Bulletin de la Société Royale des Sciences de Liège, Vol. 80, 2011, p. 279 - 284

Mixing of CNO-cycled matter in massive stars

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Abstract: Anomalies in the light element abundances in massive stars on the main sequence and more pronounced in their evolved stages are known since long. These are explained by evolution models for rotating stars as the consequence of mixing of nuclear-processed matter into the stellar atmosphere. However, recent analyses of large star samples have challenged the concept of rotational mixing. We report on the abundances of helium, carbon, nitrogen and oxygen in a sample of Galactic massive stars covering the main sequence to the blue supergiant stage in the mass range $\sim$9 to 25 $M_\odot$. High-quality spectra are homogeneously analysed throughout the optical to near-IR using improved NLTE line-formation and comprehensive analysis strategies. Extremely tight trends among the light element abundances are found for the first time, tracing the nuclear paths of the CNO-cycles quantitatively. The improved observational constraints will facilitate model predictions to be tested in unprecedented detail and they may guide future improvements to the models.

1 Introduction

Energy production in massive stars is governed by the CNO-cycles throughout most of their lifetimes. While CNO-burning itself is catalytic, i.e. the total number of C, N and O nuclei is not changed, transmutations occur and lead to a buildup of nitrogen at the expense of carbon and (to much lower extent) oxygen, while the burning product, helium, is accumulated.

Observational evidence for the actions of the CNO-cycles is not only found in late stages of massive star evolution, as in the Wolf-Rayet stars of WN subtype, but also much earlier. Traces of mixing of CNO-cycled products from the stellar core to the stellar surface have been found in OB-type stars on the main sequence (MS) and their evolved progeny, the blue supergiants (BSGs, see e.g. Maeder & Meynet 2000, and references therein). A qualitative understanding of this early mixing could be achieved within the framework of evolution calculations for rotating stars, where meridional circulation and turbulent diffusion act as transport mechanisms (Maeder & Meynet 2000; Heger & Langer 2000). The interplay of rotation and a magnetic dynamo may enhance the transport efficiency even further (Maeder & Meynet 2005), or not (Heger, Woosley & Spruit 2005).

The only means to verify the models is via systematic comparison with observations. Here, we address the topic of early mixing of CNO-cycled products in massive stars from a fundamental perspective. We compare the model predictions for the relative changes within the C:N:O abundance ratios and the buildup of helium with observations.

2 Theoretical Considerations

At the centre of the present investigation are diagnostic plots of an abundance ratio vs. another one, such as N/C vs. N/O or helium vs. N/O. The predicted trends depend on both the changes produced by nuclear reactions and the dilution effects produced by mixing. We may estimate the slope $\frac{\mathrm{d}(N/C)}{\mathrm{d}(N/O)}$ produced by the nuclear effects at the beginning of CNO burning. Apart from the very massive stars ($M > 40\,M_\odot$), one may assume that, at the beginning of the burning, the ^{14}N enhancement comes from the ^{12}C destruction via the CN cycle, while oxygen remains about constant. Thus, one has $\mathrm{d}C = -\frac{6}{7}\mathrm{d}N$ (in mass fractions) since ^{14}N globally results from the addition of two protons to ^{12}C,

$$\begin{aligned} \mathrm{d}(N/O) &= \mathrm{d}N/O \,, \\ \mathrm{d}(N/C) &= \frac{\mathrm{d}N}{C} - \frac{N}{C^2}\frac{\mathrm{d}C}{\mathrm{d}N}\mathrm{d}N = \frac{\mathrm{d}N}{C}\left[1 + \frac{6}{7}\frac{N}{C}\right] \,. \end{aligned} \tag{1}$$

This gives the slope

$$\frac{\mathrm{d}(N/C)}{\mathrm{d}(N/O)} = \frac{(N/C)}{(N/O)}\left[1 + \frac{6}{7}\frac{N}{C}\right] \,, \tag{2}$$

which is determined by the initial CNO abundances solely. For initial ratios N/C and N/O of 0.31 and 0.11, respectively, it adopts a value of 3.77. The relation turns slightly upward as N/C is increasing owing to the term in brackets in Eq. (2). However, at some advanced stage in evolution, corresponding to WN stars not shown here, the curve will saturate and turn down slightly (Maeder 2009, p. 699), since the CN cycle is then at equilibrium, while ^{16}O is still turned to ^{14}N. Dilution mixes a fraction f of N + ΔN enriched and C depleted materials with a fraction $(1 - f)$ of the original N and C. Under the same assumptions as above, it is easy to show that, to the first order, the slope for the relative enrichments in the N/C vs. N/O plot behaves the same way as in Eq. (2) independently of f.

The value of f, however, determines the amplitudes of the departures from the cosmic ratios. Our models with rotational mixing (e.g. Meynet & Maeder 2003) or with rotation and magnetic fields (Maeder & Meynet 2005), as illustrated later in Fig. 2, have an initial slope $\frac{\mathrm{d}(N/C)}{\mathrm{d}(N/O)} \approx 4$, which is in excellent agreement with our estimate above. The amplitude f of the mixing depends on the various model assumptions, models that include both rotation and magnetic field predict the largest mixing.

Finally we consider the behaviour of the helium surface content Y_s vs. N/O. Strictly and only at the very beginning of the CN burning, and under the assumption of an initially constant oxygen, we get $\mathrm{d}Y_\mathrm{s} = \frac{2}{7}\mathrm{d}N$, since when 4 units of mass of helium are made, 14 units of mass of nitrogen are produced. The slope is $\frac{\mathrm{d}Y_\mathrm{s}}{\mathrm{d}(N/O)} = \frac{2}{7}O \approx 0.286 \times 0.009 = 0.0026$ i.e., it is essentially flat initially. Later in the evolution, both N and O change simultaneously, and one has to rely on numerical models. The resulting slope in the models can vary, see Fig. 2. This depends on whether the matter that arrives at the surface comes from inner regions that are at both CN and ON equilibria, or only at CN equilibrium. There is, of course, a range of intermediate cases.

3 Observational Constraints

Numerous studies of CNO abundances in massive stars of the Milky Way are available in the literature, mostly for early B-type stars close to the MS and for BSGs. Overall, a wide range of N/O–N/C combinations is found, scattering widely around the predicted trends, see Fig. 1 of Przybilla et al. (2010). However, error margins in the individual elements are typically about a factor 2 at 1σ-level. Consequently, such data are of limited use to draw *firm* conclusions on the quality of stellar evolution models. Improved modelling is required to reduce the uncertainties in the abundance determinations.

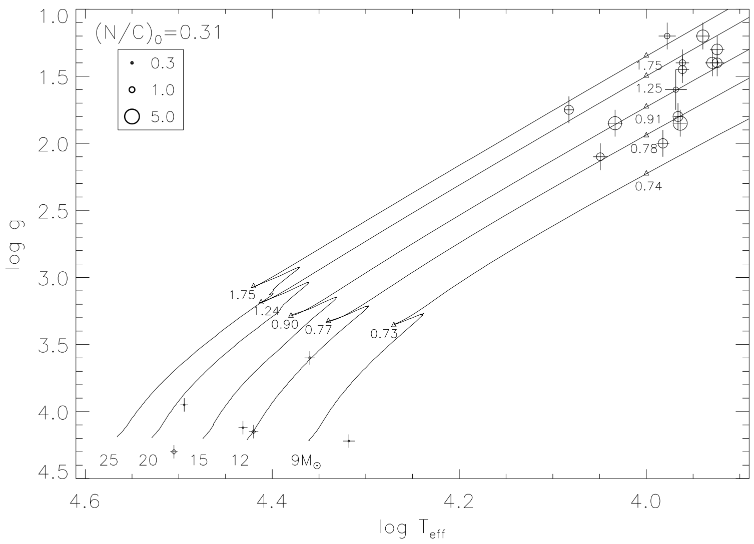

Figure 1: Sample stars in the $\log T_{\rm eff}$–$\log g$-plane. The symbol size encodes the N/C ratio (by mass), with typical values exemplified in the legend. Error bars correspond to 1σ-uncertainties. Evolutionary tracks for rotating stars of metallicity $Z = 0.02$ (Meynet & Maeder 2003) are shown. Predicted N/C ratios are indicated along the tracks (small triangles). From Przybilla et al. (2010).

We have published a series of high-accuracy studies of massive stars in the solar neighbourhood over the past years. Data on 6 slowly-rotating early B-type stars near the MS (Nieva & Przybilla 2006, 2007, 2008, Przybilla, Nieva & Butler 2008) and on 14 BA-type supergiants (Przybilla et al. 2006, Firnstein 2006, Schiller & Przybilla 2008) are available. The studies were based on high-resolution and high-S/N spectra ($S/N > 300$) with wide wavelength coverage (obtained with FOCES@Calar Alto Observatory and FEROS@ESO/La Silla). The analyses were performed homogeneously using a hybrid NLTE approach (Przybilla et al. 2006, Nieva & Przybilla 2007) and state-of-the-art atomic input data. In contrast to all previous work, multiple H lines, the He lines, multiple metal ionization equilibria and the stellar energy distributions were reproduced *simultaneously* in an iterative approach to determine the stellar atmospheric parameters. Chemical abundances were derived from analysis of practically the entire observable spectrum per element. The rewards of such a comprehensive, but time-consuming procedure are unprecedentedly small statistical error margins and largely reduced systematics. We reanalysed the supergiants for the present work, taking advantage of improved model grids. Our new results agree with the earlier ones within the uncertainties but are more accurate.

The sample is displayed in the $\log T_{\rm eff}$–$\log g$-plane and compared to evolutionary tracks in Fig. 1. The stars have initial masses between about 9 to 25 $M_\odot$. There is good qualitative agreement between the observations and predictions for the N/C ratios, finding low values close to the initial (solar) ratio on the main sequence and enhanced values in the supergiants. However, the observed N/C ratios reach much higher values than predicted by the models, provided these stars have recently left the main sequence and evolve now into red supergiants (RSGs).

The behaviour of light element abundances in the whole star sample is shown in Fig. 2. A clear and tight trend is found for the first time, confirming the predicted locus of N/O–N/C abundance ratios. However, as already indicated above, the models for rotating stars evolving towards the RSG stage (Meynet & Maeder 2003, solid line in Fig. 2) predict mixing that is too low, i.e. too low f (Sect. 2), in particular for most of the supergiants. The magnetic model (Maeder & Meynet 2005) fits observations better in this context. The observations are also compatible with first dredge-up values, which, however, are reached only after the stars have become red supergiants. Helium abundances provide further constraints (Fig. 2), which in the case of BA-type supergiants are determined for

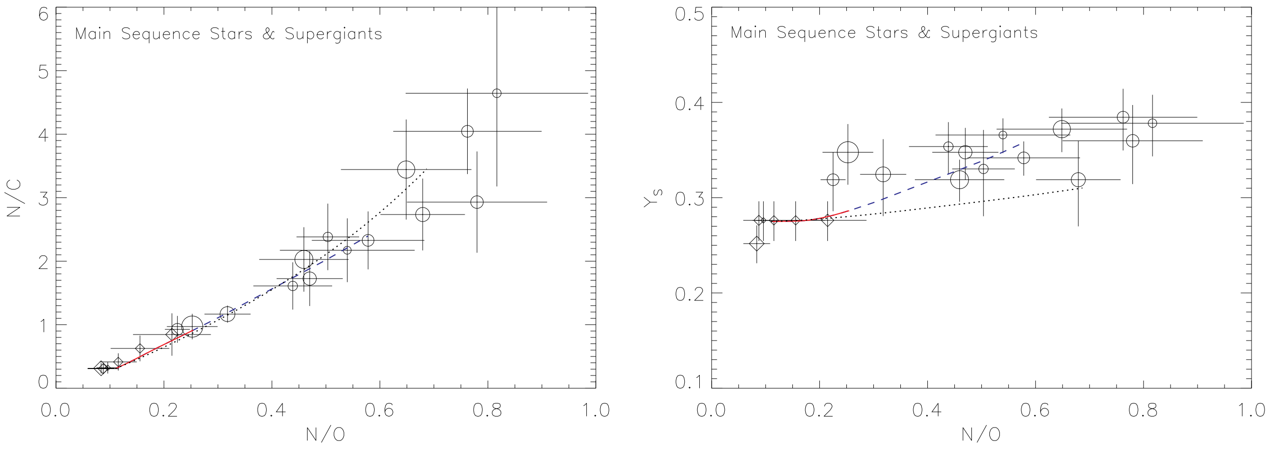

Figure 2: Left panel: N/C vs. N/O abundance ratios. Right panel: Surface helium abundance Y_S vs. N/O ratio (both by mass fraction) for our sample stars. B-type main sequence stars are displayed as diamonds, BA-type supergiants as circles. The symbol size encodes the stellar mass and error bars give 1σ-uncertainties. The different lines describe model predictions for $15\,M_\odot$ stars: for a rotating star ($v_\mathrm{ini} = 300\,\mathrm{km\,s^{-1}}$, Meynet & Maeder 2003; until the end of the MS: solid red line, until the end of He burning: dashed blue line) and for a model that in addition takes a magnetic dynamo into account (Maeder & Meynet 2005; until the end of the MS: dotted line). The predicted trends are similar for the entire mass range under investigation and they are independent of v_ini (except for the amount of mixed material). From Przybilla et al. (2010).

a significant number of stars for the first time in a self-consistent analysis. On the MS no helium surface enrichment is observed, as predicted in the models for stars with masses below about $20\,M_\odot$. He-enrichments at the level observed in the present supergiants are compatible with models having undergone a dredge-up in the RSG phase. Depending on the rotation velocity, the presence of a magnetic field or its absence, models will populate diverse parts of the region in the plane Y_S versus N/O after the RSG phase, as illustrated e.g. by the dashed and dotted lines in Fig. 2.

Actually, the interpretation of the BSG data can become really constraining only when we obtain additional hints on the previous evolution of the stars. Have the BSGs evolved directly from the MS, or have they evolved into that stage after going through a RSG stage? The problem is visualised in Fig. 3, which displays the evolution of the N/C-ratio as a function of $\log g$. The surface gravity decreases in general with increasing age of the star, except for blue-loop episodes like the one close to the end of the $9\,M_\odot$ track. The observed N/C-ratios are compatible with first dredge-up values (N/C $\approx$ 2-3) from a previous RSG stage for most of the BSGs, which is not predicted by the models (models with rotation do not predict blue loops for masses higher than $\sim$9 $M_\odot$). Moreover, given the extremely short period that the models predict the stars to spent in the BA-type supergiant regime (cf., however, Salasnich, Bressan & Chiosi 1999), there are way too many objects observed in this particular evolution stage. Magnetic models on the other hand may reach the observed N/C-ratios during their redward evolution from the MS, but they need to be computed further through core He-burning to facilitate detailed investigations.

Already from the small sample of stars on the MS it appears that other factors need to be considered in the models to explain some outliers (Fig. 3). An analysis of a larger sample of MS stars indicates that while the majority of objects is described well by evolution models for rotating stars, (fossil) magnetic fields may play a role in some cases, see Przybilla & Nieva (2010) for details.

Overall, our improved spectral modelling and the novel analysis techniques provide observational constraints of unprecedented accuracy and precision to stellar evolution models. Further investiga-

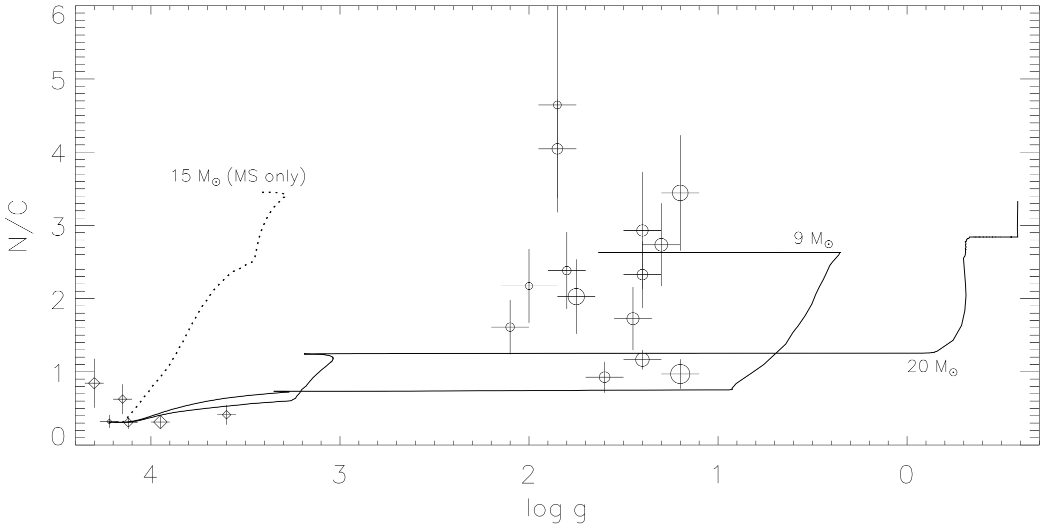

Figure 3: Sample stars in the $\log g$–N/C-plane. Symbol and line encoding as in Fig. 1. In addition, a magnetic model is displayed which has been evolved only to the end of H-burning (Maeder & Meynet 2005, dotted line). The symbol size is proportional to stellar mass. From left to right, the evolution proceeds from the MS over the BA-type supergiant regime to the RSG stage, potentially entering a blue loop (where $\log g$ develops towards higher values), like for the 9 $M_\odot$ model.

tions need to encompass larger sample sizes to cover all relevant quantities in the multi-dimensional parameter space (mass, age, rotational velocities, metallicity, etc.). This may finally lead to a deeper understanding of the fundamental processes governing the evolution of massive stars, single ones and those in close binary systems (e.g. Wellstein, Langer & Braun 2001).

Acknowledgements

NP and MFN would like to thank the staff at Geneva Observatory for their hospitality. MF acknowledges funding by the *Deutsche Forschungsgemeinschaft, DFG* under project number PR 685/3-1.

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Discussion

S. Owocki: Very interesting result about the anomalous high N/C for τ Sco, which as you note has a detected complex magnetic field. While your suggestion is that this might be explained by magnetic enhancement or internal mixing, it seems one should also consider atmospheric diffusion, which is understood to cause the peculiar abundance of magnetic A_p/B_p stars. Also, it would be interesting to look at the abundances of the emerging class of magnetic massive stars being detected by the MiMeS project.
N. Przybilla: Diffusion requires a very stable atmosphere to take place, in particular the absence of a wind, which is not the case for τ Sco. We have analyzed more magnetic stars and will report on the results soon.

J. Puls: Very nice work; your biggest discrepancies are in the supergiant range. Might it be that a certain part is due to neglected mass-loss in your models, though your objects have a decent mass-loss rate, as obvious from the Hα-spectra?
N. Przybilla: Most of the sample objects have negligible winds. The highest mass-loss rates in a few objects are of the order $10^{-7}\,\mathrm{M}_\odot$ yr^{-1}, which we don't expect to affect the photospheric line spectra.