HEATING OF HEAVY IONS ON AURORAL FIELD LINES

DEQ3 006546

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ABSTRACT

Heating of heavy ions is studied in the presence of large amplitude hydrogen cyclotron waves. A three wave decay process, in which a large amplitude pump hydrogen cyclotron wave decays into a daughter hydrogen cyclotron wave and a low frequency oxygen cyclotron wave, is studied theoretically and by numerical simulations. The numerical simulations show a decay instability resulting in strong heating of both the oxygen ions and the hydrogen ions. In particular, the high energy tail of the oxygen ions is observed in the perpendicular distribution.

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I. INTRODUCTION

Electrostatic hydrogen cyclotron (EHC) harmonic waves of large amplitude have been found to grow on auroral field lines as observed by satellites (Mozar et al., 1977; Kintner et al., 1979) and by rocket measurements (Yau et al., 1982). The S3-3 satellite data suggest the presence of upstreaming energetic H^+ and O^+ ions whose energies range up ~ 10 keV (Shelly et al., 1976; Ghielmetti et al., 1978). It has recently been recognized that heavy ions are important in the dynamics and stability of different regions in the earth's magnetosphere. At altitudes ~ 1500 km, measurements from the ISIS-1 and ISIS-2 satellites report the existence of ion distributions with enhanced particle fluxes at pitch angles between 90-130 degrees (Sharp et al., 1977; Klumprar, 1979; Ungstrup et al., 1979). Such distributions are commonly termed ion conic distributions. Gorney et al. (1981) found ion conics were observed uniformly at altitudes above 2000 km, suggesting the generation of conics at low altitude. At such low altitudes, the recent S3-3 data show that the ion composition can vary from more than 10% oxygen to 90% oxygen (Mizera et al., 1980).

A source of free energy for the production of EHC waves could be the field aligned currents which are a pertinent feature of the auroral zone (Drummond and Rosenbluth, 1962; Kindel and Kennel, 1971; Mozar et al., 1977). The heating of both hydrogen and oxygen ions is studied in the presence of currents (Okuda and Ashour-Abdalla, 1981; Ashour-Abdalla et al., 1981). They found both the ions are accelerated by the cyclotron waves excited by the electron flow. Rysak et al. (1980) and Papadopoulos et al. (1980) examined the acceleration of heavy ions in the presence of a coherent large amplitude electrostatic hydrogen cyclotron wave where the heavy ions are a minority constituent of many magnetospheric multi-ion plasmas. They found

that when the wave amplitude exceeds a certain critical value, the particle orbits become stochastic and therefore the heavy ions can be accelerated by the wave.

In this letter we consider the acceleration of heavy ions along auroral field lines via three wave decay instabilities by large amplitude hydrogen cyclotron waves (Nakach et al., 1981). In Sec. II, we present the theoretical analysis of the three wave decay process in which a large amplitude pump hydrogen cyclotron wave decays into a daughter hydrogen cyclotron wave and a low frequency oxygen cyclotron wave propagating at an arbitrary angle among each other. The simulation model and results are presented in Sec. III. In Sec. IV, we present concluding remarks and discussions.

II. THEORETICAL ANALYSIS

We consider a plasma consisting of cold hydrogen and oxygen ions, and warm electrons immersed in an external homogeneous magnetic field $\mathbf{B}_0$ in the presence of a large amplitude hydrogen cyclotron wave. This system is described in the framework of a fluid model. Neglecting all dissipative effects, the basic equations are

$$\frac{\partial \mathbf{v}_H}{\partial t} + \mathbf{Q}_H \times \mathbf{v}_H + \frac{e}{m_H} \nabla \phi = - (\mathbf{v}_H \cdot \nabla) \mathbf{v}_H \quad (1)$$

$$\frac{\partial n_H}{\partial t} + \nabla \cdot (n_H \mathbf{v}_H) = 0 \quad (2)$$

$$\frac{\partial \mathbf{v}_O}{\partial t} + \mathbf{Q}_O \times \mathbf{v}_O + \frac{e}{m_O} \nabla \phi = - (\mathbf{v}_O \cdot \nabla) \mathbf{v}_O \quad (3)$$

$$\frac{\partial n_O}{\partial t} + \nabla \cdot (n_O \mathbf{v}_O) = 0 \quad (4)$$

$$n_H + n_O = \bar{n}_e \exp\left(\frac{e\phi}{T_e}\right) \quad (5)$$

The subscripts H, O, and e stand for hydrogen, oxygen, and electron, respectively. Equation (5) corresponds to the quasi-neutrality condition. We assumed that the external magnetic field B_0 is taken in the y-z plane and all the wave vectors are taken in the x-y plane.

We study the decay process in which the large amplitude pump hydrogen cyclotron wave (ω_{k_0}, k_0) decays into the daughter hydrogen cyclotron wave (ω_{k_1}, k_1) and the low frequency oxygen cyclotron wave (ω_{k_2}, k_2) . This decay process satisfies the matching conditions, $\omega_{k_0} = \omega_{k_1} + \omega_{k_2}$ and $k_0 = k_1 + k_2$. We consider the large amplitude hydrogen cyclotron wave in the form of $E_0 \{\exp[i(k_0 \cdot r - \omega_{k_0} t)] + c.c.\}$ where $E_0 \parallel k_0$ and E_0 is the amplitude of the electric field.

In order to obtain a nonlinear dispersion relation describing decay instabilities, Eqs. (1)-(4) are first linearized to find small amplitude perturbations which are then iterated to the second order (see for example, Nishikawa, 1976). The nonlinear dispersion relation is given by

$$\left(1 - \frac{\alpha_H C_H^2 k_1^2}{\omega_{k_1}^2 - \Omega_H^2}\right) D_{k_1} = \frac{\alpha_H C_H^2 \omega_{k_1} k_1^2}{2(\omega_{k_1}^2 - \Omega_H^2)} \left[\frac{\lambda_{k_1}(k_0, -k_2)}{(\omega_{k_1}^2 - \Omega_H^2) k_0^2 (-k_2)^2} + \frac{\mu_{k_1}(k_0, -k_2)}{\omega_{k_1}} \right] D_{k_0} D_{-k_2} \quad (6)$$

$$\left(1 - \frac{\alpha_H C_H^2 k_2^2}{\omega_{k_2}^2 - \Omega_H^2} - \frac{\alpha_O C_O^2 k_2^2}{\omega_{k_2}^2 - \Omega_O^2}\right) D_{k_2} = \frac{\alpha_H C_H^2 \omega_{k_2} k_2^2}{2(\omega_{k_2}^2 - \Omega_H^2)} \left[\frac{\lambda_{k_2}(k_0, -k_1)}{(\omega_{k_2}^2 - \Omega_H^2) k_0^2 (-k_1)^2} + \frac{\mu_{k_2}(k_0, -k_1)}{\omega_{k_2}} \right] D_{k_0} D_{-k_1} \quad (7)$$

where

$$\begin{aligned} \lambda_k(\tilde{k}', \tilde{k}'') &= \tilde{k}' \cdot \tilde{k}'' [\tilde{k}^2 + \frac{\Omega_{Hz}^2}{\omega_k} (\frac{\tilde{k} \cdot \tilde{k}'}{\omega_{k'}} + \frac{\tilde{k} \cdot \tilde{k}''}{\omega_{k''}}) + \hat{z} \cdot (\tilde{k}' \times \tilde{k}'') (\frac{\Omega_{Hz}}{\omega_{k''}} - \frac{\Omega_{Hz}}{\omega_{k'}})] \\ &+ \hat{z} \cdot (\tilde{k}' \times \tilde{k}'') [\frac{\Omega_{Hz}}{1\omega_{k'}} \tilde{k} \cdot \tilde{k}'' - \frac{\Omega_{Hz}}{1\omega_{k''}} \tilde{k} \cdot \tilde{k}' + \frac{\Omega_{Hz}^3}{1\omega_k \omega_{k'} \omega_{k''}} (\tilde{k}''^2 - \tilde{k}'^2) \\ &+ \frac{\Omega_{Hz}}{\omega_k} \hat{z} \cdot (\tilde{k}' \times \tilde{k}'') (\frac{\Omega_{Hz}}{\omega_{k'}} + \frac{\Omega_{Hz}}{\omega_{k''}}) + \frac{2\Omega_{Hz}^2}{\omega_k \omega_{k''}} \hat{z} \cdot (\tilde{k}' \times \tilde{k}'')] \end{aligned} \quad (8)$$

$$\mu_k(\tilde{k}', \tilde{k}'') = \frac{\tilde{k} \cdot \tilde{k}'}{\tilde{k}'^2 \omega_{k'}} + \frac{\tilde{k} \cdot \tilde{k}''}{\tilde{k}''^2 \omega_{k''}} + \frac{\hat{z} \cdot (\tilde{k}' \times \tilde{k}'')}{1\omega_{k'} \omega_{k''}} (\frac{\Omega_{Hz}}{\tilde{k}'^2} - \frac{\Omega_{Hz}}{\tilde{k}''^2}) \quad (9)$$

$$D_{k_1} = \tilde{k}_1 \cdot \tilde{v}_{k_1}, \quad D_{k_2} = \tilde{k}_2 \cdot \tilde{v}_{k_2}, \quad D_{k_0} = 1 - \frac{\omega_{k_0} (e/m_H) \tilde{k}_0 \cdot \tilde{E}_0}{\omega_{k_0}^2 - \Omega_H^2}$$

$$\alpha_H = \frac{\tilde{n}_H}{\tilde{n}_e}, \quad \alpha_O = \frac{\tilde{n}_O}{\tilde{n}_e}, \quad C_H^2 = \frac{T_e}{m_H}, \quad C_O^2 = \frac{T_e}{m_O},$$

$$\Omega_H = \frac{eB_0}{m_H}, \quad \Omega_O = \frac{eB_0}{m_O}, \quad \Omega_{Hz} = \frac{eB_{0z}}{m_H}, \quad \omega_{-k_1} = -\omega_{k_1}, \quad \omega_{-k_2} = -\omega_{k_2}$$

Here, $\tilde{v}_k$ is Fourier amplitude of the velocity field. Here $\tilde{\omega}_{k_1}$ and $\tilde{\omega}_{k_2}$ are the frequencies of the daughter wave and the low frequency oxygen wave in the presence of pump electric field E_0 .

Writing $\bar{\omega}_{k_2} = \omega_{k_2} + \Delta\omega$ and $\bar{\omega}_{k_1} = \omega_{k_1} - (\omega_{k_2} + \Delta\omega) = \omega_{k_1} - \Delta\omega$ and using Eqs. (6) and (7), we obtain the growth rate γ

$$\gamma^2 = \frac{M_{k_1} M_{k_2} (e\omega_{k_0} k_0 \cdot E_0)^2 / [m_H (\omega_{k_0}^2 - \Omega_H^2)]^2}{1 + [n_0 m_H (\omega_{k_2}^2 - \Omega_H^2)^2] / [n_H m_0 (\omega_{k_2}^2 - \Omega_0^2)^2]} \quad (10)$$

where $\Delta\omega = i\gamma$, and

$$M_{k_1} = \frac{\lambda_{k_1}(k_0, -k_2)}{k_0^2 k_2^2} + \frac{(\omega_{k_1}^2 - \Omega_H^2) \mu_{k_1}(k_0, -k_2)}{\omega_{k_1}}$$

$$M_{k_2} = \frac{\lambda_{k_2}(k_0, -k_1)}{k_0^2 k_1^2} + \frac{(\omega_{k_2}^2 - \Omega_H^2) \mu_{k_2}(k_0, -k_1)}{\omega_{k_2}}.$$

In the case of one dimensional simulation in which $E_0 \parallel k_0 \parallel k_1 \parallel k_2$, we find $\gamma^2 > 0$ for the numerical values of λ and μ corresponding to the simulation results to be discussed. This suggests a presence of a three wave decay instability.

III. SIMULATION MODEL AND RESULTS

In the present work, we consider a three component plasma consisting of background electrons, hydrogen ions, and oxygen ions. We assume Maxwellian distribution for both ions and Boltzmann distribution for electrons. The simulation code used is 1-spatial dimension and 3-velocity dimensions. This

code retains the full ion dynamics in 3-D velocity space. We use a system length $L = 256 \Delta$ where Δ is the grid space which is equal to the electron Debye length, λ_e , $T_e = T_H = 16T_0$ initially, $\Omega_{ce}/\omega_{pe} = 10$, $m_H/m_e = 1837$, $m_O/m_H = 16$, $n_{\lambda_e} = 50$, $k_{\parallel}/k_{\perp} = 0.025$, and $\bar{n}_H = \bar{n}_O = (1/2)\bar{n}_e$. Here, we consider a case where oxygen temperature is much lower than that of hydrogen, because of the fact that the hydrogen ions are initially heated due to the presence of large amplitude hydrogen cyclotron waves.

The large amplitude hydrogen cyclotron wave is applied externally in the form of $E_{ox} \cos(\omega_b t - k_{ox}x)$ where E_{ox} , ω_b , and k_{ox} are the amplitude, the frequency, and the wave number of applied field. (The external magnetic field B_0 is taken in the $x-z$ plane.)

Figure 1 shows results from a simulation study at $\Omega_{Ht} = 871$ using the model described above for $E_{ox}^2/4\pi n T_e = 0.02$ ($e\phi_0/T_e = 1.44$), $\omega_b = 1.17\Omega_H$ and $k_{ox} = 2\pi \times 4/L$. Note such large amplitude hydrogen cyclotron waves have been detected by the S3-3 satellite (Kintner *et al.*, 1979). Shown in the figure are (a) the electrostatic potential $e\phi/T_e$, (b) the hydrogen density $n_H/\bar{n}_H$, and (c) the oxygen density $n_O/\bar{n}_O$, plotted versus position, where $\bar{n}$ is the average density. The electrostatic energy versus mode number is shown in panel (d). It should be noted that the two peaks at modes 8 and 12 in the wave spectrum are excited by the applied hydrogen cyclotron whose mode number is 4.

From the consideration of the ω and k spectrums and the density perturbations of both ions, one of the most dominant decay processes satisfies the matching conditions: $\omega_b = \omega_1 + \omega_2$, $k_{ox} = k_{1x} + k_{2x}$ where $\omega_b = -1.17\Omega_H$, $\omega_1 = -\Omega_H$, $\omega_2 = -3\Omega_O$, $k_{ox} = 2\pi \times 4/L$, $k_{1x} = -2\pi \times 4/L$, and $k_{2x} = 2\pi \times 8/L$. These matching conditions have been observed in the simulations as shown in Fig. 2.

To confirm the presence of the excited oxygen cyclotron wave, the power spectrum at the 8th mode for oxygen density and its time history are shown in Fig. 3. The oxygen cyclotron wave grows until $\Omega_{Ht} = 300$ and after that it decays as a result of oxygen heating.

Strong heating of both ions have been observed as a result of decay instability. We show in Fig. 4 perpendicular velocity distributions for hydrogen and oxygen ions. It should be noted that the high energy tail of the oxygen ions is generated. While the parallel distributions for both ions remain almost unchanged, the perpendicular distributions are strongly heated.

The time evolution of the kinetic energy for both ions are shown in Fig. 5. The saturation occurs around $\Omega_{Ht} = 800$, beyond which time the velocity distributions remain almost the same.

One of the candidates for the saturation mechanism may be the frequency mismatch. A distinct frequency shift is observed in the 8th mode for oxygen ions. The frequency for the earlier stage ($0 < \Omega_{Ht} < 445$) is less than $3\Omega_0$. However, the frequency after the saturation ($0 < \Omega_{Ht} < 1783$) becomes larger than $3\Omega_0$. The frequency shift is caused by perpendicular ion heating associated with instability (Okuda and Ashour-Abdalla, 1981).

IV. CONCLUSIONS

We have considered the heating of oxygen ions assuming a presence of large amplitude hydrogen cyclotron waves which are commonly observed on auroral field lines. In particular, the three wave decay process, in which a large amplitude pump cyclotron wave decays into a daughter hydrogen cyclotron wave and a low frequency oxygen cyclotron wave, has been investigated theoretically and by numerical simulations.

The results of simulations indicate the decay instabilities and resultant strong heating of both ion species. In order to distinguish the heating of oxygen ions associated with the decay instability from the stochastic heating, we performed a simulation with only the applied field and neglected the self-consistent electric field. This test particle simulation resulted in no heating of oxygen ions, confirming that heating is due to the decay instability.

In order to study ion heating for a different pump amplitude E_0 , three more simulations have been carried out using $e\phi_0/T_e = 0.36, 0.72$, and 1.08 . All the other parameters remained the same. The results of simulations show that the heating of both ions decreases slowly with the decreasing pump amplitude. For the case of $e\phi_0/T_e = 0.36$, for example, bulk oxygen ions are heated five times the initial temperature in addition to forming a high energy tail.

We have also carried out numerical simulations using the different ratios of hydrogen and oxygen concentrations and found the heating of both ions can take place. Details will be reported in a future communication.

ACKNOWLEDGMENTS

The work performed at Princeton was supported by the National Science Foundation Grant ATM81-15257 and by the United States Department of Energy Contract # DE-AC02-76-CHO-3073.

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FIGURE CAPTIONS

FIG. 1. Spatial structure of electrostatic potential $e\phi/T_e$, (a); hydrogen density $n_H/\bar{n}_H$, (b); oxygen density $n_O/\bar{n}_O$ (c); and the electrostatic energy versus mode number (d). The wave spectrum peaks at mode 4 corresponding to the applied hydrogen cyclotron wave. The parametric instability excites the other peaks at modes 8 and 12. This snapshot was taken at time $\Omega_H t = 871$.

FIG. 2. The power spectrums which correspond to dominant decay process; $\omega_0 = \omega_1 + \omega_2$ and $k_{0x} = k_{1x} + k_{2x}$: ($\omega_0, k_{0x} = 2\pi \times 4/L$) (a), ($\omega_1, k_{1x} = -2\pi \times 4/L$) (b), ($\omega_2, k_{2x} = 2\pi \times 8/L$) (c). These power spectrums are diagnosed for the wave during $0 < \Omega_H t < 1783.7$.

FIG. 3. The excited oxygen cyclotron wave; frequency spectrum of 8th mode for oxygen density (a). This power spectrum is diagnosed for the wave during $0 < \Omega_H t < 1783.7$. The time-history of the 8th mode of oxygen density perturbation (b).

FIG. 4. Ion perpendicular velocity distributions at $\Omega_H t = 0$ and 871. (a) Hydrogen ion $v_\perp/v_{Ht}$ vs. $f_H(v_\perp)$. (b) Oxygen ion $v_\perp/v_{Ot}$ vs. $f_H(v_\perp)$. Note the presence of high energy tails in the oxygen distribution (b).

FIG. 5. Heating of hydrogen and oxygen ions.

Figure 1

Figure 2

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Figure 3

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Figure 4

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Figure 5