From Convection to Explosion: End-to-End Simulation of Type Ia Supernovae

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Abstract. We present our end-to-end capability for computing the convective phase through the explosion phase of Type Ia supernovae. We compute the convective phase up to the time of ignition using our low Mach number code, MAESTRO, and the subsequent explosion phase using our compressible code, CASTRO. Both codes share the same BoxLib software framework and use finite-volume, block-structured adaptive mesh refinement (AMR) to enable high-resolution, three-dimensional full-star simulations that scale to 100,000+ cores. We present preliminary results from the first-ever simulations of convection preceding ignition using MAESTRO with AMR. We also demonstrate our ability to initialize a compressible simulation of the explosion phase in CASTRO using data obtained directly from MAESTRO just before ignition. Some care must be taken during this initialization procedure when interpreting the size and distribution of hot spots.

1. Introduction

The most widely accepted model for a Type Ia supernova is the thermonuclear runaway and subsequent explosion of a white dwarf that is accreting mass from a binary companion (see [3] for a review). Two key phases of this process are the convective phase and the explosion phase. During the convective phase, which lasts hundreds of years, carbon burning near the core drives convection throughout the star along with a gradual temperature rise. At some point the burning becomes vigorous enough that a hot spot does not cool quickly enough as it buoyantly rises, and a flame front is born, i.e., the star ignites. The flame propagates through the star, possibly transitioning into a detonation, and burns vigorously enough to cause the star to explode within a few seconds.

Previously, we have used our astrophysical code suite to compute the convective phase and explosion phase independently. To compute the convective phase, we use our low Mach number code, MAESTRO [5], and for the explosion phase, we use our compressible hydrodynamics code, CASTRO [2]. Both codes solve the equations of reacting flow constrained by an equation of state. The physical processes are numerically coupled together using Strang splitting, with a Godunov advection scheme and a pointwise ODE solver for reactions. Additionally, both codes share the same BoxLib software framework and use finite-volume, block-structured adaptive

mesh refinement (AMR) to enable high-resolution three-dimensional full-star simulations. In [1], we described how both codes scale to 100,000+ cores using a hybrid MPI/OpenMP approach to parallelization.

In [6], we used MAESTRO to compute the convective phase up to ignition at 8.7 km resolution without AMR. We are currently performing studies using AMR, allowing us to compute the ignition flow field at unprecedented 4.3 km resolution, as well as study the general flow field properties at 2.2 km. In Section 2 we will give more details about the MAESTRO code, as well as give preliminary results from our newest high-resolution simulations.

In [4] we described compressible simulations using CASTRO of the explosion phase at 0.5 km resolution. We have observed, as have others, that the characteristics of the explosion phase are highly dependent on the initial conditions, in particular, the size and distribution of the hot ignition points. Unlike with previous simulations, we are now in the unique position of being able to use simulation data from the convective phase to initialize a simulation of the explosion, thus allowing for a true end-to-end simulation of a Type Ia supernova event. In Section 3 we will provide our first observations from using MAESTRO ignition data to initialize a CASTRO simulation.

2. Convection Preceding Ignition

The convective phase preceding ignition is characterized by subsonic convection and gradual temperature rise over hundreds of years. We have modeled the last few hours of convection preceding ignition using our low Mach number hydrodynamics solver, MAESTRO [5]. MAESTRO is based on a low Mach number equation set that filters acoustic waves from the system while retaining local compressibility effects due to reaction heating and compositional changes. The time step constraint in MAESTRO is based on the fluid velocity rather than the sound speed, resulting in an average reduction in the number of time steps by a factor of $1/M$, i.e. the ratio of the sound speed to characteristic fluid velocity. For our simulations of convection preceding ignition, a MAESTRO time step is roughly a factor of 70 greater than a CASTRO time step would be. Our scaling studies indicate that for a 576^3 simulation with no AMR, a MAESTRO time step uses approximately 2.5 times the computational time of a CASTRO time step, primarily due to the linear solvers. Thus, MAESTRO uses approximately a factor of $\sim 70/2.5 = 28$ times less computational time than CASTRO would to simulate the convection preceding ignition.

We define ignition in MAESTRO as the point in time when the peak temperature exceeds 8×10^8 K. In [6], we presented our results describing the convective patterns and likely ignition radius using 8.7 km resolution simulations. Since then, we have performed simulations taking advantage of AMR to obtain convective patterns with 2.2 km resolution, and ignition properties at 4.3 km resolution (computer allocations have prevented us from running the 2.2 km case to ignition). See Figure 1 for a snapshot of the AMR grid structure and convective patterns a few minutes prior to ignition from the 2.2 km resolution simulation. In this simulation, there are approximately 664 million grid cells at the finest resolution, and 1.0 billion grid cells overall. By contrast, if the entire domain were at the finest resolution there would be over 12 billion grid cells.

We also note the presence of a strong outward jet in the velocity field. Our new high-resolution simulations have led to a better understanding of the convective flow, and the behavior is more accurately described as an outward flowing jet, rather than a dipole as we have previously reported. We observe that the jet changes direction over the course of the simulation. We also noted in [6] that the addition of a small amount of rotation, included by modifying the
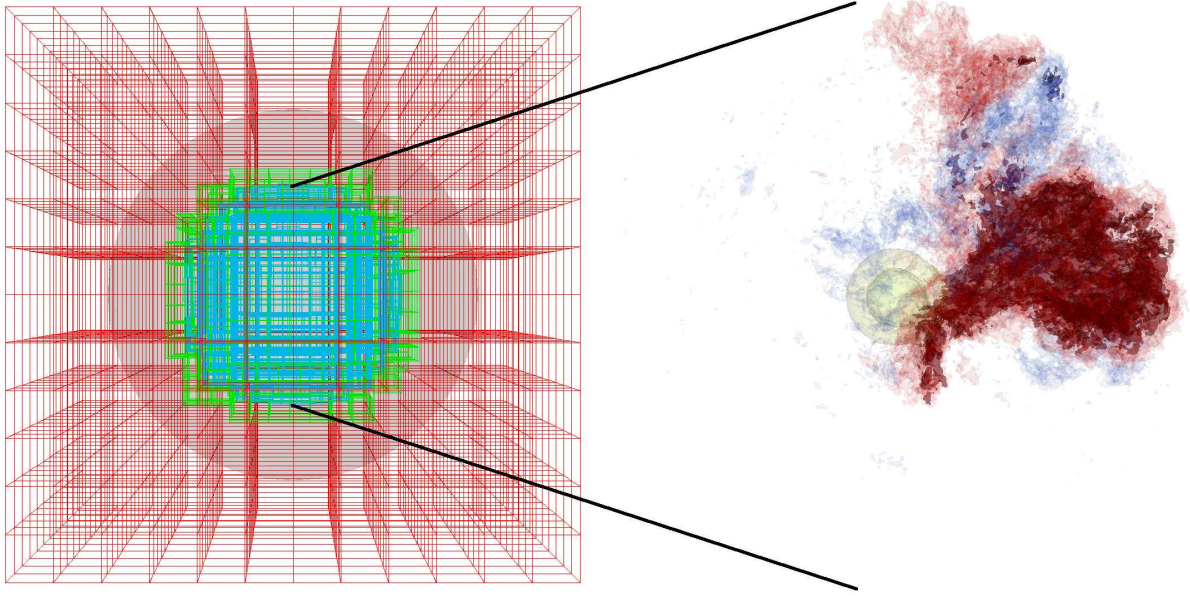
Figure 1: (Left) Grid structure from a MAESTRO simulation with three total levels of AMR. There are $\sim 2000 - 4000$ grids at each level of refinement, and each grid contains up to 48^3 grid cells. The grids marked in blue have 2.2 km resolution cells. (Right) Snapshot of convection within the inner ~ 1000 km radius region around the core, which is marked by the blue grids. The red/blue contours indicate regions of outward/inward flow and the yellow/green contours indicate increasing burning rates.

forcing term in the momentum equation, causes the jet to break up at lower resolution. In the near future we will perform simulations of rotating stars with AMR to get a clearer picture of this behavior.

In [6], we discovered that the likely ignition radius is $\sim 50 - 100$ km off-center. It appears as if this result is robust at higher resolution, but further analysis is required. We also plan to analyze our data to determine the likelihood of multiple ignition points at different locations in the star.

3. Explosion Phase

To model the explosion phase, we use the general compressible code, CASTRO [2]. We have previously performed simulations of the explosion phase using artificially seeded hot spots [4], but here we will use the data from MAESTRO directly. We begin with the state of the star at the point of ignition from our 4.4 km MAESTRO simulations. In Figure 2, we show contours of increasing temperature near the core at the time of ignition. The actual ignition point in MAESTRO occurs within exactly one cell, which is marked by the red contour.

When mapping data into CASTRO, there is some uncertainty as how to define the ignition region, as required by the flame model in CASTRO. Our first approach was to simply define all cells where $T > 7.5 \times 10^8$ K (as indicated in blue contours in Figure 2) as having ignited. The resulting flame evolved over the first 0.5 s as shown in the left panel of Figure 3. Note that we have added additional resolution around the flame front, as seen by the black grids, denoting regions where the resolution is 1.1 km. However, subsequent simulations in MAESTRO in which we disabled the burning very close to the ignited cell show that the other nearby hot spots (the gold contours in Figure 2), rise and cool, and therefore do not ignite in the near
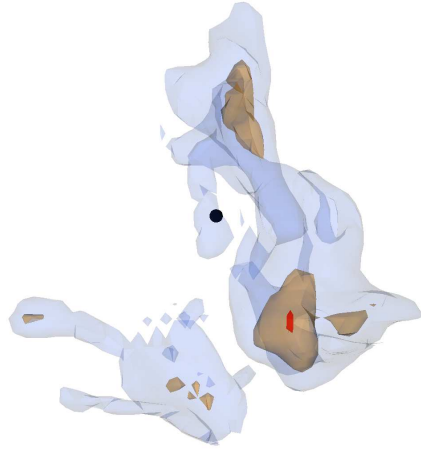
Figure 2: Temperature contours at the innermost ~ 75 km of the white dwarf at ignition. The black dot is the center of the star and has diameter 4.4 km, corresponding to the cell size from the MAESTRO simulation. The red contour encapsulates the region (one grid cell in this case) where $T > 8 \times 10^8$ K, the gold contours encapsulate regions where $T > 7.8 \times 10^8$, and the blue contours encapsulate regions where $T > 7.5 \times 10^8$.

future. Based on this observation, we started another CASTRO simulation in which we define the ignition region as the single gold contour that is directly connected to the red ignition point. The subsequent flame evolution is shown in the right panel of Figure 3. The differences are striking, and before we continue the evolution of the explosion phase we must be certain that we are choosing a physically reasonable hot spot distribution. We also note that this flame model is preliminary and more work is needed to define a realistic flame model for these calculations. Nevertheless, these simulations serve as a proof-of-concept for our capability to perform end-to-end simulations of SNe Ia.

Acknowledgements

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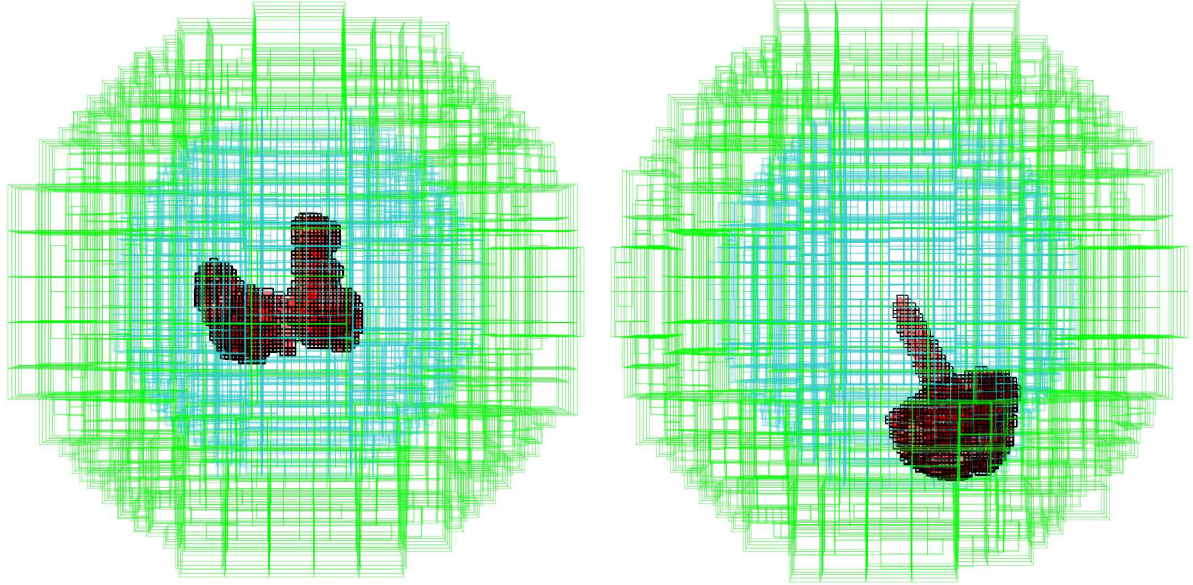
Figure 3: Innermost ~ 1500 km of white dwarf after less than one second of evolution in CASTRO using two different initial conditions. The green, blue, and black grids are at 4.3 km, 2.2 km, and 1.1 km resolution, respectively. The red contour encapsulates the region burned by the flame. (Left) We initialize the flame to be in the location of the blue contours in Figure 2, where $T > 7.5 \times 10^8$ K. (Right) We initialize the flame to be in the location of the single gold contour connected to the red ignition point in Figure 2.

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