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Progenitor stars calculated with small reaction networks should not be used as initial conditions for core collapse

M. Renzo,[1] J. A. Goldberg,[2] A. Grichener,[3] O. Gottlieb,[2] and M. Cantiello[2]

[1] *University of Arizona, Department of Astronomy & Steward Observatory, 933 N. Cherry Ave., Tucson, AZ 85721, USA*
[2] *Center for Computational Astrophysics, Flatiron Institute, 162 5th Avenue, New York, NY 10010, USA*
[3] *Department of Physics, Technion, Kiryat Hatechnion, Haifa 3200003, Israel*

ABSTRACT

Core collapse initial conditions are a bottleneck in understanding the explosion mechanism(s) of massive stars. Stellar evolution codes struggle after carbon burning, and either stop or adopt numerical simplifications missing crucial physics. The use of small nuclear reaction networks (NRN) that account for energy production but bypass weak reactions is typical, but insufficient to study the dynamics of the collapse. We advise against the use of progenitors computed with small NRN in expensive multidimensional simulations of core collapse, bounce, (jet formation), and explosion.

1. INTRODUCTION

Massive stars ($\gtrsim 7-10\,M_{\odot}$, Doherty et al. 2015; Poelarends et al. 2017) end their life collapsing and possibly exploding (e.g., Janka 2012; Burrows & Vartanyan 2021; Soker 2024). Although a consensus around the "neutrino-driven" paradigm is establishing (e.g., Wang & Burrows 2023; Nakamura et al. 2024), the details remain debated (e.g., Shishkin & Soker 2022; Soker 2022), especially in terms of magnetic fields and rotation (e.g., Symbalisty 1984; Mösta et al. 2015; Aloy & Obergaulinger 2021).

The collapse and possible explosion is sensitive to the initial conditions (e.g., Ott et al. 2018; Kuroda et al. 2018; Burrows et al. 2023; Nakamura et al. 2024), determined by poorly understood late core evolution of the progenitor stars. Only limited sets of non-rotating progenitors computed sufficiently late are available (Woosley et al. 2002; Sukhbold et al. 2016; Farmer et al. 2016; Renzo et al. 2017; Wang et al. 2024) and even fewer rotating progenitors (Heger et al. 2000; Aguilera-Dena et al. 2018).

Farmer et al. (2016) showed the impact of algorithmic choices on the final core-structure of non-rotating stars, and demonstrated that small ($\sim$ 20-isotope) nuclear reaction network (NRN) are insufficient to produce reliable progenitors for multidimensional core collapse studies. These NRNs allow for deleptonization through one single compound reaction (e.g, $^{56}\mathrm{Fe}+2e^{-} \rightarrow {}^{56}\mathrm{Cr}+2\nu_{e}$). This predetermines the Y_e profile *throughout* the core, thus the effective Chandrasekhar (1931) mass $\propto {Y_e}^2$, and ultimately the outcome of the collapse. This affects stellar evolution models computed with the `approx` family of nuclear reaction networks (Timmes et al. 2000). Here, we extend this result to fast rotating progenitors.

2. MODELING UNCERTAINTIES COMPOUND

We ran two $40\,M_{\odot}$ low-metallicity (Z=0.001) stars initially rotating at 60% of breakup with MESA (Paxton et al. 2011, 2013, 2015, 2018, 2019; Jermyn et al. 2023, version r24.03.1). Files to reproduce these two models are available at doi:10.5281/zenodo.11375523. They differ only in the NRN adopted, `mesa_128` (orange in Fig. 1), sufficient to follow the deleptonization (Farmer et al. 2016), and `approx21_plus_cr56` (blue). We include rotational mixing (Heger et al. 2000), magnetic torques (Spruit 2002), and hydrodynamics. We expunge spurious velocities in layers not in sonic contact with the innermost core (CO, Si, or Fe). We carried out resolution tests (increasing the mesh size up to $\gtrsim 10\,000$), and found that, for both NRNs, numerical resolution affects convection in the inner $5\,M_{\odot}$ and consequently the inner structure (e.g., Sukhbold & Woosley 2014; Schneider et al. 2023). This emphasizes the importance of checking the numerical resolution (Farmer et al. 2016; Farag et al. 2022). The models we present have identical resolution requirements and are representative of the range of structures that can be obtained.

Both models experience blueward rotationally-induced chemically homogeneous evolution (e.g., Maeder & Meynet 2000) and are computed until the infall velocity exceeds $300\,\mathrm{km\ s^{-1}}$. Fig. 1 (right) shows the Hertzsprung-Russell diagram (HRD). The two tracks are observationally indistinguishable, with most differences confined to fast evolutionary phases: small NRNs are sufficient to simulate surface properties of stars.

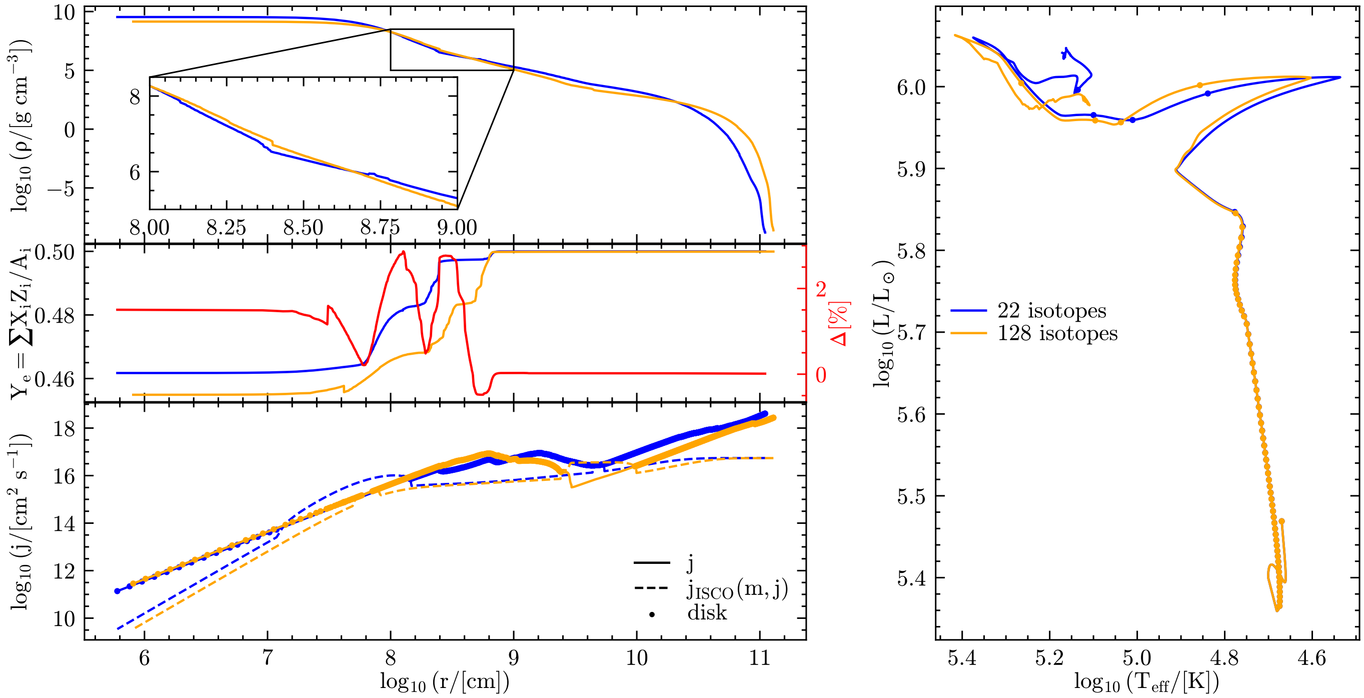

Figure 1. Comparison of chemically homogeneous models at the onset of core-collapse. Right: HRD (dots mark intervals of 10^5 years). Top left: density. Middle left: Y_e, relative difference in red (right vertical axis). Bottom left: specific angular momentum j. The dashed line shows j_{ISCO} assuming the accretion of the enclosed m and j. Dots correspond to regions that collapse forming a disk, $j \geq j_{\mathrm{ISCO}}$.

Nevertheless, the interior structure of the two models are significantly different: the compactness parameter (O'Connor & Ott 2011) of the small (large) NRN model is $\xi_{2.5} = 0.376$ (0.262). The $\sim 44\%$ variation in $\xi_{2.5}$ is comparable to uncertainties introduced by numerical resolution (Farmer et al. 2016), mass-loss rates (Renzo et al. 2017), and convective boundary mixing (Davis et al. 2019). No single parameter is sufficient to characterize the "explodability" (e.g., Ertl et al. 2016; Vartanyan et al. 2021), and we show in the left panels of Fig. 1 the internal structure of the stars.

The top panel shows the density profiles, with an inset focusing on the region where the success or failure of an explosion is decided (e.g., Ertl et al. 2016; Boccioli et al. 2023; Burrows et al. 2023).

The middle panel shows the Y_e profile. All the mass collapsing interior to 10^9 cm shows *structured* variations of $\sim 1-3\%$ shown in red on the righ vertical axis as $\Delta = (Y_e(\text{small NRN}) - Y_e(\text{large NRN}))/Y_e(\text{large NRN})$. The range of Y_e found in a collapsing core is $0.4-0.5$, and $\sim 1-3\%$ variations are not negligible. Moving outwards, where weak reactions are unimportant, Δ decreases.

The bottom left panel shows the specific angular momentum profile (j, solid lines) and the innermost stable orbit angular momentum assuming the mass and specific angular momentum inside the abscissa for the compact object (j_{ISCO}, dashed lines, Bardeen et al. 1972). Whenever $j \geq j_{\mathrm{ISCO}}$ we expect the formation of an accretion disk (thicker lines). In both cases the inner $\sim 10^7$ cm retain too much angular momentum to directly collapse, and we expect a proto-neutron-star phase. After the collapse of this material, the 128-isotope model shows the formation of a disk immediately, while the 22-isotope model only after $\gtrsim 1$ s. From disk formation onwards the evolution will diverge because of feedback processes (disk wind, jet, etc., Gottlieb et al. 2022). This difference occurs because of the different evolution of the density and consequently the angular momentum caused by the different treatment of nuclear physics.

3. AVOID SMALL-NETWORK PROGENITOR FOR MULTIDIMENSIONAL SIMULATIONS

Core collapse is a $\sim 1\%$ problem: only this fraction of the gravitational potential released needs to be "harvested" to produce a successful supernova. Therefore, predictive simulations require high accuracy initial conditions. Many uncertain processes occur in massive stars (e.g., Woosley et al. 2002; Langer 2012), and modeling choices matter, including resolution (Farmer et al. 2016), mass loss (Renzo et al. 2017), mixing (Davis et al. 2019), spurious envelope velocities (e.g., Farmer et al. 2016; Aguilera-Dena et al. 2018), and dimensionality of the simulations (e.g., Fields 2022). We advise against running expensive multidimensional simulations of core-collapse with initial conditions that are known to not include enough physics to address the questions motivating such simulations in the first place. This means not using models computed only until carbon depletion, models wiht small NRN, and/or underresolved models.

At fixed angular momentum transport, small NRN result in significantly different rotationally-powered explosions for the same core-collapse physics, making robust conclusions impossible.

Progenitors computed with small NRN remain useful for studying the outer layers of stars up to collapse, and possibly to make relative statements, but require care to marginalize any conclusion against this large systematic modeling uncertainty in the progenitor.

REFERENCES

Aguilera-Dena, D. R., Langer, N., Moriya, T. J., & Schootemeijer, A. 2018, ApJ, 858, 115, doi: 10.3847/1538-4357/aabfc1

Aloy, M. Á., & Obergaulinger, M. 2021, MNRAS, 500, 4365, doi: 10.1093/mnras/staa3273

Bardeen, J. M., Press, W. H., & Teukolsky, S. A. 1972, ApJ, 178, 347, doi: 10.1086/151796

Boccioli, L., Roberti, L., Limongi, M., Mathews, G. J., & Chieffi, A. 2023, ApJ, 949, 17, doi: 10.3847/1538-4357/acc06a

Burrows, A., & Vartanyan, D. 2021, Nature, 589, 29, doi: 10.1038/s41586-020-03059-w

Burrows, A., Vartanyan, D., & Wang, T. 2023, ApJ, 957, 68, doi: 10.3847/1538-4357/acfc1c

Chandrasekhar, S. 1931, ApJ, 74, 81, doi: 10.1086/143324

Davis, A., Jones, S., & Herwig, F. 2019, MNRAS, 484, 3921, doi: 10.1093/mnras/sty3415

Doherty, C. L., Gil-Pons, P., Siess, L., Lattanzio, J. C., & Lau, H. H. B. 2015, MNRAS, 446, 2599, doi: 10.1093/mnras/stu2180

Ertl, T., Janka, H.-T., Woosley, S. E., Sukhbold, T., & Ugliano, M. 2016, ApJ, 818, 124, doi: 10.3847/0004-637X/818/2/124

Farag, E., Renzo, M., Farmer, R., Chidester, M. T., & Timmes, F. X. 2022, ApJ, 937, 112, doi: 10.3847/1538-4357/ac8b83

Farmer, R., Fields, C. E., Petermann, I., et al. 2016, ApJS, 227, 22, doi: 10.3847/1538-4365/227/2/22

Fields, C. E. 2022, ApJL, 924, L15, doi: 10.3847/2041-8213/ac460c

Gottlieb, O., Lalakos, A., Bromberg, O., Liska, M., & Tchekhovskoy, A. 2022, MNRAS, 510, 4962, doi: 10.1093/mnras/stab3784

Heger, A., Langer, N., & Woosley, S. E. 2000, ApJ, 528, 368, doi: 10.1086/308158

Janka, H.-T. 2012, Annual Review of Nuclear and Particle Science, 62, 407, doi: 10.1146/annurev-nucl-102711-094901

Jermyn, A. S., Bauer, E. B., Schwab, J., et al. 2023, ApJS, 265, 15, doi: 10.3847/1538-4365/acae8d

Kuroda, T., Kotake, K., Takiwaki, T., & Thielemann, F.-K. 2018, MNRAS, 477, L80, doi: 10.1093/mnrasl/sly059

Langer, N. 2012, ARA&A, 50, 107, doi: 10.1146/annurev-astro-081811-125534

Maeder, A., & Meynet, G. 2000, ARA&A, 38, 143, doi: 10.1146/annurev.astro.38.1.143

Mösta, P., Ott, C. D., Radice, D., et al. 2015, Nature, 528, 376, doi: 10.1038/nature15755

Nakamura, K., Takiwaki, T., Matsumoto, J., & Kotake, K. 2024, arXiv e-prints, arXiv:2405.08367, doi: 10.48550/arXiv.2405.08367

O'Connor, E., & Ott, C. D. 2011, ApJ, 730, 70, doi: 10.1088/0004-637X/730/2/70

Ott, C. D., Roberts, L. F., da Silva Schneider, A., et al. 2018, ApJL, 855, L3, doi: 10.3847/2041-8213/aaa967

Paxton, B., Bildsten, L., Dotter, A., et al. 2011, ApJS, 192, 3, doi: 10.1088/0067-0049/192/1/3

Paxton, B., Cantiello, M., Arras, P., et al. 2013, ApJS, 208, 4, doi: 10.1088/0067-0049/208/1/4

Paxton, B., Marchant, P., Schwab, J., et al. 2015, ApJS, 220, 15, doi: 10.1088/0067-0049/220/1/15

Paxton, B., Schwab, J., Bauer, E. B., et al. 2018, ApJS, 234, 34, doi: 10.3847/1538-4365/aaa5a8

Paxton, B., Smolec, R., Schwab, J., et al. 2019, ApJS, 243, 10, doi: 10.3847/1538-4365/ab2241

Poelarends, A. J. T., Wurtz, S., Tarka, J., Cole Adams, L., & Hills, S. T. 2017, ApJ, 850, 197, doi: 10.3847/1538-4357/aa988a

Renzo, M., Ott, C. D., Shore, S. N., & de Mink, S. E. 2017, A&A, 603, A118, doi: 10.1051/0004-6361/201730698

Schneider, F. R. N., Podsiadlowski, P., & Laplace, E. 2023, ApJL, 950, L9, doi: 10.3847/2041-8213/acd77a

Shishkin, D., & Soker, N. 2022, MNRAS, 513, 4224, doi: 10.1093/mnras/stac1075

Soker, N. 2022, Research in Astronomy and Astrophysics, 22, 122003, doi: 10.1088/1674-4527/ac9782

—. 2024, The Open Journal of Astrophysics, 7, 31, doi: 10.33232/001c.117147

Spruit, H. C. 2002, A&A, 381, 923, doi: 10.1051/0004-6361:20011465

Sukhbold, T., Ertl, T., Woosley, S. E., Brown, J. M., & Janka, H. T. 2016, ApJ, 821, 38, doi: 10.3847/0004-637X/821/1/38

Sukhbold, T., & Woosley, S. E. 2014, ApJ, 783, 10, doi: 10.1088/0004-637X/783/1/10

Symbalisty, E. M. D. 1984, ApJ, 285, 729, doi: 10.1086/162551

Timmes, F. X., Hoffman, R. D., & Woosley, S. E. 2000, ApJS, 129, 377, doi: 10.1086/313407

Vartanyan, D., Laplace, E., Renzo, M., et al. 2021, ApJL, 916, L5, doi: 10.3847/2041-8213/ac0b42

Wang, N. Y. N., Shishkin, D., & Soker, N. 2024, arXiv e-prints, arXiv:2401.06652, doi: 10.48550/arXiv.2401.06652

Wang, T., & Burrows, A. 2023, ApJ, 954, 114, doi: 10.3847/1538-4357/ace7b2

Woosley, S. E., Heger, A., & Weaver, T. A. 2002, Reviews of Modern Physics, 74, 1015, doi: 10.1103/RevModPhys.74.1015