Core-Collapse Supernovae Simulations with CHIMERA: Towards Multi-Messenger Observables

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Multi-messenger From Core-Collapse Supernovae
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Monday, December 2, 13
CHIMERA Collaboration

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- Former Team Members
  - Reuben Budjiara, Austin Chertkow, Ted Lee

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Post-bounce profile

Hillebrandt, Janka, & Müller 2006 (Sci Am)

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Neutrino heating depends on neutrino luminosities, spectra, and angular distributions. Must compute neutrino distribution functions.

\[ \dot{\epsilon} = \frac{X_n}{\lambda_0^3} \frac{L_{\nu_e}}{4 \pi r^2} \langle E_{\nu_e}^2 \rangle \langle \frac{1}{F} \rangle + \frac{X_p}{\lambda_0^3} \frac{L_{\bar{\nu}_e}}{4 \pi r^2} \langle E_{\bar{\nu}_e}^2 \rangle \langle \frac{1}{F} \rangle \]

Must compute neutrino distribution functions.

\[ f(t, r, \theta, \phi, E, \theta_p, \phi_p) \]  

\[ E_R(t, r, \theta, \phi, E) = \int d\theta_p \, d\phi_p \, f \]  

\[ F_R(t, r, \theta, \phi, E) = \int d\theta_p \, d\phi_p \, ...f \]

Requires a closure prescription:
- MGFLD
- MGVEF/MGVET
Important neutrino emissivities/opacities

“Standard” Emissivities/Opacities

\[ e^- + p, A \leftrightarrow \nu_e + n, A' \]
\[ e^+ + e^- \leftrightarrow \nu_{e,\mu,\tau} + \bar{\nu}_{e,\mu,\tau} \]
\[ \nu \ + n, p, A \rightarrow \nu \ + n, p, A \]
\[ \nu + e^-, e^+ \rightarrow \nu + e^-, e^+ \]

- Nucleons in nucleus independent.
- No energy exchange in nucleonic scattering.

- Include correlations between nucleons in nuclei.

- (Small) Energy is exchanged due to nucleon recoil.
- Many such scatterings.


- Additional source of neutrino-antineutrino pairs.


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\[ \nu + e^-, e^+ \rightarrow \nu + e^-, e^+ \]

\[ N + N \leftrightarrow N + N + \nu_{e,\mu,\tau} + \bar{\nu}_{e,\mu,\tau} \]

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Essential physical realism in neutrino transport


ReducOp = Bruenn (1985) – NES + Bremsstrahlung (no neutrino energy scattering, IPM for nuclei)

See also B. Mueller et al. 2012. *Ap.J.* 756, 84 for a comparison in the context of 2D models, with similar conclusions.
How is the supernova shock revived?

**Known, Potentially Important Ingredients**

- Gravity
- Neutrino Heating
- Convection
- **Shock Instability (SASI)**
- Nuclear Burning
- Rotation
- Magnetic Fields

Need multidimensional models with all of the above, treated with sufficient realism.
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Stationary Accretion Shock Instability (SASI)

Shock wave unstable to non-radial perturbations.


- Decreases advection velocity in gain region.
- Increases time in the gain region.
- Generates convection.

SASI has axisymmetric and nonaxisymmetric modes that are both linearly unstable!
• “Ray-by-ray-Plus” MGFLD Neutrino Transport
  - O(v/c), GR time dilation and redshift, GR aberration

• 2D PPM Hydrodynamics
  - GR time dilation, effective gravitational potential
  - adaptive radial grid

• Lattimer-Swesty EOS + low-density BCK EOS
  - K=220 MeV
  - low-density EOS (BCK+NSE solver) “bridges” LS to network

• Nuclear (Alpha) Network
  - 14 alpha nuclei between helium and zinc

• 2D Effective Gravitational Potential

• Neutrino Emissivities/Opacities
  - “Standard” + Elastic Scattering on Nucleons + Nucleon–Nucleon Bremsstrahlung
The early phase

- For the first ~100 ms after bounce, the supernova shock is essentially spherical, with 1D models identical to 2D models.

- Neutrino-driven convection precedes the development of the SASI at low mass ($12 M_\odot$) and trails the development of the SASI at high mass ($25 M_\odot$).

- One notable feature is the considerable delay in launching an explosion. (cf. Herant et al. (1994): <100ms)
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Working neutrinos

- Gain surface begins to become non-spherical ~70 ms after bounce.
- After ~120 ms, the heating region is characterized by low-entropy downflows and high-entropy upflows.
Explosion energies (& definitions)

- Estimate the explosion energy by assuming efficient conversion of $E_i \Rightarrow E_k$.

- One can construct a “diagnostic” energy, $E^+ = E_i + E_g + E_k$, summed over zones where $E^+ > 0$.

- Add contributions from nuclear recombination and removing the envelope.
Explosion energies vs. observations

Fig. 1. The explosion energy and the ejected $^{56}$Ni mass as a function of the main sequence mass of the progenitors for several supernovae/hypernovae.

The new ingredients taken into account in the present nucleosynthesis models are: (i) the variation of $E$ (hypernovae, normal SNe, and faint SNe), (ii) the mixing and fallback, and (iii) neutrino processes that affects neutron excess near the mass cut.

3.1. Energy dependence

In core-collapse supernovae/hypernovae, stellar material undergoes shock heating and subsequent explosive nucleosynthesis. Iron-peak elements are produced in two distinct regions, which are characterized by the peak temperature, $T_{\text{peak}}$, of the shocked material. For $T_{\text{peak}} > 5 \times 10^9$ K, material undergoes complete Si burning whose products include Co, Zn, V, and some Cr.

Nomoto, Tominaga, et al. (2006)
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Nickel mass

- Another important observable, related to the explosion energy and very relevant to the nucleosynthesis, is the mass of $^{56}\text{Ni}$.

- Results are reasonable, though fallback over longer timescales is uncertain. Recent studies are finding differing results on fallback.

**Figure 11**

(a) $^{56}\text{Ni}$ mass versus main-sequence initial mass, reprinted from *Nuclear Physics A*, Copyright 2006 (Nomoto et al. 2006), with permission from Elsevier. The initial masses in this plot are estimated from the ejecta masses derived from lightcurve modeling.

(b) The $^{56}\text{Ni}$ masses for nearby supernovae for which there are reliable restrictions on the progenitor masses from direct constraints (Smartt et al. 2009).
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![Graph showing Nickel mass versus main-sequence initial mass](image)

![Diagram showing Initial mass versus Nickel mass](image)

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PNS masses

Proto-Neutron Star: Mass vs Time
12 - 25 W-H Progenitors

Mass [M\(_{\odot}\)]

Time from Bounce [ms]

12 M\(_{\odot}\)
15 M\(_{\odot}\)
20 M\(_{\odot}\)
25 M\(_{\odot}\)

Lattimer and Prakash (2010)
Neutrino emission

sensitive to $X_p$ and phase transition density
GR: Higher luminosity, harder spectrum
Reduced opacities: Narrower breakout burst, $<E>$ spike seen by Thompson et al. (2003)
No Observer Corrections: Greatly reduced breakout burst and luminosity in accretion phase
Recovering “realistic” ν fluxes from RbR simulations

Sanchez, Messer, et al. in prep.
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Example of multi-messenger observables: Anatomy of a GW signature

Yakunin et al. *Class. Quantum Grav.* 27 194005 (2010)

- Lower-frequency envelope: SASI-induced shock excursions
- Higher-frequency variations: Impingement of downflows on PNS from neutrino-driven convection and SASI
- Prompt Convection
- Early Shock Deceleration
- Later Rise: Prolate Explosion/Deceleration at Shock
Using nucleosynthesis tracer particles for a different purpose

- Follow tracer particle hydro evolution at given epochs to determine from where the signal is emanating.
- E.g., convection/SASI-induced features emanate from < 50 km (PNS).
SASI in 3D

SASI in 3D

Entropy
15 M☉ (W-H 2007)
512x45x90

Currently running on O(60,000) cores
Equatorial slice
Summary

- Necessary Realism: Multifrequency neutrino transport with relativistic effects and a state-of-the-art weak interaction set, and general relativity.

- Ongoing CHIMERA models confirm successful prolate explosions across a range of progenitors from 12-25 M☉ driven by neutrino heating and SASI with outcomes consistent with observations.

- Though differences persist with simulations from Garching group, self-consistent CHIMERA simulations point to a successful neutrino-reheating mechanism, with the explosion delayed by 300 ms or more after bounce, at least in 2D.

- A three-dimensional counterpart simulation is underway, for the 15 M☉ progenitor, and has already reached >150 ms post-bounce.