The Wolf-Rayet hydrogen puzzle – an observational point of view

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Abstract. Significant amounts of hydrogen were found in very hot early-type single WN stars in the SMC and the LMC. Recently, we found similar evidence in the Wolf-Rayet star of a short-period LMC binary. We discuss here the relevance of hydrogen for WR star classification, models, the relation to metallicity, and the GRB progenitors.

1. The first hints

Hydrogen is obviously a crucial element in stellar evolution, even in core helium-burning Wolf-Rayet (WR) stars. It has been found in the SMC that about half of the WR population consists of hot, single, hydrogen-containing single WN3 and WN4 stars (classified WN3-4ha or (h)a, Foellmi et al. 2003a; Foellmi 2004). For such early spectral types, significant amounts of hydrogen were not expected, since such hot WN stars are believed to have peeled off their outer H-rich layers by a very strong and optically thick wind, combined with internal convective mixing to expose core-processed material. Contrary to expectations, blue-shifted absorption lines of HI and HeII were detected in the spectra of all single SMC WNE stars, and Foellmi et al. argued that they originate in a WR wind. Given their dominance in the SMC, it is likely that these stars have a low initial mass (say 25-40 $M_\odot$) and are formed mainly thanks to high rotational velocity.

Hydrogen has also a direct impact on our understanding of the WR classification (especially of the WN sequence), as shown in Fig. where two WNE stars are plotted. The differences are not only qualitative. For instance, Hamann et al. (1995) noted the physical property jump in their models of WN stars between the stars with broad lines (i.e. using the "b" label, following Smith et al. 1996) and the other (weak lined) WN stars. Moreover, Smith and Maeder (1998) have shown that the notations "ha-h-(h)-o" in the Smith et al. classification scheme are probably an evolutionary sequence. Finally, Foellmi et al. (2003b) have shown a clear distinction between the WN stars with broad lines (such as in BAT99-7, see Fig. and those labelled "ha/h/(h)" among the 61 WNE stars in the LMC: only two of them have a mixed subtype "b(h)".

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2. Massive-star classification.

All these evidence led Foellmi et al. (2003b) to propose a new classification for massive stars that is complementary to that of Smith et al. (1996). This evolutionary classification is recognizable by putting an "e" in front of the class, and is based this time on the hydrogen content, i.e. the broad line criterion becomes the principal classification criterion. To summarize, the stars classified as O, Of, WN6 and WN7 are called "eO" since they are certainly core hydrogen-burning (see Foellmi et al. 2003b, for a discussion on the very massive WN6 and WN7 stars). The transition objects RSG, LBV, WN9-11 are called "eOW". The WR stars with hydrogen (whatever their ionization subclass, except WN6 and WN7) are eWNL, while the real hydrogen-free WN stars (i.e. with broad lines) are labeled "eWNE". With this classification, models and observations agree (see e.g. Foellmi et al. 2003b, Meynet and Maeder 2005, and also Fig. 1). While the ionization subclass is thought to be metallicity-dependent (see e.g. Crowther 2000), the evolutionary classification is valid at all Z, following which the H-rich WN stars in the SMC are "hot eWNL stars".

Recently, Foellmi et al. (2005) have found a significant amount of hydrogen in a short-period binary in the LMC (see Fig. 2). The WR component is classified WN3ha. According to a first modeling (P. Crowther, private communication), the amount of hydrogen is similar to that found in SMC stars, i.e. the H/He ratio (by number) is about unity, while the temperature reaches $T_{\text{eff}} \sim 90kK$! The evolutionary classification is therefore also applicable to binary stars.

Hot eWNL stars were also found in the LMC (about one third of the WNE population; Foellmi et al. 2003b), and more recently, one such star in our Galaxy, in a region where the ambient metallicity may resemble that of the LMC: WR3,
3. Progenitors of GRBs

We recall here the main theoretical ingredients to form a GRB, following MacFadyen and Woosley (1999): (1) A massive core is needed to form a black hole, (2) enough angular momentum must remain in the core to produce bipolar jets and (3) the star must have lost its hydrogen envelope to allow the radiation to reach the surface and escape. The third point implies that if a WR star at low metallicity is indeed to become a progenitor of a GRB, it must go through an H-free WC phase.

Following the models of rotating WR stars by Meynet and Maeder (2005), at low metallicity, only stars with an initial mass above or equal to $60 M_\odot$ will
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go through a non-negligible WC phase. Very few stars will be massive enough to
reach the WO stage. Thus, it is very unlikely that the hot eWNL stars are good
GRB candidates ones, and the GRB progenitors must be found among
higher-mass stars. This idea is reinforced by the recent modeling of [Hirschi et al.
(2005), who claim that basically only the stars that reach the WO stage will be
capable of producing GRBs.

However, the supernova SN1998E associated with GRB980910 showed hy-
drogen in its spectrum [Rigon et al. 2003]. Moreover, recently Starling et al.
(2005) also found hydrogen in significant quantities in the afterglow of GRB021004.
As suggested by the analysis of WR3 in our Galaxy [Marchenko et al. 2004],
the absorption lines form relatively close to the stellar core. It is likely that
the absorbing material is then gradually accelerated to the terminal wind ve-
locity. Since we have shown that it is not unusual to see a significant amount
of hydrogen in single and binary WN stars at low metallicity, it might not be
too surprising to observe high-velocity hydrogen absorption features in GRB
afterglows, such as described by [Starling et al. 2003] on GRB 021004.

On the other hand, van Marle et al. (2005) argue that the presence of an
intermediate velocity component in the afterglow of GRB 021004 implies that
the WR phase was short, i.e. that the WR shell was still intact when the star
exploded. This implies that the initial mass of the progenitor must have been
small (i.e. about $25 M_\odot$), since the smaller the initial mass, the shorter the
WR phase (see Fig. 9 in Meynet and Maeder 2005). But such stars have a
very short H-free WC stage. Although this is possibly in contradiction with the
requirement of no hydrogen left in the atmosphere [MacFadyen and Woosley
1999], it favors the idea of hot eWNL stars as GRB progenitors.

It is interesting to note that theoretical models seem to produce two very
different types of GRB progenitors. On one hand, models require H-free pro-
genitors and [Hirschi et al. 2005] claim that single (initially massive) WO type
stars are the best GRB candidates,. On the other hand, the presence of hydro-
gen in GRB afterglows, the results of van Marle et al. (2005) and the fraction
of hot eWNL point toward lower mass WR stars. Could the solution come
from short-period binaries? Possibly, the only way to reconcile the need for a
non-negligible WC phase and low initial mass (i.e. $< 60 M_\odot$) could be in an in-
teracting short-period binary, such as BAT129 in the LMC [Foellmi et al. 2005].
In that context, the unique WO 16-day binary star of the SMC (WR8) deserves
probably much more attention (see e.g. Bartzakos et al. 2001).

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