Toward 2D and 3D Simulations of Core Collapse with Magnetic Fields

A Progress Report

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Abstract

We describe a code development and integration effort aimed at producing a numerical tool suitable for exploring the effects of stellar rotation and magnetic fields in a neutrino-driven core-collapse supernova environment. A one-dimensional, multi-energy group, flux-limited neutrino diffusion module (MGFLD) has been integrated with ZEUS-MP, a multi-dimensional, parallel gas hydrodynamics and magnetohydrodynamics code. With the neutrino diffusion module, ZEUS-MP can simulate the core-collapse, bounce, and explosion of a stellar progenitor in two and three space dimensions in which multidimensional hydrodynamics are coupled to 1D neutrino transport in a ray-by-ray approximation. This paper describes the physics capabilities of the code and the technique for implementing the serial MGFLD module for parallel execution in a multi-dimensional simulation. Because the development and debugging of the integrated code is not yet complete, we provide a current status report of the effort and identify outstanding issues currently under investigation.

1 Science Goals

Despite remarkable advancements in the state of the art, self-consistent simulations of stellar core collapse have not yet conclusively identified the nature of the explosion mechanism. This state of affairs leads one to ask whether success requires improved treatments of processes already present in modern simulation codes, or the inclusion of physics heretofore ignored or at best treated in a very approximate way. (That the correct answer may be "both" can not be ruled out.) We have undertaken an investigation along the second path: our effort aims to incorporate magnetic fields and stellar rotation into calculations featuring multi-dimensional hydrodynamics and ray-by-ray neutrino transport via multi-group flux-limited diffusion. Our goal is to investigate whether rotation and magnetic fields, acting in concert via the magnetorotational instability, can alter the dynamics of a post-bounce core-collapse environment in a manner facilitating an explosion. Because our code development and debugging is incomplete, this is a progress report rather than a science presentation.

2 Numerical Tools

2.1 ZEUS-MP

We compute the hydrodynamic evolution of our models with ZEUS-MP, a massively parallel 3D implementation of the ZEUS code (Stone & Norman , 1992a,b). The TSI version of ZEUS-MP has been dramatically re-engineered and extended with respect to the copy which has been publicly available on the World Wide Web. Capabilities and features in ZEUS-MP/TSI include: (1) 1D, 2D, and 3D hydrodynamics modules, (2) 2D and 3D MHD modules, (3) multi-species advection, (4) a thermodynamically consistent tabular form of the Lattimer-Swesty EOS, (5) 2D and 3D Poisson solvers, and (6) a moving-mesh algorithm.

2.2 The TCT EOS

We use a thermodynamically-consistent tabular equation of state based upon the Lattimer-Swesty EOS in wide use among supernova modelers. The TCT EOS and auxiliary routines covering the low-ρ regime of the stellar model have kindly been provided to us by F. D. Swesty.

2.3 MGFLD

Transport of all 3 neutrino species and their antiparticles is computed with a multi-group flux-limited diffusion module based upon the method described by Bruenn (1985). The flux-limiter currently in use has been calibrated against 1D Boltzmann transport and described in Liebendörfer *et. al* (2004). While not yet in use in our simulations, general relativity has been added as described in Bruenn *et. al* (2001), and additional neutrino processes, such as neutrino-nucleon elastic scattering (Reddy *et. al* , 1998) and nucleon-nucleon bremsstrahlung (Hannestad & Raffelt , 1998), have been added.

2.4 The Global Arrays Toolkit

ZEUS-MP distributes 2D and 3D problem data by subdividing the domain along each coordinate axis and assigning each contiguous data chunk to a unique processor. In contrast, MGFLD is a 1D code designed for serial execution. The task of interfacing the two codes presented a non-trivial design challenge; our solution employs the Global Arrays Toolkit[1] (GAT) library which simulates shared-memory access on distributed-memory computers. The GAT library functions create globally-defined arrays of the required field variables accessible by all processors in a parallel simulation. Each processor simultaneously executes the MGFLD solution along a radial ray extracted from the global data; updated ray data is then mapped back onto distributed ZEUS-MP field arrays (e.g. ρ, T, e, Y_e) via the GAT interface.

3 Initial Models

We evaluate our code with core-collapse calculations employing the "s15s7b" 15 $M_\odot$ progenitor of Woosley and Weaver (Woosley & Weaver , 1995). For computing 2D collapse with rotation, we adopt the simple rotation law published by Buras *et. al* (2003) for their studies of a similar progenitor with ray-by-ray Boltzmann transport. For tests with magnetic fields, we initialize a uniform seed field aligned with the polar axis.

4 Signs of Progress

Figure 1 presents a time series of plots showing entropy vs radius during the first 100 ms of a 1D radiation hydrodynamic (RHD) core-collapse simulation. This "proof-of-principle" exercise demonstrates qualitatively reasonable behavior in 1D, although we find that the measured value of the total energy experiences a large ($\sim$ 1 foe) transient at core bounce, followed by a net change in $E_{\rm tot}$ also ~ 1 foe. A number of numerical factors have been found to contribute to this behavior, and we are currently revising parts of the computational procedure in order to resolve the problem.

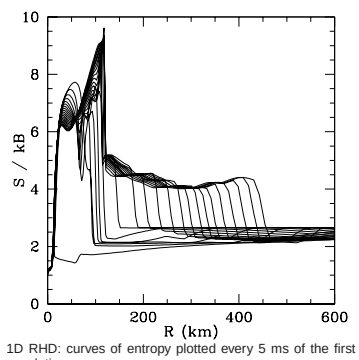

FIGURE 1: 1D RHD: curves of entropy plotted every 5 ms of the first 100ms of post-bounce evolution.

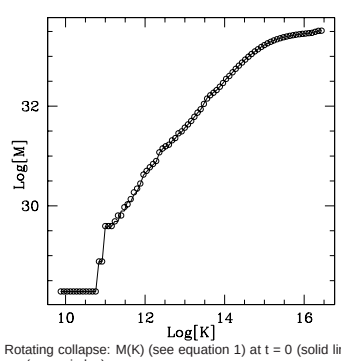

FIGURE 2: Rotating collapse: M(K) (see equation 1) at t = 0 (solid line) and 1 ms before bounce (open circles).

The goal of computing core-collapse supernova models with rotating progenitors motivates us to note a strength of ZEUS-MP bearing strongly on our science agenda: conservation of angular momentum. Following Norman *et. al* (1980), we define the *specific angular momentum spectrum*, $M(K)$, such that $M(K)$ is the total mass in the system with specific angular momentum less than or equal to K ($K \equiv J/\rho$):

$$M(K) = \int_0^K dM(k). \qquad (1)$$

$M(K)$ as defined here is a constant of motion in the absence of external torques and is therefore a useful metric for gauging angular momentum conservation. Figure 2 shows the calculation of $M(K)$ by ZEUS-MP for the adiabatic collapse of our 15 $M_\odot$ progenitor augmented by the initial rotation profile used in Buras *et. al* (2003). Integrated mass is computed in solar units; K is expressed in CGS units. The solid line shows the spectrum computed at the start of the simulation; the open circles correspond to the time at which the central density reaches 3×10^{14} g cm^{-3}, roughly 1 ms prior to core bounce. The horizontal portion of the curve at the lower left is an artifact of grid resolution.

Due to ongoing development and debugging, we are not yet able to present preliminary images from 2D core-collapse simulations. Nonetheless, one useful measure of the parallel performance of the integrated code is available. Figure 3 plots timing results for a fixed number of timesteps for a sequence of models which have 256 angular zones and vary only by the number of angular rays present. Since the number of processors must always equal the number of rays, the amount of work per processor remains constant. Perfect scaling is therefore represented by a horizontal line. Relative to the 1-processor 1D baseline (in which the GAT library is not called), there is a fixed overhead in the multi-processor calculations which is roughly uniform from 8 to 128 processors. Considering the multi-processor calculations alone, the CPU cost (which is dominated by the transport), is roughly independent of the size of the angular mesh, an agreeable result which augers well for our desired program of study.

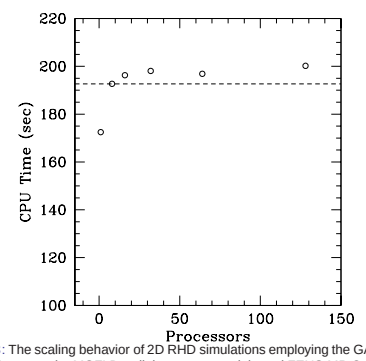

FIGURE 3: The scaling behavior of 2D RHD simulations employing the GAT parallel interface between the MGFLD radial transport module and ZEUS-MP. Calculations were run on Seaborg at NERSC.

5 Currently:

Energy conservation issues are being addressed;

2D RHD and RMHD runs are being attempted at NERSC;

An updated TCT EOS is being implemented,

Code bugs are being hunted, captured, and brought to justice, *and...*

A new public version of ZEUS-MP is being prepared for release!

Stay tuned...

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