Massive Stars Across Redshifts in the Era of JWST and Large Surveys
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Dense Circumstellar Medium around Pulsating Massive Stars Powering Interacting Supernovae

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Abstract. We investigate the evolution of red supergiant (RSG) progenitors of core-collapse (CC) supernovae (SNe) with initial masses between $12-20$ $M_\odot$ focusing on the effects of enhanced mass loss due to pulsation-driven instabilities in their envelopes and subsequent dynamical ejections during advanced stages of nuclear burning. Using time-dependent mass loss from detailed MESA stellar evolution models, including a parameterized prescription for pulsation-driven superwinds and time-averaged mass loss rates attributed to resulting shock-induced ejections, we construct the circumstellar medium (CSM) before the SN explosion. We calculate resulting CSM density profiles and column densities considering the acceleration of the stellar wind. Our models produce episodes of enhanced mass loss $10^{-4}-10^{-2}$ $M_\odot$ yr^{-1} in the last centuries-decades before explosion forming dense CSM ($>10^{-15}$ gcm^{-3} at distances $<10^{15}$ cm) – consistent with those inferred from multi-wavelength observations of Type II SNe such as SN 2023ixf and SN 2020ywx.

Keywords. Supernovae, red-supergiants, mass-loss, pulsations, stellar winds, shocks, CSM

1. Introduction

The evolution of massive stars in their late phases remains ill understood - in particular, the effects of mass loss on the final fate of these stars (Smith 2014; Meynet et al. 2015). A number of factors have been invoked to explain mass loss from massive stars like stellar winds, rotation, radial pulsations, episodic ejections/eruptions and binarity (Woosley et al. 2002; Langer 2012), which result in the observed diversity of CCSNe, which are broadly classified as Type I (b/c) – which do not show any hydrogen lines in their spectra – and Type II (P/L/n/b) which do so, but with varying strengths and time evolution of light curves (Filippenko 1997). There is a growing consensus that a high fraction of Type II SNe are preceded by phases of heavy mass loss (Hinds et al. 2025), with visible signatures in their post-explosion shock interaction with the circumstellar medium (CSM) created by the wind of the SN progenitor (Dwarkadas 2025; Chandra 2025). The circumstellar densities infered from flash-ionization spectroscopy, X-ray and radio observations of SNe like SN 1998S (Chugai et al. 2002) and SN 2023ixf (Chugai et al. 2023) point toward mass loss rates of $\sim 10^{-3}-10^{-1}$ $M_\odot$ yr^{-1} – far exceeding those associated with steady winds of red supergiants (RSGs) and at odds with latest mass loss prescriptions inferred from large samples of observed RSGs (Beasor et al. 2020; Yang et al. 2023; Antoniadis et al. 2024; Decin et al. 2024) as well as empirical mass loss rates

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derived from much smaller samples of stars (de Jager et al. 1988; Nieuwenhuijzen and de Jager 1990) that are commonly used in stellar evolution codes (Massey et al. 2023).

2. Pulsation-driven mass loss from RSGs

Many RSGs exhibit large-amplitude radial pulsations with periods of several hundred days (Soraisam et al. 2018; Ren et al. 2019), driven by the so-called κ-mechanism (Baker and Kippenhahn 1965; Gastine and Dintrans 2008) - an interplay between excess radiation pressure and gravitational pull on the outer layers of the RSG envelope. These pulsations can grow in amplitude to produce shocks at the stellar surface that may levitate material above the photosphere, reducing the effective gravity and allowing other processes e.g., radiation pressure on dust and molecules (van Loon 2025) to accelerate the material outward. However, the exact mechanism of mass loss due to the complex interplay of pulsations and convection in RSG envelopes remains ill-understood (Gastine and Dintrans 2010; Goldberg et al. 2022, 2025; Ma et al. 2025).

2.1. *Pulsation-driven super-winds (PDSW)*

Yoon and Cantiello (2010) first proposed a pulsation-driven wind mass loss prescription for high mass RSGs with high luminosity-to-mass ratios, which they hypothesized could, in principle, achieve the high rates ($\dot{M} \sim 10^{-2}$ $M_\odot$ yr^{-1}) required to explain observed properties of CSM around Type IIn SNe (Morozova et al. 2018). Yoon and Cantiello (2010) showed that the growth rate (η) of the amplitude of the surface velocities increases with L/M ratio and/or decreasing thermal (Kelvin-Helmholtz) time-scale of the envelope ($\tau_{KH,env}$). Using the open-source MESA (Jermyn et al. 2023) code, we evolve stellar model sequences with initial masses between $12 - 18$ $M_\odot$ using the PDSW prescription of Yoon and Cantiello (2010) beyond core helium burning for $\eta > 1$, $T_{\rm eff} < 4000$ K, given by:

$$\dot{M} = \eta^{\alpha} \dot{M}_{\rm Dutch}, \tag{1}$$

where α is a free parameter and $\dot{M}_{\rm Dutch}$ is the Dutch wind scheme of MESA scaled with a factor of 0.2, for the empirical mass loss rate estimates to be consistent with latest observations of RSGs (Beasor et al. 2021; Massey et al. 2023).

2.2. *Shock-driven dynamical ejections*

Clayton (2018) further extended the pulsation-driven mass loss into the shock-dominated regime with hydrodynamic MESA models showing launch of ejections upon the surface breakout of strong compression shocks, followed by sufficiently fast expansion that raises material on to an escape trajectory. Clayton (2018) proposed the following mass loss prescription for $\log((L/L_\odot)/(M/M_\odot)) \gtrsim 4.1 - 4.15$:

$$\log(\dot{M}/M_\odot\ yr^{-1}) = 5.93 \times \log[(L/L_\odot)/(M/M_\odot)] - 26.6, \tag{2}$$

which we employ to model the possibility of such repeating mass ejections in pulsationally unstable RSG envelopes when the luminosity to mass ratio of the star exceeds the cut-off value of $\log((L/L_\odot)/(M/M_\odot)) = 4.15$.

3. Comparison with multiepoch observations of Type II SNe

We calculate the CSM density and column density of neutral hydrogen along the line of sight assuming spherical symmetric mass loss and an accelerated wind profile from the RSG, given by a simple β-law (Moriya et al. 2018), with $\beta = 1.2$ – consistent with observations of single RSGs (Bennett 2010). Our model results are in good agreement with observations of Type II SNe like 1998S, 2005ip, 2017hcc (Sengupta et al. 2025) as well as multi-epoch observations of more recent events like SNe 2023ixf (see Figure 1)

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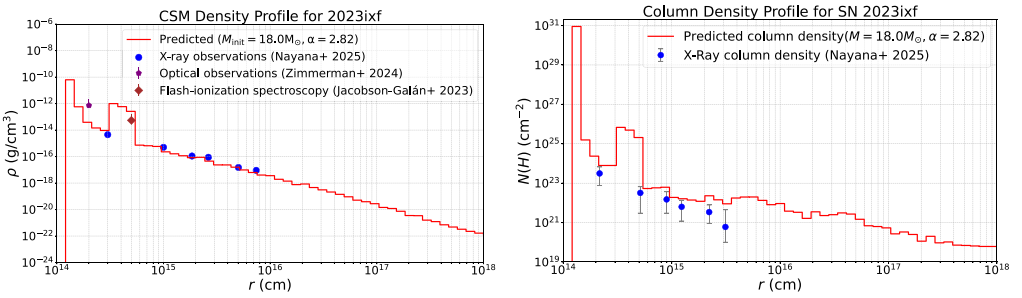


Figure 1. (left) CSM density profiles for the model sequence with $M_{init} = 18$ M$_\odot$, $\alpha = 2.82$ (solid red curve), compared with inferred densities from multi-wavelength observations (Jacobson-Galán et al. 2023; Zimmerman et al. 2024; A. J. et al. 2025) and (right) the column density of neutral hydrogen (solid red) compared to X-ray measurements (in solid blue) for SN 2023ixf (A. J. et al. 2025).

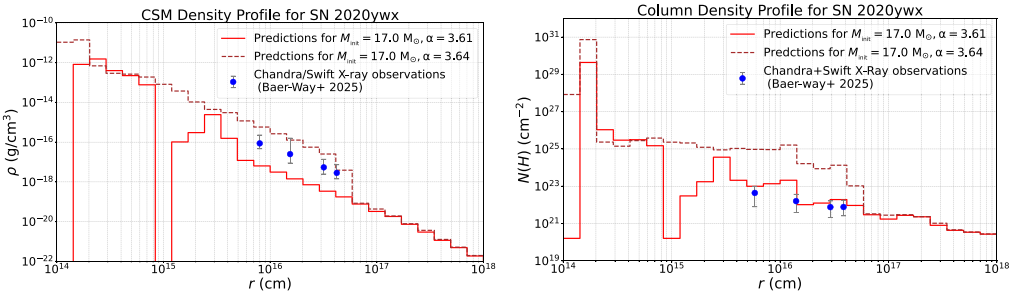


Figure 2. (left) CSM density profiles for the two MESA model sequences for $M_{init} = 17$ M$_\odot$, with $\alpha = 3.61$ sequence given by the solid red curve and the $\alpha = 3.64$ sequence given by the dashed brown curve, compared with estimates from measured X-ray luminosities and (right) the column density of neutral hydrogen calculated for the same model sequences, compared to the measured X-ray column densities (blue points) from observations (Baer-Way et al. 2025).

and SN 2020ywx (see Figure 2), although some systematic differences are seen in the column densities which could arise due to explosion asymmetry (Kozyreva et al. 2025) or clumping along line of sight effects (Baer-Way et al. 2025).

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