Evaluation of Numerical Properties of Constrained-Transport-Type Schemes for Hybrid Simulations

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Numerical simulations of space and astrophysical plasmas need an accurate method for solving Maxwell's equations. The divergence-free property of the magnetic field is the fundamental constraint in the system that must be satisfied in a numerical solution because otherwise, the simulation will become unstable. The Constrained-Transport (CT) scheme, which exactly preserves the discrete divergence-free property, has been quite successful in numerical Magnetohydrodynamics (MHD). In recent years, the CT scheme for Maxwell's equations has been ingeniously combined with an HLL-type (Harten-Lax-Van Leer) Riemann solver for the hydrodynamics part in a consistent fashion. The scheme known as the HLL-UCT shows excellent performance in numerical MHD as well as two-fluid plasma simulations.

It is straightforward to apply the same technique to kinetic Particle-in-Cell (PIC) type simulation method. However, the numerical properties of the scheme as applied to kinetic simulations are not known very well. In fact, artifacts arising from numerical noise inherent in the PIC method (which is absent in a grid-based fluid code) should carefully be analyzed.

In this study, we apply the HLL-UCT scheme to a quasi-neutral plasma hybrid code in which ions are treated as kinetic macroparticles whereas electrons are assumed to be a fluid. We found that naive application of HLL-UCT to a hybrid code may lead to artificial heating and/or cooling of ions, presumably because of excessive dissipation in the HLL-UCT scheme. We thus quantify the numerical artifact by extensive numerical experiments with varying mesh size, the number of particles per cell, plasma beta, etc. We found that the numerical heating/cooling may be explained by absorption (or dissipation) of spontaneous emission of waves arising from a discrete particle effect. Practical workarounds to minimize the numerical artifact for long time simulations will be discussed.

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