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Gyrokinetic Particle Simulation of Compressional Electromagnetic Modes

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Abstract. A gyrokinetic particle simulation model is developed for simulations of the compressional electromagnetic turbulence driven by the mirror instability. Results of the linear simulations of mirror modes agree well with the analytic dispersion relation. Nonlinear simulations of a single mode find that the mirror instability saturates via a phase-space trapping due to the nonlinear wave-particle interaction when the instability drive is weak.

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Key words: Mirror instability, compressional electromagnetic turbulence, particle-in-cell simulation.

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1 Introduction

The gyrokinetic particle simulation [1] is very popular for studying the electrostatic modes [2] or incompressible shear Alfven waves [3, 4]. The extension of the gyrokinetic particle simulation to compressible modes, such as mirror instability, could be useful. The mirror instability is a low frequency electromagnetic mode destabilized by the pressure anisotropy in plasmas with high-β ($\beta = 8\pi P/B^2$, the ratio between kinetic and magnetic pressure). It has long been studied in space plasmas, such as planetary and cometary magnetosheaths, in which the velocity distribution of charged particles can deviate substantially from the canonical Maxwellian distribution because collisions occur very rarely. In such environments, the pressure anisotropy can give rise to the excitation of collective modes. Particularly, when the perpendicular temperature exceeds the parallel temperature i.e., $T_\perp > T_\parallel$, a magnetic mirror instability at very low frequencies $\omega \ll k_\parallel v_i$ can occur (v_i is the ion thermal velocity and $k_\parallel$ is the wave vector parallel to the magnetic field.

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Here and in the rest of the article, subscripts $\|$ and $\perp$ correspond to B-parallel and perpendicular components respectively). This instability has attracted considerable interest because of its probable importance in the contribution to the low-frequency compressible magnetic turbulence in magnetized plasmas.

Much attention has been paid to the theoretical analysis of the mirror mode under various conditions [5–10]. A discussion of the physical mechanism of the linear mirror instability in the cold electron temperature limit (i.e., $T_{e,\|} \sim T_{e,\perp} \ll T_{i,\|}$) was offered by *Southwood* and *Kivelson* [11]. The authors showed that the mirror instability results from a resonant interaction between ions with small parallel velocities and low frequency electromagnetic fluctuations. The nonlinear evolution of the mirror instability has also been studied by *Kivelson, Southwood* and *Pantellini* [12, 13]. The linear theories in the long wavelength limit find that the linear growth rate of the mirror instability increases with $k_\perp$. Therefore, it is obvious that the finite Larmor radius (FLR) effects can play an important role when the perpendicular wavelength becomes comparable to the ion gyroradius. In fact, some observations in the Earth magnetosphere [14–20] and the Jovian magnetosheath [21, 22] revealed evidence for the presence of such short perpendicular wavelengths. Thus, in some papers [8, 10, 23–25], the FLR effects on the mirror mode were considered. Nonetheless, it is desirable to develop a kinetic theory with a transparent physics picture that also provides an efficient tool for nonlinear studies of the mirror instability, both analytically and computationally. Here we adopt the gyrokinetic theory [26, 27] instead of the Vlasov theory. The gyrokinetic theory is a powerful approach for the nonlinear analysis and simulation of the low-frequency instabilities. It employs the gyrokinetic ordering that the characteristic frequency of wave and the gyroradius are small compared with the gyro-frequency and unperturbed scale length, respectively, and that the perturbed parallel scale lengths are of the order of the unperturbed scale lengths. Such an ordering enables us to get rid of the explicit dependence of the Vlasov equation on the gyrophase angle while retaining the FLR effects and the nonlinear dynamics.

A gyrokinetic particle-in-cell (PIC) simulation for the compressible mirror mode [28] has been developed and applied for the study of the mirror instability in this work. This is the first time that gyrokinetic particle model is extended to treat the compressional electromagnetic modes. Among the various methods used in the plasma simulation, particle simulation is promising. Numerical PIC simulation has proven to be a powerful tool in understanding the kinetic physics of various fundamental plasma processes, especially where the plasma dynamics is of nonlinear nature under realistic conditions. However, the PIC simulation also has its share of limitations. For example, in the conventional PIC models, many high frequency modes can be produced. It is generally agreed that conventional PIC models are not efficient for studying the low-frequency phenomena, because of the disparate time and spatial scales involved. Motivated by the inadequacy in the existing simulation models, we extend the gyrokinetic PIC simulation model [1] for the mirror mode, in which the rapid gyromotion is removed through gyroaveraging while the vital FLR effects and nonlinear dynamics are retained. By eliminating the gyromotion of particles, we can remove the high frequency modes and use much larger time steps to