Time-dependent feedback of Supernovae from massive binary progenitors via detailed binary population synthesis models

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ABSTRACT

Supernovae (SNe) represent energetic events marking the end of the evolution of massive stars. Feedback from SNe is a critical factor in the chemical evolution and overall evolution of galaxies, as the injection of energy, momentum and metals into the surrounding medium regulate the rate and efficiency of star formation within galaxies, drive outflows and turbulence in the interstellar medium and disperse metals synthesized in stars. Given that most massive stars are born in binary star systems, binary interactions can drastically alter the evolution of massive supernovae progenitors and their feedback to the environment. To understand better the mechanical and energetic feedback from SNe, we conducted a population synthesis study using the next-generation, state-of-the-art **POSYDON v2** (Fragos+2023, Andrews in prep.) binary population synthesis code, based on the much higher accuracy of detailed MESA binary models, taking into account effect such as tides, stripping during mass transfer, mass accretion and merging (in a simplified way), for two different metallicities and inferring the outcome of SNe using different prescriptions.

QUESTIONS

- **Which stars** will end their lives as SNe and **what type**?
- **When** will these stars detonate their SNe?
- What will be the **energy** and **mass returns** of these SN events?

METHODOLOGY

In this study, we used POSYDON v2 (Fragos+2023, Andrews+ in prep) to create stellar populations at two metallicities, drawing primary and single star masses from a Kroupa (Kroupa 2001) initial mass function $(5-250\,M_\odot)$. Secondary star masses are uniformly sampled within the mass ratio (q = M2/M1) range [0,1] (Sana+2013). We assume a fixed binary fraction of 0.7 and initial orbital periods are drawn following Sana+2013 in the range [0.75-3000 days].

Our populations adhere to POSYDON's default stellar model assumptions (Fragos+2023). For binaries that merge, we proceed with the evolution of the merged star by aligning it with a single star model that closely matches in terms of mass, central abundances, and helium core mass.

We model SN explosions and compact object formation using Patton & Sukhbold (2022) prescription for core-collapse SNe (ccSNe), the Podsiadlowksi+(2004) prescription for electron capture SNe (ECSNe), and the Marchant+(2019) prescription for pair-instability and pulsational pair instability SNe (PISN and PPI, respectively).

To estimate the SN energies:
For CCSN we use a fit to the numerical results in Schneider+(2021), where the explosion energies appear correlated to the M4 and mu4 parameters, for PPISN we extracted the energies from Renzo+(2020). For PISN we associate an energy of 10^{52} erg to every SN explosion (e.g. Takahashi 2018, Kozyreva+2014), while for ECSN we associate an energy of 10^{50} erg (e.g. Kitaura+2006 & Wanajo+2009).

The classification of the type of SNe has been made based on the mass of the envelope in hydrogen at the end of core carbon burning (Gilkis & Arcavi (2022)):

$$Type\ Ib/c: M_{H,env} < 0.033\,M_\odot$$

$$Type\ IIb: 0.033\,M_\odot < M_{H,env} < 0.5\,M_\odot$$

$$Type\ II: M_{H,env} > 0.5\,M_\odot$$

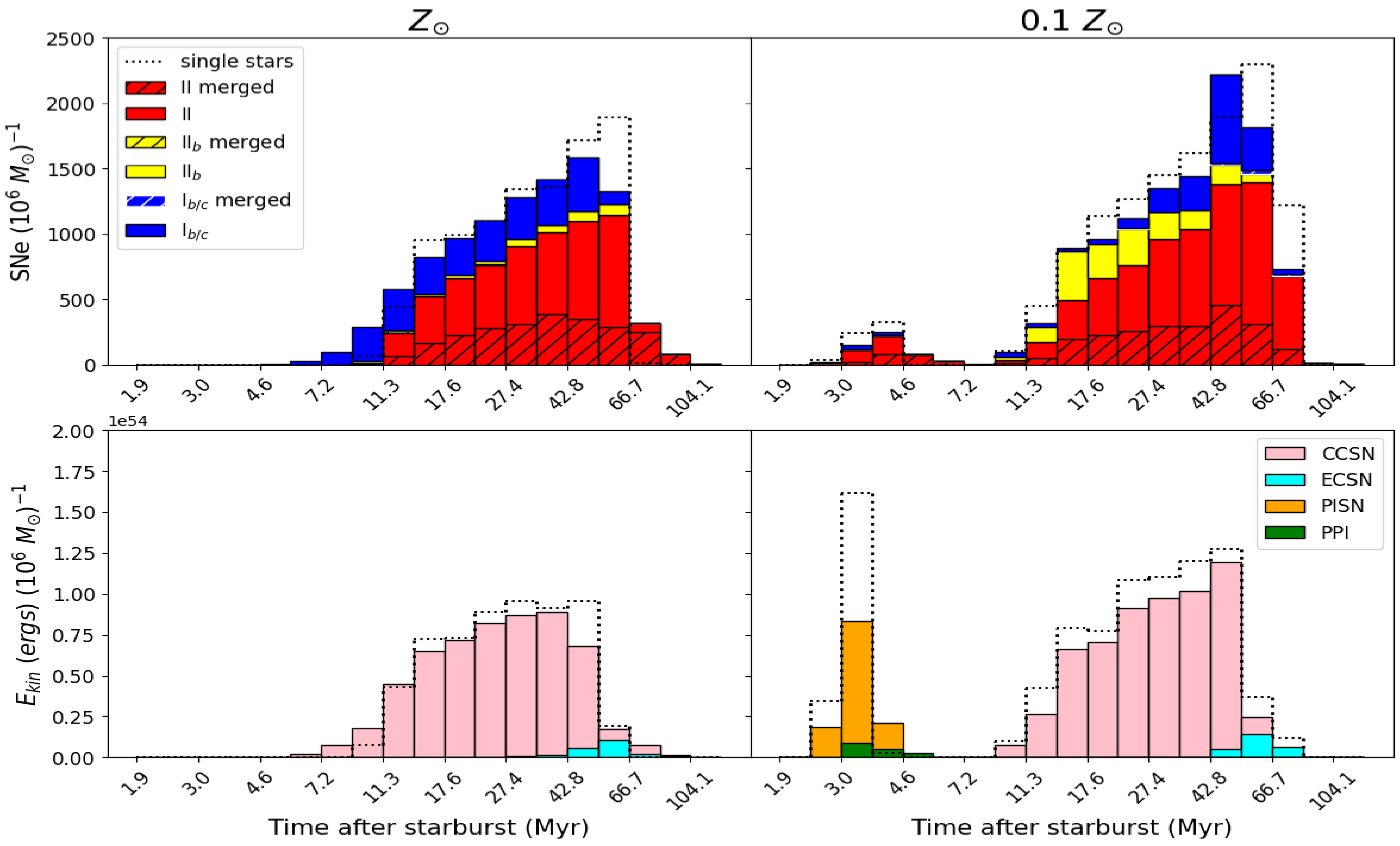

Figure 1: The delay-time distribution of SNe for a population with 70% binary systems is compared to that of a population consisting solely of single stars (black dotted line) for two metallicities. Top panel: This distribution shows the number of events per logarithmic time bin for a starburst with a total mass of $10^6\,M_\odot$ along with the classification of the observed types. Bottom panel: This distribution depicts the summed SN energy per logarithmic time bin for a starburst with a total mass of $10^6\,M_\odot$, along with the classification of the explosion mechanism.

CONCLUSIONS

- In $Z_\odot$, early feedback (5.2 – 9.7 Myr) is dominated by type Ib/c SNe from interacting binaries, with the maximum initial mass for a ccSN around $45\,M_\odot$ (either primary or secondary). For single stars, the maximum initial mass is about $21\,M_\odot$, with feedback occurring after 9.8 Myr. Type Ib/c SNe are produced solely from binaries because single stars need initial masses over $23.5\,M_\odot$ to lose enough hydrogen to become SN Ib/c progenitors, and such massive stars collapse directly into black holes rather than explode as SNe.
- In $0.1Z_\odot$, early supernova feedback may occur as early as ~2.5 Myr due to PISN and PPI SN. More PPI and PISN occur in single stars because binary interactions can prevent stars from reaching the necessary helium core mass for these events. However, more massive stars in binaries can reach the needed conditions, with maximum initial masses of $250\,M_\odot$ for PISN and $200\,M_\odot$ for PPI SN, compared to $160\,M_\odot$ and $100\,M_\odot$ for single stars. Mergers, a major channel for PPI SN, account for nearly half of these events in binaries, extend timescales to 7.6 Myrs (versus 4.5 Myrs for single stars), and can lower the initial mass of the primary star to $28\,M_\odot$.
- The parameter space for type IIb ccSNe at solar metallicity is limited (4% of all ccSNe) due to stronger winds stripping residual hydrogen post-mass transfer. Most originate from high orbital period binaries (>600 d) with mass ratios above 0.55 and primary initial masses below $17\,M_\odot$, undergoing early case B mass transfer. In contrast, Type Ib/c SNe at low metallicity (11% of all ccSNe) come from very short orbital period binaries (<100 days) with mass ratios between 0.35-0.95, experiencing multiple mass transfer phases. The combined ratio of type IIb and Ib/c ccSNe to total ccSNe stays around 30%, regardless of metallicity.
- Binary interactions expand also the time and the initial masses of stars that result to ECSN. The earliest feedback from ECSN at $Z_\odot$ can be as early as 20 Myr (51 Myrs for single stars) and initial primary star masses in the range [4.8-14 $M_\odot$ (including mergers)] (6.4-7.3 $M_\odot$ for single stars).
- Mergers significantly contribute to Type II SNe in both metallicity environments, accounting for nearly 1/4 of all successful SNe (based on a simplified treatment).
- Small tail of delay time after singles SNe (~66 and ~74 Myrs at $Z_\odot$ and 0.1 $Z_\odot$, respectively), ~4%, significantly smaller than Zapartas+2017 potentially due to our partially 5.5 initial mass primary limit and limited merger evolution, but potentially also physical due to fewer common envelope triggers.
- A population of mixed stars ejects at Z = Zsolar an energy of $5.58\,x\,10^{54}$ erg from all successful SNe $(CCSN: 5.38\,x\,10^{54}, ECSN: 2\,x\,10^{53})$, while the same population ejects at Z=0.1Zsol $7.53\,x\,10^{54}(CCSN: 5.93\,x\,10^{54}, ECSN: 2.6\,x\,10^{53}, PISN: 1.18\,x\,10^{54}, PPI: 1.65\,x\,10^{53})$ (in ergs). In the low Z environment, even if the fraction of PISN and PPI SN are relatively small (account only for 4.5% of the total SNe), the contribution in energy (~25% of the total energy) is important. A coeval population of single stars eject in total at Z=0.1 an energy of $9.1\,x\,10^{54}$ ergs while at Z=1 Zsol eject an energy of $5.85\,x\,10^{54}$ ergs.
- More SNe occur in lower metallicity environments due to a slightly lower merger efficiency rate, delayed mass transfer initiation, and less efficient winds. These factors result in higher final core masses, leading either to PISN and PPISN for the very massive stars or preventing the formation of core masses below the ECSN threshold, especially for stars under 14 solar masses.
- A mixed stellar population ejects less mass during SNe than a coeval single stellar population at any metallicity. However, accounting for pre-SNe mass loss due to stellar winds and binary interactions, the mixed population releases more total mass into the interstellar medium over extended timescales. In these mixed populations, the pre-SNe mass ejection consistently surpasses the mass ejected during SNe, a trend not seen in populations dominated by single stars.

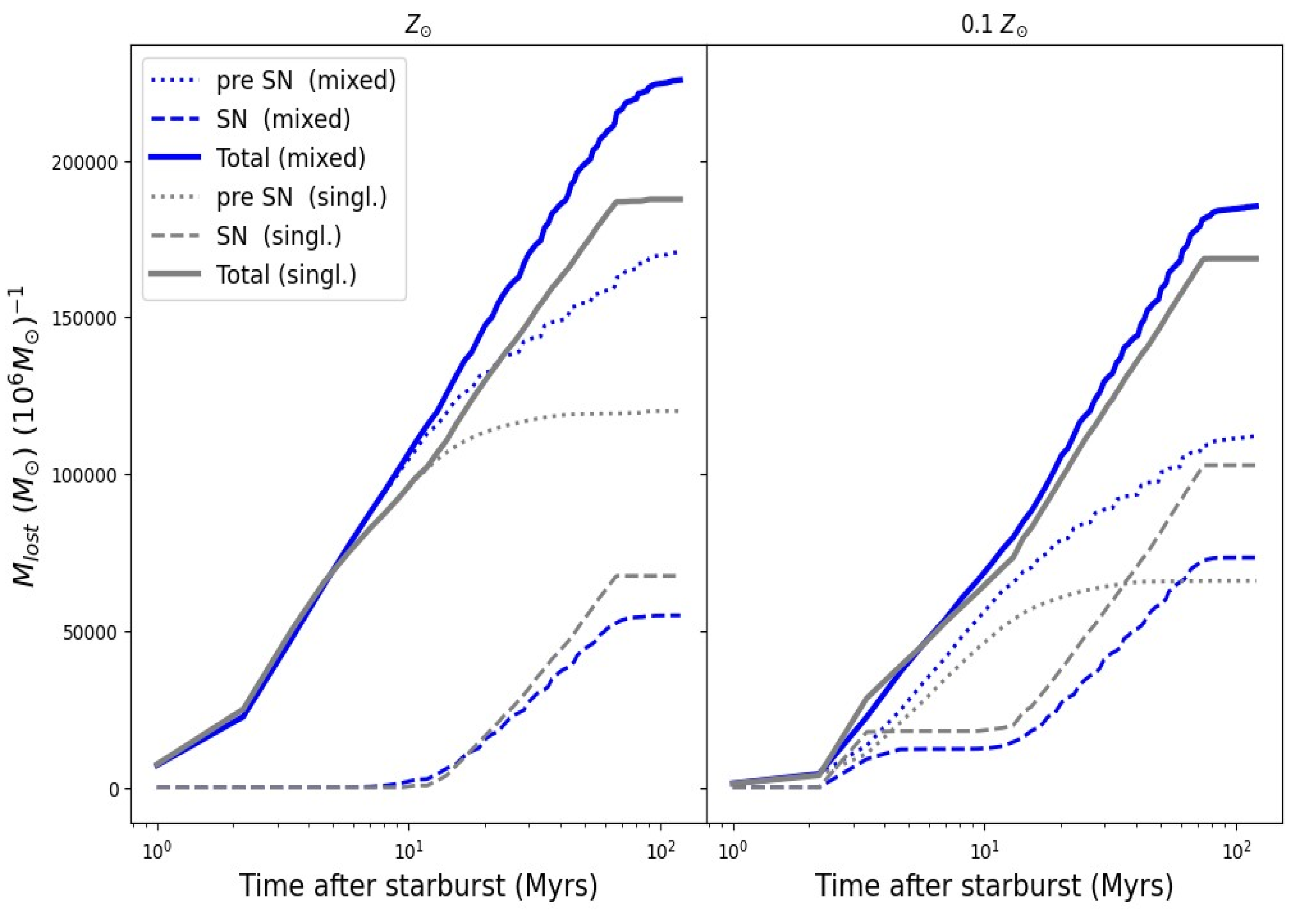

Figure 2: Cumulative mass ejected by pre SNe and SNe evolution into the ISM during the lifetime of a mixed and single stellar population with initial mass $10^6\,M_\odot$ and metallicity $Z = Z_\odot$ and $0.1\,Z_\odot$.

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