運動論的線形解析の固有値問題としての定式化

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Eigenvalue Problem Formulation for Linear Kinetic Plasma Dispersion Analysis

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The quality of space plasma measurements by in-situ spacecraft observations have been improved remarkably in recent years. The high temporal, energy, and angular resolutions of distribution function measurements in space allows us to look into detailed structures in velocity space. The distribution functions that deviate substantially from conventional Maxwellian or bi-Maxwellian are now commonly observed in many space plasma environments. Similarly, non-Maxwellian distribution functions are found in Particle-In-Cell (PIC) simulations as well.

Linear kinetic dispersion analysis has conventionally been performed assuming that the zeroth-order velocity distribution function can be represented by a superposition of Maxwellian distribution functions. It is very well known that the linear response for Maxwellian velocity distribution function is described by the standard plasma dispersion function. This allows us to make use of the conventional methodology in plasma physics in pursuing linear analysis. However, if the distribution function is far from Maxwellian, we need to adopt a different approach.

Another problem in conventional linear dispersion analysis is that it is essentially a root-finding problem. In other words, we usually start with an initial guess and try to find a solution iteratively. If we know a good initial guess, the convergence to the solution can be quite fast. Otherwise, we need trial and error with various (often randomly chosen) initial guesses. Since it is difficult to find all the (physically relevant) solutions, in general, we can not prove whether or not the system is stable (i.e., no mode with a positive growth rate) with this approach. Similarly, it is not easy to write a computer code that automatically surveys physical solutions for a wide range of parameter space.

In this report, we present a formulation of kinetic plasma dispersion analysis as an eigenvalue problem. The advantage of the eigenvalue problem formulation is that all the solutions (or eigenvalues) can be automatically obtained numerically without an iterative root-finding procedure. The basic idea is to expand the linearized distribution function with an appropriate orthogonal function basis that allows analytic continuation into the lower half of the complex velocity plane. As a proof of concept, we present the result obtained for the simplest example of electrostatic waves in an unmagnetized electron plasma. We will also discuss extensions of the method, including, multiple species, magnetized plasmas, electromagnetic waves, and non-Maxwellian distribution functions.