

Jittering jets in stripped-envelope core-collapse supernovae

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(Dated: February 2025)

ABSTRACT

Using the one-dimensional stellar evolution code MESA, we find that all our models in the initial mass range of $M_{\text{ZAMS}} = 12M_{\odot}$ to $M_{\text{ZAMS}} = 40M_{\odot}$, regardless of whether they have hydrogen-rich, hydrogen-stripped, or helium+hydrogen-stripped envelopes, have at least one significant strong convective zone in the inner core, which can facilitate the jittering-jets explosion mechanism (JJEM). We focus on stripped-envelope CCSN progenitors that earlier studies of the JJEM did not study, and examine the angular momentum parameter $j(m) = rv_{\text{conv}}$, where r is the radius of the layer and v_{conv} is the convective velocity according to the mixing length theory. In all models, there is at least one prominent convective zone with $j(m) \gtrsim 2 \times 10^{15} \text{ cm}^2 \text{ s}^{-1}$ inside the mass coordinate that is the maximum baryonic mass of a neutron star (NS), $m \simeq 2.65 M_{\odot}$. According to the JJEM, convection in these zones seeds instabilities above the newly born NS, leading to the formation of intermittent accretion disks that launch pairs of jittering jets, which in turn explode the star. Our finding is encouraging for the JJEM, although it does not show that the intermittent accretion disks indeed form. We strengthen the claim that, according to the JJEM, there are no failed CCSNe and that all massive stars explode. In demonstrating the robust convection in the inner core of stripped-envelope CCSN progenitors, we add to the establishment of the JJEM as the primary explosion mechanism of CCSNe.

Keywords: Core-collapse supernovae; Stellar jets; Massive stars

1. INTRODUCTION

The identification of point-symmetric morphologies in more than 12 core-collapse supernova (CCSN) remnants (CCSNRs) in 2024-2025 marks a breakthrough in the study of the jittering jets explosion mechanism (JJEM) of CCSNe that predicts such morphologies (Soker 2024a,b for reviews). With the identification of a total of 16 point-symmetric CCSNRs and the attribution of these morphologies to the JJEM, the JJEM became one of two heavily studied CCSN explosion mechanisms; the second being the neutrino-driven mechanism (the delayed neutrino explosion mechanism). Neutrino heating might boost the jets' energy in the JJEM (Soker 2022a), but jets supply most of the explosion energy.

Researchers of the neutrino-driven mechanism in recent years have focused their studies on the three-dimensional simulations of the explosion process by the delayed-neutrino mechanism, from core collapse to shock

revival, and have attempted to show that some observations are compatible with some predictions of the neutrino-driven mechanism (e.g., Andresen et al. 2024; Boccioli & Fragione 2024; Burrows et al. 2024; Janka & Kresse 2024; Maunder et al. 2024; van Baal et al. 2024; Wang & Burrows 2024; Bamba et al. 2025; Boccioli et al. 2025a; Eggenberger Andersen et al. 2025; Huang et al. 2025; Imasheva et al. 2025; Janka 2025; Laplace et al. 2025; Maltsev et al. 2025; Mori et al. 2025; Müller et al. 2025; Nakamura et al. 2025; Sykes & Müller 2025; Paradiso & Coughlin 2025; Schneider et al. 2025; Vink et al. 2025; Wang & Burrows 2025; Willcox et al. 2025; Mukazhanov 2025; Antoni et al. 2025; Fang et al. 2025; Raffelt et al. 2025; Vartanyan et al. 2025). However, the neutrino-driven mechanism has no explanation for point-symmetric CCSN morphologies. The magnetorotational explosion mechanism posits that a pair of opposite jets, aligned along a fixed axis, explode the star. The fixed angular momentum axis along which the accretion disk launches the jets requires a rapidly rotating pre-collapse core (e.g., Shibagaki et al. 2024; Zha et al. 2024; Shibata et al. 2025 and references therein to much older

papers), a very rare property; the magnetorotational explosion mechanism attributes the majority of CCSNe to the delayed neutrino explosion mechanism. For this reason, the magnetorotational explosion mechanism is part of the neutrino-driven mechanism and can explain point symmetry only in rare cases of CCSNRs. However, point-symmetric CCSNRs are common. The neutrino-driven mechanism attributes the extra energy of some CCSNe with explosion energies above what the neutrino mechanism can supply to an energetic magnetar, i.e., a rapidly spinning neutron star (NS). However, many magnetar models of such energetic (superluminous) CCSNe have explosion energies of $E_{\text{exp}} \gtrsim 3 \times 10^{51}$ erg (e.g., Aguilar & Bersten 2025; Orellana et al. 2025, for some most recent examples) that imply explosion by jets (e.g., Soker & Gilkis 2017; Kumar 2025).

For their utmost importance in determining the CCSN explosion mechanism, most likely the JJEM, we list here the 16 point-symmetric CCSNRs: SNR 0540-69.3 (Soker 2022b), CTB 1 (Bear & Soker 2023), the Vela CCSNR (Soker 2023a; Soker & Shishkin 2025), N63A (Soker 2024c), the Cygnus Loop (Shishkin et al. 2024), SN 1987A (Soker 2024d,e), G321.3-3.9 (Soker 2024f; Shishkin & Soker 2025), G107.7-5.1 (Soker 2024f), W44 (Soker 2024g), Cassiopeia A (Bear & Soker 2025), the Crab Nebula (Shishkin & Soker 2024), Puppis A (Bear et al. 2025), SNR G0.9+0.1 (Soker 2025a), S147 Shishkin et al. (2025), N132D (Soker 2025b) and RCW 89 (Soker 2025c).

CCSNe interact with circumstellar material lost by the CCSN progenitor (e.g., Chiotellis et al. 2021, 2024; Velázquez et al. 2023; Meyer et al. 2022, 2024b) and with the interstellar medium (e.g., Wu & Zhang 2019; Yan et al. 2020; Lu et al. 2021; Meyer et al. 2024a). These interactions in general smear the point-symmetric morphology, although in some cases might add point-symmetric morphological features, but only in the outer SNR regions, as some studies suggest for type Ia supernova remnant (e.g., Soker 2024h). Other processes contribute to the smearing of point symmetry, including the NS natal kick and instabilities that occur during the explosion process, as well as post-explosion processes such as a pulsar wind nebula, if it exists, and heating processes like the reverse shock and radioactive decay. In many cases, these smearing processes make point-symmetric morphology identification challenging, if not impossible. Magnetic fields in the ISM, as in the scenario of Yu & Fang (2025), might explain one pair of ears in rare SNRs, but are unable to explain point-symmetrical structures, either in SNRs or in planetary nebulae; at best, they might account for rare cases.

The point-symmetric morphologies of metal ejecta in some CCSNRs indicate that shaping occurs during the explosion when nucleosynthesis takes place, and the point symmetry in the inner regions of some CCSNRs suggests that it is not an interaction with an ambient medium that shapes them. The large volume of some point-symmetric morphological features shows that the energy involved in the shaping is a large fraction, or all, of the explosion energy (for a discussion of all these arguments, see Soker & Shishkin 2025). The point-symmetric morphology is the only property that decisively distinguishes between the predictions of the JJEM and the neutrino-driven mechanism (e.g., review by Soker 2024b): the JJEM predicts that many, but not all, CCSNRs possess point-symmetric morphologies, while the neutrino-driven mechanism has no explanation. Therefore, it is possible that the sixteen-point-symmetric CCSNRs rule out the neutrino-driven mechanism and strongly suggest that the JJEM is the primary explosion mechanism of CCSNe.

The point-symmetric morphologies have led to more insights about the JJEM. The first is that the two opposing jets may be unequal. The reason is that many jet-launch episodes last for shorter or not much longer than the relaxation time of the short-lived accretion disk that launches the jets (Soker 2024c). In addition to being unequal in power and opening angle, the two jets might also not be exactly opposite each other, i.e., the angle between them can be $< 180^\circ$ (Shishkin et al. 2025; Soker 2025b). The point-symmetric morphologies led to the newly suggested kick by early asymmetrical pair (kick-BEAP) mechanism (Bear et al. 2025). In the kick-BEAP mechanism, one jet is significantly more powerful. It carries a much larger momentum than the opposite jet, implying that the NS acquires velocity, or a kick, in the opposite direction of the more powerful jet. Since the jets are along the angular momentum axis of the accreted mass, the kick-BEAP mechanism accounts for spin-kick alignment that observations find in some pulsars (e.g., Johnston et al. 2005; Noutsos et al. 2012; Biryukov & Beskin 2025).

Studies of the JJEM cannot follow the evolution from core collapse to jet-launching. Instead, the different evolutionary phases are studied separately. This type of study is done, for example, in examining the shaping of planetary nebulae, where the binary interaction that leads to accretion disk formation (e.g., De Marco et al. 2025 for a review) is separated from the study of the planetary nebula shaping processes at a later phase (e.g., Akashi & Soker 2021; García-Segura et al. 2022). In general, the simulations of mass transfer in binary systems are extremely complicated (e.g., Kashi et al. 2022), in

particular when accretion disks are formed (e.g., [Kashi 2023](#)), and do not allow for the inclusion of jet launching. The same holds for the JJEM because the launching of jets by the intermittent accretion disks around the newly born NS in the JJEM involves violent magnetic field reconnection events. The current numerical codes cannot resolve the small-scale magnetic field reconnection and cannot simulate the JJEM ([Soker 2025d](#)). Therefore, simulations for the powering of the explosion and the shaping of the ejecta (e.g., [Papish & Soker 2014](#); [Akashi & Soker 2022](#); [Abdikamalov & Beniamini 2025](#); [Braudo et al. 2025](#)) differ from the tools used to study the source of the angular momentum in intermittent accretion disks.

Some JJEM studies focus on demonstrating that the pre-collapse core’s convection zones exhibit large fluctuations in both velocity and angular momentum, which are characterized by significant variations in magnitude and direction. Instabilities above the NS (for instabilities and turbulence in the gain region, see, e.g., [Abdikamalov et al. 2016](#); [Kazeroni & Abdikamalov 2020](#); [Buellet et al. 2023](#)) amplify these stochastic angular momentum fluctuations (e.g., [Gilkis & Soker 2014, 2016](#); [Shishkin & Soker 2021, 2023](#); [Wang et al. 2024](#)). These JJEM studies simulated hydrogen-rich progenitors, i.e., type II CCSNe, demonstrating the large convective velocity fluctuations in the silicon and oxygen burning zones in the core. The exact convection structure depends on accurately following a large number of nuclear reactions at the final phases before collapse, which is a difficult task by itself (e.g., [Grichener et al. 2025](#)).

This study aims to examine the pre-collapse convective and velocity fluctuations in progenitors that have lost most of their hydrogen and helium, specifically stripped-envelope CCSNe (SECCSNe). We describe our method in Section 2 and the results in Section 3. Both single and binary evolution can form hydrogen and helium-depleted massive stars (e.g., [Shenar et al. 2020](#) on single star evolution and [Hirai et al. 2020](#) on binary interaction; see [Gilkis et al. 2025](#) for a recent thorough study of binary interaction). As massive stars are in most cases part of a multiple system (e.g., [Offner et al. 2023](#)), the study of stripped-envelope CCSN progenitors is detrimental to observed transients (e.g., [Schulze et al. 2025](#) for an ultra-stripped CCSN). In some cases of binary interaction, the companion spins up the core of the CCSN progenitor. We do not consider pre-collapse core rotation in this study. In Section 4 we discuss the explosion time according to the JJEM and the delayed neutrino explosion mechanism. We summarize this study in the context of the JJEM in Section 5.

2. NUMERICAL SCHEME

We use the one-dimensional stellar evolution code MESA (Modules for Experiments in Stellar Astrophysics; version 24.08.1; [Paxton et al. 2011, 2013, 2015, 2018, 2019](#); [Jermyn et al. 2023](#)) to model five different masses of SECCSNe, having zero-age main sequence masses ranging from $M_{\text{ZAMS}} = 12M_{\odot}$ and up to $M_{\text{ZAMS}} = 40M_{\odot}$. For each mass we simulated three scenarios of envelope stripping: a regular wind that leaves a hydrogen-rich envelope at the explosion (“full envelope”), evolution that includes an extra mass loss that removes the hydrogen but leaves helium (“H-stripped envelope”), and the removal of both hydrogen and helium (“He-stripped envelope”).¹

We use the default controls in the ‘20M_pre_ms_to_core_collapse’ test suite². This includes the Ledoux criterion ([Heney et al. 1965](#)) with mixing length theory (MLT) coefficient $\alpha_{\text{MLT}} = 1.5$ and semi-convection coefficient $\alpha_{\text{SC}} = 0.01$. The MLT option is selected to be TDC (time-dependent convection), which converges to the MLT described in [Cox & Giuli \(1968\)](#) in the long term ([Jermyn et al. 2023](#)). We set `Pextra_factor` = 4 to help stabilise the atmosphere during envelope removal. The MESA parameter ‘relax_to_this_tau_factor’ is set to 1.5×10^6 to avoid some numerical difficulties when stripping the envelope and is applied to all models, including those with a full envelope. Due to these modifications, the envelopes of the stellar models are not described accurately. This might influence the composition and properties of the outer core. For instance, hydrogen shell burning during the helium burning phase is ignored (e.g., [Iben & Renzini 1984](#); [Paxton et al. 2011](#); [Jones & Gore 2015](#)). These are beyond the scope and interest of this paper, as we focus on the inner core layers.

As we manually remove the envelope, we use the default wind scheme and settings. Mass loss by wind is

¹ Our final models, inlists and added schemes are available online in a Zenodo upload: [doi:10.5281/zenodo.17252524](https://doi.org/10.5281/zenodo.17252524).

² The MESA EOS is a blend of the OPAL ([Rogers & Nayfonov 2002](#)), SCVH ([Saumon et al. 1995](#)), FreeEOS ([Irwin 2004](#)), HELM ([Timmes & Swesty 2000](#)), PC ([Potekhin & Chabrier 2010](#)), and Skye ([Jermyn et al. 2021](#)) EOSes. Radiative opacities are primarily from OPAL ([Iglesias & Rogers 1993, 1996](#)), with low-temperature data from [Ferguson et al. \(2005\)](#) and the high-temperature, Compton-scattering dominated regime by [Poutanen \(2017\)](#). Electron conduction opacities are from [Cassisi et al. \(2007\)](#) and [Blouin et al. \(2020\)](#). Nuclear reaction rates are from JINA REACLIB ([Cyburt et al. 2010](#)), NACRE ([Angulo et al. 1999](#)), and additional tabulated weak reaction rates [Fuller et al. \(1985\)](#); [Oda et al. \(1994\)](#); [Langanke & Martínez-Pinedo \(2000\)](#). Screening is included via the prescription of [Chugunov et al. \(2007\)](#). Thermal neutrino loss rates are from [Itoh et al. \(1996\)](#).

turned on for the envelope removed models from ZAMS up until the first envelope removal episode (hydrogen envelope removal) with a ‘Dutch_scaling_factor’ of 1.0.

We use the `mesa_80` nuclear network, which includes many isotopes of intermediate elements (Oxygen to Silicon) not found in the default `approx21` massive stars network. `mesa_80` was found to give a composition comparable to those from larger networks (Grichener et al. 2025). Using larger networks might give slightly more accurate composition and Ye fractions at the onset of core-collapse (e.g., Renzo et al. 2024), but remains computationally demanding. Recent works have presented a possible neural-network approach solution (Grichener et al. 2025).

We remove the H envelope when the radius of the photosphere reaches $R_* = 800R_\odot$, which occurs roughly at the time of central H depletion (He core formation). The model is then computed until central He depletion, at which point He envelope stripping happens for stellar models with both H and He envelopes stripped. We perform a comparison between our envelope removal scheme and the default scheme used for massive stars in the ‘20M_pre_ms_to_core_collapse’ MESA example in Appendix A.

The envelope removal is done using ‘relax_initial_mass_to_remove_H_env’ and a similar handle ‘relax_initial_mass_to_remove_He_env’, the latter of which we implemented directly into the MESA code and is available in the Zenodo upload. These handles remove mass outside

$$M_{\text{remain}} = M_{\text{core}} + M_{\text{ret}} \quad (1)$$

where M_{core} is the He core mass or the CO core mass determined by MESA, where the He core mass is used to remove the H envelope and the CO core mass is used to remove the He envelope. The retained mass $M_{\text{ret}} = 5 \times 10^{-3}M_\odot$ is the same as the default in MESA and is not altered for the main part of this paper. A more detailed study on the effect of this retained mass is done in Appendix B.

Nearing the onset of collapse, we refine the time steps further (by adjusting ‘time_delta_coeff’) to avoid the sudden emergence of high infall velocity in the core that terminates the simulation and to ensure several stellar profiles at the onset of collapse.

We terminate the simulation when the infall velocity at the iron core exceeds $v_{\text{infall}}^{\text{Fe}} = 300 \text{ km s}^{-1}$, but choose an earlier time for our analysis of the onset of collapse, $v_{\text{infall}}^{m < 4M_\odot} = 100 \text{ km s}^{-1}$, i.e., the first time that a point in $m < 4M_\odot$ reaches an infall velocity of 100 km s^{-1} . Shishkin & Soker (2021) have shown that convective velocities at the Fe/Si interface can further

increase beyond the onset of collapse as these layers are compressed and heated, but we prefer to avoid these fast-infall regimes in favour of numerical stability.

3. CONVECTION IN SECCSN PROGENITORS

3.1. Stripped envelope models

We simulate massive stellar models up to core-collapse, as detailed in Section 2, with initial masses in the range: $M_{\text{ZAMS}} = 12 - 40 M_\odot$. Each initial stellar model has three different mass removal prescriptions: mass loss by the regular stellar wind that leaves a hydrogen-rich envelope (full envelope) for a Type II CCSN, extra mass removal that leaves a hydrogen-deficient envelope (H envelope removed) for a Type Ib CCSN, and an additional mass removal that strips both hydrogen and helium (H-He envelope removed) for a Type Ic CCSN.

In Figure 1 we present the composition and some other stellar properties of two models, $M_{\text{ZAMS}} = 12M_\odot$ and $M_{\text{ZAMS}} = 28M_\odot$, for the three envelope compositions, all at the onset of core collapse (totalling six cases). Note that we truncate the plots at $r = 1R_\odot$. Therefore, for the full and H-removed envelopes, we do not include the envelope. We plot as a function of radius, as it is more relevant to the specific angular momentum parameter j (defined later in equation 2) and the collapse times.

We denote several core boundaries with vertical lines. Generally, from the innermost to the outermost: the darker red dashed line marks the iron core boundary as defined by MESA, where $X_{\text{A}>46} > 0.1$ and $X_{\text{Si+S}} < 0.1$; the darker red dotted line marks the point where $X_{\text{A}>46} > 0.1$; the purple dashed line marks where $X_{28\text{Si}+32\text{S}} > 0.1$ and $X_{16\text{O}+20\text{Ne}+24\text{Mg}} < 0.1$; the purple dashed-dotted line where $X_{\text{Si}} + X_{\text{S}} > X_{\text{O}} + X_{\text{Ne}}$ (‘majority vote’); the purple dotted line marks where $X_{28\text{Si}+32\text{S}} > 0.1$. The mass coordinates where $X_{\text{A}>46} > 0.1$ or $X_{\text{Si+S}} > 0.1$ (dotted lines) are shown as an indicator of how much mixing is present at the edge of the core and is often indicative of active burning, and hence convective layers. In the composition panels of Figure 1, the regions between the different core boundary definitions accompany composition gradients and facilitate nuclear burning and convection. This is also relevant to the discussion of the explosion time (Section 4), as the accretion of these interface layers onto the compact remnant can fuel an explosion within the realm of the JJEM.

We note that for lower mass massive stars, which in our study are the $M_{\text{ZAMS}} = 12, 15, 18M_\odot$ models, small differences in initial mass, convection parameters, and other settings that affect burning and mixing processes can influence shell burning episodes and lead to vastly

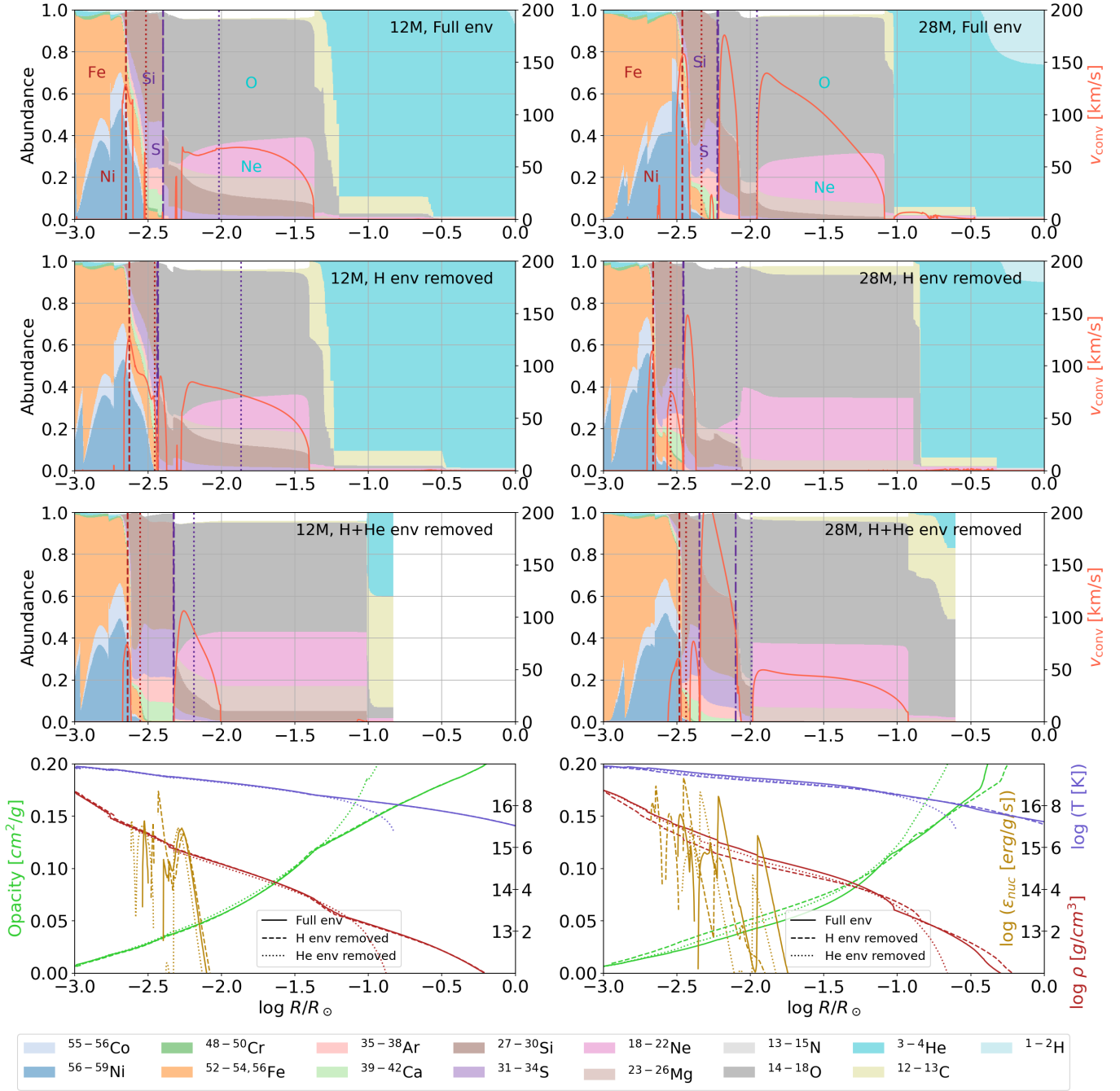


Figure 1. Composition profiles of $12 M_{\odot}$ (left column) and $28 M_{\odot}$ (right column) models at the instance when $v_{\text{infall}}^{m < 4M_{\odot}} = 100 \text{ km s}^{-1}$. In the top three panels, abundances are shown as blocks of colours corresponding to the left vertical axis. Convective velocity is shown in the red line, corresponding to the right vertical axis. Vertical lines mark the Fe/Si and Si/O boundaries. The inner and outer dotted lines marks the region where $X_A > 46$ and $X_{28\text{Si}+32\text{S}}$ are less than 0.1, respectively; the inner and outer dashed lines mark Fe/Si boundary as defined by MESA and Si/O interface where $X_{28\text{Si}+32\text{S}} > 0.1$ and $X_{16\text{O}+20\text{Ne}+24\text{Mg}} < 0.1$, respectively; the dashed-dotted purple line marks where $X_{28\text{Si}+32\text{S}} > X_{16\text{O}+20\text{Ne}+24\text{Mg}}$. The lower panels show the following properties of all three models as a function of radius: opacities are shown as increasing green lines corresponding to the left vertical axis; energy generation rate per gram in units of $\text{erg g}^{-1} \text{s}^{-1}$ are shown in gold lines with several peaks corresponding to the right inner vertical axis; temperature and density are shown in decreasing lines, being blue and red respectively and with density having a sharper drop, on the outer right vertical axis. Solid line corresponds to full envelope models, dashed lines to H envelope removed, and dotted line to H and He envelope removed. This figure shows the presence of strong convection in the Fe/Si interface and the inner oxygen layer in all models, mass coordinates that correspond to the formation of an NS.

different iron core masses and Si burning (e.g., Sukhbold et al. 2018). In Appendix C, we compare three models with very close initial masses.

As seen in the bottommost panels of Fig. 1, the lower overall mass results in lower densities and temperatures in the outer core layers of the envelope-stripped cases, thereby slowing the burning. This leads, in most cases, to less complete burning of the Si+S layers at the onset of collapse, which retains high burning (and energy generation) rates, fuelling vigorous convection up to collapse, as opposed to the full-envelope cases where burning has already completed or is located further out. Additionally, the temperature and composition gradients near the core’s edge are generally steeper. The combined effect of a steeper temperature and composition gradient causes higher opacity in the outer regions of the core in stripped-envelope models. The ONe region of the stripped envelope models at the edge of the core is, therefore, more prone to convection. Therefore, the same amount of energy generated by nuclear burning leads to higher convective velocity in the outer core of stripped-envelope models due to higher opacities and lower densities.

In Figure 2, we present in red areas the convective velocity profiles for the last $\simeq 10$ s before the onset of collapse. We define the onset of collapse here as the first time at which the maximum value of the infall velocity within $m < 4 M_\odot$ exceeds 100 km s^{-1} . Black lines are the infall velocities as a function of mass, v_{infall} ; the upper line is the first one, and the lower line is the last infall velocity profile we show. The turquoise lines show the radius as a function of mass, $r(m)$, at these times. As the star collapses, the turquoise line representing the radius decreases over time. Each profile is plotted in a faint transparent colour on top of the previous profiles. Therefore, if convection persists during this $\simeq 10$ s before collapse, it will be seen in a more opaque shade. A similar logic applies for the regions with active burning ($\epsilon_{\text{nuc}} > 10^{14} \text{ erg/g/s}$). A more opaque blue line indicates that the region is actively burning for a larger portion of this time frame. There is no indicator of time progression in Figure 2 due to the stochastic nature of convection and the location of burning.

We observe that generally, the outermost convective region in the core (the ONe layer) exhibits higher convective velocities for models where the envelope is removed. There is no distinct relation between the amount of removed envelope mass and the convective velocity in the outer core.

3.2. Angular momentum parameter

This study aims to examine angular momentum seed perturbations in the pre-collapse core. These are the seed perturbations that, according to a basic assertion of the JJEM, after amplification in the unstable zone above the newly born NS, form the intermittent accretion disks that launch the jittering jets that explode the star. For that, we use the specific angular momentum parameter that previous works used (e.g., Wang et al. 2024)

$$j = v_{\text{conv}} r. \quad (2)$$

We find that in all simulated models except for the $M_{\text{ZAMS}} = 40 M_\odot$ with H+He removed envelope, there is at least one layer with $j > 2 \times 10^{15} \text{ cm}^2 \text{ s}^{-1}$ inside the mass coordinate that forms a NS. The relevant zones for NS formation are those inward to the maximum baryonic mass for the formation of a NS (above that mass, the NS collapses to a black hole). The maximum NS gravitational mass possible is $M_{\text{NS}} \simeq 2.25 M_\odot$ (e.g., Fan et al. 2024). The corresponding baryonic mass, according to the baryonic to NS gravitational mass relation from Gao et al. (2020), is $M_{\text{NS,b}}^{\text{max}} \simeq 2.65 M_\odot$. In the case of $M = 40 M_\odot$ with H+He removed envelope there is a zone at $m \simeq 2 M_\odot$ with $j(m) > 10^{15} \text{ cm}^2 \text{ s}^{-1}$.

We present our results, specifically looking for zones with large angular momentum parameter at mass coordinates $< M_{\text{NS,b}}^{\text{max}}$. In this section, we present two models, of $M_{\text{ZAMS}} = 12 M_\odot$ and $M_{\text{ZAMS}} = 28 M_\odot$. In Appendix D we present similar graphs for other models we simulated.

In Figure 3 we present the angular momentum parameter as a function of mass, $j(m)$, in the same way we present the convective velocity $v_{\text{conv}}(r)$ in Figure 2; we also draw the other variables we present in Figure 2. In Figure 4 we present these variables for the models of $M_{\text{ZAMS}} = 20$ and $35 M_\odot$. Some earlier studies of the JJEM (e.g., Shishkin & Soker 2021) have applied this parameter to set the criterion for a convective layer to seed perturbations that lead to the formation of intermittent accretion disks, which launch the exploding jets. However, the JJEM has not yet determined the critical value of $j(m)$ for the operation of the JJEM. Following Shishkin & Soker (2022), we mark two limits, $j = 2.5 \times 10^{15} \text{ cm}^2 \text{ s}^{-1}$ and $j = 5 \times 10^{15} \text{ cm}^2 \text{ s}^{-1}$, with dotted horizontal lines in Figure 3, 4, and the Figures in Appendix D.

The main conclusion from Figures 3, 4, and Appendix D, is that in massive envelope-removed stars, the inner convective zones with large enough $j(m)$ to facilitate the JJEM tend to move to lower mass coordinates. This can be either the region fuelled by oxygen burning (as

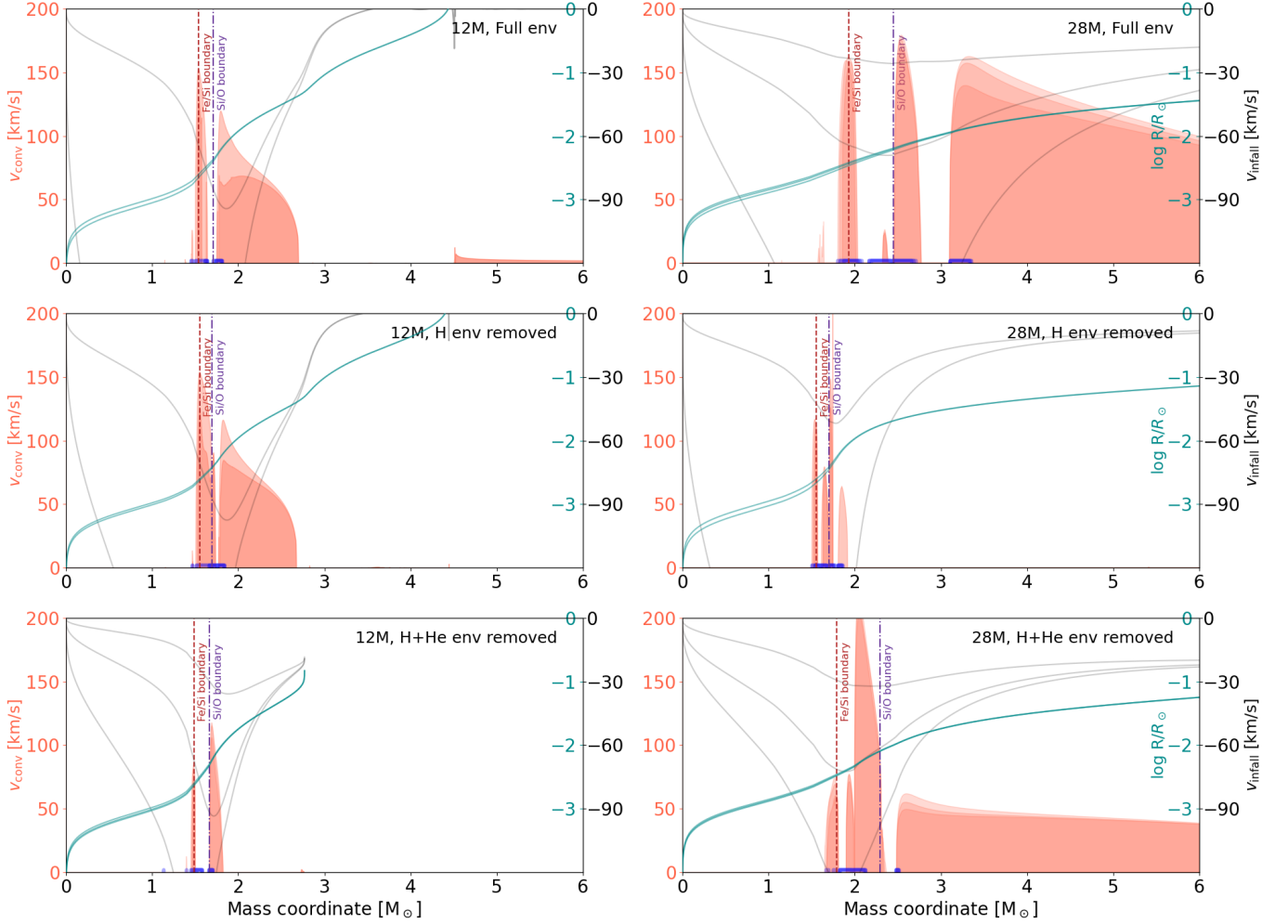


Figure 2. Convective velocity profiles, $v_{\text{conv}}(m)$ at several times shown by red area intensity, starting from $\simeq 10$ s before the time when $v_{\text{infall}}^{m < 4M_{\odot}} = 100 \text{ km s}^{-1}$ for $12M_{\odot}$ (left) and $28M_{\odot}$ (right) models. The scale of $v_{\text{conv}}(m)$ is on the left axis. A turquoise line represents the radius as a function of mass, with the scale on the inner right vertical axis. Black lines show the infall velocity $v_{\text{infall}}(m)$ at several times, the upper line at the earliest time and the lower line at the last time, with the scale on the outer right vertical axis. The Fe/Si and Si/O boundaries are marked as vertical dashed lines. We denote regions with active burning ($\epsilon_{\text{nuc}} > 10^{14} \text{ erg/s}$) as a blue line at the bottom of the panels, where again darker shades indicate more models with active burning at that mass coordinate.

in $M_{\text{ZAMS}} = 30M_{\odot}$ and $35M_{\odot}$) or silicon burning (as in $M_{\text{ZAMS}} = 25M_{\odot}$).

We note that the convective zones vary from one model to another. For example, the H-striped $28M_{\odot}$ model (middle right of Figure 3) has thin convective zones in the inner core, while in the cases of this initial model without envelope removal or with helium removal, the convective zones are more extended (upper and lower panels on the right of Figure 3). The thick convective zones on the H-striped model are sufficient to facilitate the JJEM. The pre-collapse envelope convection is robust.

4. ON THE EXPLOSION TIME

The explosion, according to the JJEM, starts when the newly born NS accretes the convective layers from the core. These are generally the regions of and near the Fe/Si interface (silicon burning zone) and the Si/O interface (oxygen burning zone). We comment in this section on the timescales of the explosion, as described by the JJEM and the neutrino-driven mechanism.

In a recent paper, Boccioli et al. (2025b) compared the time of accretion of the Si/O interface with the time the revived shock reaches a radius of 500 km in their one-dimensional (1D) simulations of the neutrino-driven mechanism. They get some successful shock revival with their 1D simulations, but many models failed to explode. Those models with solar metallicity that do explode, yield explosion energies of $0 \lesssim E_{\text{exp}}(1D) \lesssim 10^{51}$ erg (Boccioli et al. 2025a). The recent 3D simulations by Nakamura et al. (2025), which are supposed to be more accurate than 1D simulations, yield only very weak explosions $E_{\text{exp}} \lesssim 10^{50}$ erg, or not at all (see analysis of their explosion energies by Soker 2024i). Both the low explosion energies and the large fraction of failed explosions (failed SNe) are in contradiction with observations (e.g., Soker 2024j). Here, we compare the time at which the stalled shock starts to re-expand and the time of Si/O interface accretion to elaborate on the relation between the two explosion mechanisms.

In Figure 5 adapted from Boccioli et al. (2025b), they present the time the shock reaches a radius of 500 km, t_{expl} , as a function of the time the Si/O is accreted for their models that explode. It takes the shock $\Delta t \simeq 0.1 - 0.15$ s to reach 500 km from the moment it starts to rapidly re-expand. We added the zone between the two diagonal red-dashed lines to indicate where $t_{\text{rexp}} \simeq t_{\text{Si/O}}$. The red-colored models have large values of compactness, $\xi_2 \gtrsim 0.6$, which correspond mainly to massive progenitors, $M_{\text{ZAMS}} \gtrsim 22M_{\odot}$ (e.g., Sukhbold et al. 2016), hence represent rare CCSNe.

Figure 5 shows that in the majority of the models that Boccioli et al. (2023) studies, the accretion of the Si/O interface occurs before shock revival. The Fe/Si interface, which also has a convective zone (e.g., Figures 3, 4, and Appendix D), resides further inside the pre-collapse core and is accreted before the Si/O interface. To illustrate the crude timescales, we present in Figure 6 the free-fall times from the Fe/Si and Si/O boundaries in our pre-collapse stellar models, three models for each ZAMS mass. The Fe/Si interface is accreted $\simeq 0.1 - 0.3$ s before the Si/O interface in most models. Figures 5 and 6 show that in the vast majority of CCSNe, the Fe/Si is accreted before the shock revival. This interface features a convective zone that initiates the JJEM process, which can last from a second to several seconds.

We note that different definitions for the interface layer location (See Figure 1) will slightly change the free fall time but not change the overall conclusion.

The new point we state here is that the convective regions, the Fe/Si interface in the majority (and possibly all) cases, and the Si/O interface, in most models, are accreted before the neutrino-driven mechanism revives the stalled shock. *Namely, even when the neutrino-driven mechanism might have led to an explosion (but generally of too low energy), the JJEM starts to operate before the neutrino mechanism fully revives the stalled shock.* The Crab Nebula suggests this is true even in low-energy CCSNe, because the Crab Nebula is a low-energy supernova (e.g., Yang & Chevalier 2015) that possesses a clear point-symmetric morphology that we argue only a jet-driven explosion can explain (Shishkin & Soker 2024).

5. SUMMARY

The JJEM asserts that pre-core-collapse convection seeds the angular momentum perturbations that form the intermittent accretion disks that launch the jittering pairs of jets that explode CCSNe. The shaping of CCSNRs by two or more pairs of jets is a robust finding of the last two years (Section 1). Using the one-dimensional stellar code MESA (Section 2), including no magnetic fields or rotation, we examined the specific angular momentum parameter $j(m)$ (equation 2) in the cores of pre-collapse stellar models, focusing on stripped-envelope stars, i.e., progenitors of SNe Ib and Ic. Earlier studies of the JJEM used this parameter as an indication of the presence of these seed perturbations.

Our main results are the red areas in Figures 3, 4, and Appendix D. These results indicate that in all models, regardless of whether they have hydrogen-rich, hydrogen-stripped, or helium+hydrogen-stripped envelopes, there is at least one significant strong con-

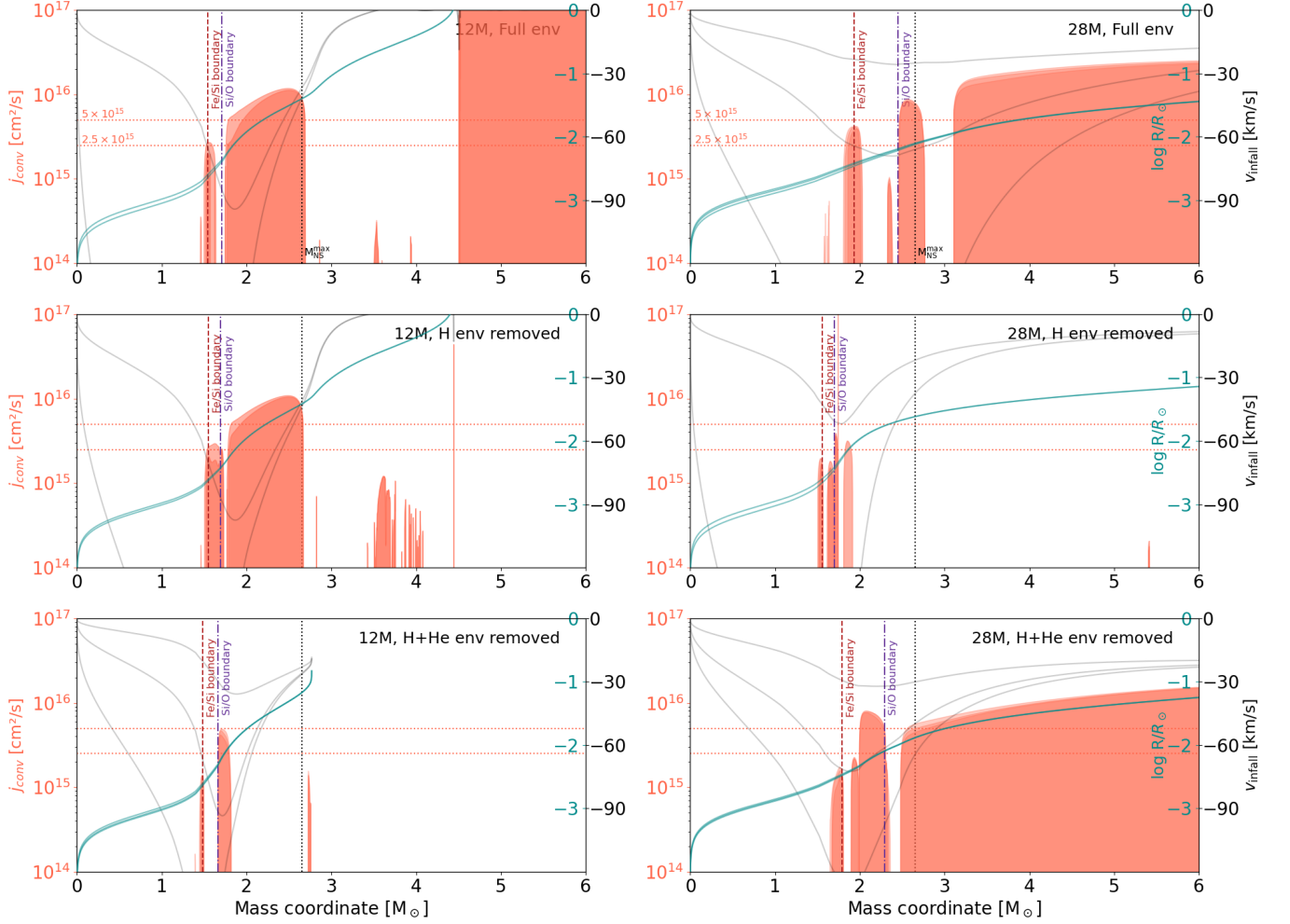


Figure 3. The angular momentum parameter as a function of mass, $j(m)$, for the six models we present in Figure 2, as well as the other variables we present in that figure, besides the convective velocity. We draw two horizontal red dotted lines at $j_{\text{conv}} = 2.5 \times 10^{15} \text{ cm}^2 \text{ s}^{-1}$ and $j_{\text{conv}} = 5 \times 10^{15} \text{ cm}^2 \text{ s}^{-1}$, the approximate criteria for JJEM that Shishkin & Soker (2022) suggested. A dotted vertical line denotes the mass coordinate (baryon mass) of $M_{\text{NS,b}}^{\text{max}} = 2.65 M_{\odot}$, corresponding to the upper limit for neutron stars. While most models obtain specific angular momentum values larger than $j_{\text{conv}} = 5 \times 10^{15} \text{ cm}^2 \text{ s}^{-1}$ below $m_{\text{NS}}^{\text{max}}$, for the envelope removed cases this pushes the oxygen burning region below this mass limit ensuring large angular fluctuations if these are to be accreted by the compact remnant as collapse occurs.

vective zone in the inner core. Namely, a prominent zone with $j(m) \gtrsim 2 \times 10^{15} \text{ cm}^2 \text{ s}^{-1}$ in the inner core. By inner core, we refer to the core inside the mass coordinate that is the maximum baryonic mass of a NS, $M_{\text{NS,b}}^{\text{max}} \simeq 2.65 M_{\odot}$ (Section 3.2). Our finding is encouraging for the JJEM, although it does not show that the intermittent accretion disks indeed form.

In this theoretical study, we examined convective motion according to the mixing length theory (MLT) as implemented in MESA. Three-dimensional simulations reveal that the maximum convection velocity in three dimensions is several times faster than the velocity that the MLT gives, particularly for low angular wavenumbers (e.g., Fields & Couch 2020; Yadav et al. 2020; Yoshida et al. 2021; Fields & Couch 2021; Georgy et al. 2024). This suggests that the convective zones we simulate in 1D correspond to large-scale motion with high specific angular momentum at the onset of collapse in real three-dimensional cases.

Moreover, actual convection just before core collapse might be more vigorous than what these simulations give. In a recent study of metal distribution in the CCSN remnant Cassiopeia A, Sato et al. (2025) concluded that within hours before explosion, there was a strong mixing of the oxygen layer with the adjacent layers in the core. This mixing requires vigorous mixing. Sato et al. (2025) comment that such perturbations in the collapsing core can facilitate shock revival in the framework of the neutrino-driven mechanism. We comment that such vigorous convection can seed large perturbations to lead to the formation of stochastic intermittent accretion disks that launch jittering jets that explode the star, i.e., the JJEM. Both the JJEM and the neutrino-driven mechanism require strong pre-collapse perturbations.

Studies of stripped-envelope CCSNe in the framework of the neutrino-driven mechanism predict many failed supernovae, namely, a direct collapse to a black hole of most of the star (e.g., Zapartas et al. 2021). We find that all our models, including stripped-envelope cases, should explode as CCSNe and leave behind an NS in the frame of the JJEM when core rotation is negligible. According to the JJEM, black holes are formed when the

pre-collapsed core is rapidly rotating (e.g., Soker 2023b). The reason is that in the case of rapid pre-collapse core rotation, the accreted gas has angular momentum along the same axis as the pre-collapse rotation, with very small jittering around this axis. The jets are not efficient in expelling gas from the equatorial plane, where the accretion disk forms. Accretion continues from the equatorial plane, transforming the remnant into a black hole while the jets explode the star along the polar directions. Namely, here is an explosion rather than a failed supernova, even when a black hole is formed, and can even be an energetic explosion (e.g., Gilkis et al. 2016). Jets in the cores of massive stars can inflate large cocoons (lobes; e.g., Gottlieb et al. 2023) that expel mass from the equatorial plane as well. This, we speculate, can be effective for lower-mass cores, but not for massive cores with masses $\gtrsim 10 M_{\odot}$. In a future study, we will examine whether this might explain the peak of black hole masses around $10 M_{\odot}$ that gravitational wave observations of merging black holes infer (e.g., The LIGO Scientific Collaboration et al. 2025).

In Section 4, we showed that in the majority of stellar models where the neutrino-driven mechanism revives the stalled shock, we expect the JJEM to start operating at earlier times. We therefore claim that there is no need for the neutrino-driven mechanism to explain CCSNe, as the JJEM can account for all CCSNe.

The progress in establishing the JJEM as the primary explosion mechanism of CCSNe has been made in many small steps. Upon analyzing observations, the identification of a new point-symmetric CCSNR represents a small step (there have been 16 such steps to date). At the same time, theoretically, there are smaller simulation steps, such as three-dimensional hydrodynamical simulations of shaping by jittering jets (e.g., Braudo et al. 2025; Soker & Akashi 2025). Our study represents a small step in demonstrating the robust convection in the inner core of stripped-envelope CCSN progenitors.

ACKNOWLEDGMENTS

NS thanks the Charles Wolfson Academic Chair at the Technion for the support.

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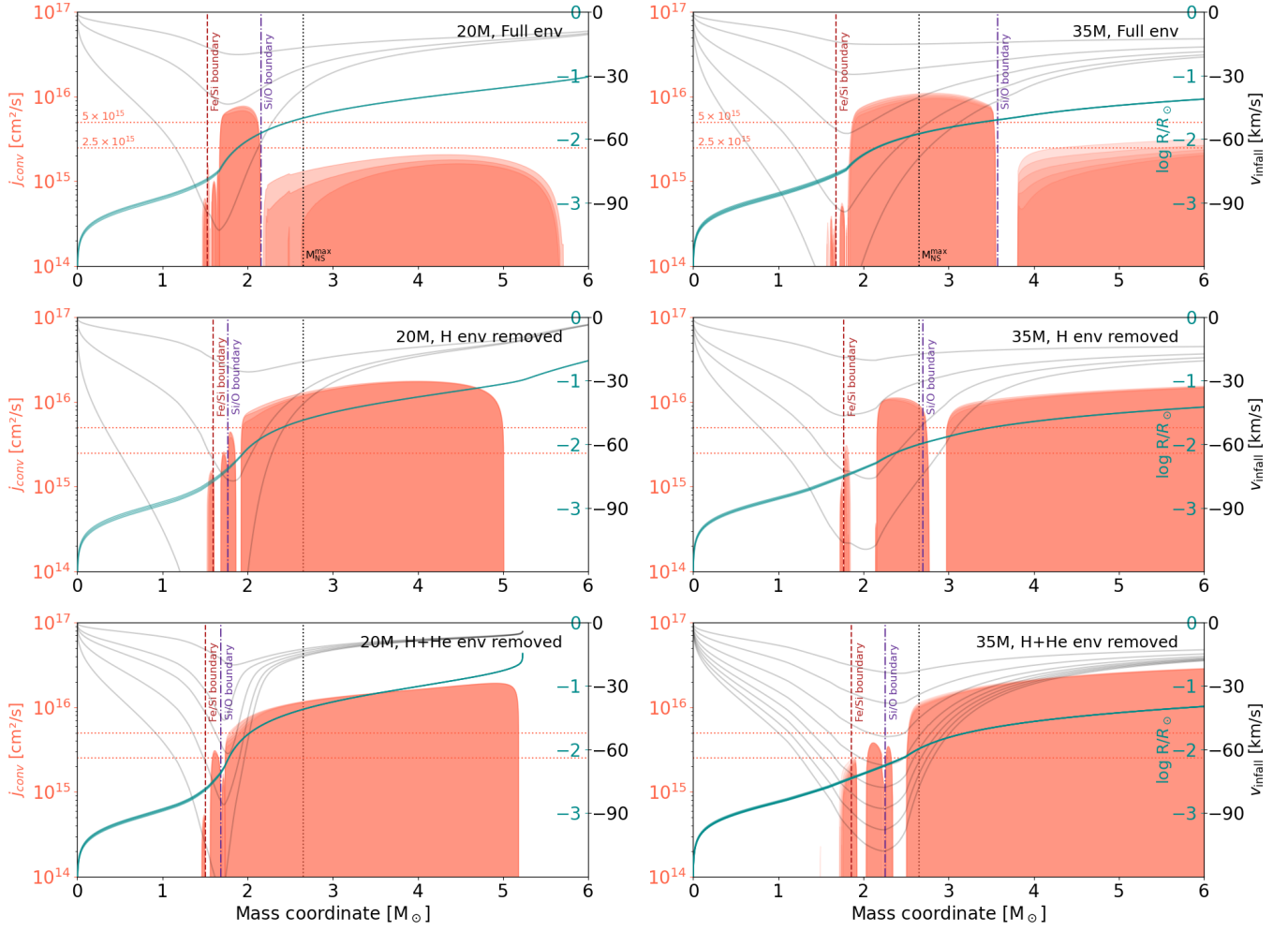


Figure 4. Similar to Figure 3 but for models of $M_{\text{ZAMS}} = 20$ and $M_{\text{ZAMS}} = 35 M_{\odot}$.

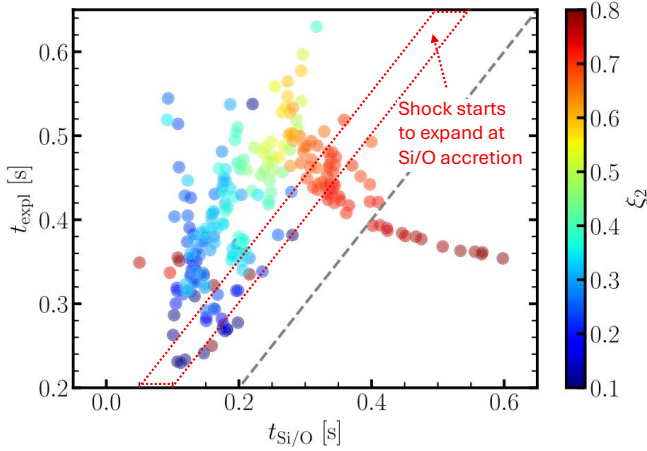


Figure 5. A figure adapted from Boccioli et al. (2023) where they show the explosion time t_{expl} , defined as the time the revived shock reaches a radius of 500 km, as a function of the time the Si/O interface from the core is accreted. Times are measured from the shock bounce. Their dashed line shows $t_{\text{expl}} = t_{\text{Si/O}}$. The revived shock reaches the radius of 500 km after $\Delta t \simeq 0.1 - 0.15$ s. We added the zone enclosed by the red-dashed lines to indicate the equality of Si/O accretion and the start of the shock re-expansion. In most of their models, the shock starts to expand after the Si/O is accreted. Only in those with large compactness $\xi_2 \equiv 500 \text{ km}/R(2) \gtrsim 0.6$ the explosion is much shorter than the Si/O accretion time; these correspond to massive stars, and are rare; $R(2)$ is the radius encloses $2M_{\odot}$ baryonic mass in the pre-collapse core.

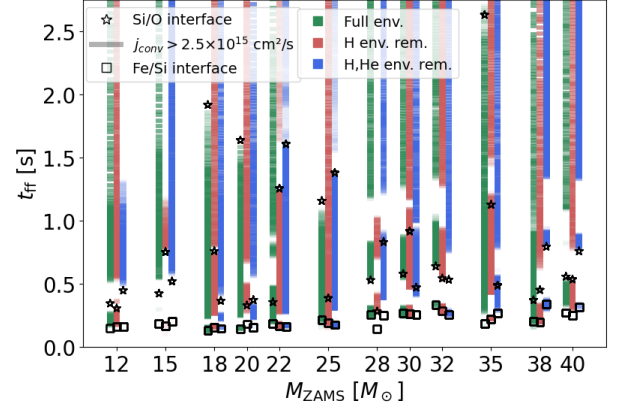


Figure 6. Free fall time from the Fe/Si and Si/O boundaries when at least one mass shell at $m < 4M_{\odot}$ has a infall velocity of $v_{\text{infall}} > 100 \text{ km s}^{-1}$, i.e., at the onset of core collapse. Hollow squares represent the place of Fe/Si boundary as defined by MESA, and stars represent the Si/O interface where $X_{\text{Si}} + X_{\text{S}} > X_{\text{O}} + X_{\text{Ne}}$. Green color represents models with a full envelope, red represents models with a hydrogen stripped envelope, and blue represents models with both a hydrogen and helium stripped envelope. In each column, we mark by color the free-fall time of convective regions where $j_{\text{conv}} > 2.5 \times 10^{15} \text{ cm}^2/\text{s}$ (otherwise it is white). We examine several times just before collapse; darker colors signify that at most or all times there was convection for that free-fall time point, while a faint color indicates that only at one or a few times that we examine before collapse, the specific location had convection. We plot all the profiles starting from the onset of collapse up to simulation termination.

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APPENDIX

A. APPENDIX A: ENVELOPE REMOVAL SCHEME

Our envelope removal scheme favors a physical criterion that is radius-dependent. Namely, we remove the hydrogen envelope at the rapid expansion when the star is nearing hydrogen depletion at the centre, specifically when the star (photosphere) reaches a radius of $R_* = 800 R_\odot$. This is different from the default scheme used for massive stars, as implemented, for example, in the ‘20M_pre_ms_to_core_collapse’ test suite, which removes the hydrogen envelope at central helium depletion.

In this section, we compare the two different removal schemes in terms the stellar parameters of mass, radius, luminosity, and temperature.

In Figure A1 we show the time evolution of each removal case for both H and H+He removal, for a $M_{\text{ZAMS}} = 25 M_\odot$ star. The top panel depicts the mass evolution, which shows that the default removal scheme of MESA retains more mass than ours after both H and H+He removal - consistent with the simulated stars reaching our radius criteria before the (MESA) composition criteria, and as a result, the core masses are slightly smaller. The middle panel shows the radius evolution of each case. Upon completion of removal, the radius of the H removal cases and the H+He removal cases by our removal scheme is similar to that of their counterparts in the MESA default case.

In the bottom panel, we present an HR diagram for the five models. The four removal cases differ greatly in their late stage of evolution, as seen in the separation of the effective temperature T_{eff} . For the MESA default removal scheme, the main difference between the two removal cases, H and H+He, is that the H removal case has a higher luminosity than the H+He removal case. The stripped envelope part of the diagram (left) connects to the same main track (right) and then follows a qualitatively similar trajectory in the HR diagram, as in the MESA prescription, both envelope removals are executed consecutively. For our removal scheme, the two removal cases follow qualitatively different trajectories in the HR diagram. Interestingly, our H+He removal case has a similar trajectory as the MESA default removal scheme, but at a lower luminosity than both cases of the MESA removal scheme. The H removal case in our removal scheme reaches a high luminosity at a lower T_{eff} than all other cases.

Figure A2 shows several stellar properties of the star when $v_{\text{infall}}^{m < 4M_\odot} = 100 \text{ km s}^{-1}$. In general, the MESA default removal schemes yield a higher mass for each removal case, H and H+He. By this, the MESA default removal scheme also yields higher binding energy E_{bin} , and Fe core mass. The temperature and density profiles appear qualitatively similar for the two removal schemes, differing only because of the mass difference. Our Si core is smaller than MESA default in the H removal case, but is roughly the same as MESA default in the H+He removal case.

Regarding the convective velocity. We find that in both removal cases, the MESA default has a higher convective velocity in the ONe layer, and our removal scheme has a higher convective velocity in the Si layer. In both cases, the convection is sufficient to facilitate the JJEM.

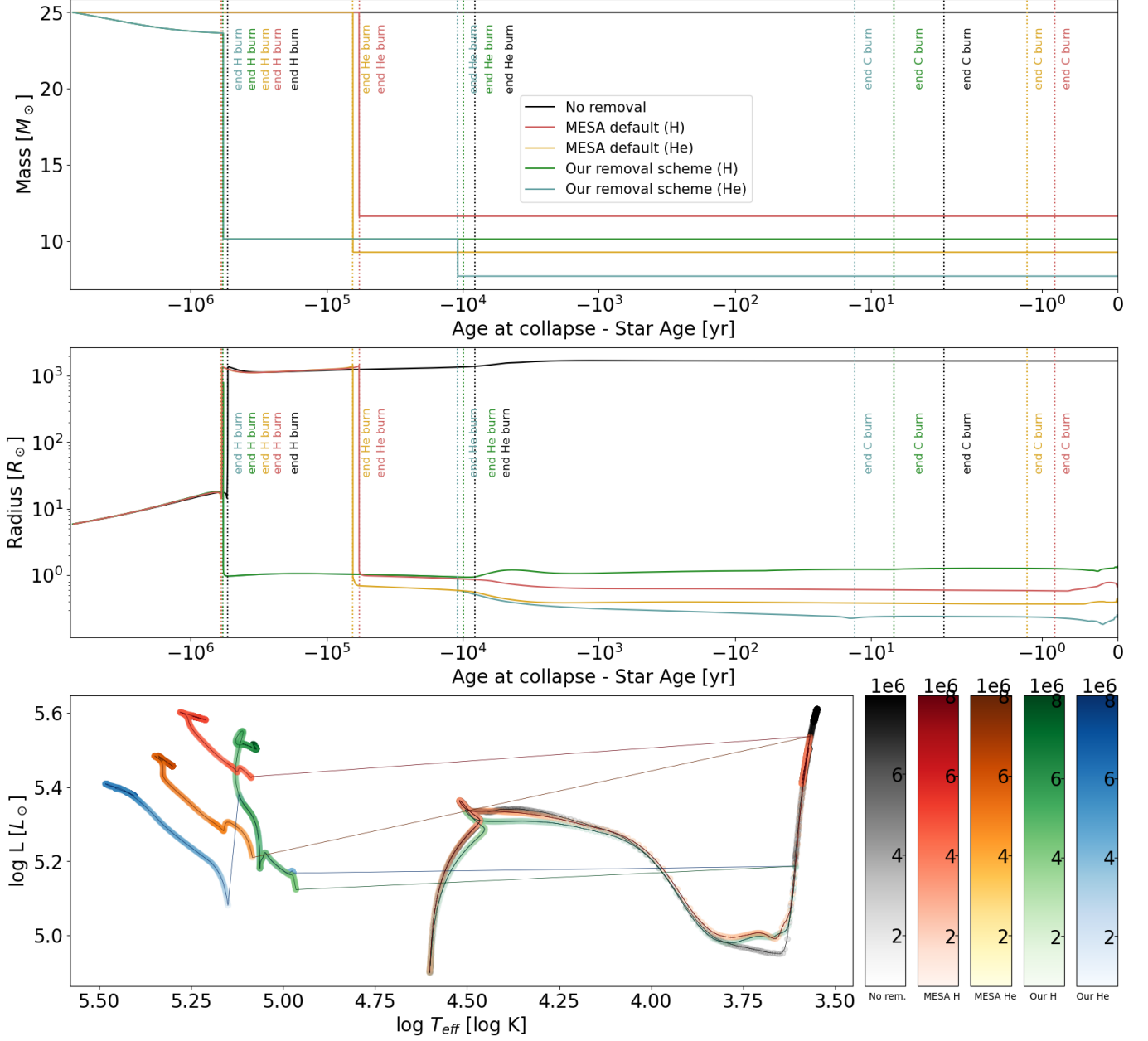


Figure A1. Time evolution of different removal schemes and different levels of envelope removal; total mass evolution as a function of time to collapse in the top panel and radius in the middle panel. The bottom plot shows the entire evolution as an HR diagram for five models with varying degrees of envelope removal and by different numerical envelope removal prescriptions. Colours progressing from light to dark represent time, scaled with colorbars on the right.

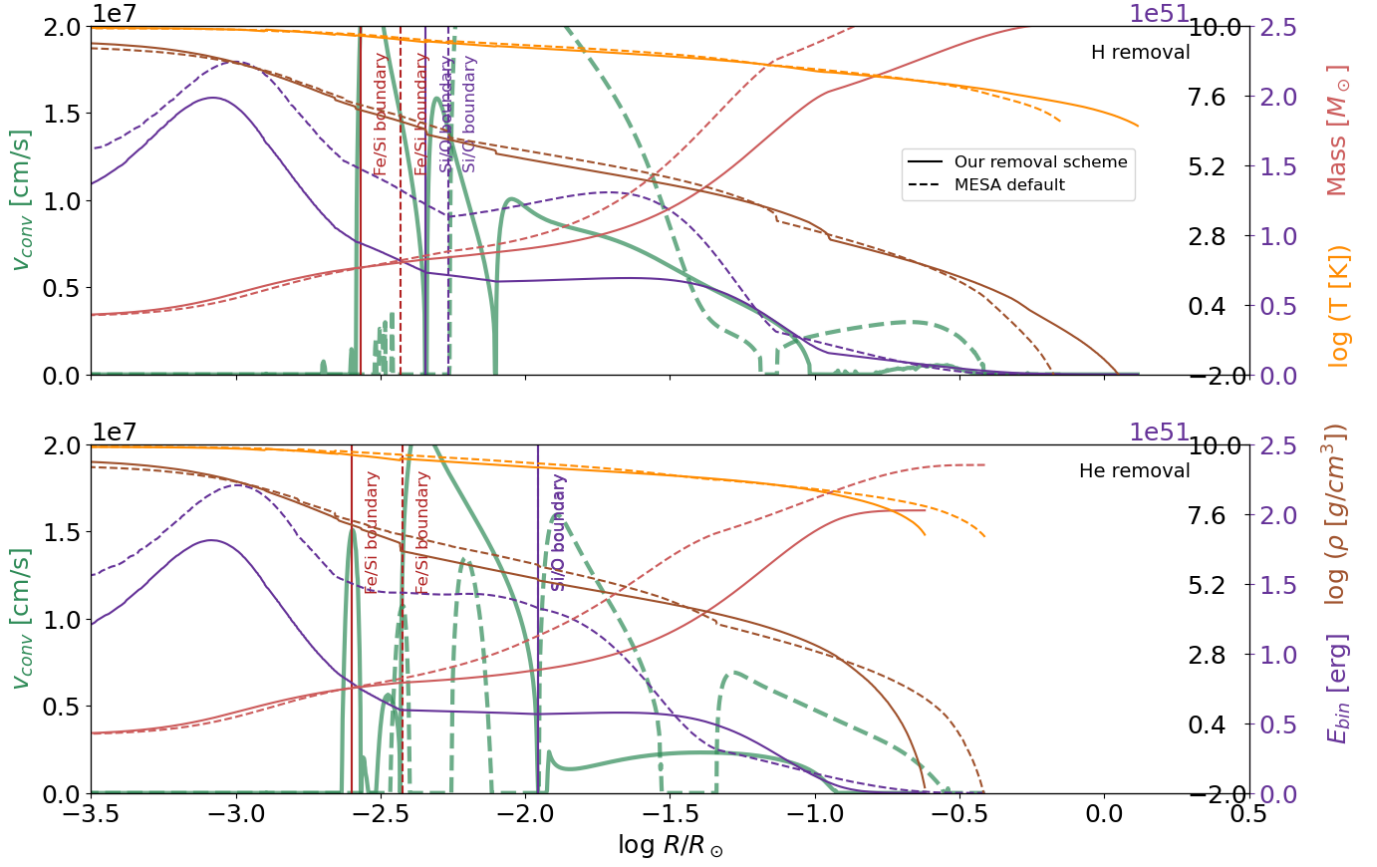


Figure A2. Comparison between the removal schemes for a $25M_{\odot}$ model. The H-removed cases of the two schemes are shown in the top panel, and both the H+He-removed cases are in the bottom panel. v_{conv} is shown on the left vertical axis in green; Mass, temperature, and density are shown on the inner vertical axis; binding energy is shown in purple on the outer right vertical axis. All profiles are selected to be when $v_{infall}^{m < 4M_{\odot}} = 100 \text{ km s}^{-1}$.

B. APPENDIX B: RETAINED ENVELOPE AFTER REMOVAL

In the MESA implementation of envelope removal, a small amount of mass is retained from the removed envelope: M_{ret} (see Section 2). The default value for this mass is $M_{\text{ret}} = 5 \times 10^{-3} M_{\odot}$. In this section, we conduct a limited parameter study to investigate the effect of this parameter on the final convective properties of the core in the $15 M_{\odot}$ He removed model. We vary the parameter between three values: $M_{\text{ret}} = 0 M_{\odot}$, $5 \times 10^{-3} M_{\odot}$, $1 \times 10^{-2} M_{\odot}$. The M_{ret} variable is thus applied to both H and He removal.

In Figure B we show the composition and other stellar parameters as a function of the radius (same as Figure 1) for the three variations in M_{ret} of the same model. In general, the three cases are qualitatively similar: density, temperature, and opacity profiles share similar shapes and only vary at the edge due to total mass differences. (The main difference between the three cases is that the O burning rate decreases as M_{ret} decreases).

All three cases display stable convection about the Fe/Si interface. $M_{\text{ret}} = 0 M_{\odot}, 5 \times 10^{-3} M_{\odot}$ cases has convection about the Si/O interface and in the oxygen layer. The convective velocities of the convective regions are comparable across the three cases. The convective velocity around the Si/O interface in the $M_{\text{ret}} = 0 M_{\odot}$ case is lower than that in the $M_{\text{ret}} = 5 \times 10^{-3} M_{\odot}$ case. In contrast, the convective velocity around the Fe/Si interface and in the oxygen layer is quite similar. In the $M_{\text{ret}} = 1 \times 10^{-2} M_{\odot}$ case, the only prominent convection occurs in the Fe/Si interface, with a higher velocity than the other two cases.

This shows the stochastic nature of convection in relation to changes in retained mass. Appendix C further explores this consistency issue. In all cases, we find that at least one zone in the inner core, a mass coordinate that forms an NS, has a strong enough convection to facilitate the JJEM.

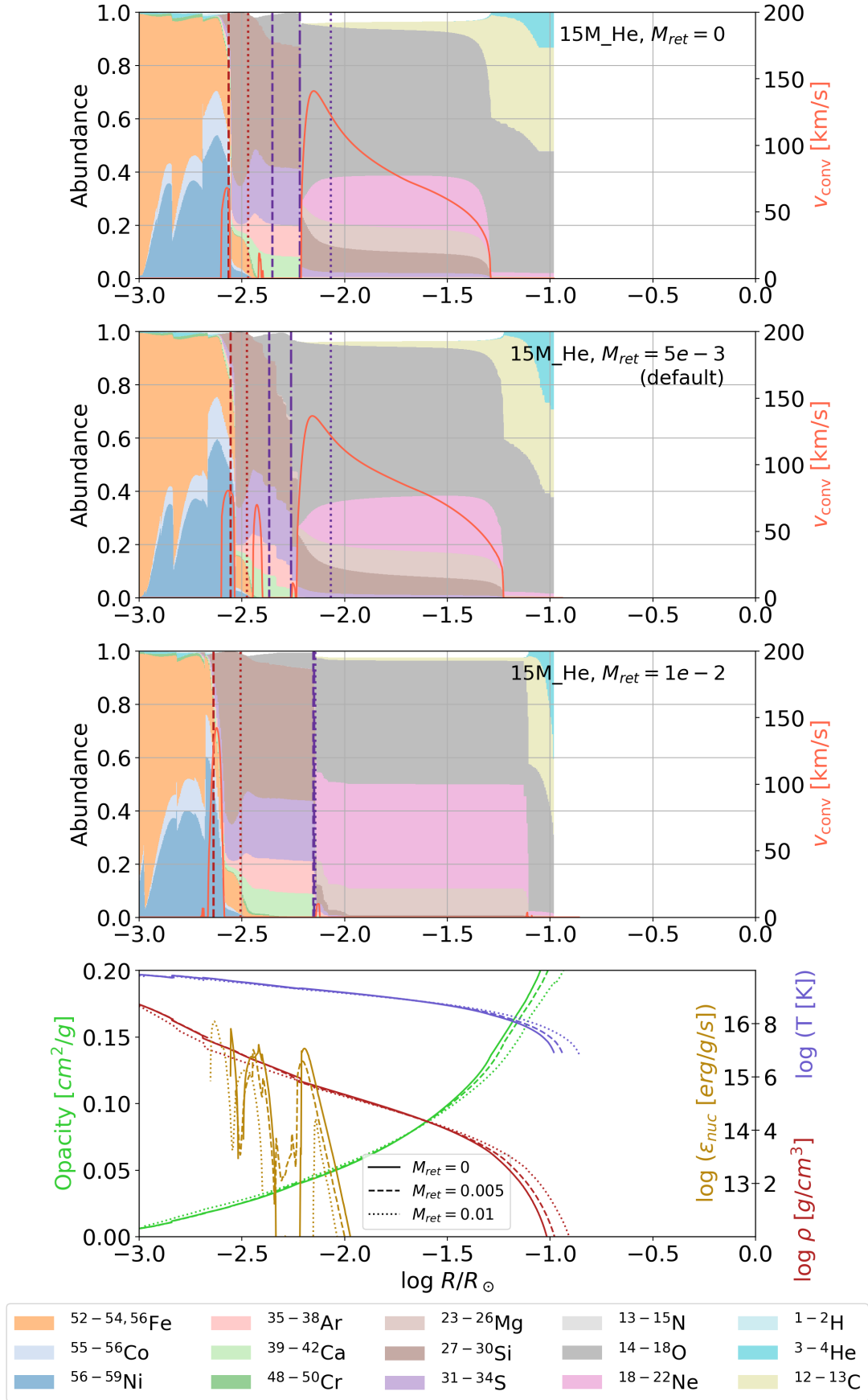


Figure B. Same as Fig. 1 but for the three cases of retained mass.

C. APPENDIX C: NUMERICAL CONSISTENCY

To test numerical consistency between different simulations, we varied the initial mass of the $15M_{\odot}$ model by $\pm 0.01M_{\odot}$ and simulated the two resulting models to completion.

In Figure C4, we show the composition and other stellar parameters as a function of radius (the same as in Figure 1) for the three models.

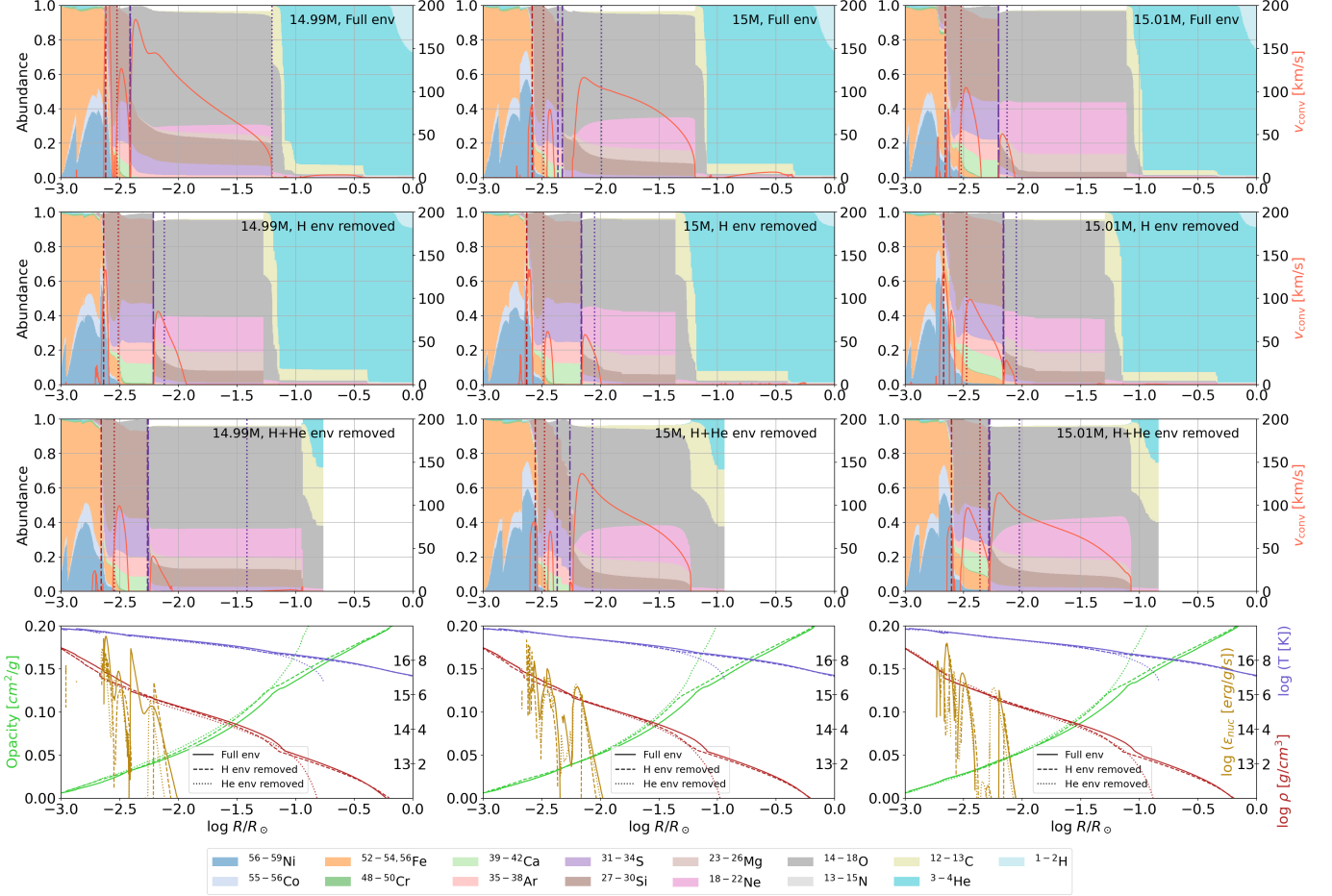


Figure C4. Same as Fig. 1 but for $14.99 M_{\odot}$ (left column), $15.00 M_{\odot}$ (centre column), and $15.01 M_{\odot}$.

While core masses, total mass fraction, and density/temperature profiles appear qualitatively similar, there are variations in the intermediate layers: The $14.99M_{\odot}$ model has a wide region with $X_{\text{Si,S}} > 0.1$ and a very gradual transition to the Si/S layer, which is absent in the $15M_{\odot}$ and $15.01M_{\odot}$ models. The $15.01M_{\odot}$ model also has a wider Si/S layer, similar to that in the H envelope-removed models. The $15M_{\odot}$ He model (H+He removed) also has a smaller radius than the $14.99M_{\odot}$ He and $15.01M_{\odot}$ He models.

In Figure C5 we present the angular momentum parameter $j(m)$ in the snapshots taken starting from 10 seconds before collapse (same as Figure 3) for the $15 \pm 0.01M_{\odot}$ models. For the three masses, the hydrogen-removal models exhibit very sporadic and localized convective zones in the oxygen layer. There's a consistent convective zone at the edge of the Si/O boundary as well as one at the Fe/Si interface. The interface convective zones appear in both the full envelope and H+He-removed cases. The $14.99M_{\odot}$ and $15M_{\odot}$ models have a large convective zone in the oxygen layer, while the $14.99M_{\odot}$ does not (upper row). The $14.99M_{\odot}$ He model similarly differs from the $15M_{\odot}$ and $15.01M_{\odot}$, with a slower, more localized convective zone around $m = (3 \pm 0.2)M_{\odot}$, where the oxygen convective zone extends at least $m = 2 - 3M_{\odot}$.

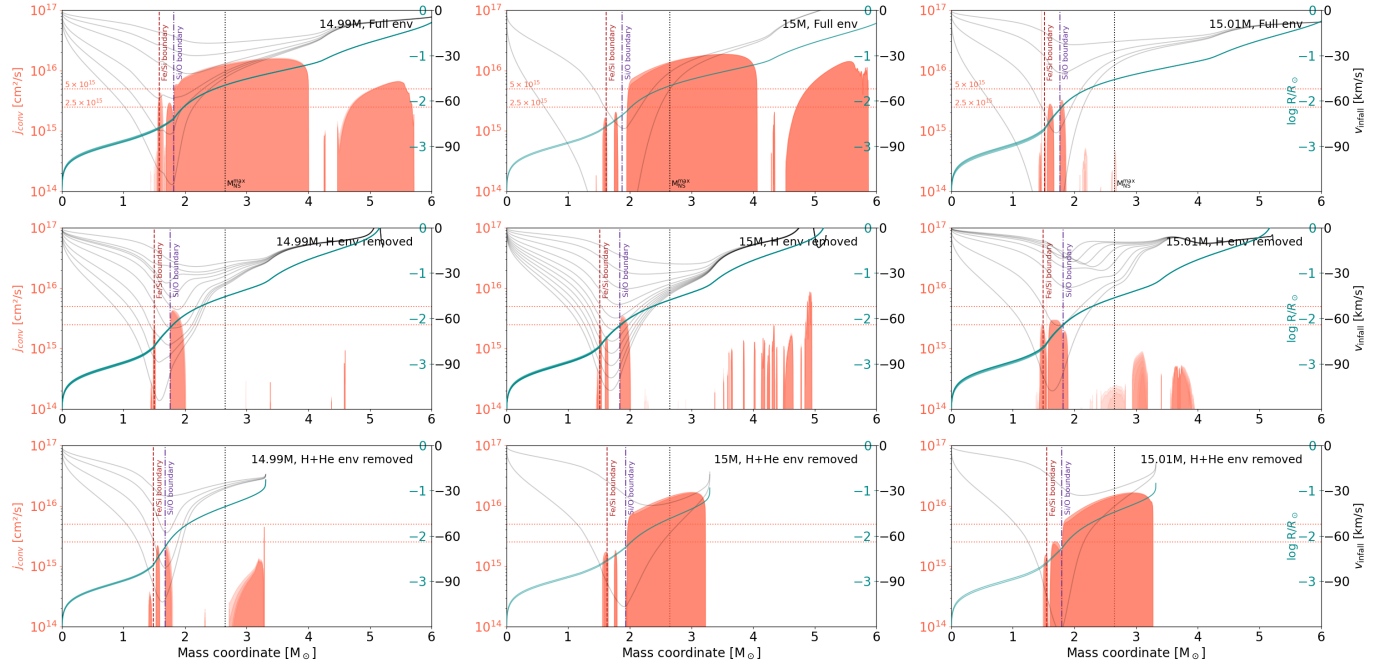


Figure C5. Same as Fig. 3 but for $14.99 M_{\odot}$ (left column), $15.00 M_{\odot}$ (centre column), and $15.01 M_{\odot}$.

Differences in the core masses, intermediate layer locations, and mass fractions are expected even for small changes to the initial mass (see Section 3.1). These are evidently present in our models, where for a $\pm 0.01 M_{\odot}$ difference to initial mass we get a similar total mass, but slightly different compositions (Figure C4) and potentially very different convective zone locations, extent, and velocities approaching collapse (Figure C5).

This, however, does not alter our main conclusion, as the presence of convective layers in the inner core, for mass coordinates that form an NS, is robust. Most models have a specific angular momentum parameter of $j(m) > 2.5 \times 10^{15}$ in the inner core. A few models have a maximum value just a little below this value.

D. APPENDIX D: OTHER MODELS

Our focus in this paper is on the consistency and presence of vigorous convective zones at the seconds approaching collapse. As such, we present below a version of Figure 3 for the remaining models not shown in the main text. Figure D6 for models $15 M_{\odot}$, $18 M_{\odot}$, $22 M_{\odot}$, Figure D7 for models $25 M_{\odot}$, $30 M_{\odot}$, $32 M_{\odot}$, and Figure D8 for models $38 M_{\odot}$, $40 M_{\odot}$.

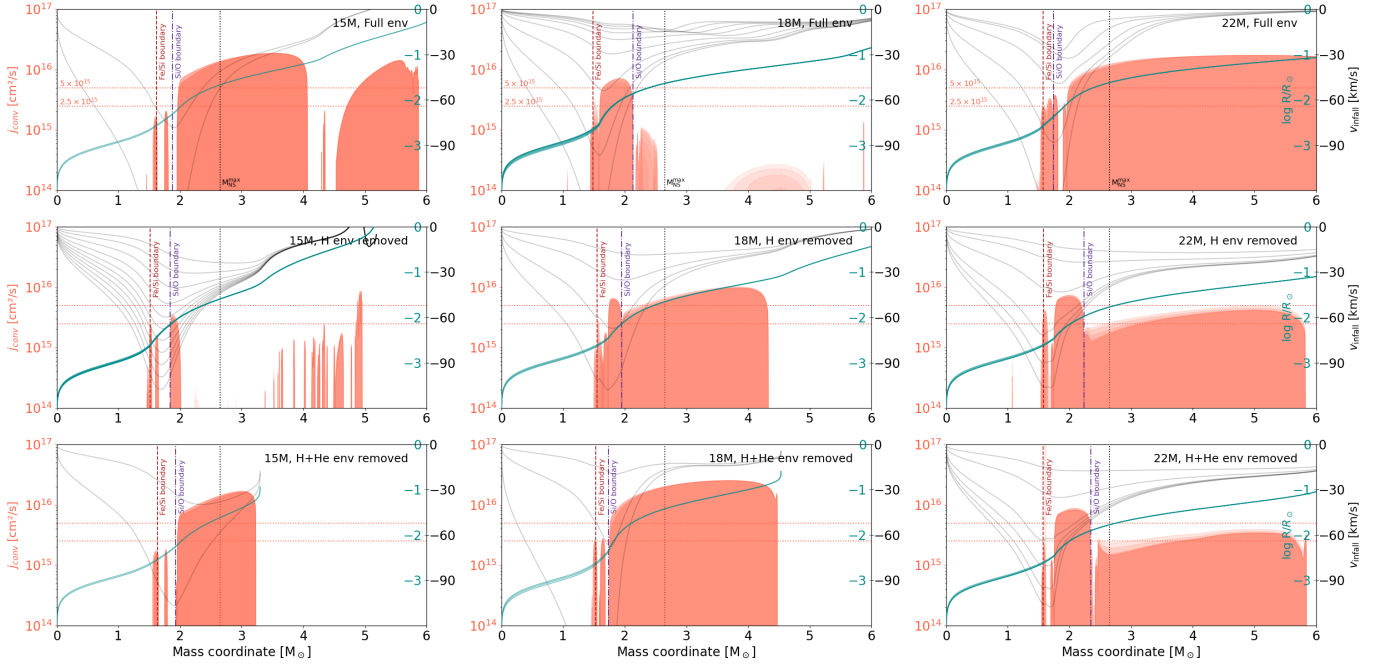


Figure D6. Same as Fig. 3 but for $15 M_{\odot}$ (left column), $18 M_{\odot}$ (centre column), and $22 M_{\odot}$.

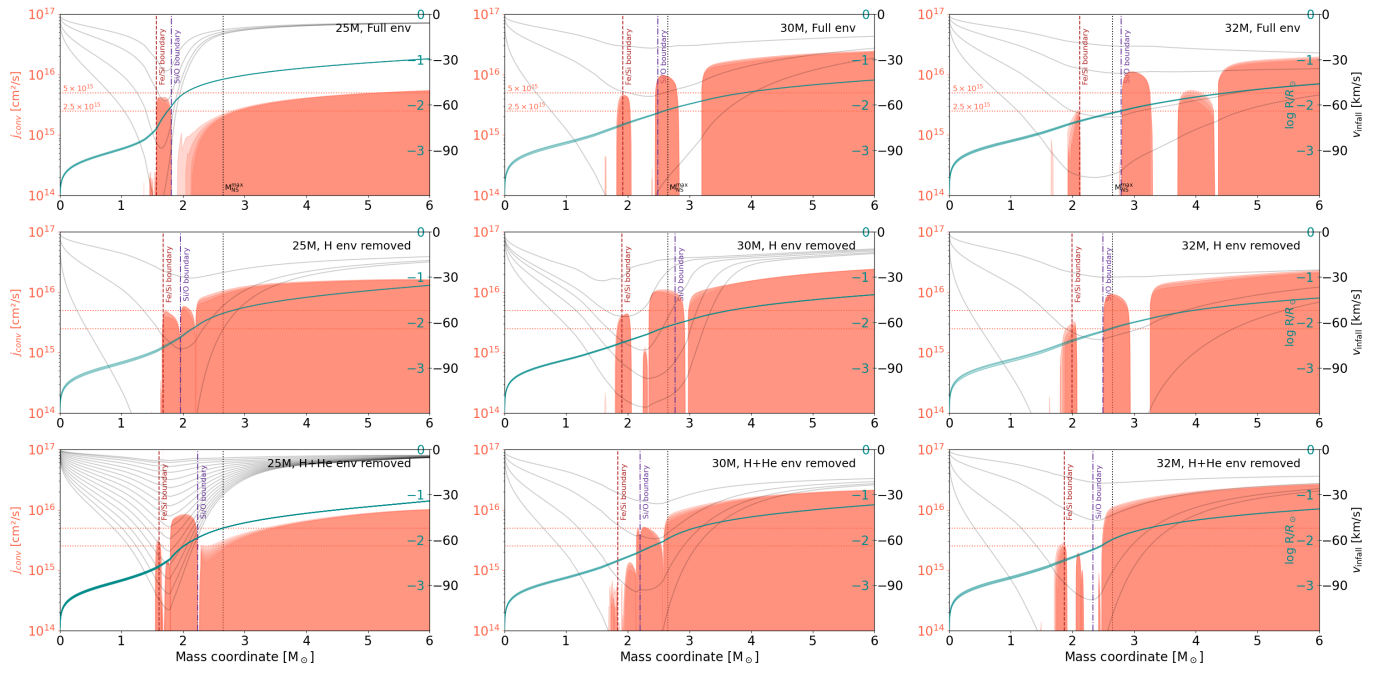


Figure D7. Same as Fig. 3 but for 25 $M_{\odot}$ (left column), 30 $M_{\odot}$ (centre column), and 32 $M_{\odot}$.

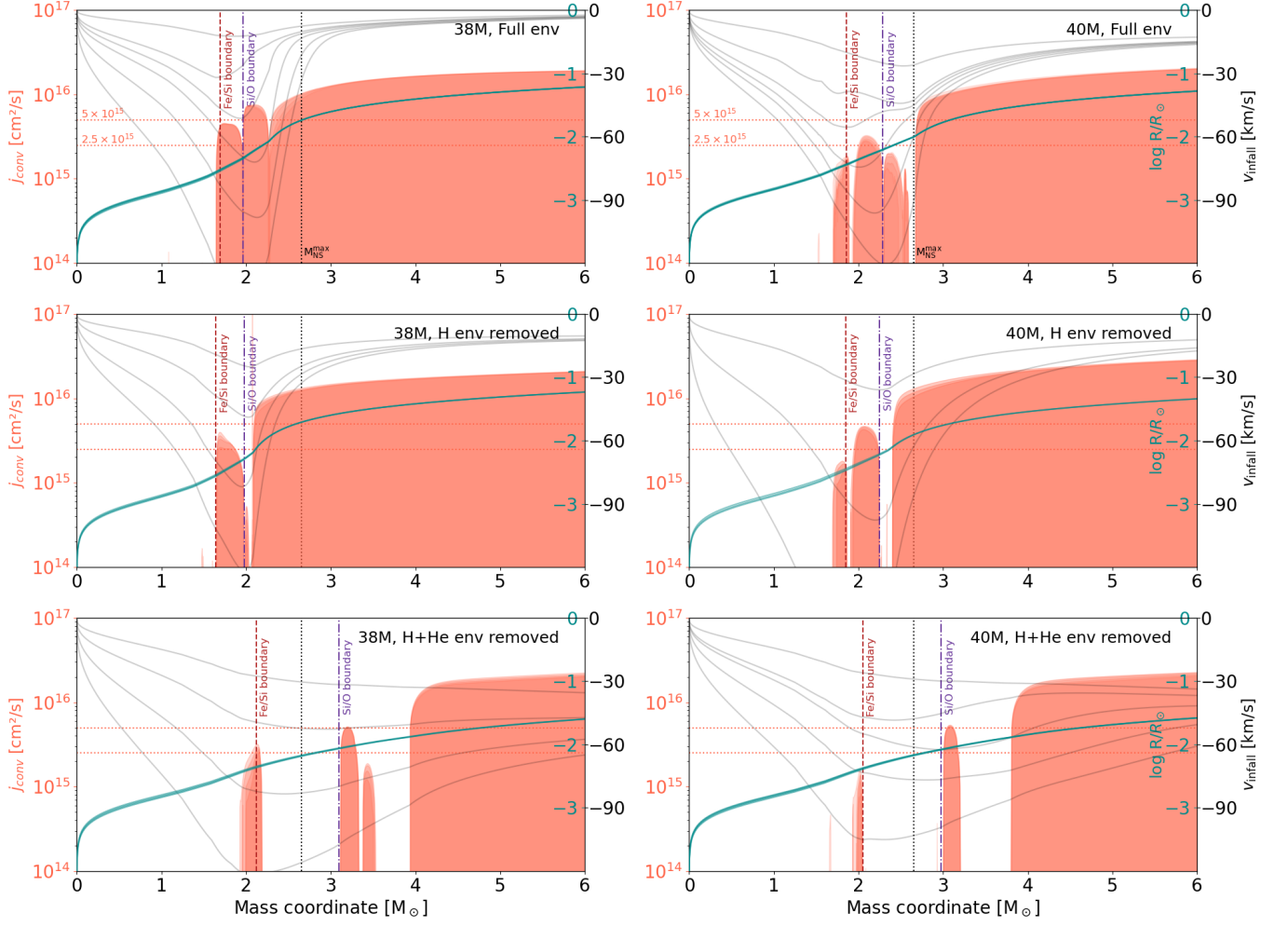


Figure D8. Same as Fig. 3 but for 38 $M_{\odot}$ (left column), and 40 $M_{\odot}$ - the two most massive models we simulated.