**Wolf-Rayet Stars**
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# The end stages of massive star evolution: WR stars as SN Ibc progenitors

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The morphological appearance of massive stars across their post-Main Sequence evolution and before the SN event is very uncertain, both from a theoretical and observational perspective. We recently developed coupled stellar evolution and atmospheric modeling of stars done with the Geneva and CMFGEN codes, for initial masses between 9 and 120 $M_\odot$. We are able to predict the observables such as the high-resolution spectrum and broadband photometry. Here I discuss how the spectrum of a massive star changes across its evolution and before death, with focus on the WR stage. Our models indicate that single stars with initial masses larger than 30 $M_\odot$ end their lives as WR stars. Depending on rotation, the spectrum of the star can either be that of a WN or WO subtype at the pre-SN stage. Our models allow, for the first time, direct comparison between predictions from stellar evolution models and observations of SN progenitors.

## 1 The need for combined stellar evolution and atmospheric modeling

Massive stars are essential constituents of stellar populations and galaxies in the near and far Universe. They are among the most important sources of ionizing photons, energy, and some chemical species, which are ejected into the interstellar medium through powerful stellar winds and during their extraordinary deaths as supernovae (SN) and long gamma-ray bursts (GRB). For these reasons, massive stars are often depicted as cosmic engines, because they are directly or indirectly related to most of the major areas of astrophysical research.

Despite their importance, our current understanding of massive stars is still limited. This inconvenient shortcoming can be explained by many reasons, such as uncertainties related to mass loss, rotation, binary interaction, and how to compare observations and models of massive stars. Here we focus on this last topic.

Our understanding of different classes of stars is often built by comparing evolutionary models and observations. However, mass loss may affect the spectra, magnitudes, and colors of massive stars, thus making the comparison between evolutionary models and observations a challenge. In addition to luminosity, effective temperature, and surface gravity, the observables of massive stars can be strongly influenced by a radiatively driven stellar wind that is characteristic of these stars. The effects of mass loss on the observables depend on the initial mass and metallicity, since they are in general more noticeable in MS stars with large initial masses, during the post-MS phase, and at high metallicities. When the wind density is significant, such as in Wolf-Rayet (WR) stars, the mass-loss rate, wind clumping, wind terminal velocity, and velocity law have a strong impact on the spectral morphology. This makes the analysis of massive stars a difficult task, and obtaining their fundamental parameters, such as luminosity and effective temperature, is subject to the uncertainties that comes from our limited understanding of mass loss and clumping. Furthermore, the definition of effective temperature of massive stars with dense winds is problematic and, while referring to an optical depth surface, it does not relate to a hydrostatic surface. This is caused by the atmosphere becoming extended, with the extension being larger the stronger the wind is. Stellar evolution models are able to predict the stellar parameters only up to the stellar hydrostatic surface, which is not directly reached by the observations of massive stars when a dense stellar wind is present. Since current evolutionary models do not thoroughly simulate the physical mechanisms happening at the atmosphere and wind, model predictions of the evolution of massive stars are difficult to be directly compared to observed quantities, such as a spectrum or a photometric measurement.

To improve the comparison between models and observations of massive stars, we recently devised coupled calculations of stellar evolution with the Geneva code and atmospheric and wind modeling with the CMFGEN code. This approach opens up the possibility to investigate stellar evolution based not only on interior properties, but also from a spectroscopic point of view. Essentially, the atmospheric models allow the physical quantities predicted by the stellar evolution model to be directly compared to observed features.

## 2 Predicting the look of stars at the pre-SN stage

Our group recently analyzed the properties of massive stars just before the SN explosion in a series of papers (Groh et al. 2013b,c,a, 2014; Groh 2014). Our models indicate that rotating stars with initial mass

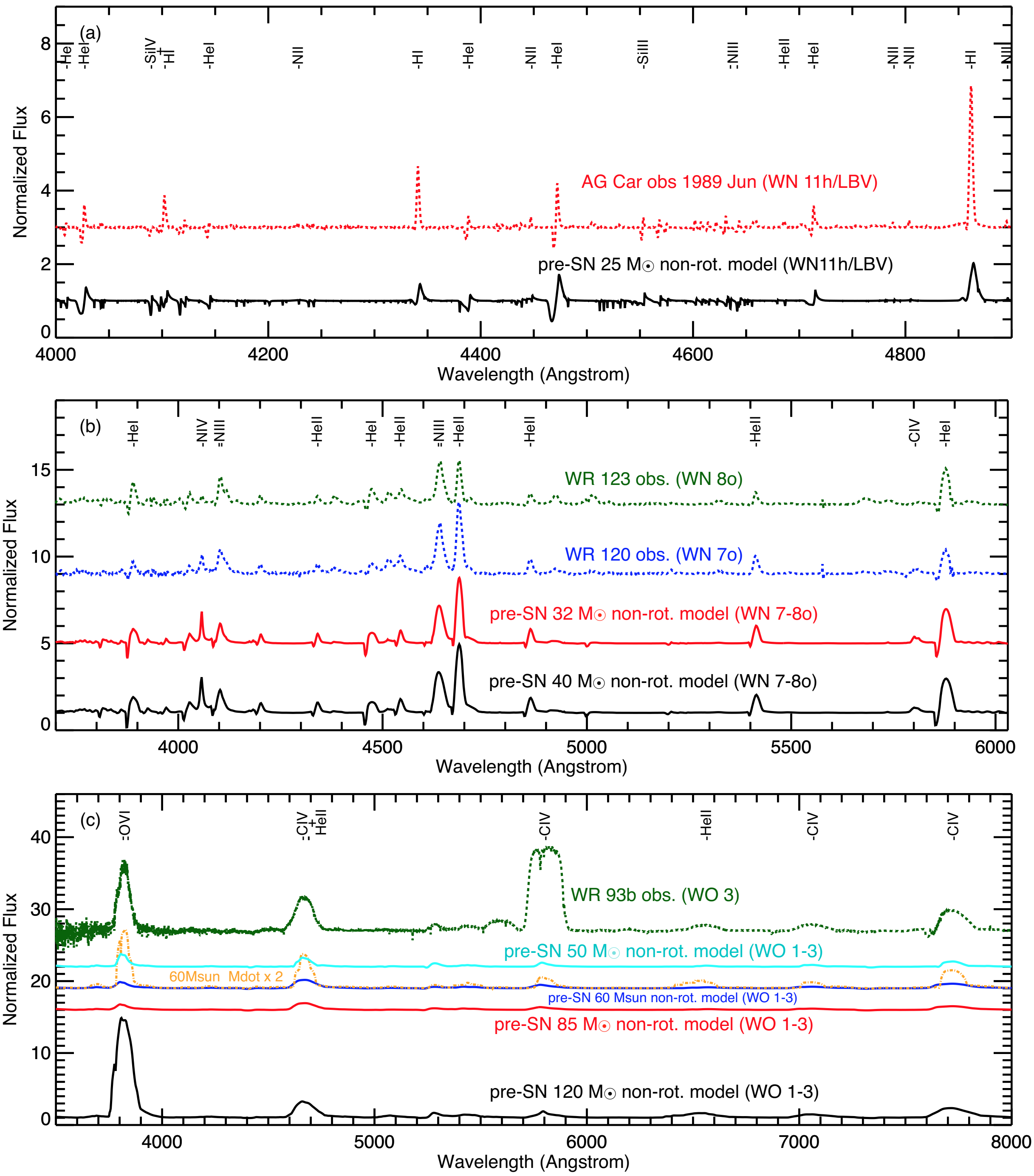


**Fig. 1:** Montage of the synthetic optical spectra of massive stars at the pre-SN stage from non-rotating stellar evolution models. Observations of stars with similar spectral type (dashed) are shown to support the spectroscopic classifications. The strongest spectral features are indicated. The spectra have been offset in flux for better visualization. *(a)*: The 25 $M_\odot$ model (black), which has a WN11h/LBV spectral type. The 1989 June observations of the LBV AG Car (red) are also shown, when it showed a WN11h spectral type Smith et al. (1994); Stahl et al. (2001); Groh et al. (2009). *(b)*: The 32 $M_\odot$ (red) and 40 $M_\odot$ (black) models, which have spectral type WN7–8o, are compared to observations of Galactic WN7o (WR120) and WN8o (WR123) stars, form the catalogue of Hamann et al. (1995). *(c)*: The 50 $M_\odot$ (cyan), 60 $M_\odot$ (blue), 85 $M_\odot$ (red), and 120 $M_\odot$ (black) models, which have WO1–3 spectral type. The spectrum of the 60 $M_\odot$ model with the mass-loss rate enhanced by a factor of two at the pre-SN stage is shown (orange dot-dashed). The optical spectrum of the Galactic WO 3 star WR 93b (green, from Drew et al. 2004) is also displayed.

($M_{\rm ini}$) in the range 20–25 $M_\odot$ surprisingly end their lives as luminous blue variable (LBV) stars. The fate of single massive stars with $M_{\rm ini} = 9 - 120\ M_\odot$ was investigated in Groh et al. (2013c), where we showed that massive stars, depending on their initial mass and rotation, can explode as red supergiants (RSG), yellow hypergiants (YHG), LBVs, and Wolf-Rayet (WR) stars of the WN and WO subtype. We applied these models to investigate the nature of the candidate progenitor of the SN Ib iPTF13bvn, concluding that a single WR star with initial mass $\sim 31 - 35\ M_\odot$ could explain the properties of the progenitor (Groh et al. 2013a). Figure 1 presents a subset of synthetic spectra of massive stars at the pre-SN stage for non-rotating models.

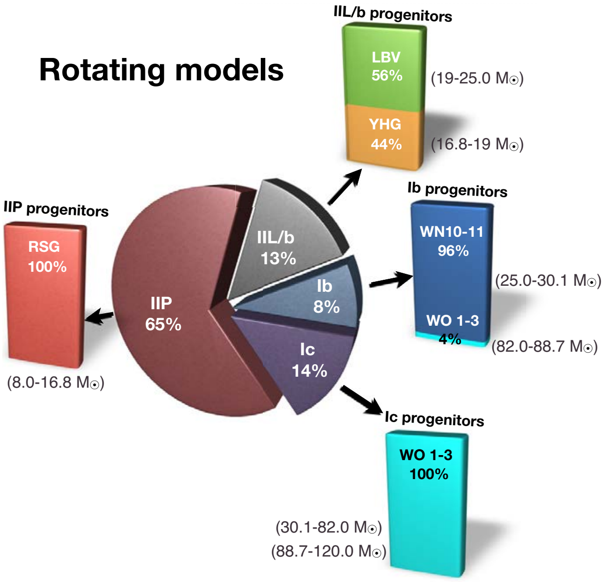


**Fig. 2:** Diagram illustrating, for different core-collapse SN types, their relative rates and the types of progenitors and their respective frequencies. Initial mass ranges (indicated in parenthesis) and SN types are based on the criteria outlined in Georgy et al. (2012), assuming that the minimum amount of He in the ejecta to produce a SN Ib is 0.6 $M_\odot$. We show here the predictions for non-rotating models.

Figure 2 shows the different channels that link the spectral types of SN progenitors to the core-collapse SN types according to our models. For rotating models, we obtained the following types of SN progenitors: WO1–3 ($M_{\rm ini} \geq 32\ M_\odot$), WN10–11 ($25 < M_{\rm ini} < 32 M_\odot$), LBV ($20 \leq M_{\rm ini} \leq 25\ M_\odot$), G1 Ia$^+$ ($18 < M_{\rm ini} < 20\ M_\odot$), and RSGs ($9 \leq M_{\rm ini} \leq 18\ M_\odot$). For non-rotating models, we found spectral types WO1–3 ($M_{\rm ini} > 40\ M_\odot$), WN7–8 ($25 < M_{\rm ini} \leq 40\ M_\odot$), WN11h/LBV ($20 < M_{\rm ini} \leq 25 M_\odot$), and RSGs ($9 \leq M_{\rm ini} \leq 20\ M_\odot$). Our rotating models indicate that SN IIP progenitors are all RSG, SN IIL/b progenitors are 56% LBVs and 44% YHGs, SN Ib progenitors are 96% WN10-11 and 4% WOs, and SN Ic progenitors are all WO stars. We find that not necessarily the most massive and luminous SN progenitors are the brighter ones in a given filter, since this depends on their luminosity, temperature, wind density, and how the spectral energy distribution compares to a filter bandpass. We find that SN IIP progenitors (RSGs) are bright in the $RIJHK_S$ filters and faint in the $UB$ filters. SN IIL/b progenitors (LBVs and YHGs), and SN Ib progenitors (WNs) are relatively bright in optical/infrared filters, while SN Ic progenitors (WOs) are faint in all optical filters.

To conclude, our analyses showed that it is crucial to produce an output spectrum out of evolutionary calculations to properly interpret the observations of massive stars at different evolutionary stages, in particular those with dense winds such as WR stars.

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**Vikram Dwarkadas:** There is considerable observational evidence that RSG stars above 9 $M_\odot$ do not give rise to II-P SNe. You manage to fit that in your latest models. What has changed? What happens to RSG stars > 19 $M_\odot$? What SNe do they rise to, and does it agree with the SN rate?

**Jose Groh:** The main change is the increased $\dot{M}$ for the most luminous RSGs due to being close to the Eddington limit. These stars evolve back to the blue and potentially explode as type IIb or IIn (or II-L even). We still have to look at the SN rates predicted by models.

**Francisco (Paco) Najarro:** 1) Apart from the lack of WOs there was also a lack of WNLs. Are they coming from a different channel?
2) Is your $T_{\rm eff}$ measure at $\tau = 20$ or $\tau = 2/3$?

**Jose Groh:** 1) We think they come from less massive stars in the $\sim$ 28–45 $M_\odot$ range. 2) The ones I showed are quoting $T_{\rm eff}$ at 2/3, which I think is more appropriate for comparing observations and models. Using $T_*$ is very dangerous since the non wind-corrected $T_{\rm eff}$ quoted by the models have little to do with $T_*$ derived from spectroscopic analyses.

Jose Groh (with microphone) asking a question. Also visible in this picture are F. Najarro (left, sitting), M. Corcoran (standing behind Jose), and A. Liermann (right, standing).