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Revisiting hybrid and Hall MHD models for space plasma simulations

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One of the outstanding difficulties for modeling space plasma phenomena is the huge gap between many different temporal and spatial scales. Accordingly, there exist several physical models suitable to describe phenomena occurring on a specific scale. The well-known magnetohydrodynamics (MHD) description gives an adequate view for macroscopic phenomena like global magnetospheric dynamics. On the other hand, key phenomena such as reconnection at the near earth neutral line is believed to be crucial even for the global dynamics of the magnetosphere. This calls for a more sophisticated model that is able to, at least in an approximate manner, describe kinetic effects controlling the key processes, while keeping the global dynamics yet computationally tractable. It is known that when the spatial scale becomes of the order of ion inertial length, the Hall term starts to play a role. Indeed, the importance of the Hall term in reconnection physics has been recognized for years. The Hall MHD model would therefore be the simplest model beyond ideal MHD. One may also includes kinetic effects by treating ions as an ensemble of macroscopic particles rather than a fluid. The hybrid model usually do so while approximating electrons as a massless charge-neutralizing fluid, thus ignoring their finite inertia and kinetic effects. Since these models do not include high frequency waves associated with electron scale physics, computational requirement is much less than the fully kinetic model in which both electron and ions are treated as kinetic particles. It appears that they are useful tools to describe physics beyond ideal MHD. In reality, however, they tend to be numerically unstable when dealing with the scale length smaller than the ion inertial length. Because of this, the applicability of the models have been severely limited to date.

Here, we look for the reason for the numerical difficulty and reconsider the formulation of these models. By analyzing the linearized magnetic field induction equation including the Hall current, we find that the problem seems to become ill-conditioned for the high frequency whistler mode branch. Namely, for whistler waves, even a small numerical error in the ion fluid velocity would be substantially amplified, implying a numerical instability. We suggest that the problem may be resolved by retaining an approximate non-zero electron inertial current term. Since the exact expression for the electron inertial current is not desirable for our purpose of describing waves with frequency much smaller than the electron cyclotron frequency, we assume that electrons are magnetized. Under this assumption, the electron inertial current may be approximated by a temporal derivative of the electric drift velocity, which makes the equation of motion of the electron fluid as essentially an equation describing time evolution for the electric field. In this model, the induction equation no longer involves explicit dependence on the ion fluid velocity. Linear analysis has been carried out to find that the present model gives an adequate description for scales larger than the electron inertial length. Comparisons with other models (MHD, Hall MHD, two fluid) as well as the applicability of the model will be addressed.

Keywords: space plasma, numerical simulation