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RECENT APPLICATIONS USING ATHENA

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RESUMEN

Athena es un nuevo código numérico para MHD astrofísica, que preserva la condición de divergencia nula en forma exacta, conserva la energía total, y trabaja con mallas anidadas y adaptativas. Se describe el estado actual del código. Athena está siendo usado para un número de aplicaciones, y se presenta una selección de éstas, incluyendo la inestabilidad de Rayleigh-Taylor magnética, la interacción choque-nube MHD, y la disipación de turbulencia MHD supersónica. Se da una reseña de las futuras aplicaciones y del desarrollo de algoritmos.

ABSTRACT

Athena is a new numerical code for astrophysical MHD which preserves the divergence-free constraint exactly, conserves total energy, and works with nested and adaptive meshes. The current status of the code is summarized. Athena is being used for a number of applications, a selection of which are described here, including the magnetic Rayleigh-Taylor instability, MHD shock-cloud interaction, and the decay of supersonic MHD turbulence. Future applications and algorithm developments are summarized.

Key Words: hydrodynamics — MHD — methods: numerical

1. INTRODUCTION

Athena is a numerical code for compressible MHD based on higher-order Godunov methods. At the last MFU conference, the code was very much still under development. In two papers presented at that meeting, the basic numerical algorithms were described, important test problems were reviewed, and the first application to the magneto-rotational instability (MRI) was presented (Stone & Gardiner 2006; Gardiner & Stone 2006). Since then, the code has matured significantly. Several papers describing the numerical algorithms have been published, and a number of applications of the code to a variety of problems in astrophysical gas dynamics have been completed. This, the second in what will hopefully be a long series of MFU meetings, has provided an opportunity to review progress in the development of Athena, and to document the first applications of the code. This paper summarizes both.

2. THE ATHENA CODE

The numerical algorithms in Athena are based on directionally-unsplit, higher-order Godunov methods, which are ideal for used with static and adaptive mesh refinement. The mathematical foundations of the methods are described in two papers (Gardiner & Stone 2005, 2008). The methods include several innovations, including (1) the extension of two different directionally unsplit integration algorithms to MHD, including the corner transport upwind (CTU) method of Colella (1990) and a simpler predictor-corrector method (hereafter referred to as the VL+CT algorithm), (2) the method by which the Godunov fluxes are used to calculate the electric fields needed by CT, and (3) the extension of the dimensionally-split spatial reconstruction scheme in the piecewise parabolic method (PPM) of Colella & Woodward (1984) to multidimensional MHD. A complete description of the implementation of the CTU+CT method, along with an exhaustive series of test problems, is given in Stone et al. (2008). The VL+CT integrator is described in detail in a separate paper (Stone & Gardiner 2009).

A variety of additional physics beyond ideal MHD has been implemented in Athena, including self gravity computed using both FFTs and multigrid methods, and advection of an arbitrary number of passive scalars (useful for studying multifluid flows). The primary areas for future development are (1) extension to use AMR grids, (2) extension to special relativistic MHD, and (3) extension to include radiation transport. Significant progress is being made in all three areas. For example, Figure 1 shows the results of the 2D implosion test given by Liska & Wendroff (2003) using an AMR grid. Note the formation of the jet along the diagonal, as expected, implying the code continues to hold symmetries extremely well. In fact, comparison of the results in

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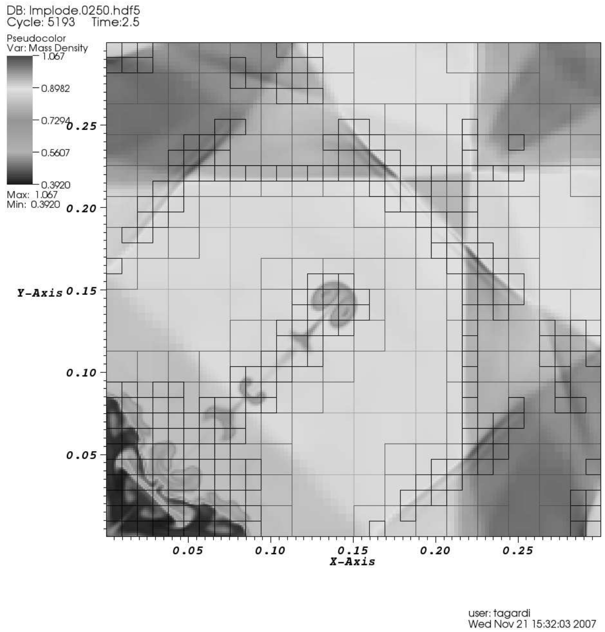

Fig. 1. Grayscale image of the density, with AMR grid overlaid, at late time in the 2D hydrodynamical implosion test described by Liska & Wendroff (2003). The results computed with single uniform grid are essentially identical, and are given in Stone et al. (2008).

Figure 1 with those computed using a uniform grid with the same resolution as the finest AMR level shows virtually no difference. At the moment, the AMR algorithms in Athena are still not parallelized, and so are not being used for applications.

Of course, Athena is not the only MHD AMR code being used in astrophysics, others include RIEMANN (Balsara 2000), BATS-R-US (Powell et al. 1999), AMRVAC (Tóth 1996; Nool & Keppens 2002), Nirvana (Ziegler 2005), RAMSES (Fromang, Hennebelle, & Teyssier 2006), PLUTO (Mignone et al. 2007), and AstroBEAR (Cunningham et al. 2007). Athena implements algorithms that differ from each of these other codes in both small and in some cases substantial ways. Diversity of numerical algorithms is very good as it allows cross-checking of results on the same application. Only when different codes get the same quantitative solution for a given problem can we really be sure our results are unaffected by numerics. Thus, Athena will hopefully be one of many numerical tools used to study astrophysical MHD.

3. A SURVEY OF APPLICATIONS

Athena has moved beyond the code development stage and is now being used for applications. The first published results were for hydrodynamics, in particular a study of the evolution of vortices in Keplerian shear flows (Shen, Stone, & Gardiner 2006), and the dynamics of colliding winds in close binary systems in full 3D (Lemaster, Stone, & Gardiner 2007). In the following subsections, we describe results from selected MHD applications that have recently been published.

3.1. *MHD Rayleigh-Taylor Instability*

When a light fluid accelerates (or supports against gravity) a heavier fluid, the interface between the two is subject to the Rayleigh-Taylor instability. There are a number of astrophysical systems in which the magnetic Rayleigh-Taylor instability (RTI) is expected to be important, for example accretion onto magnetized compact objects, buoyant bubbles generated by radio jets in clusters of galaxies, the emergence of magnetic flux from the solar interior and the formation of flux tubes, and at both the contact discontinuity between the shocked circumstellar medium and ejecta in supernovae remnants, and in the thin shell of ejecta swept up by a pulsar wind. We have used Athena to study the nonlinear evolution of the magnetic Rayleigh-Taylor instability using three-dimensional MHD simulations.

Our simulations consider the idealized case of two inviscid, perfectly conducting fluids of constant density separated by a contact discontinuity perpendicular to the effective gravity g, with a uniform magnetic field $\mathbf{B}$ parallel to the interface. Modes parallel to the field with wavelengths smaller than $\lambda_c = \mathbf{B} \cdot \mathbf{B}/(\rho_h - \rho_l)g$ are suppressed (where ρ_h and ρ_l are the densities of the heavy and light fluids respectively), whereas modes perpendicular to $\mathbf{B}$ are unaffected. We study strong fields with λ_c varying between 0.01 and 0.36 of the horizontal extent of the computational domain. We use a grid of $256 \times 256 \times 512$ cells.

Our results were summarized in two papers (Stone & Gardiner 2007a, b), and a full description of the setup of this problem, the parameters used, and the results are given in those papers. The first paper focused on the rate of growth of bubbles and fingers in the nonlinear regime, and how magnetic fields affects mixing between the heavy and light fluids. The second paper studied a more astrophysically motivated problem: the effect of rotation of the direction of the magnetic field across the interface. Strong magnetic fields do not suppress instability, in fact by inhibiting secondary shear instabilities, they reduce mixing between the heavy and light fluid, and cause the rate of growth of bubbles and fingers to increase in comparison to hydrodynamics. Fields parallel to, but whose direction changes at, the interface produce long, isolated fingers separated by the critical wavelength λ_c, which may be relevant to the morphology of the optical filaments in the Crab nebula (Hester et al. 1996).

For example, Figure 2 plots isosurfaces of the density, along with slices of the density at the edges of the computational domain, from two runs in which the field is rotated by 45 and 90 degrees at the interface. At late times, the interface is strongly distorted by RTI. Isolated, large scale bubbles dominate, with very smooth surfaces, and bulbous tips. The spacing between bubbles is roughly the critical wavelength λ_c. The structure of the 90 degree rotated field is particularly interesting. The fingers in this case are nearly isotropic, and have a length which significantly exceeds λ_c. The surface of the bubbles is extremely smooth, whereas for the field rotated by 45 degrees there is some evidence for wrinkling due to interchange modes. The interface between the light and heavy fluids is remarkably thin. All of these properties are characteristic of the fingers in the Crab (Hester et al. 1996).

3.2. *MHD Shock-Cloud Interaction*

The interaction of shock waves with density inhomogeneities ("clouds") in the interstellar medium (ISM) is thought to be an important dynamical process in a multiphase medium. We have studied the magnetohydrodynamic evolution of a dense spherical cloud as it interacts with a strong planar shock as a model for this process. The cloud is assumed to be small enough that radiative cooling, thermal conduction, and self-gravity can be ignored. A variety of initial orientations (including parallel, perpendicular, and oblique to the incident shock normal) and strengths for the magnetic field are investigated. The results are presented in Shin, Stone, & Snyder (2008).

During the early stages of the interaction (less than twice the time taken for the transmitted shock to cross the interior of the cloud) the structure and dynamics of the shocked cloud is fairly insensitive to the magnetic field strength and orientation. However, at late times strong fields substantially alter the dynamics of the cloud, suppressing fragmentation and mixing by stabilizing the interface at the cloud surface. Even weak magnetic fields can drastically alter the evolution of the cloud compared to the hydrodynamic case. Weak fields of different geometries result in different distributions and amplifications of the magnetic energy density, which may affect the thermal and non-thermal x-ray emission expected from shocked clouds associated with, for example, supernovae remnants.

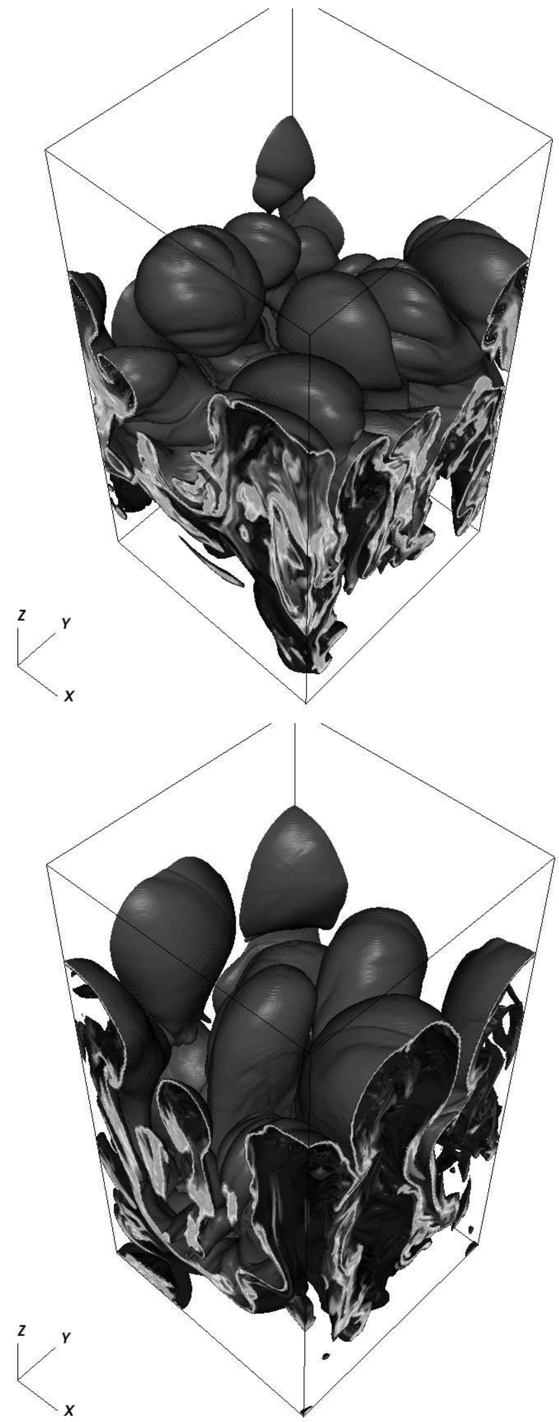

Fig. 2. Isosurfaces of the density at 99% and 1% of the density difference at late time in runs with the magnetic field rotated by 45° (top) and 90° (bottom) across the interface. Also shown are slices of the density at the edges of the computational domain.

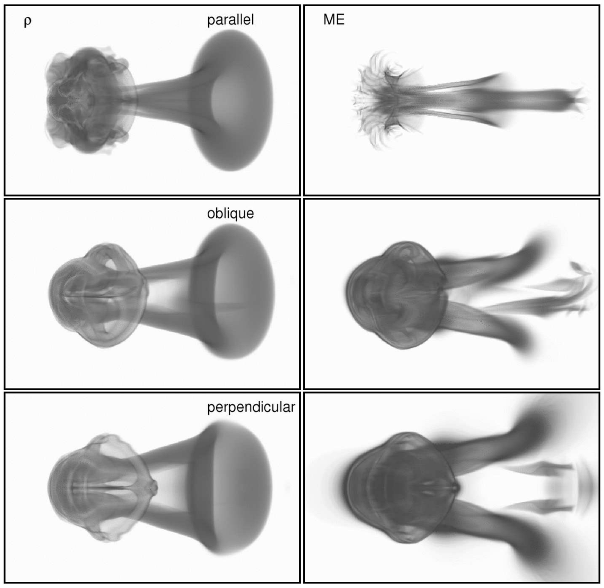

Fig. 3. Volumetric rendering of the cloud density (left column) and magnetic energy density B^2 (right column) for weak field ($\beta = 10$) parallel, perpendicular and oblique shocks. Each plot is shown at 7.9 cloud-crushing times; see Shin, Stone, & Snyder (2008) for definitions of these parameters.

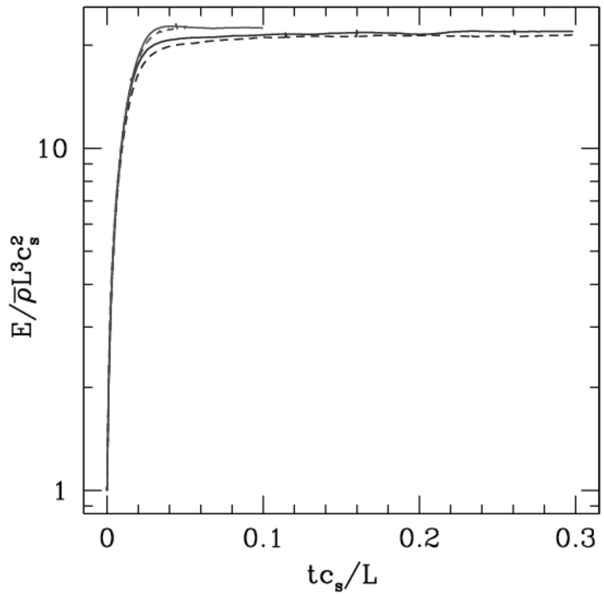

Fig. 4. Evolution of energy in fluctuations at two different numerical resolutions (256^3 and 512^3) for both ZEUS (dashed line) and Athena (solid line). Both codes converge to the same result.

As an example of the structure produced by shock-cloud interaction in MHD, Figure 3 shows volumetric renderings of the density and magnetic pressure for weak fields that are initially parallel, oblique (inclined at 45 degrees), and perpendicular to the shock normal. For the parallel shock case, the density at the tip of the cloud is strongly affected by MHD instabilities, and already shows a filamentary appearance. The magnetic energy is dominated by a strong "flux-rope" behind the cloud, formed by lateral compression of the mean field by refraction of the incident shock. This structure was discussed extensively in 2D MHD simulations presented by Mac Low et al. (1994). The field at the tip of the cloud is weak and filamentary. In contrast, for both the perpendicular and oblique shocks, the density distribution at the head of the cloud is much smoother, and dominated by a ring just downstream of the head of the cloud. Apparently even a weak transverse field can suppress the Richtmyer-Meshkov instability (which affects shock accelerated interfaces), Kelvin-Helmholtz instability, and Rayleigh-Taylor instability (see previous section) at the tip of the cloud that are present in the parallel shock case. The magnetic energy in the perpendicular and oblique shocks is also substantially different than the parallel shock. Now, most of the energy is associated with a smooth cap draped over the head of the cloud, and the single flux-rope behind the cloud becomes two parallel filaments.

The changes in the morphology of the density and magnetic energy with field geometry are important because of the potential observational consequences. Both thermal x-ray emission from shock-heated cloud material, and non-thermal synchrotron emission from shock-accelerated particles, is expected from shock-cloud interaction. It is clear from Figure 3 that the synchrotron emission from the perpendicular and oblique field shocks will be quite different, with strong emission from the sheath at the head of the cloud, as well as the twin flux tubes downstream.

3.3. *Supersonic MHD Turbulence*

One of the most surprising results obtained with the ZEUS MHD code in recent years is that the decay rate of supersonic MHD turbulence is extremely rapid (Stone, Ostriker, & Gammie 1998; Mac Low 1999). Previously, it has been thought that strong fields would prevent rapid decay of the turbulence.

It has been suggested that the rapid decay is an artifact of high numerical dissipation in ZEUS. As part of a larger study of energy dissipation and heating by supersonic MHD turbulence in molecular clouds using Athena, we have compared the saturation levels of turbulence computed with both codes

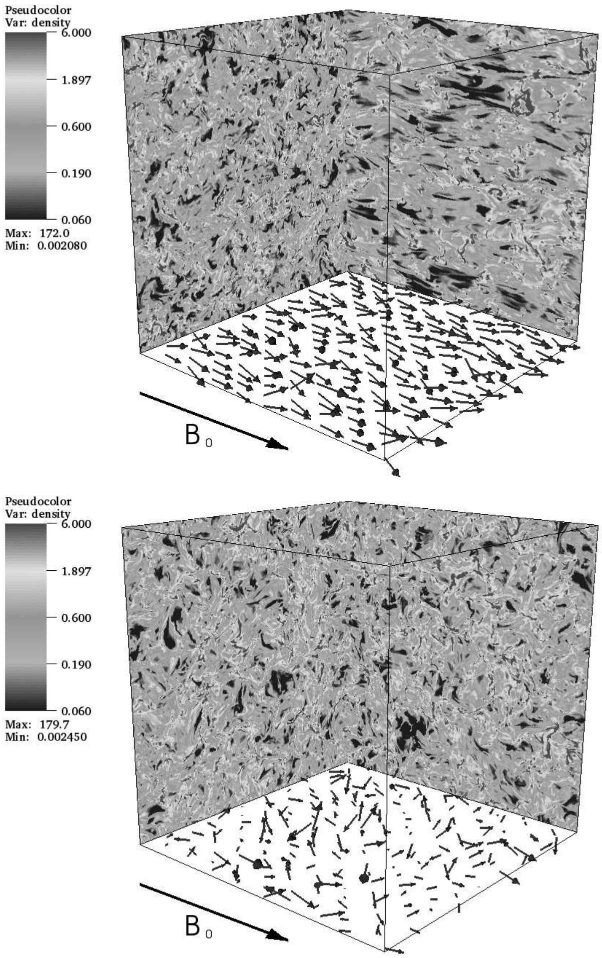

Fig. 5. Structure of the density and magnetic field in driven supersonic MHD turbulence for strong (top) and weak (bottom) fields.

using identical parameters, driving, and grids. The details of the initial conditions and driving mechanism is given in Stone, Ostriker, & Gammie (1998). The results are shown in Figure 4. Clearly both codes are converging to the same amplitude.

Figure 5 shows the typical structure observed with strong ($\beta = 0.01$) and weak ($\beta = 1$) magnetic fields in driven turbulence computed on a 512^3 grid. The density fluctuations, shown on the faces of the computational domain, are anisotropic in the strong field case. The magnetic field, shown by the vectors, is highly tangled in the weak field case.

In a companion paper by M.N. Lemaster (2009), further results on the saturation energies, power spectra, probability density functions (PDFs), and intermittency indicators in the turbulence is presented. Generally we find results that agree with previous work. These results will be published shortly in two separate papers (Lemaster & Stone 2008, b). Evolving driven supersonic MHD turbulence at high Mach number has proved to be a very challenging problem for the numerical algorithm. The fact that Athena has been able to produce results at high resolution and for such a large parameter set (see the list of runs in Lemaster & Stone 2008a,b) indicates the methods in Athena are robust.

3.4. *Other Applications*

Two other recent applications with Athena that were presented at the conference, but will not be described in this paper, are the nonlinear evolution of the magneto-thermal instability (MTI), and the nonlinear evolution of the magneto-rotational instability (MRI).

The numerical study of the MTI has been published in a series of papers (Parrish & Stone 2005; Parrish & Stone 2007). It has required extending Athena to include anisotropic heat conduction along magnetic field lines. The MTI is essentially convection in a thermally stratified atmosphere. It saturates as vigorous convective motions with significant heat transport. It has important implications for the dynamics of weakly collisional plasmas in a variety of contexts, such as Bondi accretion, and the structure of cooling flows in the hot gas in clusters of galaxies.

The first results on the MRI computed with Athena were presented at the first MFU conference (Gardiner & Stone 2006). Currently, we are extending the code to use the FARGO algorithm (Masset 2000) in order to study big boxes, and are repeating the investigation of Fromang & Papaloizou (2007) on the effect of finite dissipation on the saturation amplitude of turbulence with no net magnetic flux. Results from these investigations will be reported elsewhere.

4. SUMMARY

Within the Athena development collaboration, it has been extremely useful to evaluate the progress since the last MFU conference three years ago. Of course, we wish we had made more progress. However, the lesson is that understanding the physics of MHD flows revealed by numerical simulation always takes longer than expected. Of course, code development is always more work than expected.

We emphasize that Athena is available for use by anyone. The complete source code and documentation is available from the web.

The primary applications of Athena in the future at Princeton will be focused on the MRI, on gravitational fragmentation in supersonic MHD turbulence, and continued development of methods for

AMR with MHD. I hope to report on results from these problems at the next MFU conference.

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