CASTRO: A New AMR Radiation-Hydrodynamics Code for Compressible Astrophysics

Michael Singer[a], Louis Howell[a], Ann Almgren[b], John Bell[b], Marc Day[b], Eric Myra[c], and Michael Zingale[c]

[a] LLNL, Livermore, CA; [b] LBNL, Berkeley, CA; [c] SUNY Stony Brook, NY

Astrophysics with CASTRO

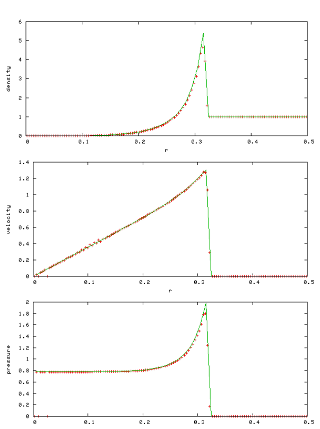
CASTRO is a new, parallel, 3D radiation-hydrodynamics code currently under development for compressible astrophysics. Block-structured adaptive mesh refinement (AMR) and sub-cycling in time enable the use of high spatial resolution where it is most needed. The hydro equations are solved using an unsplit, piecewise linear, Godunov scheme; other physics packages are added in an operator-split fashion and may be implicit. Gravity is incorporated by solving a Poisson equation for the gravitational potential. The radiation algorithm is based on Howell and Greenough (2003) and implicitly couples to hydro though the fluid energy. Well-defined interfaces facilitate plug-n-play of different equations of state; CASTRO currently has gamma-law and stellar EOS modules.

CASTRO's initial target application is multi-group neutrino diffusion for core collapse supernovae, but other applications of radiation diffusion are also of interest.

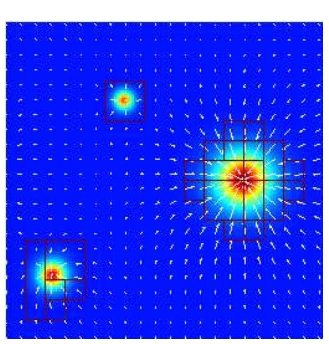
Hydrodynamics

CASTRO runs several hydro test cases, including the Sod shock tube and Sedov blast wave problems. These tests validate the core hydro integrator for all geometries (Cartesian, cylindrical, spherical) and spatial dimensions.

The results show profiles from the Sedov problem in 2D; the finest grid is 256^2. Numerical results are indicated by the '+' symbols; the solid line is the analytical solution obtained from Frank Timmes' Sedov3 code.



Gravity

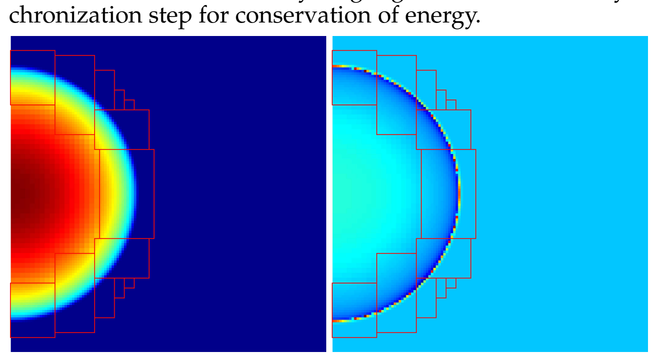


This shows the gravity solver run on a system containing three spheres of varying sizes. Gravity is computed by solving $\nabla^2\phi = -4\pi G\rho$, then $g = \nabla\phi$. The colors represent density; the vectors represent gravity. The computational domain is covered by $64 \times 64 \times 32$ zones, and one level of factor 2 refinement.

Single-group Radiation

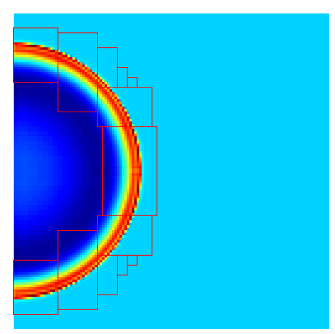
Thermal wave

To demonstrate the AMR implementation, this 2D thermal wave expands from a point on the axis in RZ coordinates. Refinement is time-dependent and based on energy gradients. High resolution grids are concentrated near the wave front, as are solution errors: there is no significant grid-imprinting on the solution. The sub-cycling algorithm includes a synchronization step for conservation of energy.



fluid energy　　solution error

With hydro coupled to radiation, the 2D thermal wave begins to transition into a shock. Parameters for this problem were chosen so that most of the energy moves into the radiation field at early time, then returns to the fluid at late time as the hot region expands and cools. The wave slows dramatically as it cools so timesteps increase by more than 12 orders of magnitude.

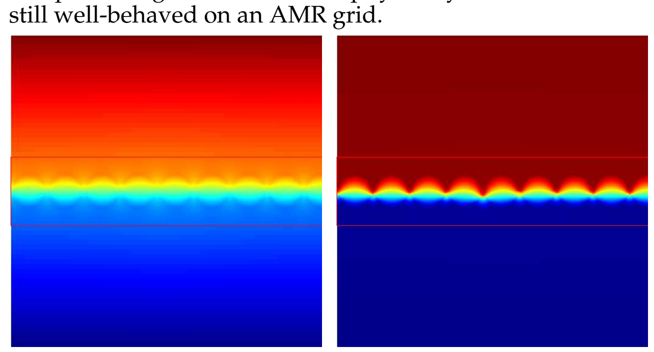


density

Flux Limiter and AMR

In this pure-scattering test, radiation diffuses through narrow gaps between optically-thick "clouds". A low resolution calculation (not shown) would drastically underestimate the flux because the gaps would not be resolved. The picture on the left shows the energy density computed with an adaptive grid where the coarse level alone would not give an accurate solution—the AMR solution is nearly the same as would be obtained with a fully-resolved fine grid.

As a separate issue, though, note the high gradients in the cloud layer: the flux is excessive here due to a breakdown in the diffusion approximation itself. The picture on the right was computed with a flux limiter that corrects for this effect, cutting the transmitted flux by more than a factor of three and producing a solution that is physically more realistic but still well-behaved on an AMR grid.



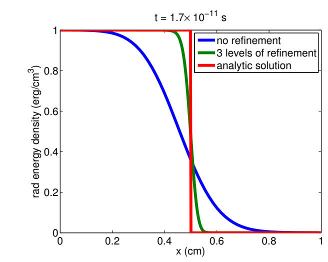
AMR with no limiter　　AMR with flux limiter

Light front with AMR

The light-front problem tests the ability of the code to propagate a radiation front in the optically thin limit. This is a challenging test for flux-limited diffusion as this regime is maximally distant from pure diffusion.

The test follows a radiation front from the left edge of the domain until it reaches a point halfway into the domain. Collision integrals are zero, and the front is initiated and maintained by boundary conditions at the left-hand edge.

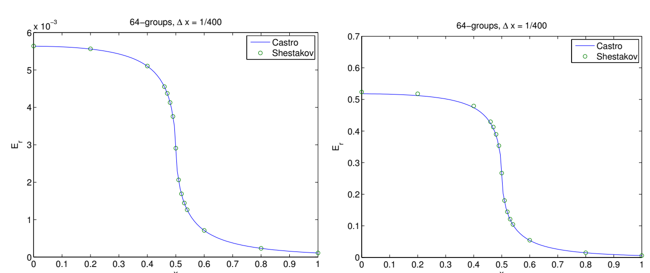
The timescale is based on a front traveling at speed c. Results are shown for gray diffusion in 1D Cartesian coordinates, using AMR at three levels of refinement in the more resolved case. Analogous results can be obtained using monochromatic transport, by performing the problem in higher dimensionality, or by using other geometries.



Multigroup Radiation

Linear diffusion

The two-dimensional multifrequency diffusion problems of Shestakov and Bolstad (2005) are solved with a multigroup implementation based on partial temperatures. The model uses an ideal gas equation of state, and opacities are proportional to the inverse of the cube of the frequency.



localized matter energy　　explicit energy source

Analytical solutions are compared with computational results; errors are less than 1%. Additional grid levels of AMR, with refinement based on energy gradients, reduces the error further.

Multigroup neutrino diffusion

We are developing an algorithm for multigroup, multi-species neutrino diffusion based on a mixed-frame, two-moment formulation similar to that of Hubeny and Burrows (2007),

$$\frac{1}{c}\frac{\partial J}{\partial t} + \frac{\partial H^j}{\partial x^j} = \eta_0^{\mathrm{th}} - \kappa_0 J + \Xi_j H^j,$$

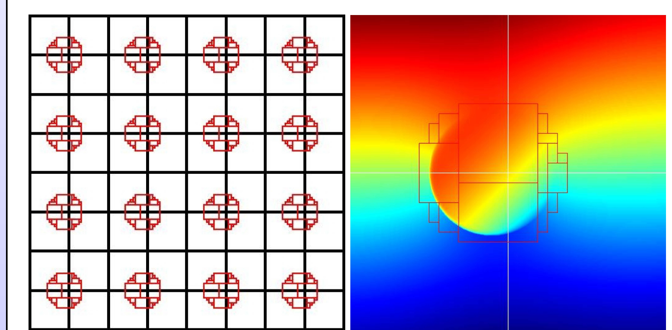
$$\frac{1}{c}\frac{\partial H^j}{\partial t} + \frac{\partial (f^{ij} J)}{\partial x^i} = \frac{\nu_j}{c}\tilde{\eta}_0 - (\kappa_0 + \sigma_{\mathrm{tr}})H^j + \xi_j J.$$

Radiation and fluid quantities are computed in the fixed and co-moving frames, respectively.

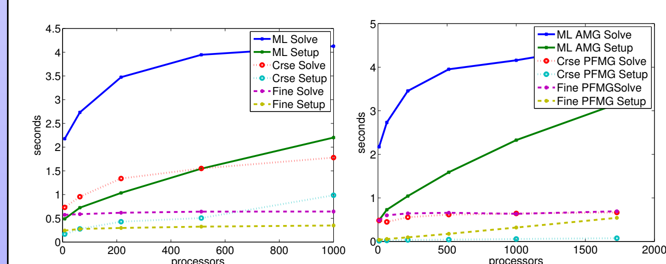
Coupling to the fluid momentum equations is explicit, and discretizations of the velocity-dependent terms (Ξ and ξ) ensure contributions of neutrino elastic scattering to the fluid energy sum to zero. Multigroup convergence acceleration is based on the linear multifrequency-grey algorithm of Morel, Larsen, and Matzen, extended to support implicit coupling to the lepton fraction as well as to the fluid energy. The algorithm has been designed but is not yet implemented.

Parallel Radiation Performance

The radiation diffusion equations are solved using the *hypre* library developed in CASC at LLNL. To demonstrate weak scaling for AMR applications, we use a tiling approach where similar grid configurations are replicated a variable number of times. 2D example grids are shown but the main scaling results are for 3D.



This particular test case augments the radiation equations with nonsymmetric terms corresponding to diffusion by a moving fluid (advection of the radiation field) correct to $O(v/c)$. In a purely scattering medium, the fluid velocity is a constant $0.05c$ towards the lower left, but the scattering coefficient varies by a factor of 10^4. Advection dominates in the optically thick circular regions, diffusion elsewhere.



Timings are for 3D AMR runs on an Opteron-based Linux cluster with 8 processors per node. On the left, GMRES preconditioned with algebraic multigrid (AMG) is used for both single-level and multilevel solutions. On the right, the structured multigrid scheme PFMG replaces AMG as the preconditioner for the single-level systems. While the solve phase is scaling well, multigrid setup costs approach those of a solve by around 2000 processors.

Work in Progress

The main current focus is implementing the multigroup neutrino algorithm. We are also working to incorporate astrophysical material properties, construct a V&V infrastructure that includes a radiation test suite, and strengthen ties with astrophysicists to solve other astrophysical problems.

Farther down the road, we'll accommodate variable Eddington tensors for the two-moment system and look at multigroup and neutrino acceleration algorithms

CASTRO code development is supported by the SciDAC Program of the DOE Office of Mathematics, Information, and Computational Sciences under contract No. DE-AC02-05CH11231. Some of the V&V work is supported by LLNL LDRD and performed at Stony Brook. The work at LLNL is performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.　　LLNL-POST-406755