A Grid of Core Collapse Supernova Remnant Models Evolved from Massive Progenitors

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Abstract

We present preliminary results from modeling core-collapse supernovae evolved from pre-main sequence models with wind-driven mass-loss. We construct a software pipeline to follow cradle-to-grave massive star evolution beginning with progenitor modeling up to iron core collapse with MESA [6]. We then use the Supernova Evolution Code (SNEC) to explode the star and follow the evolution of the ejecta with the cosmic ray hydro (ChN) code. ChN allows us to model the remnant's dynamics and broadband spectrum as a function of age. We quantify the impact of progenitor evolution on the bulk observable characteristics of the remnant, including its dynamics and spectral properties.

Introduction

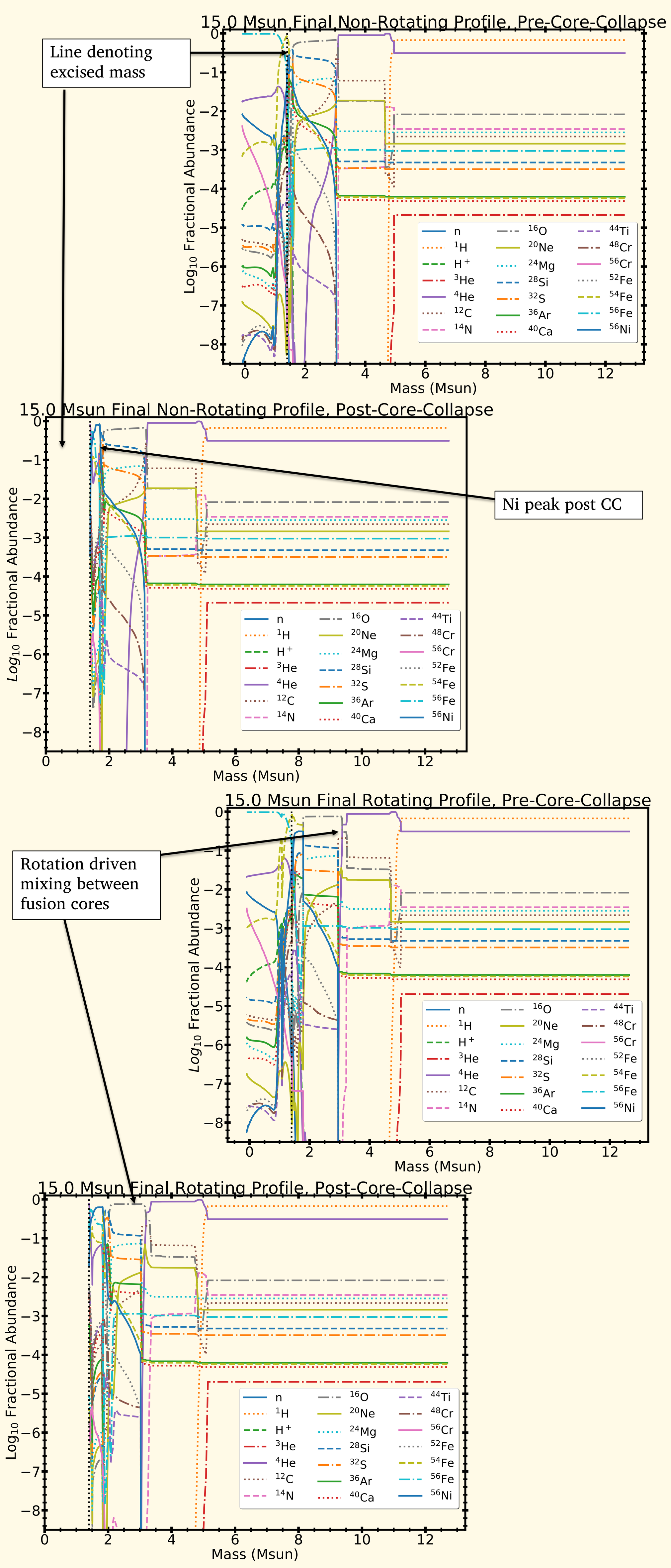
The late time behavior of supernova remnants is heavily influenced by the circumstellar environment's (CSM) interaction with the expanding supernova ejecta. Often, the CSM is largely composed of material blown into space by the star during its lifetime. The same mass-loss also determines the evolutionary track of the star, and the characteristics of the resulting supernova [5]. To properly describe observations of remnants, we must therefore model the entire star/CSM system from the pre-main-sequence until the present.

To do this, we have constructed a grid of MESA models evolved with wind-driven mass-loss enabled, and tracked both their evolution and mass-loss-rates until core-collapse. We then exploded the models using SNEC, to produce the supernova, and used VH-1 to build up a description of the CSM based on observed mass-loss rates. These two outputs are combined in ChN to produce a remnant that takes into account the unique system produced by the star during its lifetime.

Progenitor Modeling and Stellar Profiles at Core-Collapse

Progenitor modeling was done using the prebuilt MESA routine `make_pre_ccsne`. Models were produced from 12.5 to 22.7 M_{sun} with a resolution of 0.1 M_{sun}. ~95% of all models reached core-collapse with the failures struggling to handle the numerical complexity of their particular parameter space as the Fe core approached the Chandrasekhar limit. The full grid was run for stars with no rotation enabled, stars with angular momentum, but no initial surface velocity, and stars with a surface velocity of $0.55 v_{crit}$. Successfully collapsed models were piped into the SuperNova Evolution Code (SNEC), where the inner 1.4-1.6 M_{sun} of material was excised as being part of the central compact object, and the remainder of the material was injected with ~1e51 ergs of energy. The ejecta were then tracked through the next 100 days, with the same nuclear burning net applied.

The pre- and post-core-collapse profiles of a 15 M_{sun} model are presented below, and the bulk properties of the grid are presented in the results section.



Results from MESA and SNEC

MESA models are saved at several key points, such that the models can be restarted with new mass-loss physics at those moments. The full output of a given model are saved within a git repository so that they are easily transportable, and can be cloned to allow for iteration on parameters. SNEC is also contained within each repository so the entire pipeline can be initiated with minimal effort.

The results presented here assume the MESA 'Dutch' wind-scheme, with the de Jager scheme defining the behavior during the RSG phase. Rotating models assume a Spruit-Taylor dynamo for angular momentum transfer and diffusion through the star. The effect of these additional parameters can be seen in Figure 1.

SNEC models assume a constant energy in the explosion, and currently do not implement mixing between the cells. Total masses of key elements were compiled for each SNEC run, and used as both a sanity check, and a description of the overall behavior of the SN. These results are presented in Figure 2.

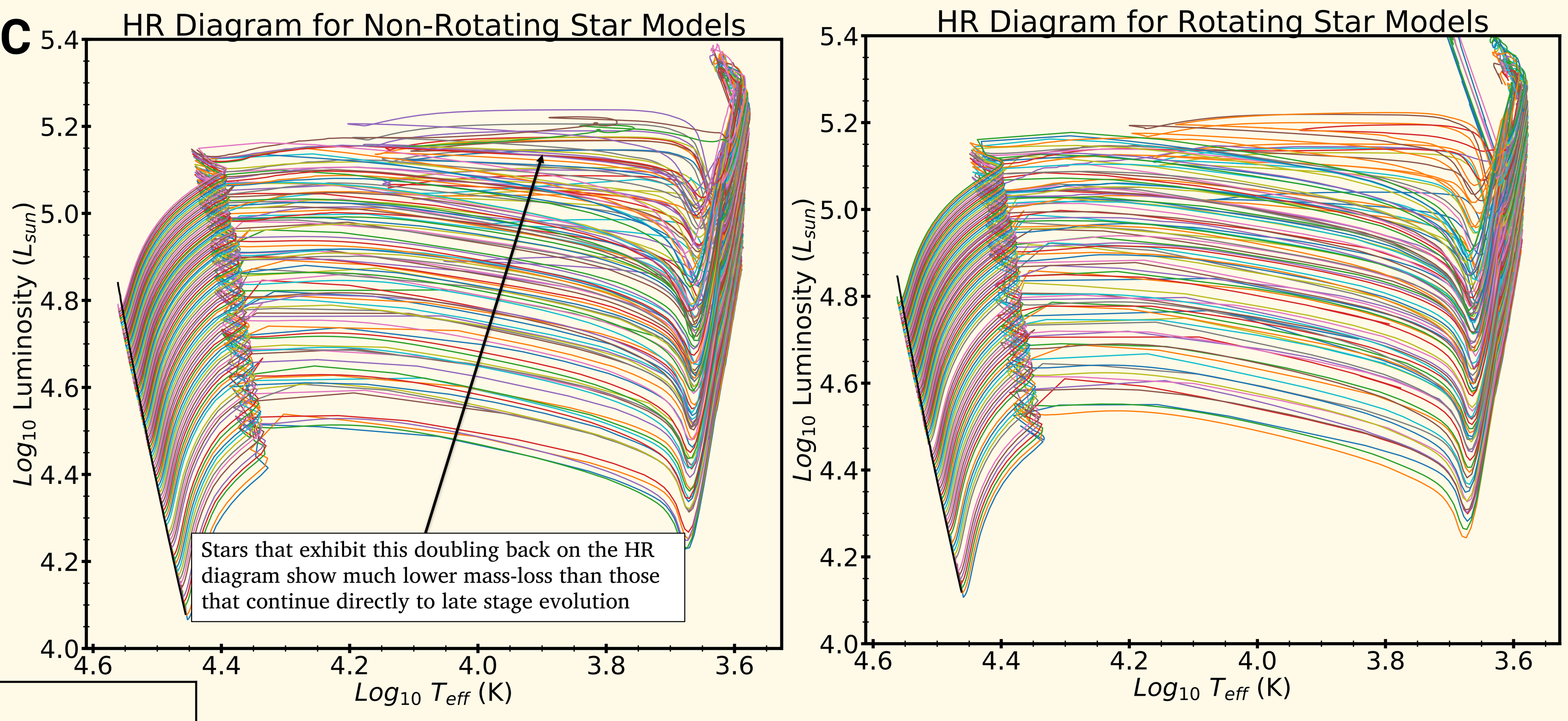


Figure 4: HR diagrams for non-rotating and rotating MESA models. All models presented reached core-collapse (Fe core infall velocity of 1000 km/s). Overall, there is little difference between the rotating and non-rotating models, although the parameters do change which stars undergo blue loops, and thus shed less overall mass.

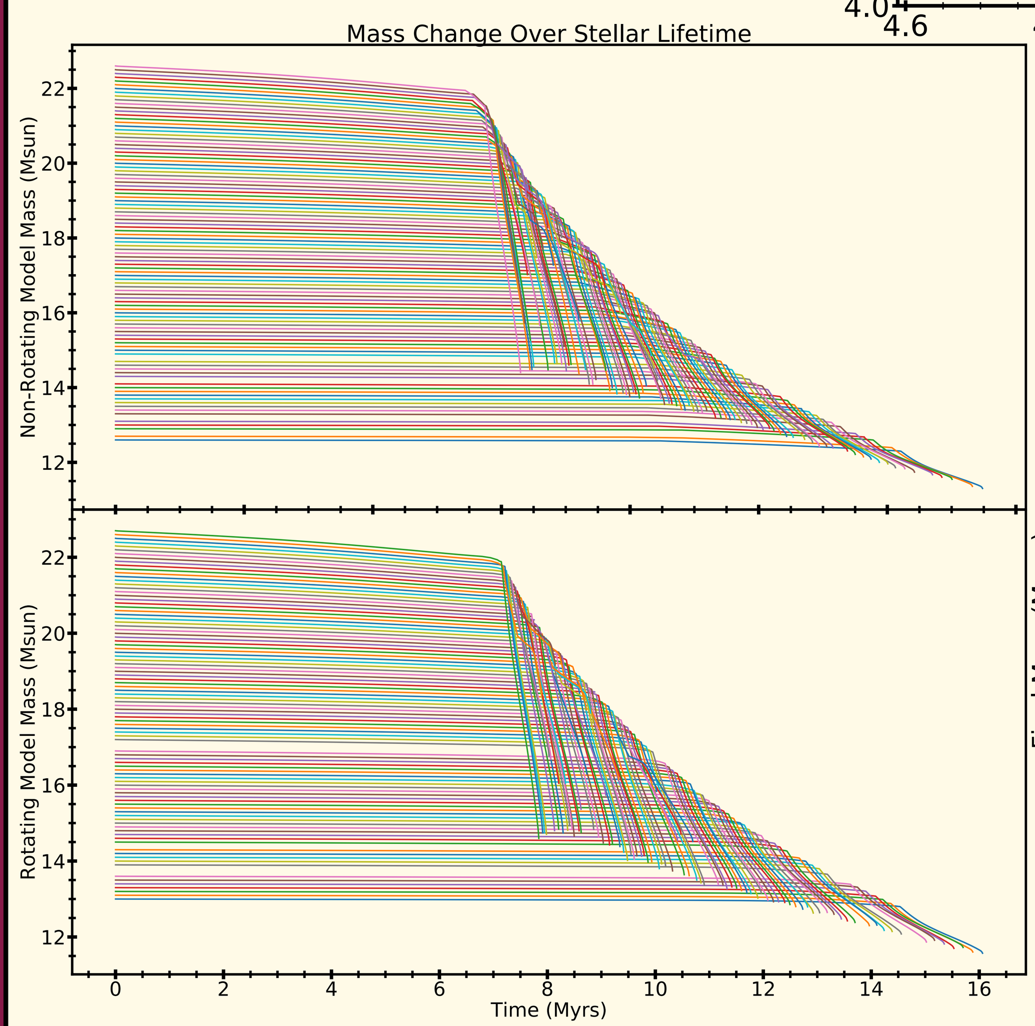


Figure 1: Cumulative mass-loss for every model that reached core-collapse. Most mass-loss occurs within the last million years of the model, with the result being final masses of all progenitors being more tightly spaced than those of their ZAMS. Grey lines indicate the ZAMS mass of each model. Models with several late-stage mass loss phases are those that exhibit the blue loops in Figure 4.

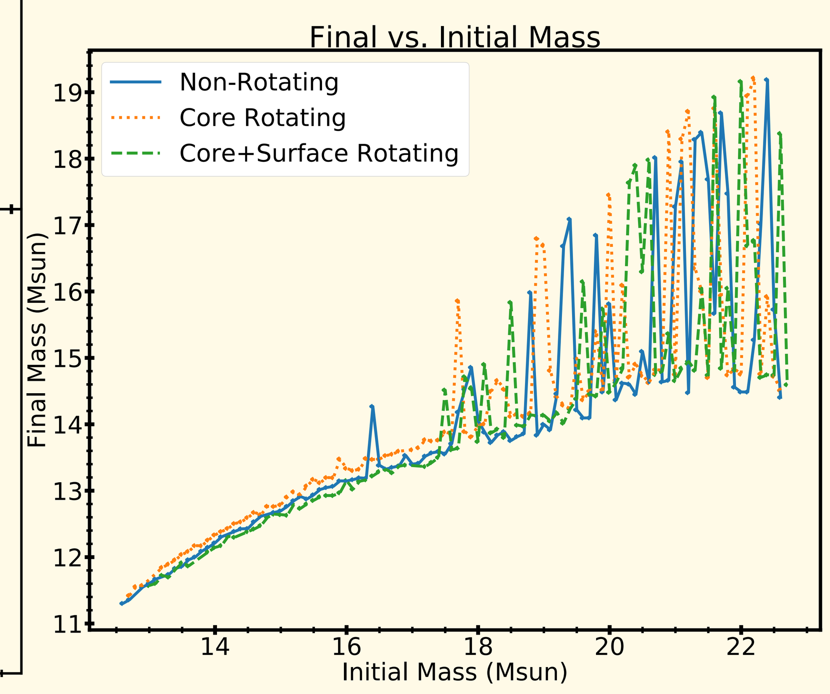


Figure 3: Final Mass vs. ZAMS mass for the three grids. Lower mass stars exhibit little variation between parameters, but higher mass stars seem to exhibit more volatility in their mass-loss rates depending on the internal conditions of the star.

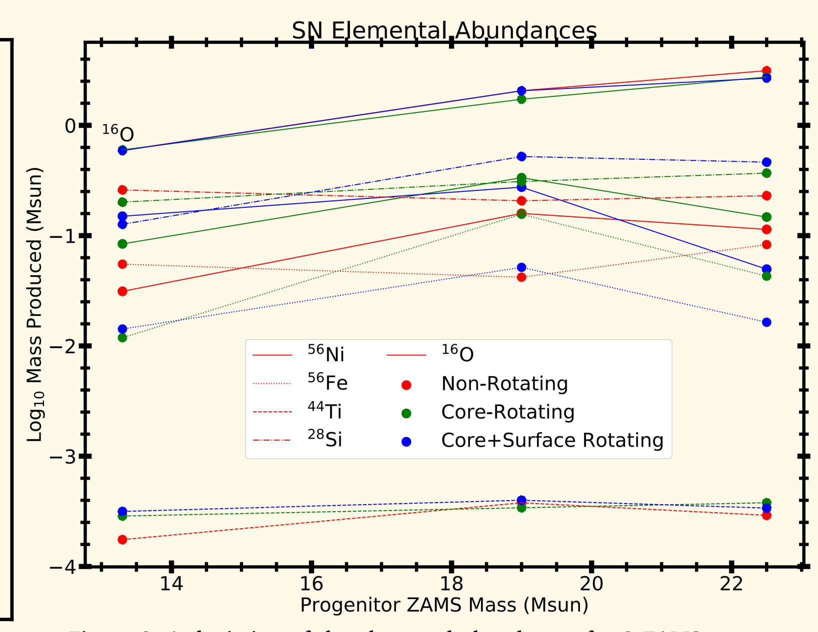


Figure 2: A depiction of the elemental abundances for 3 ZAMS masses, for each of the grids. All had the initial 1.6 M_{sun} excised and were injected with 8e50 erg of energy at Core-Collapse. There is no strong mass or parameter dependence between elements. Parameters such as O and Ti do not seem to be heavily effected by rotation-modified evolution, other elements can vary by almost an order of magnitude.

Describing the CSM with VH-1

Proper remnant modeling requires understanding the environment created by the progenitor during its lifetime. Circumstellar environments are constructed using mass-loss rates from Figure 5. While MESA provides the complete mass-loss history of the progenitor, mass-loss during the main sequence phase blows a bubble out to radii > 10 pc. According to Figure 5, most of the mass is lost in the last $\lesssim$ 1e6 years. Even over this time period, the mass-loss is not steady, but rises until the point of core-collapse. For this program, we assume a constant mass-loss derived from the average over the last 5e5 yrs of stellar evolution. While the mass-loss rates in Figure 5 suggest a circumstellar environment where $\rho \propto r^{-n}$ and n > 2, here we assume steady mass-loss, with n = 2.

MESA reports wind velocities at the base of the photosphere. However, these velocities are typically well below the ~ 50 - 100 km/s escape velocities of RSGs, and also below the observed velocities of RSG winds, suggesting that the model requires additional physics to drive the material off the star. We therefore adopt the canonical wind speed of 15 km/s which is frequently used in modeling SNR interactions with RSG winds. Taking the average final mass-loss rates from Figure 5 and the wind speeds of 15 km/s, we can estimate the location of the wind-blown shell of material in each case:

$$R(t) = 0.88(L_w/\rho_{amb})^{1/5} t^{3/5}$$

For a RSG phase of 8e5 years, an average main-sequence wind number density of 0.1/cm^3, and a wind luminosity given as. $0.5 \dot{M} v_w^2$, the average location of the shell is ~10 pc. For this study, we are modeling the SNR to ages of 1000 years, and we do not expect the SNR blastwave to get to 10 pc in 1000 years. Therefore, we do not consider its evolution in this study.

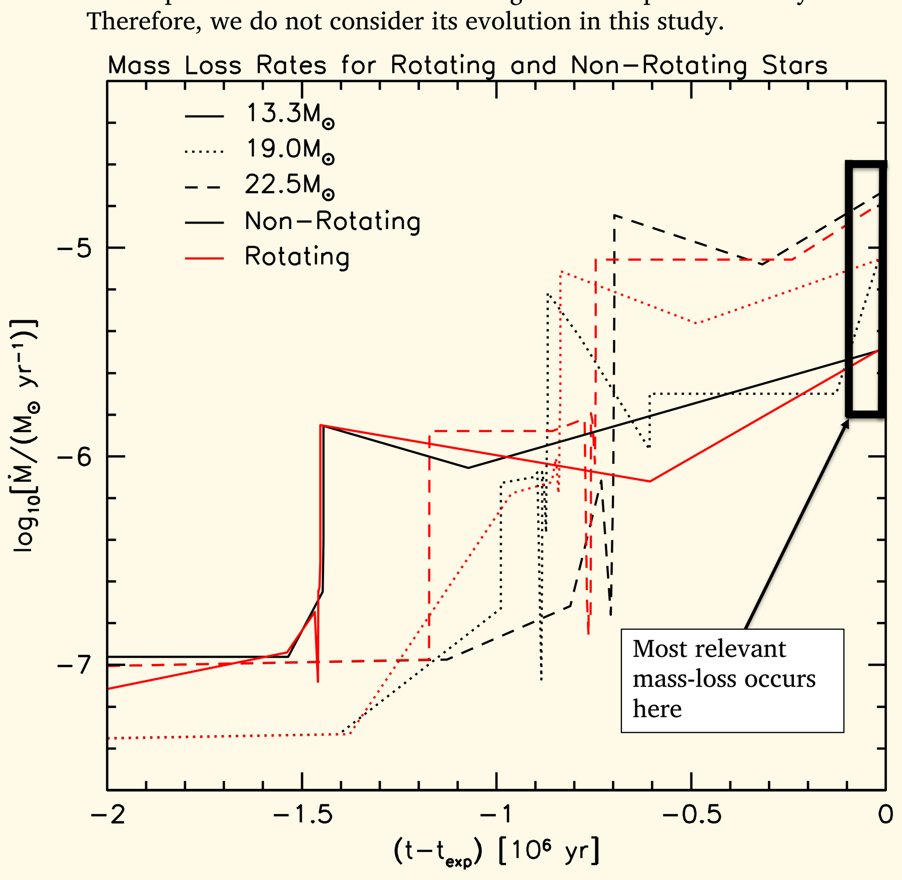


Figure 5: Smoothed mass-loss rates for 13.3, 19, and 22.5 M_{sun} rotating and non-rotating progenitors. The x-axis shows time before core-collapse, in units of 1e6 years. The plot only shows the last ~ 2e6 years of evolution. Black curves correspond to non-rotating models, while red curves correspond to rotating models. For the rotating models, we assume a rotation velocity of $0.55 v_{crit}$.

Results from ChN

The models from SNEC were coupled to ChN, a 1D Lagrangian hydrodynamics code which includes a self-consistent treatment for diffusive shock acceleration, a treatment for non-equilibrium ionization, and the ability to consider complex environments and variable chemical compositions. Here, we simulate the ejecta evolution from the high and low mass progenitor models as they expand into the environments created by the mass loss histories shown in Figure 6. The low mass model has a final ejecta mass of 11.8 M_{sun} and explosion energy of 1e51 erg, while the high mass model has a final ejecta mass of 15.9 M_{sun} and explosion energy of 8e50 erg. The models are evolved to a final age of 1000 years. At 1000 years, the low mass model has evolved to a forward shock radius of 5 pc, while the high mass progenitor model has evolved to a radius of 3.4 pc, though the reverse shock has made it almost to the constant density core of the ejecta.

Synthetic 1.5 - 2.5 keV spectra, from a simulated 50 ksec XRISM observation, are shown in Figure 7. Spectra are simulated with AtomDB using the self-consistently computed nonequilibrium ionization and plasma conditions computed by ChN. The high mass model, which is evolving into a significantly denser environment, shows evidence for strong radiative recombination continua (RRC) above 1.75 and 1.95 keV. Dense red supergiant winds have been postulated as a possible source of RRC [5], and these models can place limits on the conditions required to form RRC in an isotropic wind.

There is considerable evidence that efficient particle acceleration modifies the hydrodynamics and broadband emission in SNRs. ChN was originally developed to investigate and understand this phenomenon. While it can accurately model this process, in this preliminary study we do not consider the additional effects that shock acceleration can have on the emitted thermal X-ray spectra.

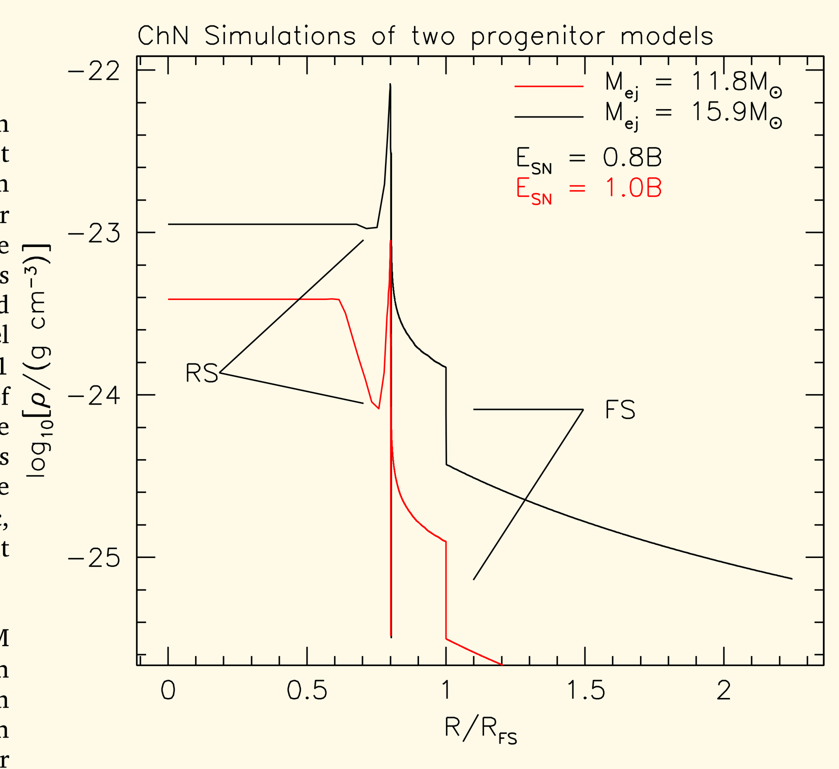


Figure 6: Density vs shock radius (normalized to the forward shock position) for the low and high ejecta mass models. The forward and reverse shocks are marked.

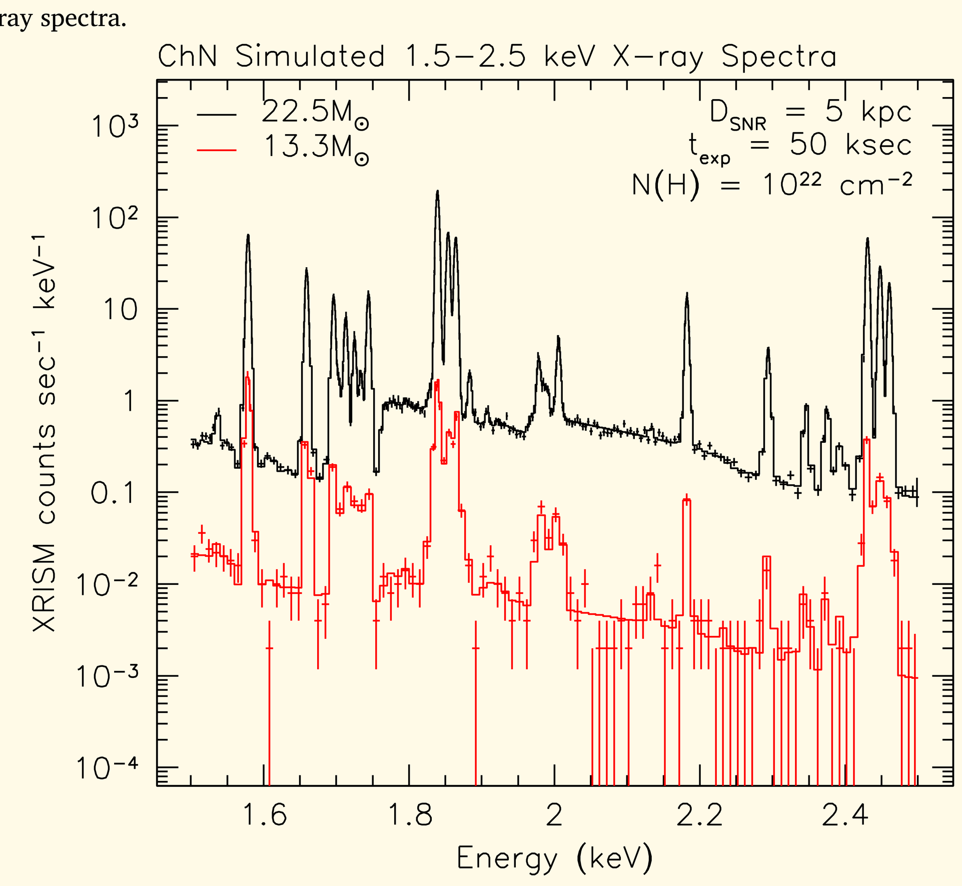


Figure 7: Synthetic 1.5-2.5 keV X-ray spectra for the models shown in Figure 6. While we compute the X-ray spectrum from 30 eV to 10 keV, we highlight this bandpass to show how the dense environment gives rise to the strong RRC. Models are for a 50 ksec observation of a fiducial SNR at 5 kpc, through an absorbing column of 1e22/cm^2. In this plot, we denote the two spectra by their ZAMS masses, while in the hydrodynamics plot, by their ejecta masses.

Literature cited

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Conclusions and Future Work

We have presented preliminary results from a grid of models where we followed the cradle-to-grave evolution of massive stars from the pre-main sequence into the remnant phase. Our results suggest that the late stage progenitor evolution has a profound and observable impact on the properties of the supernova remnant. While we have only considered one mass-loss prescription, we intend to extend our work to study cool dusty winds where mass-loss is expected to be higher. Additionally, we will investigate episodic mass loss effects on SNe/SNR evolution. We aim to extend our grid to consider a wide range of progenitor scenarios which can be directly compared against the observational properties of Galactic and extragalactic supernova remnants.

Acknowledgments

T. Jacovich is a Chandra X-ray Center Predoctoral Fellow funded through NASA contract 80NSSC18K0566 as part of the NASA Astrophysics Theory Program.

D. Patnaude acknowledges support from NASA contract NAS8-03060 .

Software:

http://mesa.sourceforge.net/

https://stellarcollapse.org/SNEC

http://wonka.physics.ncsu.edu/pub/VH-1/

ChN: [1], [2], [3]

https://matplotlib.org/

https://jupyter.org/

http://atomdb.org/

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