Tepid Supergiants: Chemical Signatures of Stellar Evolution & The Extent of Blue Loops

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Abstract. Massive stars can develop into tepid supergiants at several stages of their post main-sequence evolution, prior to core He-burning, on a blue loop, or close to the final supernova explosion. We discuss observational constraints on models of massive star evolution obtained from the analysis of a sample of Galactic supergiants and put them in the context of the cosmic abundance standard as recently proposed from the study of their OB-type progenitors ($Z = 0.014$ for stars in the solar neighbourhood). High-precision abundance analyses for He and CNO, with uncertainties as low as $\sim 10-20\%$, trace the transport efficiency of nuclear-processed material to the stellar surface, either by rotational mixing or during the first dredge-up. A mixing efficiency higher by a factor $\sim 2$ than predicted by current evolution models for rotating stars is indicated, implying that additional effects need to be considered in evolutionary models like e.g. the interplay of circulation and magnetic fields. Blue loops are suggested to extend to higher masses and to higher $T_{\text{eff}}$ than predicted by the current generation of stellar evolution models.

1. Introduction

Massive stars of $\sim 8-40 M_\odot$ spend a short time in between the hot and cool extremes of the Hertzsprung-Russell diagram (HRD) as tepid supergiants (BA-type SGs, $T_{\text{eff}} \sim 8000-15000$ K). Possible scenarios are the first crossing from blue to red after the main sequence phase, blue loop episodes or a final crossing from red to blue in a late evolution stage close to the final supernova explosion.

Important observational constraints on the evolution of massive stars can be derived from studies of tepid SGs via the determination of stellar parameters and abundance patterns for light elements. In particular, enriched helium and nitrogen, and depleted carbon are indicative for the mixing of nuclear-processed matter from the stellar core to the atmosphere. Recent models of massive star evolution accounting for mass loss and rotation (Heger & Langer 2000; Maeder & Meynet 2000) and the interplay of rotation and magnetic fields (Heger, Woosley & Spruit 2005; Maeder & Meynet 2005) provide detailed predictions on the expected effects of chemical mixing on surface abundances. Systematic investigations of massive stars of different mass and metallicity can provide the necessary observational constraints to distinguish between competing treatments of the complex (magneto)hydrodynamic processes, which are not fully understood from first principles. These processes redistribute angular momentum, transport nuclear-processed products from the core to the surface and
replenish hydrogen, thus extending lifetimes and increasing the stellar luminosity.

Here we report results from precision analyses of Galactic tepid supergiants and a control sample of unevolved B-type stars in the solar neighbourhood, i.e. the progenitors of BA-type SGs. The derived observational constraints are confronted with present-day model predictions and the conclusions from this may guide future refinements to stellar evolution models.

2. Observations & Quantitative Spectral Analysis

High-S/N and high-resolution Echelle spectra (S/N > 200, \( R = \lambda/\Delta \lambda \approx 40-48000 \)) of Galactic BA-SGs and unevolved B-type stars were obtained using FEROS on the ESO La Silla 1.5m/2.2m and FOCES on the Calar Alto 2.2m telescopes. The wide wavelength coverage (\( \sim 3900-9200 \) \( \AA \)) provided access to all spectroscopic indicators required for the quantitative analysis.

The model calculations were carried out in a hybrid non-LTE approach as discussed in detail by Przybilla et al. (2006) and Nieva & Przybilla (2007). In brief, hydrostatic, plane-parallel and line-blanketed LTE model atmospheres were computed with ATLAS9 (Kurucz 1993; with further modifications: Przybilla, Butler & Kudritzki 2001) and non-LTE line formation was performed on the resulting model stratifications with DETAIL and SURFACE (Giddings 1981; Butler & Giddings 1985; both updated by K. Butler). The former solves the coupled radiative transfer and statistical equilibrium equations while the latter performs the formal solution with refined line-broadening theories. State-of-the-art non-LTE model atoms relying on data from ab-initio computations – avoiding rough approximations wherever possible – were utilised.

The stellar parameter and abundance determination for BA-SGs and unevolved B stars relied on the iterative analysis methodology described by Przybilla et al. (2006) and Nieva & Przybilla (2007, 2008). Numerous spectroscopic indicators like multiple ionization equilibria and Stark-broadened profiles of the higher Balmer and Paschen lines were simultaneously used to derive effective temperatures \( T_{\text{eff}} \) and surface gravities \( \log g \). The accuracy of the method allows the 1\( \sigma \)-uncertainties to be reduced to \( \sim 1-2\% \) in \( T_{\text{eff}} \) and to 0.05-0.10 dex in \( \log g \), when the atmospheric helium content, metallicity and micro turbulence are correctly accounted for in a self-consistent way. Absolute elemental abundances can then be constrained with unprecedented accuracy (\( \sim 10-20\% \), random, and \( \sim 25\% \), systematic 1\( \sigma \)-errors; see also Nieva & Przybilla, these proceedings).

3. Initial Conditions: A Cosmic Abundance Standard

It is well established that metallicity plays an important rôle in the evolution of massive stars (e.g. Maeder & Meynet 2000). Most evolution models representative for the massive star population in the solar neighbourhood assume a value of (solar) metal mass fraction of \( Z = 0.02 \).

Slowly-rotating unevolved early B-type stars were long since recognised as best targets for elemental abundance determinations at present day, as they show the simplest photospheres among the massive stars. They even allow pris-
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Table 1. Cosmic abundance standard: light elements & global mass fractions

| Element | Abundance |
|---------|-----------|
| He      | 10.98 ± 0.02 |
| C       | 8.35 ± 0.05  |
| N       | 7.76 ± 0.05  |
| O       | 8.76 ± 0.03  |

X = 0.715  Y = 0.271  Z = 0.014

tine abundances for helium, carbon and nitrogen to be derived. All previous studies of early B-type stars in the solar neighbourhood found a wide scatter in abundances – and therefore metallicity –, favouring overall sub-solar values, see e.g. [Przybilla (2008)].

In the meantime, improvements in model atmosphere analyses of cool stars lead to a revision of the solar abundances [Asplund, Grevesse, & Sauval 2005]. A wide range of systematic effects on quantitative analyses of early B stars have also been identified (Nieva & Przybilla, these proceedings), providing a sound basis for a re-investigation of elemental abundances in these stars.

This re-investigation indicates that elemental abundances of early B stars in the solar neighbourhood are in fact highly homogeneous, showing a rms scatter as low as \( \sim 10\% \) [Przybilla, Nieva, & Butler 2008], the same as reported for ISM gas-phase abundances. A cosmic abundance standard for the present-day solar neighbourhood can thus be proposed, with light element abundances (given as \( \log (\text{El}/\text{H}) + 12 \)) and mass fractions for hydrogen (X), helium (Y) and metals (Z) as summarised in Table 1. Here, pristine carbon abundances are adopted from Nieva & Przybilla (2008). In general, good agreement with the revised solar abundances [Asplund et al. 2005] is found, with some small differences in oxygen (and neon). These cosmic abundances are recommended as initial values for future stellar evolution calculations of massive stars. Note in particular the reduction of Z to 0.014 from the so far canonical value of 0.02.

4. Observational Constraints on Massive Star Evolution

Accurate atmospheric parameters and elemental abundances have been determined for 15 Galactic tepid supergiants so far [Przybilla et al. 2006; Firnstein 2006; Schiller & Przybilla 2008]. Six BA-type supergiants are located within Gould’s Belt (like all B star targets), while the remaining ones are found in the field and in associations out to distances of \( \sim 3\, \text{kpc} \) from the Sun.

All sample stars within Gould’s Belt show similar abundances of the heavier elements [Przybilla et al. 2008], corroborating the concept of chemical homogeneity of the ISM in the solar neighbourhood at present day. A slightly larger spread in abundances is found for the more distant stars, implying a total range in abundance of less than a factor of 2 (and flat Galactic abundance gradients, Figs. 18 & 19 in Przybilla 2008), which is consistent with predictions from simple models of turbulent mixing within the ISM (e.g. Roy & Kunth 1995). This is much less than the factor of \( \sim 10 \) in abundance range found in previous studies.

Data relevant for our comparison with stellar evolution models are displayed in Fig. 1. The abundance distributions show depleted carbon and enriched nitrogen relative to the cosmic abundance standard values, as expected for the evolved state of the supergiants. The upper limit of carbon abundances in the BA-type supergiants is consistent with the pristine value derived from the B
Figure 1. Comparison of carbon and nitrogen abundances in BA-type supergiants as obtained in our work and from the literature. Cosmic standard abundances (CAS) from Table 1 are indicated by vertical lines. Bin width is $\sigma/2$ of the individual studies, with $\sigma$ denoting the rms scatter.

stars, meeting a boundary condition imposed by mixing. Note that the abundance ranges covered are much smaller than in published work on similar stars (as indicated in Fig. 1) – a consequence of the largely reduced systematic uncertainties in our analysis, which applies also to the findings for other elements.

The comparison of observed N/C abundance ratios with predictions from stellar evolution models is made in Fig. 2 (preliminary results for a few highly massive supergiants in nearby galaxies are also shown). We recall that this comparison is not ideal, as the evolution calculations (Meynet & Maeder 2003) were performed for $Z = 0.02$, while the observations are on average consistent with a value of $Z = 0.014$. However, the expected effects for this metallicity difference will not change the general conclusions drawn in the following.

Most of the apparently slow-rotating B stars show N/C ratios close to the pristine value of $\sim 0.3$. A notable exception is $\tau$ Sco, which was shown recently to be a truly slow-rotating magnetic star. The situation is more complex with the BA-type supergiants. They all exhibit slow rotation because of their expanded
Figure 2. Observational constraints on massive star evolution. Displayed are results for the most sensitive indicator for mixing with nuclear-processed matter, N/C, in a homogeneously analysed sample of Galactic BA-type supergiants (circles) and their progenitors on the main sequence, B stars. The N/C ratios are encoded on a logarithmic scale, with some examples indicated. Error bars (1σ-statistical & systematic) from our work and those typical for previous work are also indicated. Stellar evolution tracks (Meynet & Maeder 2003) are displayed for rotating stars at Z⊙ = 0.02 (full lines). Starting with an initial N/C ∼ 0.3, theory predicts N/C ∼ 1 for BA-type supergiants evolving to the red, and N/C ∼ 2–3 after the first dredge-up (markers along the tracks). Since we find N/C values as high as ≳ 6 the observed mixing efficiency is higher than predicted. Also, blue loops extend to hotter temperatures than predicted. Results for a few objects in nearby galaxies are also shown.

Two important conclusions can already be drawn from this small sample. Let us concentrate first on the objects more massive than ∼ 15 M⊙. A general trend of increased mixing of nuclear-processed material with increasing stellar mass is found, in accordance with the predictions of evolution models. Moreover, the strongest mixing signature is found for the most metal-poor object, AzV 475 in the Small Magellanic Cloud, also in agreement with theory (e.g. Maeder & Meynet 2001). However, the mixing efficiency appears to be higher (by a factor of ∼ 2) than predicted by current state-of-the-art evolution computations for rotating stars with mass-loss. Stellar evolution models accounting for envelopes, irrespective of the initial rotational velocity of their progenitors on the main sequence. It appears that the objects at masses below ∼ 15 M⊙ show larger amounts of nuclear-processed material than those around ∼ 20 M⊙. Larger N/C ratios are found again for the most massive objects of the sample. Note that objects of M ≥ 30 M⊙ are located either in the Magellanic Clouds or in M31, i.e. they have a different metallicity than the Galactic stars. Note further that in view of the results discussed by Levesque et al. (these proceedings) stars of such high masses apparently avoid the red supergiant phase.
the interplay of rotation and magnetic fields may resolve this discrepancy since they find a higher efficiency for chemical mixing \cite{MaederMeynet2005}.

Larger $N/C$ ratios at $M \lesssim 15 M_\odot$ can be explained if the objects are on a blue loop, i.e. if they have already undergone the first dredge-up during a previous phase as a red supergiant, in addition to rotational mixing. This interpretation is in contrast to earlier findings of \cite{Venn1995}. Further support for the blue-loop scenario comes from lifetime considerations. Stellar evolution calculations indicate that supergiants spend a much longer time on a blue-loop (with core He-burning) than required for the crossing of the HRD from the blue to the red (the short phase of core contraction after core H-burning has ceased). E.g., in the case of a rotating $9 M_\odot$ model of \cite{MeynetMaeder2003} the difference is about a factor of 15. It is well-established that blue loops are required to explain the Cepheid variables, but their extent in the HRD – in particular the upper limits in temperature and stellar mass – are essentially unknown. The blue-loop phase is highly sensitive to the details of the stellar evolution calculations (‘... is a sort of magnifying glass, revealing relentlessly the faults of calculations of earlier phases.’ \cite{KippenhahnWeigert1990}). Consequently, a systematic study of a larger sample of massive stars could provide the tight observational constraints required for a thorough verification and refinement of the stellar evolution models. Precision analyses of stars covering the relevant part of the HRD are under way.

Acknowledgments. M. F. and N. P. gratefully acknowledge financial support of the project by the Deutsche Forschungsgemeinschaft (grant PR 685/3-1).

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