§33. Current-Driven Instabilities in a Multi-Ion-Species Plasma

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Current-driven instabilities are believed to play essential roles in heavy-ion heating in space plasmas. For example, for ^{3}He rich events in solar flares or for O^+ heating in the Earth's ionosphere, several theoretical models based on linear theories have been proposed. However, those studies have not succeeded in quantitatively explaining observations. To do this, we need to make a theory which self-consistently treats both nonlinear evolution of instabilities and energy transport among different particle species.

Using a two-dimensional, electrostatic, particle code, we studied instabilities in a plasma consisting of hydrogen (H), helium (He), and electrons with the electron temperature higher than the ion temperatures.[1)] The electrons drift along a uniform magnetic field with the initial speed equal to the electron thermal speed, $v_{\rm d} = v_{\rm Te}$. It was demonstrated that, after the development of ion acoustic waves and fundamental H cyclotron waves, the second harmonic waves are destabilized owing to the change in the electron velocity distribution function $g(v_\parallel)$ and eventually grow to the largest amplitudes, even though these waves are only marginally unstable according to the linear theory based on the initial conditions. It was shown that these waves heat He ions more than H ions. These simulation results indicate that linear theory cannot predict which wave becomes dominant and which particle species are heated.

Furthermore, we have developed a nonlinear theory predicting the dominant unstable modes and have estimated the energy gains of ions.[2)] Then, we have carried out three-dimensional simulations, in which the number of unstable waves is much larger than in the previous two-dimensional simulation.

We have theoretically analyzed the growth rates of H cyclotron waves, taking account of the effect of the change in $g(v_\parallel)$. The growth rates γ are given by

$$\gamma \simeq \alpha_n \left. \frac{\partial g}{\partial v_\parallel} \right|_{v_\parallel = \omega/k_\parallel}, \qquad (1)$$

with

$$\alpha_n = \frac{v_{\rm Te}}{\lambda_{\rm De}^2} \left[\sum_i \frac{1}{\lambda_{{\rm D}i}^2} \sum_m \frac{m\Omega_i \Gamma_m(\mu_i)}{(\omega - m\Omega_i)^2} \right]^{-1}. \qquad (2)$$

Here, ω is the frequency, and the subscript i denotes the ion species, H or He. Equation (1) suggests that the modes with the same $\omega/k_\parallel$ almost simultaneously start to grow and saturate as $g(v_\parallel)$ changes with time. Therefore, among the modes with the same $\omega/k_\parallel$, the nth harmonic wave with the largest α_n can have the greatest growth rate.

We have numerically calculated the values of α_n, using the simulation parameters. It is found that the second harmonic waves have the largest value. Therefore, the second harmonic waves are expected to become eventually dominant. We further estimate the heating rates of ions by the second harmonic waves. It is shown that the energy transfer to He ions is enhanced by the nonlinear evolution of the instabilities. Especially, the wave with $\omega/k_\parallel \simeq v_{\rm d}$ can heat He ions much more than H ions.

Furthermore, by three-dimensional simulations, it has been demonstrated that the second harmonic wave with $\omega/k_\parallel \simeq v_{\rm d}$ finally becomes dominant, as described by the theory. Figure 1 shows spectrum of H cyclotron waves as a function of the frequency and phase velocity, $v_{\rm p} = \omega/k_\parallel$. The highest peak is at $\omega \simeq 2.4\Omega_{\rm H}$ and $v_{\rm p} \simeq v_{\rm d}$. The energy transfer to He ions from the dominant wave is much greater than that to H ions, and the observed heating rate is in good agreement with the theory.

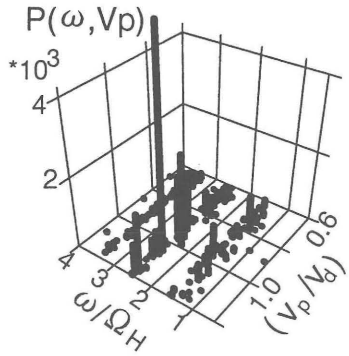

Fig. 1. Power spectrum of H cyclotron waves.

References
1) Toida, M., Maeda, T., Shiiba, I., Sugishima, A., and Ohsawa, Y.: Phys. Plasmas **7** (2000) 4482.
2) Toida, M. and Sugishima, A.: Submitted to J. Phys. Soc. Jpn.