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Evolution of Non-Spherical Core-Collapse Supernovae Toward Homology

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Introduction

We perform high-resolution multi-dimensional simulations of asymmetric Type II supernova explosion of a 15 $M_\odot$ blue super-giant progenitor. The purpose of our investigation is to compare theoretical models of supernova explosions to observations. To this aim we require computing evolution times much longer than have been previously attempted. We start our simulations shortly after shock revival and run to approximately seven days later when the flow has become homologous. After attaining expansion, we can make detailed comparisons between our explosion models and observational data.

We are interested in studying the hydrodynamic instabilities that develop along material interfaces after they have been overrun by the passing shock wave. We observe the development of Rayleigh-Taylor instabilities that appear mainly at the Si/O and (C+O)/He composition interfaces. The occurrence of these hydrodynamic instabilities is believed to be responsible for large-scale anisotropies, mixing, and clumping of products of nucleosynthesis, which are observables of supernova remnants (e.g. Cas A or SN 1987A). Of particular interest is the amount of additional mixing that may be taking place at times beyond the reach of previous computations (six hours after the shock revival). Up to that point, our models are largely consistent with the results obtained by Kifonidis et al. (2006), and observational features of SN 1987A.

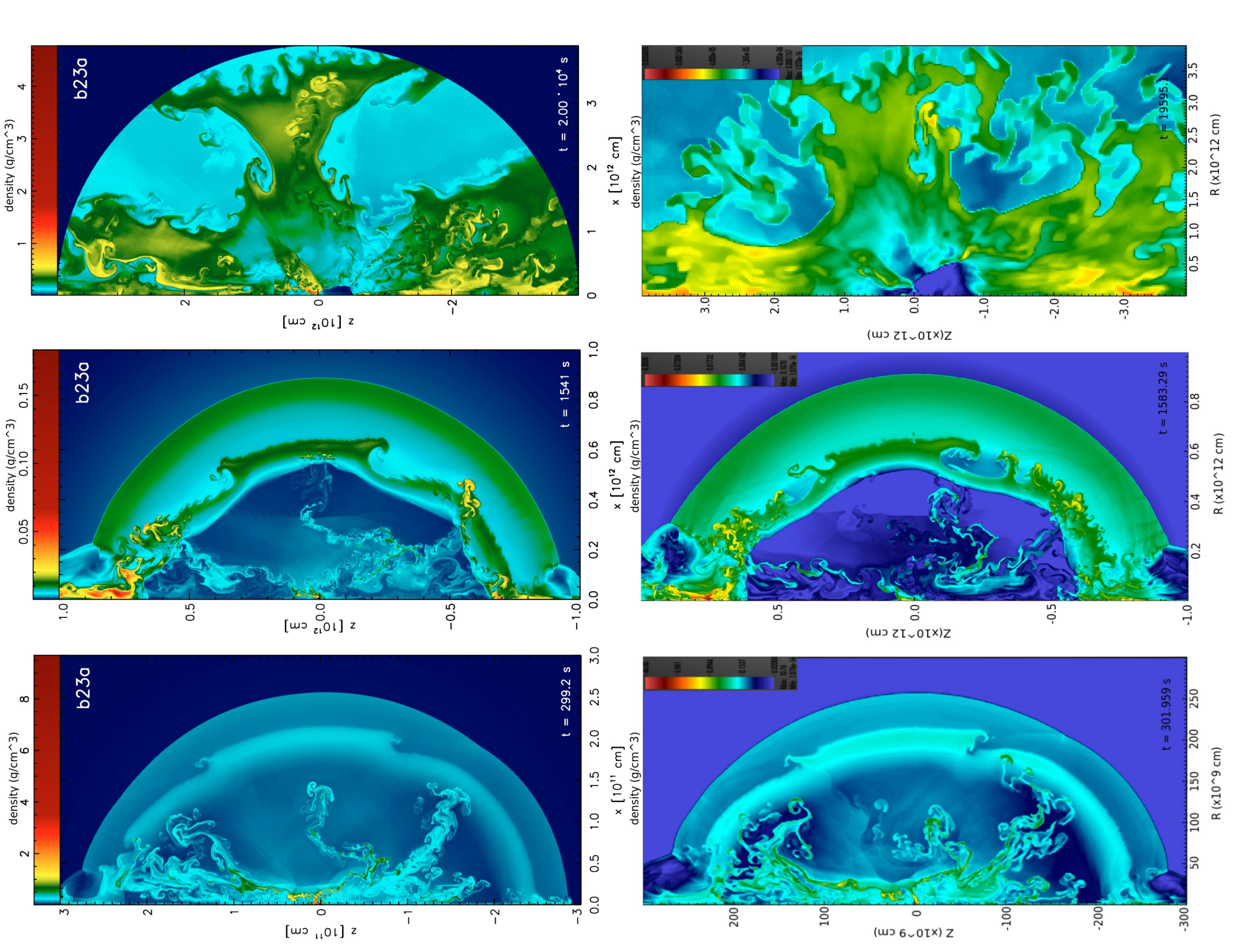


Fig. 1: On the left column we see snapshots of the density distribution of model b23a at various times, up to the final simulation time reached by Kifonidis et al. (2006). On the right column we see snapshots of the density distribution of our latest simulation at similar times. Although these computations were obtained at nominally lower radial resolution, all of the major structures observed in the old computations are present in our current computations. As can be seen, the developing Rayleigh-Taylor instabilities have already produced a great deal of mixing early on in the simulation. At later times these structures expand to produce even more mixing.

Observations

On February 23rd, 1987, the light from supernova 1987A reached Earth and has since then given scientists great insight into the inner workings of a supernova explosion. Due to its proximity, SN 1987A is the only supernova that has been visible with the naked eye in the last 383 years. It was the first supernova whose progenitor was directly identified (Sanduleak -69° 202), first to be detected in gamma-rays, and the first supernova from which neutrinos have been detected. The detection of neutrinos indicates that the progenitor star underwent core collapse. This astronomical event also revealed evidence of asymmetries and mixing in the expansion and shape of the supernova. This evidence presented itself in the form of the "Bochum event", polarization, and asymmetric structures in emission line profiles.

The "Bochum" event was observed by the Bochum telescope at La Silla, Chile, three weeks after the explosion when the photosphere was still located inside the hydrogen envelope. It was a rapid change in the P Cygni profile of the H_α line, which implies enhanced heating due to radioactive ^{56}Ni. This isotope is produced deep inside the star buried under 10 solar masses and should not have been observable until a year after the explosion. This was evidence of radioactive blobs rising from the inner ejecta to the surface. Other strong evidence for mixing came from the detections of γ-photons from the decay of ^{56}Co to ^{56}Fe. These detections occurred half a year earlier than spherically symmetric models had predicted and could only be reproduced in models in which the ^{56}Co was mixed into the hydrogen envelope artificially.

Although SN 1987A provided many firsts and a great wealth of observational data about asymmetries and mixing in supernova explosions, it has been shown that these are generic features in core collapse supernovae. Observational evidence of these hydrodynamic instabilities has now been seen in SN 1987F (Type Ib), SN 1988A (Type II), SN 1993A (Type IIb), and others.

Computational Model

The Method

To compute our simulations we are numerically solving the equations of compressible hydrodynamics in conservative form. We use the Eulerian version of the Piecewise Parabolic Method (PPM, Colella & Woodward 1984) as implemented in Ardent/FLASH, a parallel, block-structured, adaptive mesh refinement (AMR) hydrodynamic code. A new limiter that preserves accuracy at smooth extrema is implemented (Colella & Sekora 2008). To close the system of equations we use an electron-positron equation of state based on table interpolation of the Helmholtz free energy (Timmes & Swesty 1999). We are also keeping track of 19 passively advected nuclear species. These species include ^{56}Ni, which is the isotope whom's effects were unexpectedly observed at La Silla, Chile.

The Grid

In the past, simulations of core-collapse supernova have been performed with spherical coordinates, which severely limited the time step because of the extremely small grid spacing towards the center. To relax the Courant-Friedrichs-Lewy (CFL) condition and take larger time steps we computed our simulations on a 2D cylindrical grid assuming symmetry about the z-axis. This combined with mesh adaptivity allowed us to take the simulation further in time up to the point when the flow becomes homologous.

For the boundary at the axis of symmetry we used reflective boundary conditions and outflow everywhere else. Our grid extends from just after the center of the star up to a radius of $2x10^{14}$ cm. The center of the star, where the nascent neutron star resides, is approximated by a non-moving gravitational sink hole. The mass that is accreted by the sink hole is accounted for and its gravitational effect on the system adjusted accordingly.

Initial Conditions

At the start of our simulation the grid is populated with three different models. The explosion model extends up to a radius of $1.7x10^9$ cm, the stellar model extends up to $3.9x10^{12}$ cm, and the rest of the domain is taken up by the stellar wind model up to a radius of $2x10^{14}$ cm.

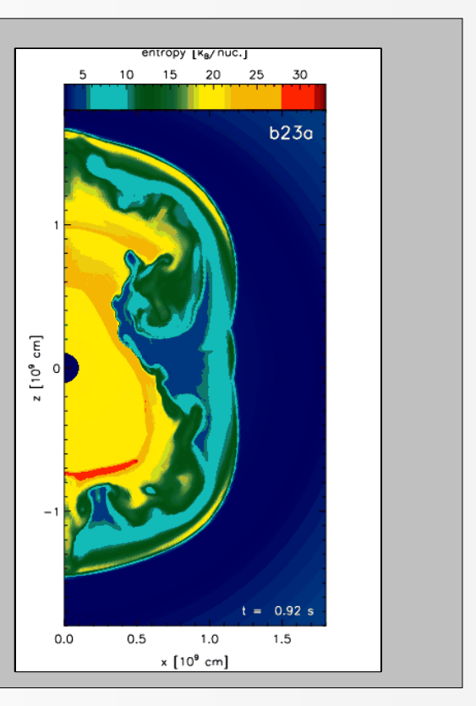
Progenitor Model

This portion of our model we took from a spherically symmetric one dimensional model that originated from the simulations Woosley, Pinto, & Ensman (1998). Bruenn (1993) followed the core collapse and bounce of this progenitor. We mapped the model to our cylindrical grid with monotonic cubic interpolation (M. Steffen 1990).

Explosion Model

The explosion model that we use is the b23a model used by Kifonidis et al. (2006). This two dimensional model is taken at 0.92 seconds after shock revival and was computed with spherical coordinates. Again we use monotonic cubic interpolation to map the model to our computational grid.

Fig. 2: Entropy distribution for model b23a at t=0.92s after bounce (Kifonidis et al. 2006). We use this model to initialize the central regions of our computational grid just outside the supernova shock radius (~$1.8x10^9$ cm).



Stellar Wind Model

In the region that extends past the stellar model we fill the grid with a spherically symmetric wind. The stellar wind model consist of a constant radial velocity of 15 km/s, a temperature of $1x10^4$ K and a constant mass rate loss of $1x10^{-5}$ $M_\odot$/yr, from which we can calculate the density distribution analytically. Having calculated the density we can then use the equation of state to compute the pressure.

Adaptive Strategy

Since Ardent/FLASH employs AMR we can have many levels of refinement depending on what is going on in the computational domain. In our case refinement is based on density, pressure, and mass fraction values. The code will add refinement levels if a density jump is > 0.2, pressure jump > 0.4, or the abundance of nickel exceeds 10% by mass. We initially start with a large number of refinement levels and then remove these levels depending on the instantaneous number of cells, to limit memory use, and the calculated step size, to limit computational time. We initially run several one dimensional models at different resolution to aid designing 2D simulations.

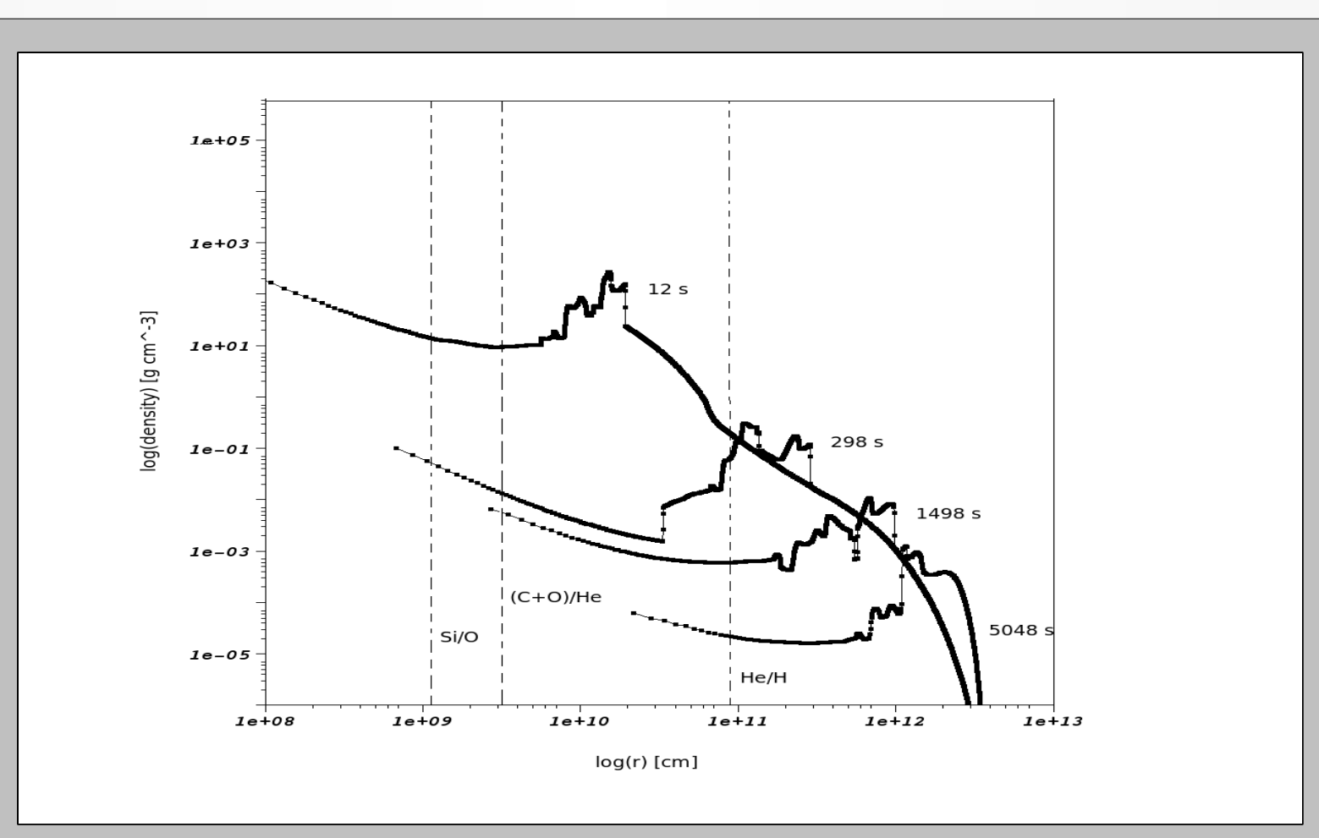


Fig. 3: Evolution of density for the one dimensional simulation of the 15 $M_\odot$ Type II supernova.

Results

The first complete 2D model that we have is at a resolution of 240 km. This model took about one week to run on a 16 processor AMD machine. Better resolved models are now being computed on larger processor partitions on Franklin Cray XT4 at NERSC. We typically use 32 processors which provides optimal balance between (relatively small) amount of data involved and communication overhead. However, compared to computations on spherical grids, our simulations allow for larger timesteps effectively allowing for increase in numerical resolution.

Having improved the time-scale, we have been able to reach a final simulation time of 7 days, much further than previous computations, which could only attain a final simulation time of ~6 hours. At these later times we have been able to observe the initial shock wave leaving the star, the outermost material interface of He/H become Rayleigh-Taylor unstable, and velocity evolution of ^{56}Ni toward ballistic motion.

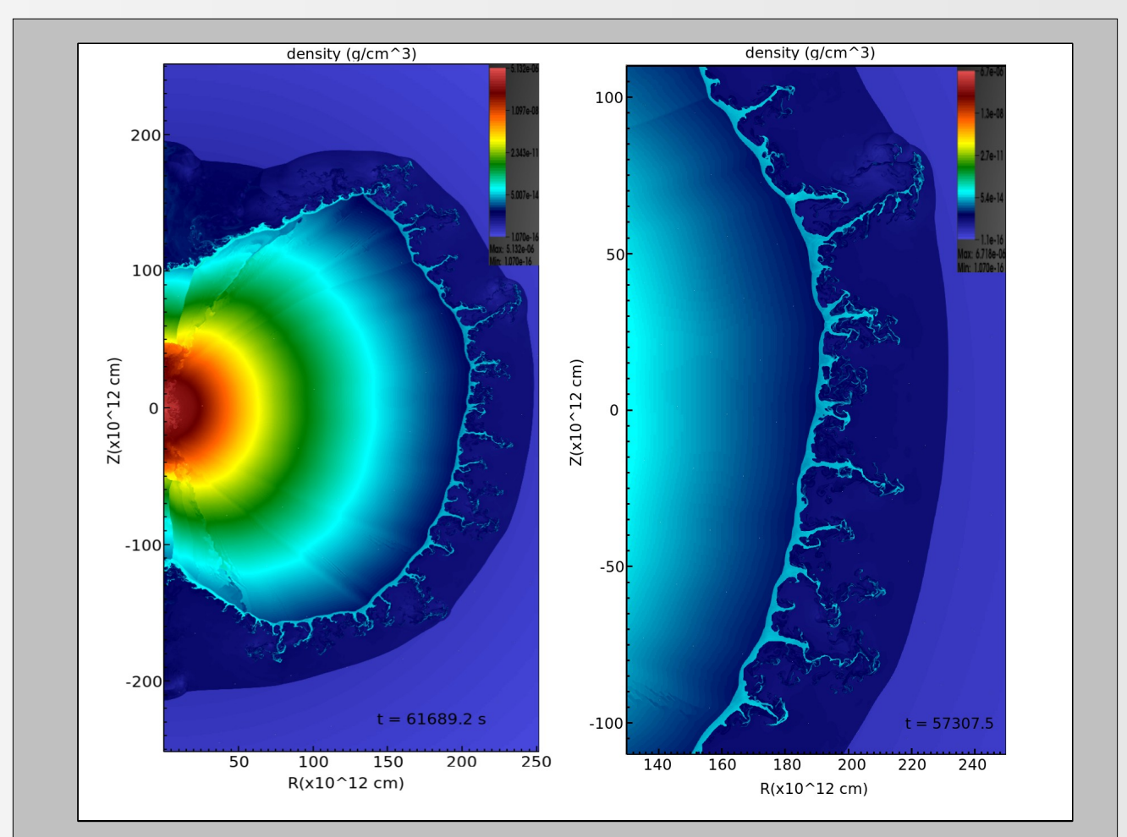


Fig. 4: On the left we have the density distribution on entire domain depicted at a simulation time of 61689.2 s. We clearly see the Rayleigh-Taylor instabilities that have developed in the He/H interface of the star. On the right we have zoomed in on the instabilities.

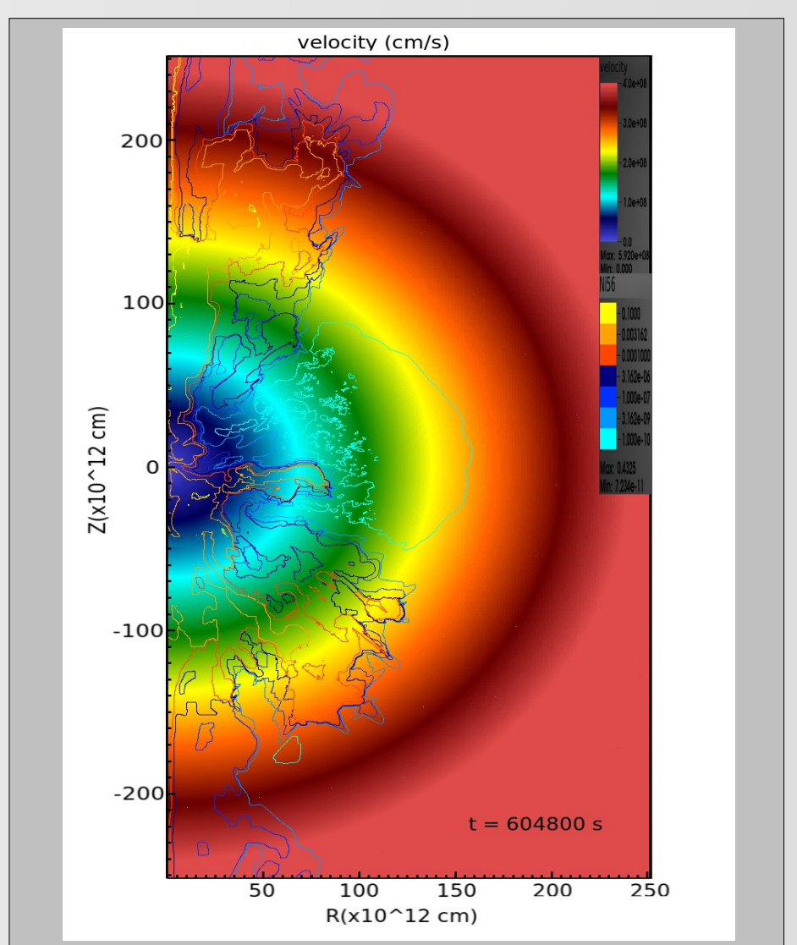


Fig. 5: Above we have ^{56}Ni abundances super-imposed on top of the velocity distribution at a simulation time of 7 days.

The latter is characterized by small ratio of internal energy to kinetic energy. At the final simulation time of 7 days, we found that there are still some portions of the flow with ~10% internal energy content. We can say that the flow is expanding homologously when the flow is dominated by the kinetic energy. At that point the flow will expand in a ballistic manner, meaning that we can then extrapolate the structure of the flow and compare directly with observations. Since some of the flow still contains some internal energy then It would be best to extend the simulation two more days when the ratio of internal energy to total energy will become negligible.

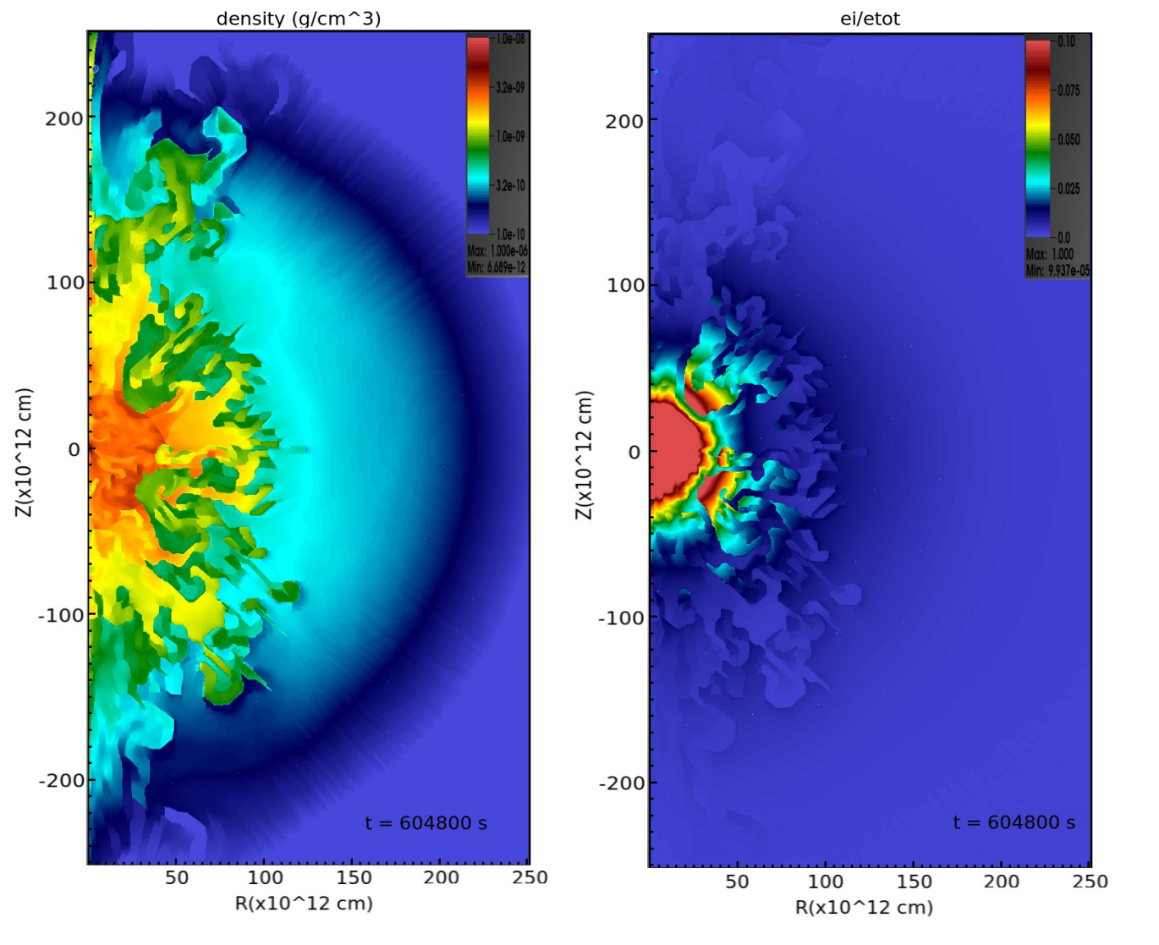


Fig. 6: In the left panel we show the density distribution at the final simulation time of 7 days. In the right panel we show the ratio of internal energy to total energy. The outer portions of the metal-rich core are expanding homologously; Note that the thermal energy content in the central regions is ~10%.

Summary and Future Work

We have performed preliminary simulations of asymmetric Type II supernova explosion of a 15 $M_\odot$ blue super-giant progenitor to a simulation time of 7 days. We found that the mixing of nucleosynthetic products continues beyond 6 hours after explosion, the most advanced evolutionary time obtained in simulations of this problem by other groups. We have also obtained velocity profiles of ^{56}Ni at these later simulations times, and they show that a substantial amount of radioactive nickel is moving with velocities ~3,000 km/s.

We are computing a series of better resolved models, also with a higher order reconstruction algorithm in the PPM hydro solver. We will evolve select models until later times toward more complete homology.

Acknowledgments

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