since the decay of a mode converted pump to upper hybrid and lower hybrid waves condenses to small wavenumbers, and since there exists a decay path of mode converted pumps to large wavenumber electron Bernstein waves near the upper hybrid frequency (see figure 4b), we conclude that electron heating is primarily due to large amplitude electron Bernstein waves.
V. CONCLUSION

We have presented the results of Vlasov simulations of ionospheric heating near the upper hybrid resonance layer in the presence of a small-scale density striation. We found that electrons in the striation were heated, the primary driver of heating was electron Bernstein waves near the upper hybrid frequency, and that the heating was a bulk, collisionless, heating and not an acceleration of suprathermal tails.

Acknowledgments

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