Evolution of Rotating 25 $M_\odot$ Population III star: Physical Properties and Resulting Supernovae

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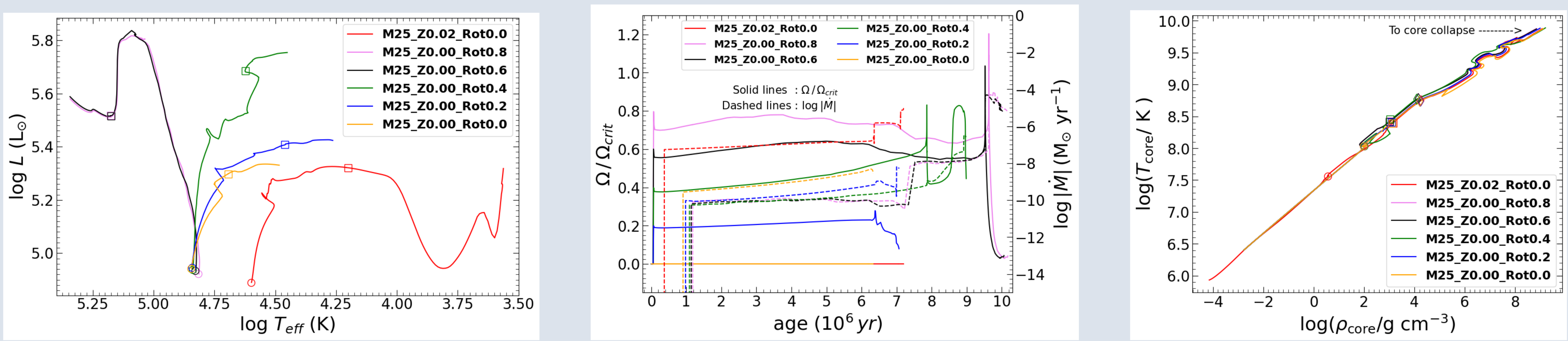
Abstract

We report the outcomes of 1-D modelling of a rotating 25 $M_\odot$ zero-age main-sequence (ZAMS) Population III star. Rapidly rotating models display enormous mass losses after the Main-Sequence stage. With models at the stage of the onset of core collapse, we perform their hydrodynamic simulations of resulting transients. The resulting supernovae span a class from weak Type II to Type Ib/c. We find that the absolute magnitudes of the core-collapse supernovae resulting from Pop III stars are much fainter than that resulting from a solar metallicity star. Our results also indicate that within the considered limits of explosion energies and Nickel masses, these transient events are very faint, making it difficult for them to be detected at high redshifts.

Introduction

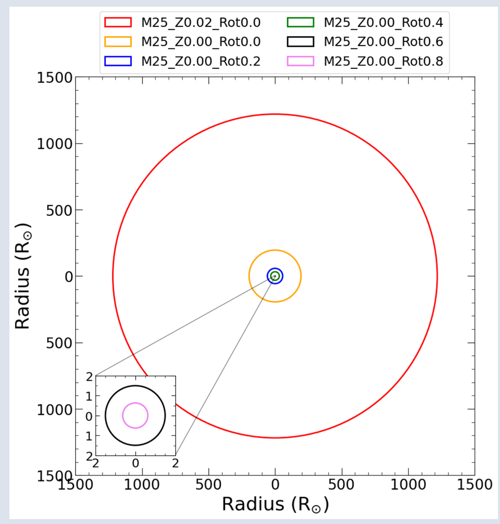
- The first generations of stars formed out of uncontaminated, pristine matter are considered the population III (Pop III) stars. Due to the insufficient coolants in the primordial gas, it is hypothesised that the Pop III stars were intrinsically massive [1].
- However, there have been multiple studies to apprehend the possibility of the existence of Pop III stars having low masses. It has been found that the formation of pristine, metal-free stars at low to intermediate masses could potentially be due to the fragmented accretion disks around massive Pop III protostars [2].
- Further, Pop III stars were responsible for the enrichment of the early universe by spreading metals heavier than He through violent supernova (SN) explosions or possibly through sporadic mass losses due to vigorous stellar winds (Ferrara et al. 2000). Pop III stars also played an important role in cosmic reionization [3].
- Moving a step ahead, we study the entire evolution of a 25 $M_\odot$ Pop III star and investigate the effect of rotation on the final fates. **For the first time in this work, we have evolved the rotating and non-rotating Pop III models together up to the onset of core collapse and further performed the hydrodynamic simulations of their synthetic explosions to show the light curves of resulting transients.** In this work, the model M25_Z0.00_Rot0.0 indicates a 25 $M_\odot$ ZAMS star with Z = 0.00, and Ω / Ω_{crit} = 0.0 and so on for other models, where Ω and Ω_{crit} represent the angular rotational velocity and critical angular rotational velocity, respectively.

Stellar Evolution of models using MESA[5]



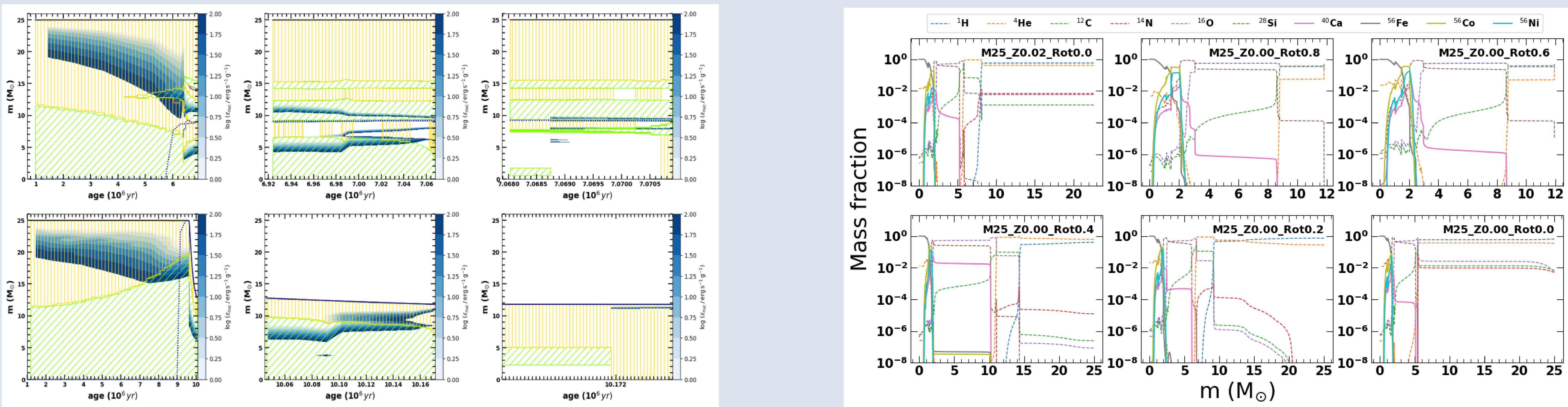
Left: Evolution of the models on the HR diagram. Hollow circles and squares mark ZAMS and core-He exhaustion stages, respectively. ***Middle:*** The evolution of angular rotational velocity and corresponding mass loss rate evolution. ***Right:*** The variations of core-temperature (T_{core}) vs core-density (ρ_{core}) curves throughout the course of evolution of the models on the HR Diagram. Diamonds mark the exhaustion of the core-C burning. Figures adapted from [4]. **[PLEASE SCAN THE QR CODE PROVIDED at THE END OF THE POSTER FOR DETAILS!].**

Pre-SN Stage



This Figure shows the pre-SN radii of the models. The rapidly-rotating models have very small pre-SN radii compared to slow-rotating models. The Rapidly rotating models have undergone enormous mass losses.

The Kippenhahn Diagram and Pre-SN stage mass fraction

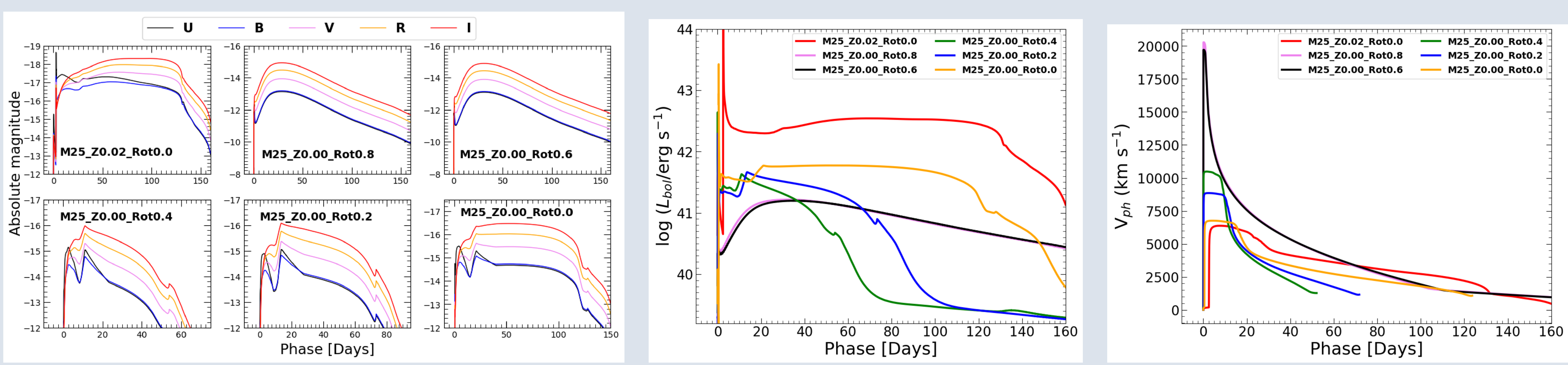


Left: The kippenhahn diagrams of the models M25_Z0.00_Rot0.2 (top) and M25_Z0.00_Rot0.8 (bottom) for a period between ZAMS to close to the pre-SN stage. Here, the green hatchings indicate the convective regions, and the dark-yellow regions mark the stellar interiors where the thermohaline mixing is going on. Also, the logarithm of the specific nuclear energy generation rate (ϵ_{nuc}) inside the stellar interiors is indicated by the blue colour gradients. The rapidly rotating model is significantly stripped. ***Right:*** combined plot showing the mass fractions of various elements for the models in this study at the pre-SN stage. The high Fe-mass fractions near the centre represent the inert Fe-cores.

	ZAMS				Pre-SN				Explosion			
Model Name	M^a_{ZAMS} ($M_\odot$)	T_{eff} K	R^b_{ZAMS} ($R_\odot$)	L^c_{ZAMS} ($L_\odot$)	M^d_{Pre-SN} ($M_\odot$)	T_{eff} K	R^e_{Pre-SN} ($R_\odot$)	L^f_{pre-SN} ($L_\odot$)	M^g_c ($M_\odot$)	M^h_{ej} ($M_\odot$)	M^i_{Ni} ($M_\odot$)	E^j_{exp} (10^{51} erg)
M25_Z0.00_Rot0.0	25.0	70069	2.01	4.94	24.99	10319	195	5.58	1.70	23.29	0.001	1.0
M25_Z0.00_Rot0.8	25.0	65107	2.26	4.91	11.79	175858	0.6	5.53	2.10	9.69	0.05	1.0
M25_Z0.02_Rot0.0	25.0	3962	5.91	4.88	22.64	3623	1219	5.36	1.90	22.74	0.001	1.0

Table 1: The ZAMS and pre-SN properties of the Pop III models using MESA along with the SNEC[6] explosion parameters for a few models. [a]Mass at ZAMS. [b]Progenitor radius at ZAMS, [c]Luminosity at ZAMS, [d]Final mass of pre-SN model, [e]Pre-SN phase radius, [f]Pre-SN phase luminosity, [g]Mass of the central remnant in simulation, [h]Ejecta mass, [i]Amount of synthesised Nickel used in the explosion, [j]Explosion energy.

Results and Conclusion



- Outcomes showing the multi-band light curves, (***Left-panel***) and the bolometric light curves (***Middle-panel***) and corresponding photospheric velocity evolutions (***Right-panel***) resulting from the synthetic explosions of the models using SNEC. The rapidly rotating models fall under weak Type Ib/c, while the slow- and non-rotating models mimic Type SNe light curves.
- One of the most intriguing results from our simulations is that although the pre-SN radius of a non-rotating H-rich Pop III model (with Rot = 0) is much smaller than a non-rotating H-rich solar Type model, both models show nearly similar plateau durations. One of the reasons for the increased plateau duration, despite a relatively smaller pre-SN radius in non-rotating Pop III CCSNe could be associated with the increased amount of Hydrogen mass as indicated in the mass fraction plot.
- The apparent plateau magnitude of our study's brightest Pop III model SN is around ~35 mag in V-band at a redshift of z = 10. Currently, no ground- or space-based observatory can go this faint to detect a Pop III CCSN resulting from an individual star. However, with the major advancement in observational technologies having large diameters could possibly detect such events in the near future.

Acknowledgement & References

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