Impact of the Si/O interface on supernova explosion

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1. Predicting supernova explosions

Context

- Determining supernova outcome still requires heavy computations.
- No clear connection between progenitor structure and supernova outcome yet.

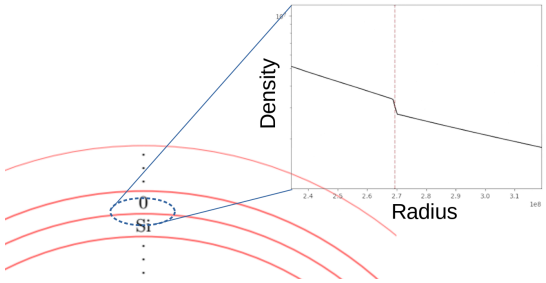
Several criteria to predict explosion have been proposed, but not sufficient for accurate prediction. Explodability criterion based on density jump at the interface between silicon and oxygen shells is of particular interest.

Goal:

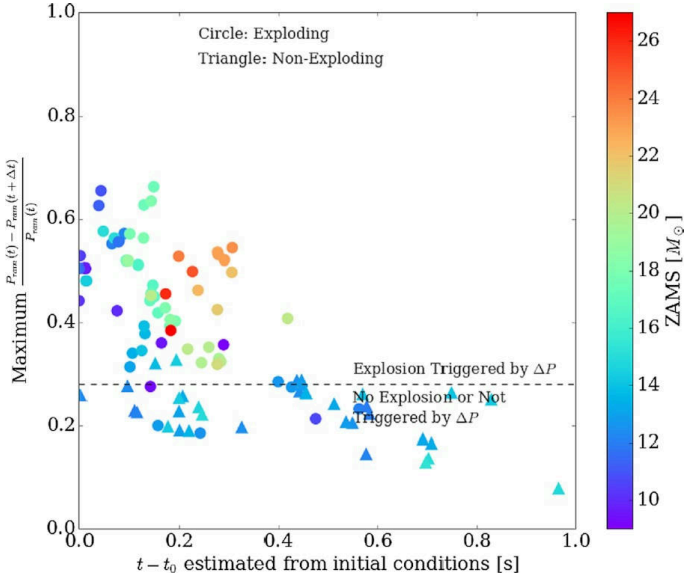
- Isolate the effect of the density gradient at the Si/O interface to find out if it is a reliable criterion to predict explosion.
  - Modify progenitors to artificially raise or lower density jumps.
  - Simulate core-collapse with precise 2D simulations.
  - Try to quantify the impact of the density jump on the explosion outcome.

Si/O interface

Si/O interface :



- Physically motivated criterion : direct link between the criterion and the explosion mechanism.
- Recent convincing results but several question remains.

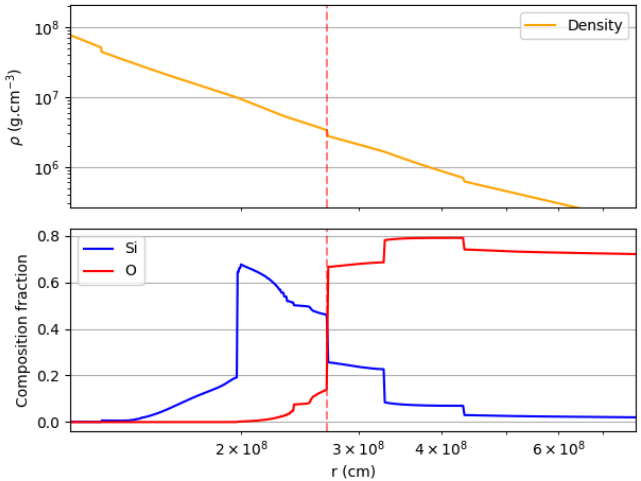


Criterion from Wang et al. (2022): Relative change in ram pressure at the shock when the Si/O interface is accreted, as a function of accretion time after bounce. Progenitors above the threshold line are more likely to explode. Figure from Wang et al. 2022.

2. Progenitors for the study

Progenitor set

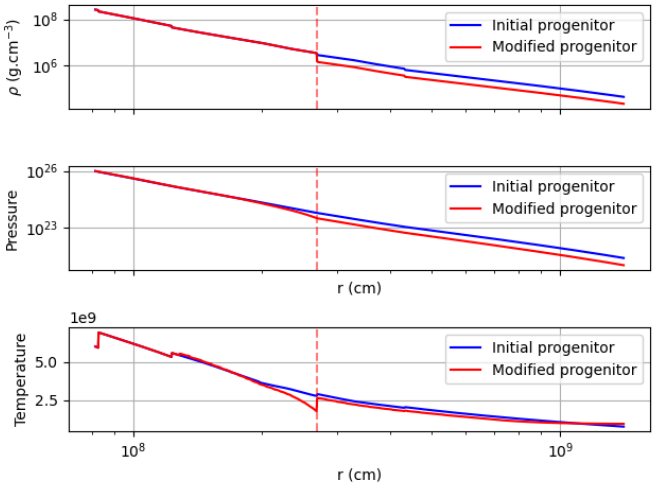
- Non-rotating, solar metallicity progenitors with varying masses from Sukhbold et al. 2018.
- Density gradients at the Si/O interface are controlled by manually modifying the progenitor's density, with corresponding adjustments to other parameters.



Density and composition profiles of a progenitor around the Si/O interface.

Modifications to the progenitors

- Density profiles are changed after the Si/O interface to either raise or lower the density jump.
- Pressure is modified to restore hydrostatic equilibrium. A tabulated equation of state is used to compute temperature profiles.
- This set of progenitors is used to isolate and study the impact of the interface on the explosion outcome.



Density, pressure and temperature profiles for a $15M_{\odot}$ progenitor (blue) the same model with an artificially increased density jump 10x larger at the interface (red).

3. Simulations setup

CoCoNuT code

- The study is done with the CoCoNuT code.
- Hydrodynamics simulations in general relativity, using the M1 scheme for neutrino radiative transfer.
- General relativity equations are solved in CFC approximation, with spectral methods using LORENE
- Simulations are performed in 1D up to core bounce, and in 2D (350x128 points) thereafter. Each run uses 800–1600 CPUs and requires approximately 4 days of computation per simulation.

There is an ongoing work to improve the neutrino treatment to have accurate heating/cooling rates.

4. M1 Scheme

M1 Scheme updates: Overview

Current workflow of the M1 neutrino transport solver :

- Hydrodynamics and metric update
- Explicit transport update
- Implicit collision solver
- Coupling with hydrodynamics

Previously, collisions were treated without iterative method, leading to inaccurate heating rates.

Explicit Transport Step

The explicit evolution of moments E and F consists of :

- transport (flux) terms,
- metric and geometry (non-flux) terms,
- energy-space advection (all orders in v/c).

The transport equations are then integrated explicitly,

$$(E^n, F_i^n) \longrightarrow (E^*, F_i^*),$$

with only the hyperbolic part considered (no collisions yet).

Implicit collision solve

Collisional sources couple (J, H) non linearly and are stiff => require an implicit integration step.
We first treat absorption and (elastic) scattering of neutrinos off nucleons :

$$Y^{n+1} = Y^* + \Delta t G(Y^{n+1}),$$

with $Y = \begin{pmatrix} E \\ F_i \end{pmatrix}$, and G the collisional source term :

$$G_\alpha = \begin{pmatrix} W\kappa_a\left(J_{\rm eq} - J\right) - \kappa_{\rm tot} H^i v_i \\ \kappa_a\left(J_{\rm eq} - J\right) u^\mu \gamma_{\mu i} - \kappa_{\rm tot}\gamma_{\mu i} H^\mu \end{pmatrix}$$

This step is solved with Powell's hybrid method, an iterative method which blends Newton-Raphson with a gradient-descent (trust-region) step, giving robust convergence even where the Jacobian of G is poorly conditioned.

Here, we solve for $\begin{pmatrix} E \\ F \end{pmatrix}$ and update J, H, and P (with closure relation) at each iteration.

Other collisions

Electron-neutrino scattering and pair processes act on (J, H) for simplicity but the closure relation on the pressure tensor P^{ij} is done on Eulerian moments . We must therefore find (E, F^i) such that:

- P satisfies the closure relation on E, F
- $\begin{pmatrix} E \\ F \end{pmatrix}$ transforms to $\begin{pmatrix} J \\ H \end{pmatrix}$ when moving to lagrangian frame

Other collisions : method

Expressing (J, H) as a function of the Eulerian moments, we get :

$$J = W^2 E - 2W u_i F^i + u_i u_j P^{ij}$$

$$H^\mu = W(n^\mu - W u^\mu)E + W h^\mu_i F^i - u_i F^i \big(n_\mu - W u_\mu\big) u_i h^\mu_j P^{ij}$$

We can replace P with its analytical closure expression. This gives (J, H) as a function of E and F. The system is essentially linear, with only one non linear term remaining : $\frac{F^i F^j}{F_k F^k}$. We solve this system through iterative method (fixed point method).

5. Current results

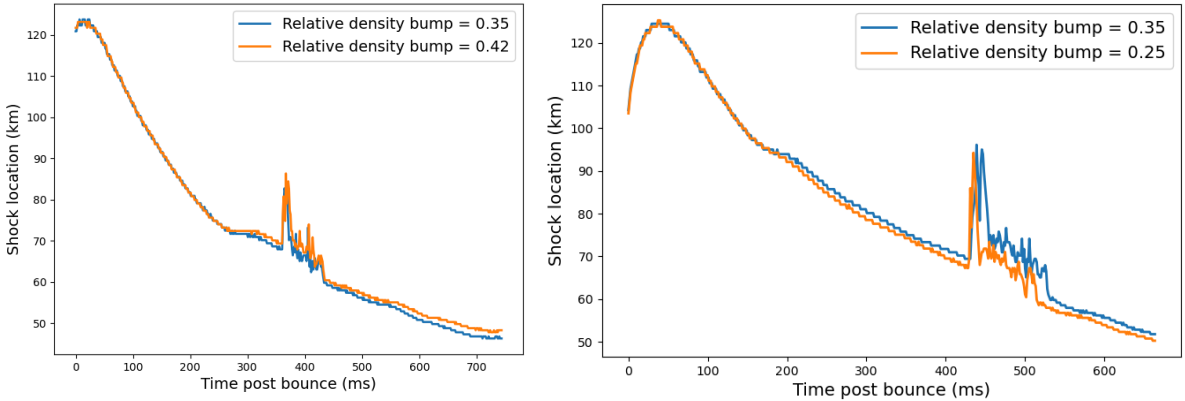
Current results : 1D simulations

1D simulations of modified $15M_\odot$ and $16M_\odot$ progenitors.
Height of the density drop is quantified by $\frac{\Delta\rho}{\rho}$ measured at the Si/O interface.

- $15M_\odot$: $\frac{\Delta\rho}{\rho} = 0.35$ and $\frac{\Delta\rho}{\rho} = 0.42$ (density jump of the original progenitor : 0.17)
- $16M_\odot$: $\frac{\Delta\rho}{\rho} = 0.25$ and $\frac{\Delta\rho}{\rho} = 0.35$ (density jump of the original progenitor : 0.5)
- Grid of 512 points, with 16 neutrino energy bins for all 3 species.

1D simulations have no turbulence model implemented and won't explode. However we can still see a difference is the shock position after accretion of Si/O interface. A shock further away can be a sign of a progenitor more likely to explode.

First results : $15M_{\odot}$ progenitors



Shock location versus time for $15M_{\odot}$ (left) and $16M_{\odot}$ (right) progenitors, with different denisty jumps.

Models with a larger density jump show a more extended shock, indicating that the interface can promote the explodability.

Perspectives

Upcoming work :

- Finalize M1 solver and validate against numerical tests
- Run the 2D simulations on the modified progenitors

Goals :

- Investigate whether a transition exists between explosion and non-explosion when varying the interface.
- Quantify the minimum density contrast required to trigger an explosion.
- Determine if the Si/O interface has the same impact on shock revival across different progenitors