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Landau fluid model for weakly nonlinear dispersive magnetohydrodynamics

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Introduction

In many spatial and astrophysical plasmas, collisions are negligible, making the usual magnetohydrodynamics (MHD) questionable. When addressing the large-scale dynamics, a hydrodynamic approach is nevertheless advantageous. It is thus of great interest to construct fluid models that extend the MHD equations to collisionless situations by including finite Larmor radius (FLR) corrections and Landau damping. In a fluid formalism, FLR corrections refer to the part of the pressure and heat flux tensors associated with the deviation from gyrotropy. They play a role when the transverse scales under consideration extend up to or beyond the ion Larmor radius (fluid models are always limited to parallel scales large compared with the ion Larmor radius). Evolving on a shorter time scale than the basic hydrodynamic fields, FLR corrections can generally be computed perturbatively.

From Vlasov equation it is easy to derive a set of exact moment equations. This fluid hierarchy is however faced with a closure problem. An interesting approach consists in closing this hierarchy by using relations, derived from the linearized kinetic theory, between given moments (for example those of fourth order) and lower order ones [1, 2]. This in particular accounts for linear Landau damping in a fluid formalism. The resulting "Landau fluid" model is thus defined by the equations for the monofluid plasma density and velocity, the gyrotropic pressures, the heat fluxes, together with the induction equation for the magnetic field, resulting from a generalized Ohm's law that retains Hall term and electronic pressure gradient. The model is however to be validated both at the level of the linear (modulational and parametric) instabilities and of their nonlinear developments.

Alfvén wave modulational instability

Alfvén waves propagating along an ambient magnetic field are amenable to a reductive perturbative expansion, directly performed from the Vlasov-Maxwell equations, when they involve scales large compared with the ion Larmor radius and amplitudes small enough to keep dispersion and nonlinearities comparable [3]. This procedure leads to the so-called kinetic derivative nonlinear Schrödinger equation (KDNLS) that was recently extended to the case of multidimensional wave trains [4]. This nonlinear wave equation correctly captures modulational instabilities, including transverse ones [5], but parametric instabilities are outside their scope. Performing the same asymptotic expansion on the dispersive Landau-fluid model (with only leading order FLR corrections retained for the pressure tensor), leads to the same KDNLS equation up to the replacement of the plasma response function by its two or four pole Padé approximants [2, 6]. This shows that the Landau fluid model is also valid in the weakly nonlinear regime for modulational-type instabilities. This statement is also verified numerically. A particular result of the simulations consists in confirming the prediction based on the (1D) KDNLS equation, that a small-amplitude parallel-propagating left-hand polarized monochromatic Alfvén wave in a plasma with uniform and time-independent density and pressures is modulationally unstable for all β [7, 8, 9]. This contrasts with the usual MHD description that predicts for $\beta > 1.4$ a dominant beat instability associated with a strong amplification of the upper Alfvén side mode.

Alfvén wave decay instability

The decay instability of parallel Alfvén waves propagating in a warm collisionless plasma was analyzed in [10] in the case where dispersion is absent. Decay instability produces a forward propagating acoustic wave and a backward Alfvén wave with a wavenumber smaller than that of the pump. We show in [11] that Landau-fluid simulations reproduce reasonably well the instability growth rates, including the observation that the ranges of unstable modes are broader and growth rates smaller than in the fluid description.

The dispersive regime is exemplified in [11] by assuming a wavelength of about 10 proton inertial length, $T_p^{(0)} = T_e^{(0)}$, $\beta = 0.42$, and a forward-propagating, right-hand polarized pump with amplitude $b_0 = 0.1$. For the chosen extension of the computational box, decay instability makes the density mode of index $m = 6$ to be the most unstable at short time. Saturation originates from Landau damping but after a while, the mode $m = 3$ starts growing, which induces a second increase of the mode $m = 6$ as an harmonics of $m = 3$. The further dynamics corresponds to an inverse cascade involving the successive amplification of the ($m = 2$) backward and ($m = 1$) forward propagating Alfvén modes.

The regime of larger wave amplitude was investigated for a forward-propagating right-hand polarized Alfvén wave of amplitude $b_0 = 0.5$ and wavenumber $k = 0.408$ (normalized with the ion inertial length) propagating in a plasma with $\beta = 0.45$. Landau fluid simulations using a pump wave of index $m = 8$ indicate that when the equilibrium electron to proton temperature ratio $T_e^{(0)}/T_p^{(0)}$ is reduced from 44. to 0., the linearly most unstable mode remains at $m = 12$ or 13 but the corresponding growth rate decreases from 0.087 to 0.056, a value roughly 40% lower than predicted by the fluid approach (hybrid simulations [12] leads to a reduction of 57 %). In this regime, electrons are seen to remain cold, which justifies their description as an isothermal fluid in the hybrid code. We observe an inverse cascade where excitation is transfered to larger and larger scales (up to $m = 1$), while the direction of the wave propagation switches at each step of the cascade, with a simultaneous increase of the ion temperature. In contrast, when $T_e^{(0)}/T_p^{(0)} = 44$, the dynamics is close to a fluid regime, with generation of many harmonics.

Independently on whether the instability is of modulational or decay type, a dominant ion heating in the parallel direction is always observed. The two instabilities have however different signatures on the mean perpendicular ion temperature and on both electron temperatures: for a decay-type instability both ions and electrons display perpendicular cooling, while for modulational instability both species are heated in the perpendicular direction.

Extension to oblique propagation

For oblique and transverse propagation a more refined model is needed [13]. In contrast with the case of parallel propagation where the heat flux tensor can be taken as gyrotropic, it is necessary to use a more complete description characterized by two vectors for the fluxes of kinetic energy in the parallel and transverse directions [14, 15]. Moreover, FLR corrections have to be taken to higher orders. A simple approach, appropriate for problems where the focus is on the large scales mainly, consists in writing fluid equations for the full pressure tensor and to treat the components at the origin of FLR corrections as quantities slaved to the gyrotropic pressure components and the monofluid velocities, a procedure that eliminates short time scale fluctuations associated with ion gyromotion. This procedure can easily capture the first two orders in a $1/\Omega_p$ expansion that are important for a proper description of kinetic Alfvén waves [16, 17]. It is hardly possible to go beyond that order and in fact it is not appropriate to do so. A finite number of fluid moments intrinsically limits the validity of FLR corrections to small values of $b = k_\perp^2 r_L^2$, where r_L denotes the ion Larmor radius.

In suitable conditions of temperature anisotropy, a mirror instability can develop, with a growth rate at hydrodynamic scales which varies linearly with the wave number. This phenomenon is accurately reproduced by the Landau fluid. Nevertheless, such an instability that makes the smallest scales of a numerical code to be the most unstable is a serious difficulty for simulations. This instability reaches in fact its maximum at a transverse wave number comparable with the ion Larmor radius and is arrested at smaller scales. Retaining such scales by coupling the fluid and the kinetic descriptions appears necessary to reproduce this effect. A promising approach consists in expressing the FLR contributions in terms of usual hydrodynamic quantities, (using the linear kinetic theory taken in a low frequency asymptotics), in order to obtain a closed description, suitable for being incorporated into the fluid equations.

It is in particular necessary to eliminate explicit reference to the plasma response function. Such an approach aimed at providing a simple alternative to gyrofluid descriptions at least in the regimes where the dominant nonlinearities are of hydrodynamic type, is presently under investigation. A simplified model, valid near threshold for a quasi-isothermal plasma, where the fluid hierarchy is closed at the level of the pressure tensor, satisfactory reproduces the variation with the transverse scale of the mirror instability growth rate, as given by the kinetic theory. The analysis in the nonlinear regime is in project.

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