The observable Metal-enrichment of Radiation-driven+Wind-blown HII Regions in the Wolf-Rayet Stage

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From stellar evolution models and from observations of Wolf-Rayet stars it is known that massive stars are releasing metal-enriched gas in their Wolf-Rayet phase by means of strong stellar winds. Although Hii region spectra serve as diagnostics to determine the present-day chemical composition of the interstellar medium, it is not yet reliably explored to what extent the diagnostic Hii gas is already contaminated by chemically processed stellar wind matter. In a recent paper, we therefore analyzed our models of radiation-driven and wind-blown Hii bubbles around an isolated 85 M⊙ star with originally solar metallicity with respect to its chemical abundances. Although the hot stellar wind bubble (SWB) is enriched with 14N during the WN phase and even much higher with 12C and 16O during the WC phase of the star, we found that at the end of the stellar lifetime the mass ratios of the traced elements N and O in the warm ionized gas are insignificantly higher than solar, whereas an enrichment of 22% above solar is found for C. The transport of enriched elements from the hot SWB to the cool gas occurs mainly by means of mixing of hot gas with cooler at the backside of the SWB shell.

1. Introduction

Hii regions are used as the most reliable targets to derive actual abundances in the Interstellar Medium (ISM). Kunth & Sargent (1986) discussed the problem of determining the heavy-element abundance of very metal-poor blue compact dwarf galaxies from emission lines of Hii regions in the light of local self-enrichment by massive stars but have more stressed the effect by supernovae type II (SNeII) ejected material. However, already during the Wolf-Rayet (WR) phase of massive stellar evolution the stellar wind peels off the outermost stellar layers, so that elements from shell-burning regimes are released into the surrounding ISM already at later stages of their normal lifetimes. Since the stellar wind energetics let one presume that this gas is deposited into the hot phase only, it was not yet reliably explored in detail how and to what extent the complex structure of the stellar wind bubble (SWB) could facilitate the cooling of wind material, by this, making it attainable for observations of the Hii gas.

That WR stars should play an important role for C enrichment of the ISM at solar metallicity was advocated by Dray et al. (2003). Their models predict that the C enrichment by WR stars is at least comparable to that by AGB stars, while the enrichment by N is dominated by AGB stars and the O enrichment is dominated by SNeII. Their investigation, however, sums over all gas phases and avoids to evaluate the abundances in specific gas phases for detailed diagnostics, like e.g. in the warm Hii gas.

In a series of models of radiation-driven and wind-blown bubbles produced by massive stars we investigated the effects of structuring and energizing the surrounding ISM for
a 15 M⊙ star (Kroeger et al. in preparation), a 35 M⊙ (Freyer et al. 2006), a 60 M⊙ (Freyer et al. 2003: Paper I), and a 85 M⊙ star (Kroeger et al. 2006b). From these, we could conclude that differently strong but significant structures are formed by the combined dynamical and radiative processes between the SWB and the enveloping HII region (in particular, see Paper I) where hot gas mixes with the warm one and cools further to "warm" phase. The mixing occurs mainly in the back of the SWB shell with photo-evaporated material and through turbulence in an interface between SWB and shell (see e.g. Fig.1).

Nevertheless, the WR stage is metal dependent in the sense that, at first, the lower the metallicity the more massive a star has to be to evolve through the WR stages and that, secondly, the lower the metallicity the shorter are the WR lifetimes and not all WR stages are reached. The first point means, that the number of WR stars decreases with decreasing metallicity. [Schaller et al.] (1992; hereafter: SSMM) found that for a metallicity of Z=0.001 the minimal zero-age main-sequence (ZAMS) mass for a WR star is > 80 M⊙ while at solar Z=0.02 it is > 25 M⊙ as already discussed by Chiosi & Maeder (1986).

2. The Model

The hydrodynamical equations are solved together with the transfer of H-ionizing photons on a two-dimensional cylindrical grid. For reasons of a refined resolution mainly in the central part around the star, the grid is structured by a nested scheme. The time-dependent ionization and recombination of hydrogen is calculated in each time step and we carefully take stock of all the important energy exchange processes in the system. A detailed description of the numerical method and further references are given in Paper I.

As initial condition an undisturbed homogeneous background gas with solar abundances (Anders & Grevesse 1989), hydrogen number density n₀=20 cm⁻³, and temperature T₀=200 K is applied for the reasons described in Paper I. The models are then started with the sudden turn-on of the ZAMS stellar radiation field and stellar wind. Since the gas is assumed as void of molecular stuff the radiation field commences immediately to ionized the environment outwards of the SWB without an enveloping photo-dissociation region. From a series of models of radiation and wind-driven HII regions around single massive stars mentioned above, for our purpose the 85 M⊙ star (Kroeger et al. 2006b) looks as the most appropriate with respect to its self-enrichment. The time-dependent parameters of this star with “standard” mass-loss and solar metallicity (Z=0.02) during its H main-sequence and its subsequent evolution are taken from SSMM. The model analysis is already published by us (Kroeger et al. 2006a).

The according exploration starts not before the onset of the WR stage, in particular with the onset of the WN stage at an age of t=2.83 Myrs. The WR star enriches the combined SWB/HII region with ¹²C, ¹⁴N, and ¹⁶O. During its WN phase the star releases 0.143 M⊙ ¹⁴N, which is more than half of its total release, but nearly no extra ¹²C or ¹⁶O is supplied. As the condition for observability within the HII region only the “warm” gas (6.0 × 10³ K ≤ T < 5.0 × 10⁴ K) is accounted for. The mass fractions of ¹²C, ¹⁴N, and ¹⁶O with respect to solar are set according to Anders & Grevesse (1989) to 4.466 × 10⁻³, 1.397 × 10⁻³, and 1.061 × 10⁻², respectively, normalized to H.

3. Results

At the end of its lifetime at t = 3.22 Myr the 85 M⊙ star has supplied 0.28 M⊙ of ¹⁴N, 13.76 M⊙ of ¹²C, and 11.12 M⊙ of ¹⁶O, which are contained in the combined SWB/HII region. Since N was released at first in the WN stage it increases slightly in this period
Figure 1. Left panel: $^{12}$C distribution within the stellar wind bubble and the HII region for comparison with the temperature distribution (Right panel). Both figures are snapshots at the end of the lifetime of a 85 $M_\odot$ star. All plots cover the whole computational domain of 60 pc $\times$ 60 pc.

Figure 2. Time-dependent abundances of $^{12}$C, $^{14}$N, and $^{16}$O in the hot (left panel) and the warm gas phase (right panel). The plot starts not before the onset of the WN phase at 2.83 Myrs and is thereafter diluted by the nitrogen-poor gas feed. These facts are discernible in the left-hand panel of Fig. 2 by a first rise and a subsequent decrease of the N abundance in the hot phase after the transition to the WC stage when C and O are released. The $^{12}$C content increases steeply and reaches an overabundance of 38 times solar while the enrichment with $^{16}$O is weaker (Fig. 2 left panel).

In Fig. 1 the C distribution as the element of largest contribution is revealed in comparison with the temperature distribution at the end of the stellar life. Two facts can be easily discerned: 1) The carbon enrichment is reasonably largest within the hot SWB; 2) also regions with the "warm" temperature range are significantly $^{12}$C enriched.

While the mixing and incorporation of $^{14}$N from the hot into the warm phase becomes only slightly detectable after about 3.1 Myrs, but occurs with a time delay after its release of almost 0.2 Myrs, the $^{12}$C enrichment in the warm phase is clearly perceivable already less than 50000 yrs after its steep rise in the hot SWB.

At the end of the 85 $M_\odot$ star’s life the element quantities measurable in emission spectra of the warm HII region gas amount to 1.22 times solar for $^{12}$C, to less than 1.01
for $^{14}\text{N}$, and to only 1.05 solar for $^{16}\text{O}$. From this model we conclude that the enrichment of the circumstellar environment with $^{14}\text{N}$ and $^{16}\text{O}$ by WR stars is negligible, if the 85 M$_{\odot}$ star is representative for massive stars passing the WR stage. Only for $^{12}\text{C}$ the enrichment of the HII region is significant. For a giant HII region containing a full set of massive stars according to a normal initial mass function and with different lifetimes and wind mass-loss rates the enrichment effect of C should, however, become smaller than modelled here for a single most massive star. A comprehensive description and discussion of the model is already published by Kroeger et al. (2006a).

Since the occurrence of a WR phase is strongly metal dependent, the enrichment with C should also depend on the average metallicity. This would mean that any radial gradient of C abundance of HII regions in galactic disks is steeper than that of O. And indeed, Esteban et al. (2005) found $\text{d}[^{\log}(\text{C}/\text{O})]/\text{d}r = -0.058 \pm 0.018 \text{ dex kpc}^{-1}$ for the Galactic disk.

In metal-poor galaxies one would expect less chemical self-enrichment because the stellar mass range of the WR occurrence is shrinked and shifted towards higher masses and the WR phases are shorter.

REFERENCES
Anders, E., & Grevesse, N. (1989). Geochem. Cosmochim. Acta, 53, 197
Chiosi, C. & Maeder, A. (1986). ARA&A, 24, 329
Dray, L. M., Tout, C. A., Karakas, A. I., & Lattanzio, J. C. (2003). MNRAS, 338, 973
Esteban, C., García-Rojas, J., Peimbert, M., et al. (2005). ApJ, 618, L95
Freyer, T., Hensler, G., & Yorke, H.W. (2003). ApJ, 594, 888 (Paper I)
Freyer, T., Hensler, G., & Yorke, H.W. (2006). ApJ, 638, 262 (Paper II)
Kroeger D., Hensler, G., & Freyer T. (2006a). A&A, 450, L5
Kroeger D., Freyer T., Hensler, G., & Yorke, H.W. (2006b). A&A, submitted (Paper III)
Kroeger D., Freyer T., Hensler, G., & Yorke, H.W. (2007). A&A, in prep. (Paper IV)
Schaller, G., Schaerer, D., Meynet, G., & Maeder, A. (1992). A&AS 96, 269

4. QUESTIONS
J.M. Vilchez: Is the $^4\text{He}$ following the same behaviour as C or O in your models?
G. Hensler: I would expect it but we haven’t yet considered it.