Competition Between the Mirror-Mode Instability and the L-Mode Electromagnetic Ion Cyclotron Instability: Results from Comparison of 2-D and 3-D Simulations

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Abstract

We performed multi-dimensional hybrid simulations to analyze the competing process between L-mode Electromagnetic Ion Cyclotron (EMIC) instability and mirror instability in the magnetosheath. Mirror instability dominates over L-mode EMIC instability in the 3D model, although the growth rate of the mirror mode is lower than that of the L-mode. Because of the efficient proton scattering by the mirror mode waves, the growth of the L-mode EMIC waves stops at an early stage and disappear from the space. We also find nonlinear evolutions of the mirror mode structures are quite different between 2D and 3D model.

1. Introduction

Downstream of the quasi-perpendicular portion of the bow shock, solar wind protons and heavier ions (Helium Ions) are preferentially heated in the perpendicular to the magnetic field direction. This heating creates strong temperature anisotropies in the perpendicular direction to the background magnetic field which lead to intense wave growth. Two instabilities can feed off of this same temperature anisotropy, the mirror mode instability and the L-mode electromagnetic ion cyclotron (EMIC) instability. Of the two, the ion cyclotron instability has generally higher linear growth rate than that of the mirror instability [1] as shown in Figure 1, which shows the dispersion relations of the each wave. However, spacecraft observations show that the mirror instability dominates over the L-mode EMIC instability in planetary magnetosheaths [2-5]. This has been a long-standing puzzle since the early 1980s after these phenomena were first observed in spacecraft data. In this study, we performed the one-dimensional (1D), two-dimensional (2D), and three-dimensional (3D) hybrid simulations and compared these results to understand this apparent discrepancy.

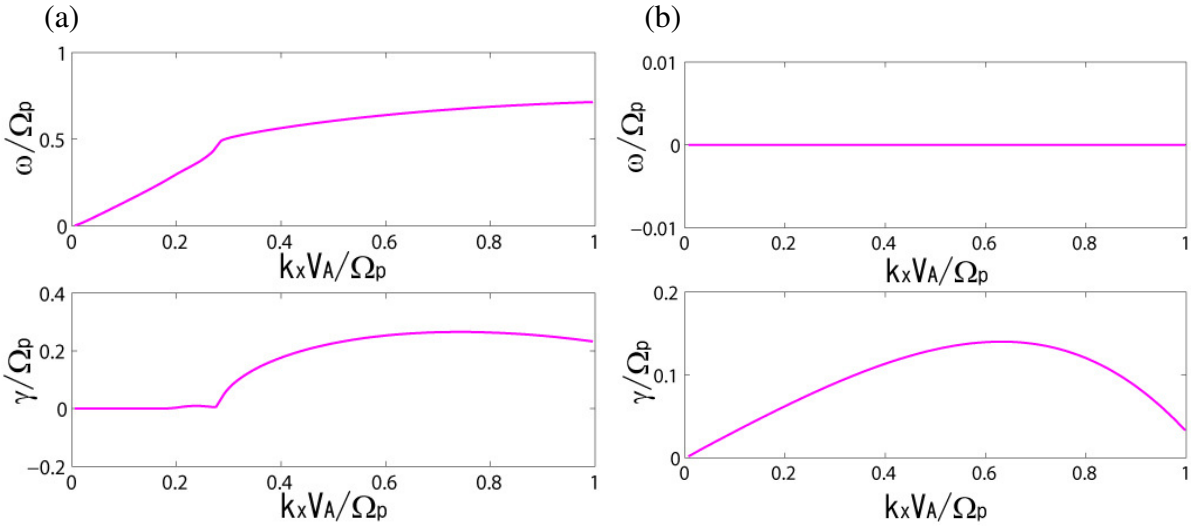

Figure 1: The dispersion relations of the L-mode EMIC waves (a) and the mirror mode waves (b).

2. Competing process between L-mode EMIC instability and Mirror instability

2.1 Linear evolution of each mode

To analyze the competing processes between the L-mode EMIC instability and the mirror instability, we performed both 2D and 3D hybrid simulations, assuming anisotropic energetic protons. In the 2D model, the energy of the L-mode wave is higher at the initial stage because its linear growth rate is larger than that of the mirror mode waves. However, in the 3D simulation, we find that the mirror mode wave can consume more free energy than the L-mode wave at the initial state of wave growth. Because the degree of freedom in the perpendicular direction increases, the mirror mode waves in the oblique direction region to the ambient magnetic field can exist in wider ranges of the wavenumbers. Figure 2 shows the time evolution of the mirror mode waves and the L-mode EMIC waves in the wavenumber vector field. The panels (a) and (b) show the electromagnetic waves in the kx-ky plane and ky-kz plane, respectively. The structures in the oblique angle and the surrounding structures are the mirror mode waves in Figures 2a and 2b, respectively. We can find that the mirror mode waves form a torus-like structure in the wavenumber vector field. Thus, many mirror mode waves are exist in the 3D model than that in the 2D model. Therefore, the mirror mode waves can gain more free energy of the temperature anisotropy than the L-mode EMIC waves against the linear theory. We also find that the L-mode EMIC waves saturates at an early stage.

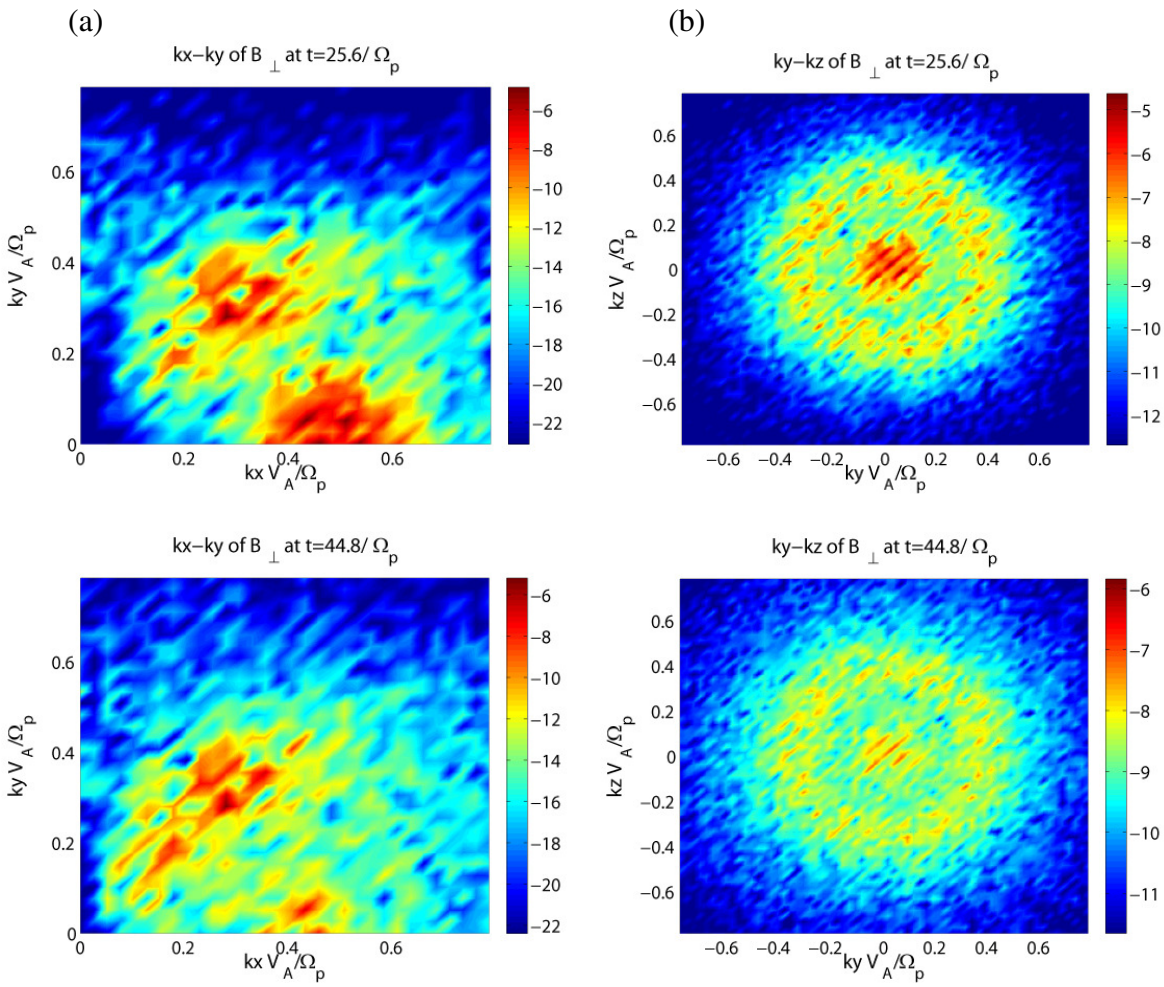

Figure 2: Time evolution of the electromagnetic waves in the wavenumber vector space.

2.2 Effect of the mirror instability on the L-mode EMIC waves and protons

The existence of the mirror mode waves that are dominant in the 3D model causes the large effects on the L-mode EMIC waves and the energetic particles. We performed parametric analyses on the effect of the mirror instability. Figure 3 shows the temperature anisotropy of protons and the saturation levels of the L-mode EMIC waves in the 1D (black line), 2D (red line) and 3D models (blue line). Although the linear growth rates of the L-mode EMIC waves are the same in all simulation models, the growth time of L-mode EMIC wave becomes shorter as the spatial dimension is increased. The saturation levels of the L-mode EMIC waves become smaller as the degree of freedom in the vertical direction to the background magnetic field increases from 1D to 3D. This is also due to the mirror mode waves which absorb the free energy of ions effectively. The protons are diffused in pitch angle to the parallel direction, thus the L-mode EMIC waves cannot diffuse the protons although the free energy remains. Therefore, the saturation levels of the L-mode EMIC waves are different in these simulation models.

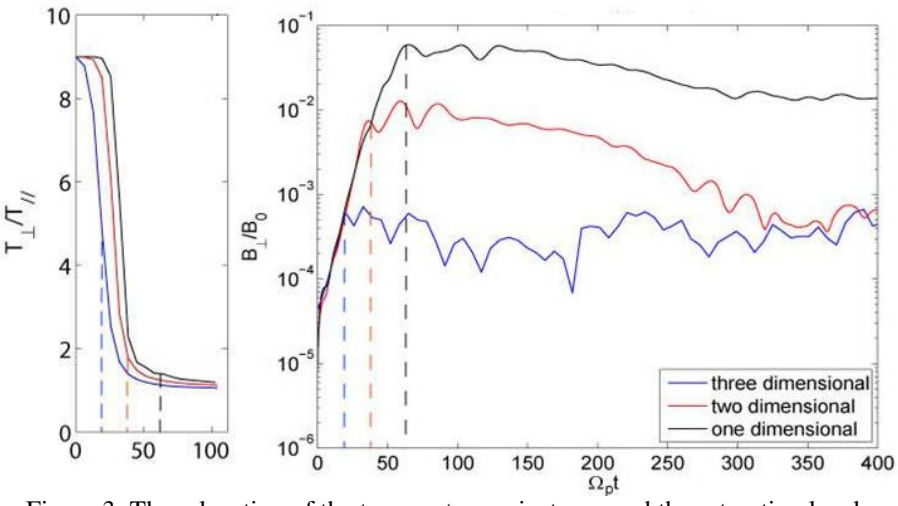

Figure 3: The relaxation of the temperature anisotropy and the saturation levels of the L-mode EMIC waves in the each model.

There is also effect on the relaxation of the temperature anisotropy of the protons. In the 1D model, where there are only L-mode EMIC waves, the temperature anisotropy is relaxed at the end of the growth of the L-mode EMIC waves. In the 2D and 3D models the temperature anisotropies are relaxed faster than that in the 1D model because of the existence of the mirror mode waves. In the 3D case, the L-mode EMIC waves stop growing at the early stage where the temperature anisotropy is not relaxed. The growth of the L-mode EMIC waves declines earlier in the 3D model than that in the 1D or 2D model, due to efficient proton scattering by the mirror mode waves. The L-mode EMIC waves are subject to inverse-cascading in the 1D and 2D models, while this is not the case in the 3D model. In the latter model runs, the amplitude of EMIC waves is not strong enough to cause the decay instability. The L-mode EMIC waves in the 3D model are damped by the nonlinear trapping of resonant particles [6] instead.

3. Nonlinear evolution of the mirror mode structure

We also find that the nonlinear evolution of the mirror waves in the 3D model is significantly different from that in the 2D model [7]. Although coalescence of the mirror mode structures takes place in both models, in the 2D case, the coalescence proceeds slowly, while in the 3D case coalescence is much more rapid. Because of this rapid change, electric fields are induced, and the energy of the electromagnetic fields is converted to the thermal energy of particles. Coalescence of the mirror mode structures is caused at the nonlinear stage in both 2D and 3D models. The stability of the structure, however, is quite different between 2D and 3D model. The topology of the mirror mode structure is different between 2D and 3D model because of the difference of the degree of freedom in the vertical direction. This causes the difference of the nonlinear evolution between each model. At the end of the nonlinear evolution, the structures in the 3D model collapse. On the other hand, in the 2D model, the large structure remains. Through the nonlinear evolution resulting plasma turbulence in the 3D model, the particles are heated by the induced electric field in

the perpendicular direction. They are diffused in pitch angles to parallel direction and to make beta in the parallel direction larger.

4. Summary

Because the degree of freedom in the vertical direction increases, more free energy is consumed by the mirror instability in the 3D model. L-mode EMIC wave cannot gain enough energy to grow in the 3D model. It disappears at an early stage. In the 3D model, where the mirror mode instability is dominant, L-mode EMIC wave cannot grow for a long time. The free energy of temperature anisotropy remains after the growth of L-mode EMIC wave stop, and mirror instability consumes this energy.

Coalescence of the mirror mode structures causes the difference of the nonlinear time evolution of energy between 2D and 3D models. Because of the coalescence of the mirror mode magnetic structures, the electric field is induced, heating ions.

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6. References

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