Simulations of Thermonuclear Supernovae of Very Massive Stars

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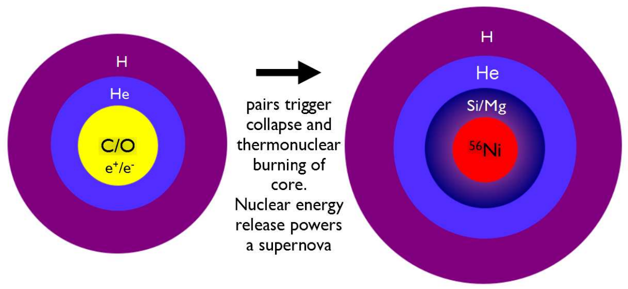
Introduction

Our current understanding of the formation of the first stars in the universe implies that these stars were very massive, having a typical mass scale of hundred times the mass of the sun and explode as Pair Instability Supernova (PSN). Whereas multi-dimensional simulations of most types of supernovae have been done extensively, few such simulations of exists for PSN. Our goal is to understand the energetics, hydrodynamic instabilities, and nucleosynthesis of these supernovae.



The evolution of PSN. (Courtesy of Daniel Kasen.)

Numerical Approach

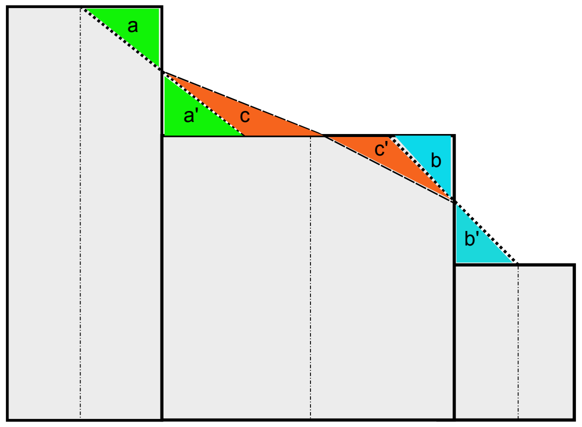
We start our simulations using one-dimensional models obtained from the `KEPLER` code, spherically symmetric Lagrangian code that followed the evolution of a star up to ten seconds before maximum compression (oxygen depleted phase). Then we map the resulting one-dimensional profiles into 2D and 3D to serve as the initial conditions for `CASTRO`.

CASTRO

`CASTRO` is a new, massively parallel, multidimensional Eulerian AMR radiation-hydrodynamics code for astrophysical applications. Time integration of the hydrodynamics equations is based on a higher-order, unsplit Godunov scheme. Block-structured adaptive mesh refinement (AMR) and sub-cycling in time enable the use of high spatial resolution where it is most needed.

Mapping of Initial Model in Multi-D

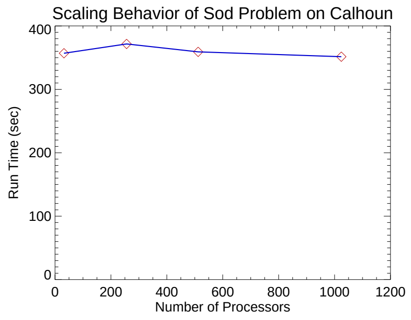
Since our initial model will be in a state close to hydrostatic equilibrium, we need to be careful how we map the 1D spherically symmetric data given on a non-uniform Lagrangian grid to a multidimensional Eulerian grid. Here we present a method that numerically conserves quantities such as mass and energy that are analytically conserved in the evolution equations. Whereas this does not guarantee that the initial data will be in perfect numerical hydrostatic balance, it is at least a physically motivated constraint and is sufficient for our simulations.

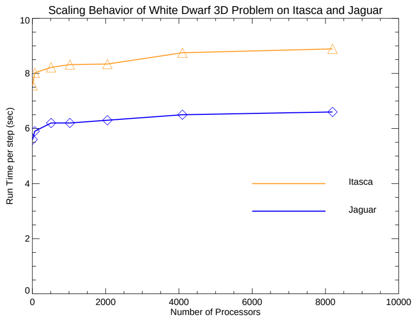


Schematic for constructing a conservative density profile.

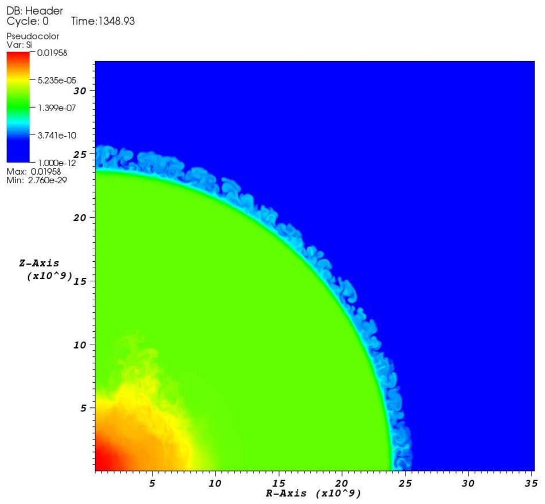
Result I

To understand the parallel efficiency of `CASTRO`, we run the Sod problem on $32 (1024 \times 256 \times 256)$, $256 (2048 \times 512 \times 512)$, $512 (2048 \times 1024 \times 512)$ and $1024 (2048 \times 1024 \times 2024)$ processors; the grid information is inside (). In the case of perfect scaling, we would expect the curve of the plot to be flat. We also compare the performance of `CASTRO` on our Itasca and Jaguar (1st of Top500 List) at ORNL by running white dwarf 3D problem on 8, 64, 512, 1024, 2048, 4096 and 8192 processors. We linearly scale the load of jobs according to number of processors

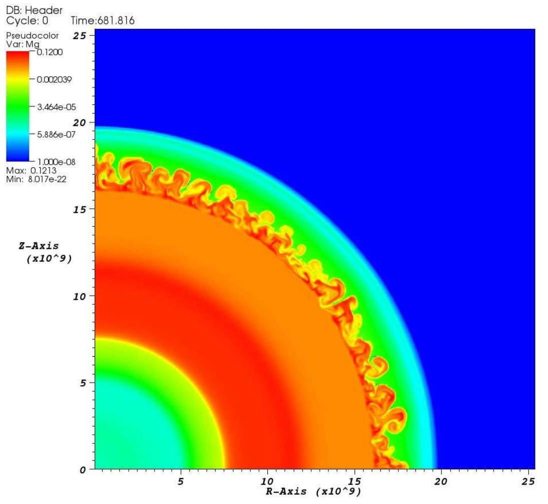




The 2D run takes more than 8,000 CPU hours and the 3D run takes more than 80,000 CPU hours. The results presented here are from 2D runs of PSN models in cylindrical symmetry where we simulated only one hemisphere.

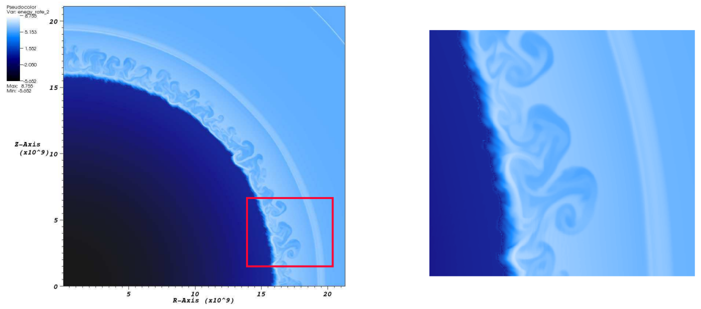


The ^{28}Si mass fraction of 150 $M_\odot$ rotational PSN after evolving ~ 1300 secs.



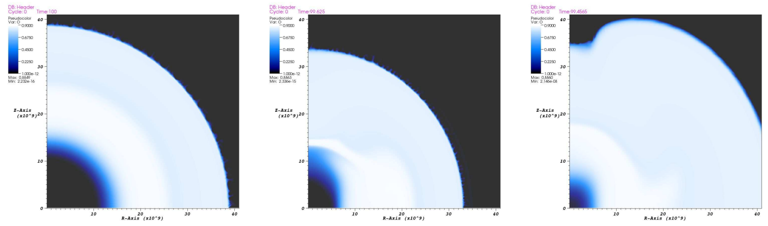
The ^{24}Mg mass fraction of 150 $M_\odot$ PSN at ~ 60 secs after bounce.

Result II



(a) (b)

Figure(a) is the map of specific nuclear energy generation rate at ~ 60 secs after bounce. We find Rayleigh-Taylor(RT) instabilities develop at the edge of the oxygen-burning shell. Later these instabilities will grow further an affect such properties as the observable light curve of the supernova. Figure(b) is a close-up of the RT instability.



The ^{16}O mass fraction map for rotational models at ~ 80 secs after bounce; they correspond to 0%, 30%, 100% of keplerian rotational rate at radius, 2.5×10^9 cm, respectively.

Summary

Discussion and Conclusion

We have presented preliminary results from our first multidimensional numerical study of the evolution of pair instability supernova using the new Eulerian AMR radiation-hydrodynamics code `CASTRO`. We simulated the formation of Rayleigh-Taylor instabilities in the explosion of pair instability supernovae. We have introduced a new mapping method that can be used to define the initial conditions for multidimensional simulations from one-dimensional initial data in such a way that conservation of physical quantities,monotonicity, and continuity are guaranteed at any resolution.

Acknowledgments

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References

1. Timmes (ApJs, 124, 241, 1999).
2. Chen, Heger, & Almgren, submitted to CPC.
3. Weaver, Zimmerman, & Woosley (ApJ 225, 1021, 1978).
4. Almgren et al. CASTRO: A New Compressible Astrophysical Solver. I. Hydrodynamics and Self-Gravity, submitted to ApJ.