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PLUTO code for computational astrophysics: News & Developments

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Abstract: We present an overview on recent developments and functionalities available with the PLUTO code for astrophysical fluid dynamics. The recent extension of the code to a conservative finite difference formulation and high order spatial discretization of the compressible equations of magneto hydrodynamics (MHD), complementary to its finite volume approach, allows for a highly accurate treatment of smooth flows, while avoiding loss of accuracy near smooth extrema and providing sharp non-oscillatory transitions at discontinuities. Among the novel features, we present alternative fully explicit treatments to include non-ideal dissipative processes (namely viscosity, resistivity and anisotropic thermal conduction), that do not suffer from the usual timestep limitation of explicit time stepping. These methods, offsprings of the multistep Runge-Kutta family that use a Chebyshev polynomial recursion, are competitive substitutes of computationally expensive implicit schemes that involve sparse matrix inversion. Several multi-dimensional benchmarks and applications assess the potential of PLUTO to efficiently handle many astrophysical problems.

1 High order, conservative, finite difference schemes

Traditional second order TVD schemes are known to introduce excessive numerical dissipation as well as distortions such as smearing and clipping that effectively limit the highest obtainable Reynolds number. In order to overcome this, we have recently extended the GLM-MHD formulation presented in [6] to a Finite Difference formalism (FD) so as to include high order reconstruction techniques to the existing interpolation schemes of the PLUTO code [5].

In this formalism we implemented four of the most recent 3rd and 5th order interpolants, namely *WENO+3* [11], *LimO3* [4], *WENO-Z* [3] and *MP5* [9]. In [7] an extensive discussion regarding implementation as well as comparative efficiency is made. Our results outline the great gain obtained with the use of higher order schemes, since the increased computational cost is largely compensated by the increase of accuracy and the reduction of dissipation.

As an example, we review the three dimensional circularly polarized Alfvén wave test problem [2]. Since the exact solution is known analytically, it is an ideal problem for convergence. Higher order schemes converge faster (Fig. 1) than lower order interpolants. The *MP5* GLM-MHD scheme needs only 1/8 of the points required by PPM-CT (2nd order) to reach the same accuracy ($L1 \sim 10^{-4}$). As a consequence, computational time is greatly reduced resulting in a speedup factor of ~ 390. High order schemes are extremely cost effective when we aim for reduced dissipation (large Reynolds numbers) as in the numerical study of astrophysical turbulence and instabilities such as accretion disc MRI.

2 Explicit treatment of parabolic terms

In many cases the modeling of astrophysical objects requires the inclusion of non ideal effects. PLUTO allows for dissipation terms in its HD and MHD modules, such as viscosity, magnetic resistivity and thermal conduction. The introduction of parabolic terms in hyperbolic conservation laws imposes a more restrictive timestep condition for diffusion dominated regimes. For a hyperbolic problem the Courant-Friedrichs-Levy (CFL) condition dictates a timestep analogous to the mesh spacing $\Delta t \sim \Delta l$,

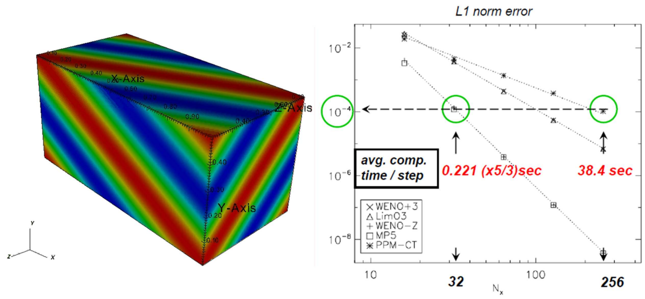

Figure 1: Convergence study for the circularly polarized Alfvén wave test problem in L1 norm.

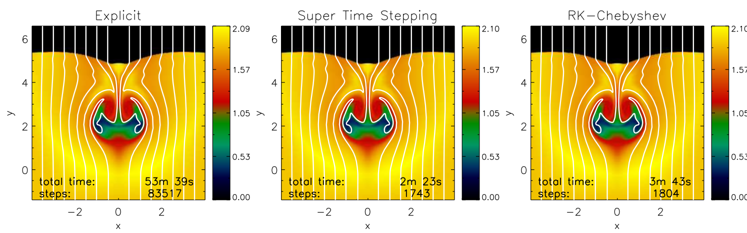

Figure 2: Density profiles and sample magnetic field lines for the shock-cloud interaction problem.

whereas a parabolic system requires $\Delta t \sim \Delta l^2$. Therefore, large diffusion coefficients coupled with high resolution, can result to prohibitive timesteps that may render computations impractical.

We have explored alternative explicit schemes, based on the multistep Runge-Kutta family of methods, that opt for increased stability while retaining a comparatively low order of temporal accuracy. The two options available with the PLUTO code are: Super Time Stepping (STS, 1st order in time) [1] and RK-Chebyshev (RKC, 2nd order in time) [10]. Even though these techniques have been known for a while in the Applied Mathematics community, they are not widely used in CFD and Godunov type codes. Both methods are easily incorporated via operator splitting and can be advantageous.

As an example we review the shock-cloud interaction problem [8] with dominant thermal conductivity (Fig. 2). The results are almost identical for all methods, in terms of shock front position, primitive variable profiles and magnetic field line shape. The indicative speedups of STS and RKC in comparison to the standard explicit approach are 22.5 and 14.4 respectively.

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