The inverse problem: Connecting Core-Collapse Supernova Observations to the Explosion

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Introduction

A star much more massive than our Sun will evolve rapidly and end its life in a catastrophic explosion when its core can no longer produce a sufficient amount of energy to support it against the force of gravity. This event is known as a core-collapse supernova (ccSN) and results in the formation of a proto-neutron star (PNS) from the core collapse and the rest of the star living on as fast-moving ejecta. While the explosion proper is a relatively short-lived event astronomically speaking, the expanding shell of ejecta created from the disruption of the star can remain easily observable for centuries, even millenia, in a phase known as the ejecta-dominated or young supernova remnant (ySNR) phase (Figure 1).

Figure 1: *Vela remnant [1]*

Of particular scientific interest, ySNRs are available for long term, nearby observations, whereas nearby ccSN are infrequent to observe during initial explosion. A ySNR provides multiple areas of observational probing to help us learn about the original explosion mechanism and progenitor star, such as:

- The mixing efficiency of various elements, nickel and helium as examples
- The amount of helium and hydrogen a progenitor star had prior to explosion
- Morphological structures that possibly originated from fluid instabilities formed during the explosion

Physics Model of ccSN

The ccSN+ySNR is a multidimensional, multi-scale, multi-physics computational problem involving, but not limited too:

- Nuclear burning and decay
- Neutrino-matter interactions and heating
- Radiative transport and gravitational forces
- Multidimensional fluid flows, shocks, and instabilities
- Timescales of 10^{-6} sec to 10^{10} sec
- Sizescales of 10^{1} km to 10^{18} km

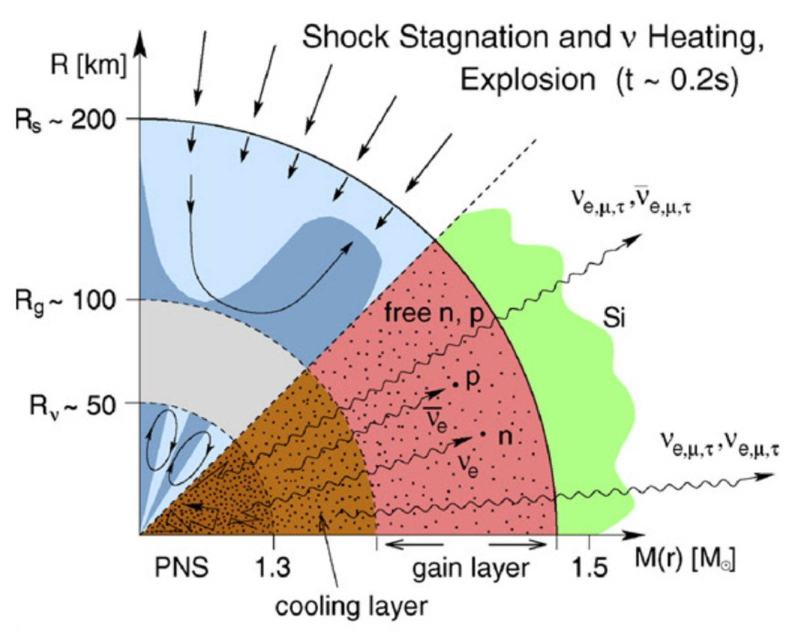


Figure 2: *Cartoon of a ccSN explosion. [2]*

Such a problem setup comes with its set of computational challenges and complications that we will talk a little more about in the next section.

Computational Model

As mentioned, we face a set of computational challanges to overcome to successfully evolve a ccSN to the ySNR phase.

One primary challenge,

- Boltzmann Transport Equation (BTE) describes neutrino transport
- BTE is computationally expensive and untenable
- Short term, highly accurate models do exist
- Solution: a simpler neutrino-matter interaction scheme calibrated to existing BTE results [3]

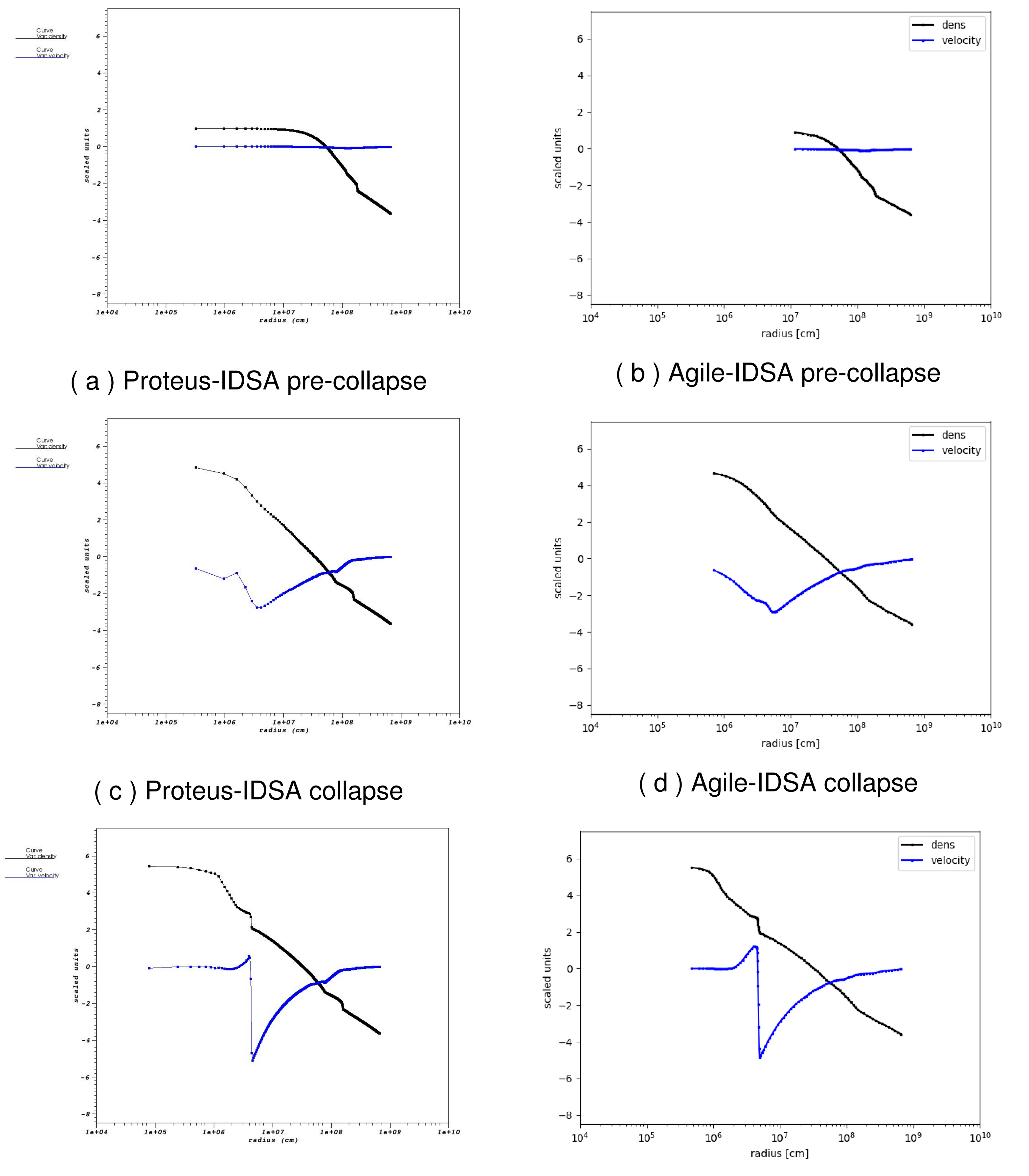
Another challenge,

- Very small PNS: strong density gradients, high mesh resolution
- Extremely high sound speed, quick domain crossing time restricting timesteps
- Solution: treat PNS as a point mass on domain boundary and track PNS real radius (r_{ib})[3]
- Fill region $r < r_{ib}$ w/ constant data profiles and impose hydrostatic equilibrium (HSE) at r_{ib}

With these implementations in mind, we should ideally be able to overcome the issues posed by different physics dominating at disparate size and time scales. Our goal is to adequately balance capturing the evolution from the milliseconds during explosion to centuries after with computational efficiency.

Work Thus Far

Our first task was to establish a 1D reference model to benchmark against results from previous studies [4], using a common 15 solar mass progenitor star model (Figure 3).



(a) Proteus-IDSA pre-collapse (b) Agile-IDSA pre-collapse

(c) Proteus-IDSA collapse (d) Agile-IDSA collapse

(e) Proteus-IDSA post-bounce shock (f) Agile-IDSA post-bounce shock

Figure 3: *Benchmarking plots of our Proteus-IDSA against Agile-IDSA [4] from other studies. Density in black, velocity in blue.*

We have had some measure of success in ensuring HSE is maintained around r_{ib} (Figure 4) with a right-biased finite differencing scheme applied to the HSE equation (presented here in 1D),

$$\frac{dP}{dx} = -\rho\frac{d\Phi}{dx}$$

$$P_{rib,i} = [(4P_{rib,i+1} - P_{rib,i+2}) + 2\rho_{rib,i}(\Phi_{rib,i+1} - \Phi_{rib,i})]/3$$

We chose this scheme to avoid using data from the "void" region as r_{ib} straddles the "void" and "real" data domains. The quantities are pressure (P), density (ρ), and gravitational potential (Φ), with the subscript rib, i indicating the cell containing r_{ib}.

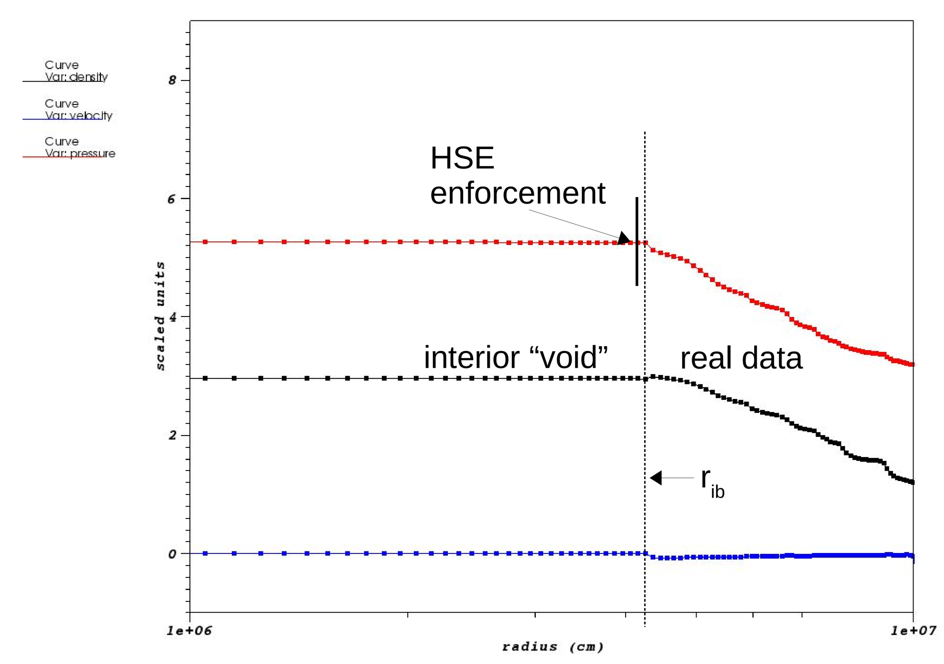


Figure 4: *Depiction of creating "void" profile interior to r_{ib} and imposing HSE for a small region around this boundary.*

References

[1] https://astrodonimaging.com/gallery/vela-supernova-remnant/

[2] H.-Th. Janka, K. Langanke, A. Marek, et. al. Theory of core-collapse supernovae *Physics Reports*, 442:38-74, 2007

[3] L. Scheck, K. Kifonidis, H.-Th. Janka, and E. Muller Multidimensional supernova simulations with approximative neutrino transport: I. Neutron star kicks and the anisotropy of neutrino-driven explosions in two spatial dimensions *Astronomy and Astrophysics*, 457(3):963-986, 2013

[4] M. Liebendorfer, S.C. Whitehouse, T. Fischer The Isotropic Diffusion Source Approximation for Supernova Neutrino Transport *The Astrophysical Journal*, 698(2):1174-1190, 2009