

# MAESTRO, CASTRO, and SEDONA — Petascale Codes for Astrophysical Applications

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Performing high-resolution, high-fidelity, three-dimensional simulations of Type Ia supernovae (SNe Ia) requires not only algorithms that accurately represent the correct physics, but also codes that effectively harness the resources of the most powerful supercomputers. We are developing a suite of codes that provide the capability to perform end-to-end simulations of SNe Ia, from the early convective phase leading up to ignition to the explosion phase in which deflagration/detonation waves explode the star to the computation of the light curves resulting from the explosion. In this paper we discuss these codes with an emphasis on the techniques needed to scale them to petascale architectures. We also demonstrate our ability to map data from a low Mach number formulation to a compressible solver.

## 1 Introduction

We present a suite of codes for studying astrophysical phenomena whose target is the end-to-end simulation of a Type Ia supernova (SN Ia) at the petascale. Each code is designed to perform optimally for a particular flow regime. For the early convective phase of a carbon/oxygen white dwarf leading up to ignition, we use MAESTRO [3], a hydrodynamics code based on a low Mach number approach that allows long-time integration of highly subsonic flow. The time step in MAESTRO is controlled by the fluid velocity instead of the sound speed, allowing a much larger time step than would be taken with a compressible code. Once the star ignites and the fluid begins to travel at speeds no longer small relative to the speed of sound, the low Mach number assumption is invalid and the fully compressible equations must be solved to simulate the final seconds of stellar evolution before the explosion. We simulate the explosion phase of SNe Ia with CASTRO [1], a fully compressible hydrodynamics code. Finally, SEDONA [2], a multidimensional, time-dependent, multi-wavelength radiation transport code, is used to calculate the light curves and spectra from the resulting ejecta, enabling direct comparison between computational results and observation. All three codes have been designed to harness the resources of the most powerful supercomputers available, and scale well to 100k-200k cores.

MAESTRO and CASTRO use structured grids with adaptive mesh refinement (AMR); SEDONA uses an implicit Monte Carlo approach. A time step in CASTRO requires the fully explicit advance of a hyperbolic system of conservation laws, as well as the computation of self-gravity. A time step in MAESTRO is composed of explicit advection as well the solution of a variable-coefficient Poisson equation that follows from the velocity constraint resulting from the low Mach number approximation. A time step in each code also involves evaluations of the equation of state as well as computation of any reactions. In addition to simulations of SNe Ia (see Figure 1), CASTRO is also being used to study core-collapse and pair-instability supernovae, and MAESTRO is being applied to convection in massive stars, X-ray bursts, and classical novae.

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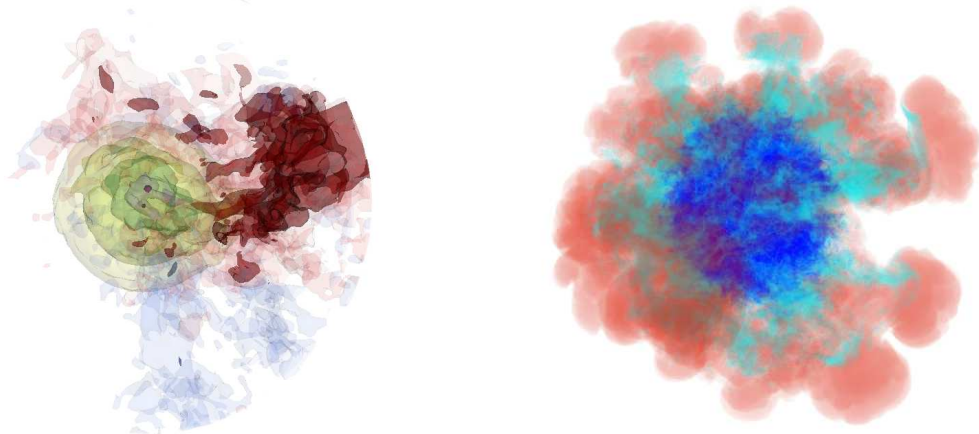


Figure 1: (Left) MAESTRO simulation of convection in a white dwarf preceding a SN Ia. Shown are contours of radial velocity (red=outward, blue=inward) and nuclear energy generation. This simulation was performed using Jaguar at OLCF with an effective  $768^3$  resolution and used approximately 1 million CPU-hours. (Right) CASTRO simulation of nucleosynthesis during the explosion phase of a SN Ia. Shown are the nuclear burning products (orange=iron, light blue=silicon and calcium, dark blue=helium). This simulation was performed by Haitao Ma at UC Santa Cruz using Franklin at NERSC with an effective  $8192^3$  resolution and used approximately 2 million CPU-hours.

## 2 Software Infrastructure

MAESTRO and CASTRO are implemented using the BoxLib framework developed in the Center for Computational Sciences and Engineering at LBNL. BoxLib is a hybrid C++ / Fortran90 software system that provides support for the development of parallel structured-grid AMR applications. In BoxLib, the memory management, flow control, parallel communication, and I/O are abstracted from the physics-specific routines, thus enabling many different applications to be built on the same software framework. SEDONA is implemented in a modern C++ framework that supports the massively parallel Monte Carlo approach.

The fundamental parallel abstraction in BoxLib is the MultiFAB, which holds the data on the union of disjoint rectangular grids at a level of refinement. A MultiFAB is composed of FABs; each FAB is an array of data on a single grid. We use a coarse-grain parallelization strategy to distribute FABs to nodes, where the nodes communicate with each other using MPI. We also use a fine-grain parallelization strategy in the physics-based modules and the linear solvers, in which we use OpenMP to spawn a thread on each core on a node. Each thread operates on a portion of the associated FAB. FABs at each level of refinement are distributed independently.

Each node contains meta-data that is needed to fully specify the geometry and node assignments of the FABs. At a minimum, this requires the storage of an array of boxes specifying the index space region for each AMR level of refinement. The meta-data can thus be used to dynamically evaluate the necessary communication patterns for sharing data between nodes for operations such as filling data in ghost cells and synchronizing the solution at different levels of refinement. Evaluating these communication patterns requires computation of the intersections of the grids themselves with rectangular patches that represent grids with ghost cells. A simple, brute force algorithm for doing so requires  $\mathcal{O}(N^2)$  operations, where  $N$  is the number of

grids. This operation becomes expensive for problems with large numbers of grids, so we have implemented a hash sorting algorithm to reduce the cost. Essentially, we subdivide the domain into multiple rectangular regions of index space, and sort the grids into these regions based on the lowest value in index space of each grid. Each region is large enough that a grid based in one region extends no further than the nearest neighbor regions. We use the knowledge of which region each grid “lives in” to restrict our search for intersecting grids to only that region and its neighbors. If  $M$  is the number of regions covering the domain, this reduces an  $\mathcal{O}(N^2)$  operation to an  $\mathcal{O}(N + N^2/M)$  operation. In order to reduce the number of times the hash sort is called, we cache communication patterns that are most frequently used.

### 3 Scaling Results

We present scaling results demonstrating that our codes can efficiently run on the largest supercomputers (see Figure 2). We use a weak scaling approach, in which the number of cores increases by the same factor as the number of unknowns in the problem. For the MAESTRO runs, we keep the one-dimensional radial base state fixed in time for this study; for the CASTRO runs we use the monopole approximation for self-gravity. In the MAESTRO and CASTRO tests, we simulate a full star on a three-dimensional grid. In the multilevel calculations the inner 12.5% of the domain is refined. The results were obtained using Jaguar at OLCF, in which two hex-core sockets share memory on a node. Thus we either assign one MPI process per socket (in which case we spawn 6 threads), or one MPI process per node (in which case we spawn 12 threads). In each case, a single thread is assigned to a single core. We note that CASTRO scaling behavior is relatively insensitive to using 6 or 12 threads. MAESTRO has better scaling performance when using 12 threads at a cost of additional thread overhead time due to threading across different sockets. The SEDONA scaling test was performed using Intrepid at ANL using a pure-MPI approach, and shows the parallel performance expected of a Monte Carlo method.

As shown in Figure 2, CASTRO scales well for the single-level and multilevel problems. We can also determine the AMR overhead using this data. Because of subcycling in time, a coarse time step consists of a single step on the coarse grid and two steps on the fine grid. Thus, we would expect that the time to advance the multilevel solution by one coarse time step would be a factor of three greater than the time to advance the single-level coarse solution by one coarse time step, plus any additional overhead associated with AMR. From the data in the figure we conclude that AMR introduces a modest overhead, ranging from approximately 15% for the 4,000 core case to 18% for the 196,000 core case. By contrast, advancing a single-level calculation at the finer resolution by the same total time, i.e., two fine time steps, would require a factor of 16 more resources than advancing the coarse single-level solution.

The overall scaling behavior for MAESTRO is not as close to ideal as that of CASTRO due to the linear solves performed at each time step. However, MAESTRO is able to take a much larger time step than CASTRO for flows in which the velocity is a fraction of the speed of sound, enabling the longer integration times needed to study convection.

### 4 End-to-End Capability

Performing an end-to-end simulation requires that a CASTRO simulation be initialized with the correctly transformed data from a MAESTRO simulation, and that SEDONA be initialized with data from a CASTRO simulation. SEDONA takes as input the density, velocity and compositional structure of the material ejected in the explosion and synthesizes emergent model spectra, light curves and polarization, which can then be compared directly against

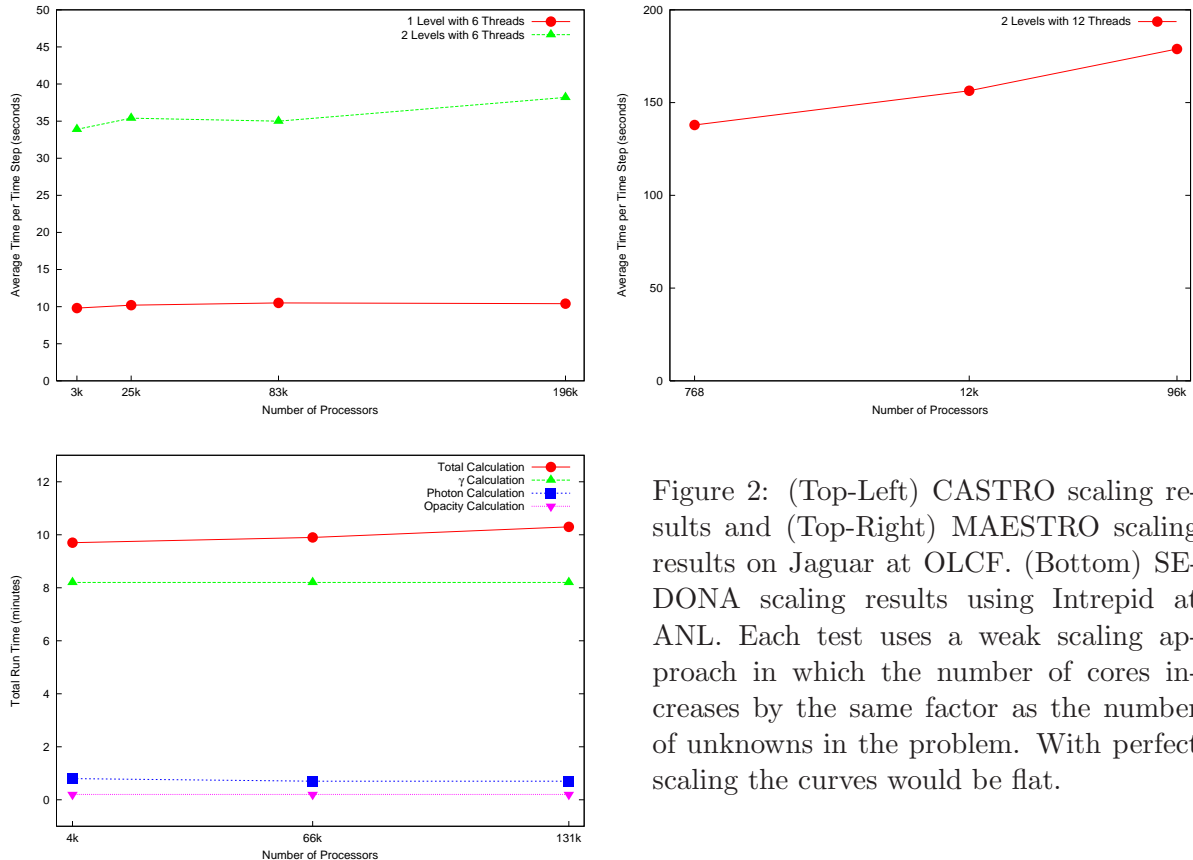


Figure 2: (Top-Left) CASTRO scaling results and (Top-Right) MAESTRO scaling results on Jaguar at OLCF. (Bottom) SEDONA scaling results using Intrepid at ANL. Each test uses a weak scaling approach in which the number of cores increases by the same factor as the number of unknowns in the problem. With perfect scaling the curves would be flat.

observations. This stage of the end-to-end simulation capability is straightforward; the only remaining task is to modify SEDONA to read the data from CASTRO’s AMR hierarchy rather than from a uniform grid.

Initializing a CASTRO simulation with data from a MAESTRO simulation is analytically more complicated due to the difference between the low Mach number approach and a fully compressible approach. However, the fact that MAESTRO and CASTRO share a common software framework makes the implementation straightforward. Here we demonstrate the successful mapping from MAESTRO to CASTRO for a two-dimensional test problem, that of an inflowing jet.

The computational domain is 1 cm on each side, and the pressure and density are set to terrestrial conditions with zero initial velocity. At the inflow face, we apply a normal velocity with a maximum Mach number of 0.1, specifically,

$$v = c_s \{0.01 + 0.045[\tanh(100(x - 0.4)) + \tanh(100(0.6 - x))]\} \text{ cm/s.} \quad (1)$$

The inflow density is set to half of the initial value inside the domain. In Figure 3, we show the density and pressure fields computed with MAESTRO and CASTRO to  $t = 300 \mu\text{s}$ . In the CASTRO simulation, an acoustic wave is launched from the inflow boundary. The acoustic signal bounces around the domain until later times, when the solution has mostly equilibrated. In Figure 4, we show the results from initializing a CASTRO simulation using the MAESTRO data from  $t = 200 \mu\text{s}$ . Shortly afterwards, the acoustic signal originating from the inflow boundary has equilibrated, and the final-time data closely matches the simulations in Figure 3.

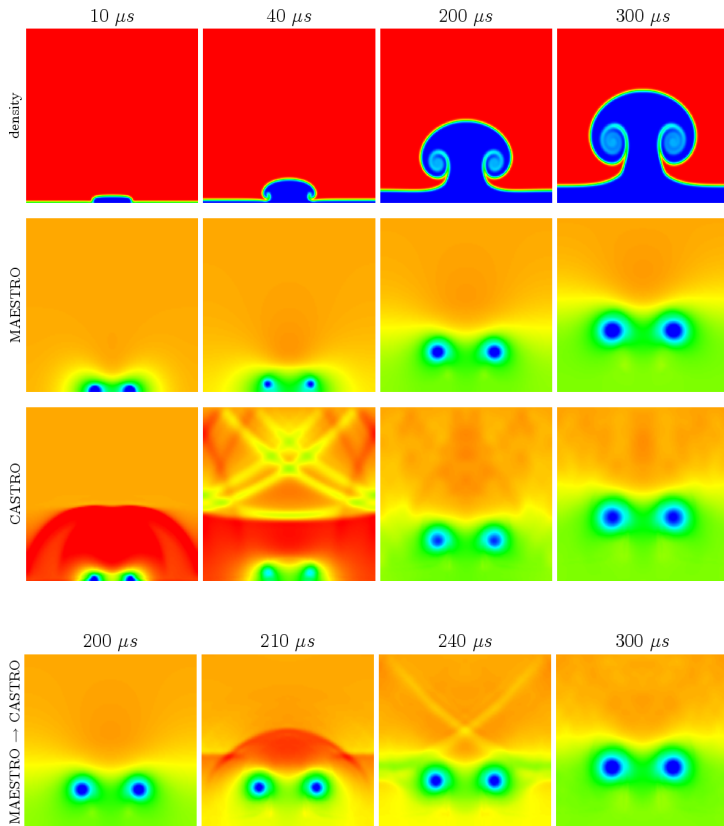


Figure 3: Evolution of a low Mach number jet showing (top) density, (middle) MAESTRO pressure, (bottom) CASTRO pressure for the inflow jet problem at 4 different times in the evolution. The density plots are indistinguishable between the MAESTRO and CASTRO simulations.

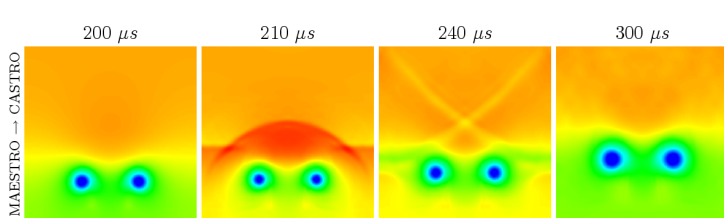


Figure 4: Jet evolution using the MAESTRO dataset from  $t = 200 \mu s$  (see Figure 3) to initialize a CASTRO simulation. Here, the time sequence corresponds to the last two columns of Figure 3.

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