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Relativistic Extended Magnetohydrodynamics: action formalism and physical properties

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Magnetohydrodynamics (MHD) is one of the most prevalent plasma models that can explain a variety of phenomena in astrophysics as well as in fusion. However, MHD can only describe "overall" dynamics of plasma, and it fails when microscopic effects are important. To overcome this drawback, MHD was extended by including various microscopic effects, such as the Hall effect [1] and the electron inertia effect [2]. Extended MHD (XMHD) [3] is a unified model that includes both the Hall and electron inertia effects.

In most astrophysical systems, plasma has relativistic temperature and flow speed. Hence, consideration of relativistic effects is essential; indeed, relativistic MHD has been used in a number of studies on high energy astrophysics. However, once again, the missing microscopic effects in the relativistic MHD imposes a limitation on its applicability. Recently, the relativistic version of XMHD was proposed [4]. However, despite of the potential usefulness of the model, there are only a few studies that employed the relativistic XMHD (e.g., [5]).

In this presentation, we will show (1) the action formalism of the relativistic XMHD and (2) some of the physical properties that are specific to the relativistic XMHD, viz., collisionless reconnection and linear wave properties [6,7].

The relativistic XMHD was originally formulated via imposing a charge neutrality *in a proper frame* to the two-fluid equations. However, we do not know whether the relativistic XHMD derived through such a way has Hamiltonian properties. We developed two types of the action principles (APs) for the relativistic XMHD: the constrained least AP [8] and the covariant bracket AP [9,10]. The first is minimization of the action under the constraints of density, entropy, and Lagrangian label conservation, i.e., $\delta S_{\text{constrained}} = 0$. This AP not only yields the relativistic XMHD but also provides a Clebsch representation for a generalized momentum and a generalized vector potential. The other AP is a noncanonical covariant bracket AP; $\{F, S_{\text{unconstraned}}\} = 0$, where $\{,\}$ is a noncanonical Poisson bracket, and F is an arbitrary functional. In this AP, the action is free of constrains while the constrains are implemented in the degeneracy of the Poisson bracket. We found that these two APs are connected via variable transformation from the Clebsch potential to the physical fields variables. Moreover, most of the other magnetohydrodynamic models (e.g., nonrelativistic Hall MHD and relativistic ideal MHD) can be derived by imposing appropriate limits to the XMHD action.

Next, we show some of the properties of relativistic XMHD. By assuming the massless electrons, relativistic XMHD is reduced to the relativistic Hall MHD. In this model, the induction equation is written as

$$\partial_t \mathbf{B}^\star + \nabla \times (\mathbf{B}^\star \times \mathbf{v}) = 0,$$

where $\mathbf{B}^\star = \mathbf{B} + \nabla \times (-d_\mathrm{i} h_\mathrm{e} \gamma \mathbf{v} + d_\mathrm{i}^2 h_e \boldsymbol{J}/n)$, d_i is the ion skin depth, h_e is the electron thermal enthalpy, and γ is the Lorentz factor of the flow speed. This equation indicates the violation of the frozen-in magnetic flux condition, and instead, a flux determined by a generalized field $\mathbf{B}^\star$ is conserved. More interestingly, if the electron temperature is sufficiently large, collisionless reconnection may occur in the ion skin depth scale. A similar result was obtained for the relativistic pair plasma [6].

We also found interesting properties of linear wave propagation. Figure 1 shows a group velocity surface for the nonrelativistic and relativistic Hall MHD with the same d_i. One finds a significant difference between the shape of the surfaces [7].

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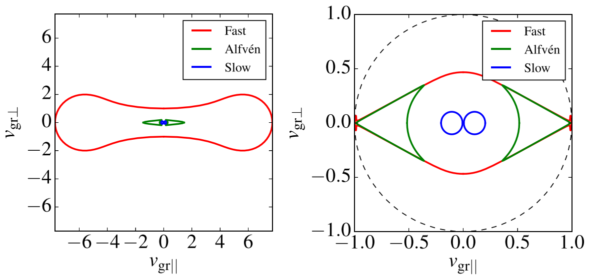

Fig. 1: The group diagram for (left) nonrelativistic Hall MHD and (right) relativistic Hall MHD