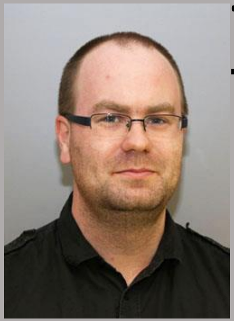

The cosmic carbon footprint of stars stripped in binary systems

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Method

We use MESA (r12115) to evolve massive single and binary stars from the zero-age main sequence to core collapse. All models have solar metallicity and are non-rotating Our single stars and the primary (initially most massive star) in the binary have initial masses between M=11-45MSun. For binary stars we set the initial period to be between 38-300 days, to ensure these are case B binaries. We model our binaries with a mass ratio $M_2/M_1=0.8$. We follow in detail the structure of the primary star and the period evolution of the system during Roche lobe overflow. To model the supernova explosion, its shock, and the resulting nucleosynthesis we place a “thermal bomb” at the center of our model. We excise a portion of the star's core, the material that will form a compact object, by placing the inner boundary of our model at the point where the entropy per baryon S=4. We then inject sufficient energy to bring the total energy of the star to 10^{51} erg/s. We follow the evolution of the hydrodynamic shock and resulting shock nucleosynthesis until just before shock breakout. We follow the stellar evolution with a small 21 isotope network. However, for modelling the supernovae, we use a larger 128 isotope network.

Nucleosynthetic yields

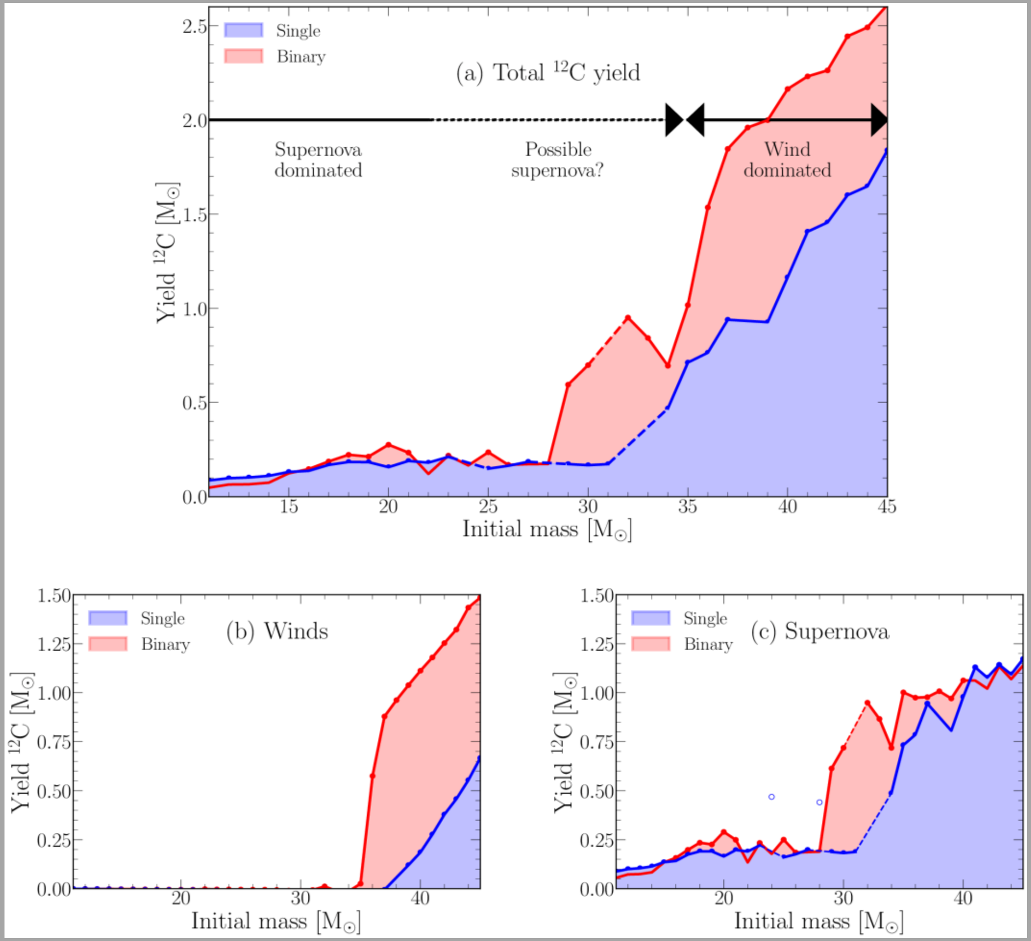
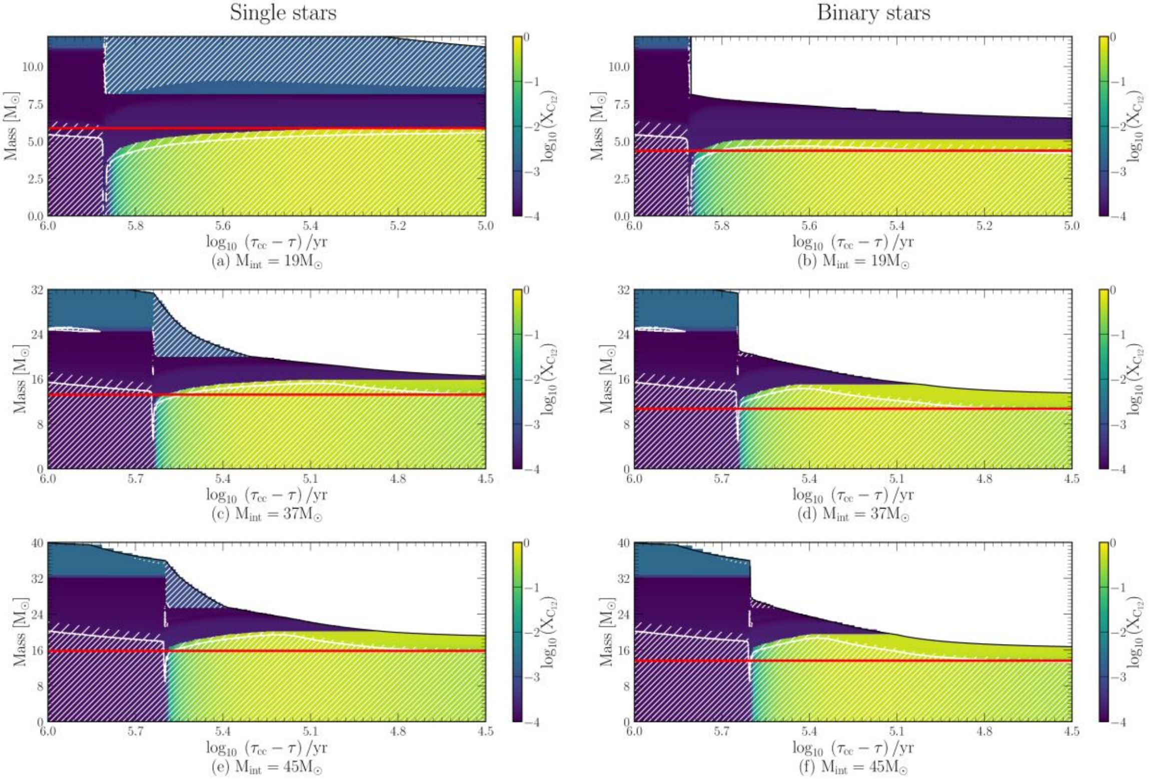


Figure 1: Top panel: The total ^{12}C yield from all ejection sources, Left Panel: The 12C yield ejected during wind mass loss, Right Panel: The ^{12}C yield ejected during core collapse. The core-collapse yields assume all stars eject their envelope. In all panels red regions denote binary models while blue regions denote single star models. Dashed lines in panels (a) and (c) denote extrapolations over the anomalous carbon-burning behavior and models which do not reach core collapse. The black arrows show the approximate location where each type of mass loss dominates the ^{12}C yield, taking into account reasonable assumptions for which stars eject their envelopes

- The ^{12}C yield from the mass loss during RLOF is negative and small ~ -0.01 MSun and approximately independent of the initial mass of the primary star.
- The mass loss due to winds (for all stars) can be broken into two groups, for stars with $M_{initial}$<35 MSun their winds are not ^{12}C enriched as compared to their initial composition, and thus not visible in Figure 1(b). Stars with $M_{initial}$>35 MSun have ^{12}C enriched winds.
- The ^{12}C yield is relatively flat as a function of initial mass for stars with initial masses below 28MSun. Above this initial mass the yield rapidly increases. The increased ^{12}C yields are due to the wind mass loss removing the hydrogen envelope but not all of the helium envelope from the stars

Differences in core structure



(a) $M_{int} = 19M_\odot$

(b) $M_{int} = 19M_\odot$

(c) $M_{int} = 37M_\odot$

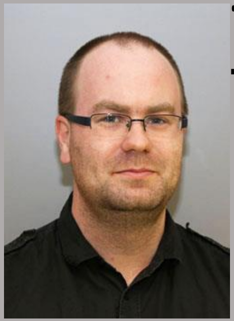
(d) $M_{int} = 37M_\odot$

(e) $M_{int} = 45M_\odot$

(f) $M_{int} = 45M_\odot$

Figure 2: Kippenhahn diagrams for the inner regions of single and binary-stripped stars with $M_{initial}$ =19, 37, and 45Msun, during core hydrogen and core helium burning. The left column shows single star models, while the right column shows binary-stripped models. The x-axis shows the time until core-collapse. Colors show the mass fraction of ^{12}C at each mass co-ordinate. Hatching shows mixing regions due to convection and overshoot. The red horizontal line shows the mass coordinate for what will become the CO core at the end of core helium burning.

- Mass during the MS and RLOF is carbon poor due to CNO cycling
- The binary-stripped star forms a smaller helium core, and the edge of the convective core recedes during core helium burning.
- Only ^{12}C that is mixed out of the core has a chance to survive until core-collapse.
- At higher masses, wind mass loss is sufficient to remove the remaining helium layers above the core.
- The mass loss due to winds is also now strong enough in the single-star case to force the helium core to recede.
- In binary systems the mass loss occurs earlier, allowing more time for winds to eject ^{12}C.



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Conclusions

- Carbon production in massive stars at solar metallicity is dominated by the carbon ejected during supernovae.
- Case B RLOF in binary systems allows the primary star to generate more net carbon, by altering the core structure of the star.
- Mass loss due to Case B RLOF in massive stars does not enrich the Universe in ^{12}C. It primarily ejects CNO processed material that is ^{12}C poor.
- However RLOF lowers the mass needed for stars to become fully stripped, which allows subsequent wind mass loss to eject more ^{12}C rich material.
- The ^{12}C yields from a supernova can be well approximated by their pre-supernova ^{12}C mass fraction of the material which is ejected, in agreement with previous works.
- There is considerable uncertainty in the final ^{12}C yields due to the behavior of carbon burning shells.
- Carbon at core collapse is an almost equal mix of carbon left over from core helium burning and helium shell burning.
- Binary-stripped massive stars can provide a ^{12}C yield greater than single massive stars. Their relative contribution to the ^{12}C in the Universe depends strongly on how many binaries are stripped and whether binaries are more successful at ejecting their envelopes after core collapse than single stars.
- The contribution of massive binary stars to the ^{12}C enrichment of the Universe should not be ignored.