WR Populations in Starbursts: WN and WC Subtypes and the Role of Binaries

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Abstract: We present the first results of a new set of population synthesis models, which utilize the latest stellar evolutionary tracks, recent non-LTE atmosphere models which include stellar winds, and observed line strengths in WR spectra to predict the relative strengths of various WN and WC/WO emission features in the spectra of starburst galaxies. Our results will be used to derive accurate numbers of WN and WC stars in starburst galaxies. We also analyze the frequency and the WN and WC content of WR-rich galaxies in low metallicity samples; the theoretical predictions are found to be in good agreement with the observed frequencies. We also discuss the possible role of massive close binaries in starburst regions. If the starburst regions are formed in relatively instantaneous bursts we argue that, given their young age as derived from emission lines equivalent widths, (1) in the majority of the observed WR galaxies massive close binaries have not contributed significantly to the WR population, and (2) nebular He II 4686 emission is very unlikely due to massive X-ray binaries.

1 Introduction

The presence of large numbers of Wolf-Rayet (WR) stars in extragalactic star-forming objects (hereafter called WR-galaxies) of quite heterogeneous types is well established (see e.g. the compilation of Conti 1991). New serendipitous discoveries of WR galaxies have resulted from studies covering a wide range of topics, from the primordial He abundance determination (cf. Izotov et al. 1996a) to the nature of Seyfert galaxies (Heckman et al. 1996), and a considerable number of new observations can be expected with the new generation of 8-10 m class telescopes.

In most cases the presence of WR stars can be used as a powerful constraint on the age of the starburst episode (typically 3–8 Myr). The luminosity in the broad “WR-bump” (centered at λ 4650) can be used to derive the total number of WR stars present in the burst. From the strength of the nebular emission lines one can also determine the numbers of OB stars, which are the dominant contributors to the Lyman continuum flux. Additional information on the slope of the Initial Mass Function (IMF) can also be obtained (Meynet 1995; Contini et al. 1995; Schaerer 1996). When compared with evolutionary models, the derived WR/O number ratios indicate that star formation occurs in “bursts” short compared to the lifetime of
massive stars (Arnault et al. 1989; Vacca & Conti 1992; Meynet 1995). We refer the reader to the contribution by Vacca in these proceedings for a more detailed discussion of the properties and analysis of WR galaxies.

Many aspects of WR galaxies remain to be explored and there are several questions regarding the effect of large numbers of WR stars on their host galaxies that remain unanswered. Among these are the following, which we hope to address in this contribution: What fraction of starbursts have gone through or are currently in a WR-rich phase (Kunth & Joubert 1985; Meynet 1995) ? How frequent are WC stars in WR-galaxies and what is their importance (Meynet 1995; Schaerer 1996) ? Are WR stars responsible for the high excitation nebular lines observed in the optical spectra of some young starbursts (Garrett et al. 1991; Motch et al. 1994; Schaerer 1996) ? How important is the formation of WR stars in binary systems for WR-galaxies (Cerviño & Mas-Hesse 1996; Vanbeveren et al. 1996) ?

Answers to these questions require a detailed knowledge of the stellar populations in the host galaxies. The aim of our work is to provide new predictions for the WR populations in young starbursts, by explicitly taking into account the two main W-R subtypes, WN and WC stars. Our synthesis approach, based on well-tested evolutionary models, recent atmosphere models for O and WR stars, and observed line-strengths in WR stars, provides a number of relevant observable quantities. (A similar, but less comprehensive attempt, was carried out by Krüger et al. 1992.) Here we present preliminary results from this on-going work, which will be used for the future analysis of a large sample of WR-galaxies. It is our hope to shed some light on some of the aforementioned questions.

2 Evolutionary synthesis models

In this Section we briefly describe the adopted model ingredients for our evolutionary synthesis models, the most important input parameters, and the synthesized quantities.

Stellar evolution: We adopt the recent tracks of the the Geneva group, which cover the metallicity range from $Z=0.001$ (1/20 $Z_{\odot}$) to $Z=0.04$ (2 $Z_{\odot}$) (see Meynet et al. 1994 and references therein). As shown by Maeder & Meynet (1994) the models with enhanced mass loss rates reproduce a large number of observations regarding massive star populations, including WR/O star ratios in various nearby galaxies. These models are preferred over the earlier models of Schaller et al. (1992) adopted in the calculations of Vanbeveren (1995) and other population synthesis models (e.g. Cerviño & Mas-Hesse 1994, 1996).

Evolution of massive close binaries: In order to explore the effects of forming WR stars via mass transfer in massive close binaries on the total population of massive stars, we adopted the following simplified treatment of binaries. We used the recent calculations for various metallicities of de Loore & Vanbeveren (1994), who assume an initial mass ratio of 0.6, Case B mass transfer, and neglect the possibility of subsequent WR formation by the secondary. For our synthesis models one free parameter $f$ determines the binary population; $f$ is defined as the fraction of stars, which are primaries in close binary systems and which will therefore experience Roche lobe overflow during their evolution. The total WR population formed through the binary channel and the distribution among the different subtypes can be derived directly from the stellar lifetimes and the duration of the respective phases (see de Loore & Vanbeveren 1994). To determine the impact of binaries on observational properties (nebular lines and broad WR emission lines) we adopted an average Lyman continuum flux of $Q_0 = 10^{49}$ photons s$^{-1}$ which roughly corresponds to the average contribution from single WR stars at the time during the evolution of a burst population when binary stars are first expected to be formed. The broad WR line emission is treated in the same manner as for single stars (see below).
Continuum spectral energy distribution: To determine the stellar continuum spectral energy distribution at each time during a burst, we relied on three different sets of theoretical models: 1) For massive stars we used the spectra from the combined stellar structure and atmosphere (CoStar) models of Schaerer et al. (1996ab), which include non–LTE effects, line blanketing, and stellar winds. These models cover the entire parameter space of O stars during their main sequence evolution. 2) For later spectral types we use the line-blanketed plane-parallel LTE models of Kurucz (1992). 3) For W-R stars, we used the spherically expanding non–LTE models of Schmutz, Leitherer & Gruenwald (1992). In addition to the stellar continuum one also needs to account for the nebular continuous spectrum. Its emission is calculated assuming $T_e = 10$ kK, $N_e = 100$ cm$^{-3}$, and solar H/He abundances.

Nebular and WR emission lines: The strengths of the nebular recombination lines (primarily H$\beta$, H$\alpha$, He $\Pi \lambda$ 4686) are calculated with the same values of the electron temperature and density as used for the nebular continuum. We have compiled average stellar line fluxes of the strongest WR emission lines for WN, WC, and WO stars. We distinguish 5 WC subtypes as well as the WO subtype, as these objects show considerable differences in their line fluxes. We also include possible emission from OfI stars. The line fluxes have been taken from the following sources: Crowther (1996, private communication) and Smith et al. (1996) for WN stars, and Smith et al. (1990ab) for WC/WO stars. More details are given in Schaerer & Vacca (1996). The WR stage, including the WC subtype (see Smith & Maeder 1991), is determined by the surface abundances predicted from the evolutionary models.

Input parameters: In the present work we consider the time evolution of an instantaneous burst of star-formation. The basic parameters of our models are therefore the metallicity, the binary fraction, and the slope and upper mass cut-off of the initial mass function. Here, we adopt a Salpeter IMF with an upper mass cut-off of $120 M_\odot$. The results do not depend on the lower mass cut-off, as long as it is less than about $5 M_\odot$. Variations of the IMF slope are considered in Schaerer & Vacca (1996).

Synthesized quantities: The major predictions from our models include: (1) the relative populations of O stars (where an O stars is defined by $T_{\text{eff}} > 30$ kK), WN stars, and WC/WO stars, (2) emission line fluxes and equivalent widths of the following broad WR lines: He $\Pi \lambda$ 1640, N $\Pi$ $\lambda$ 4640, C $\Pi$/IV $\lambda$ 4650, He $\Pi \lambda$ 4686, total $\lambda$ 4650 WR-bump, C IV $\lambda$ 5696, and C IV $\lambda$ 5808, (3) the WR contributions to H$\alpha$ and H$\beta$, (4) the ionizing photon fluxes in the H, He I, and He $\Pi$ continua, and (5) the emission line fluxes and equivalent widths of nebular lines of H$\alpha$, H$\beta$, and He $\Pi \lambda$ 4686.

3 Probing WN and WC populations in starbursts

We will illustrate the model predictions for a burst with a metallicity of $Z = 0.004$, a typical value for the WR-galaxies analyzed by Vacca & Conti (1992). [The entire set of results, which depend strongly on metallicity, will be discussed in Schaerer & Vacca (1996).] The left panels in Figure 1 present the results from our standard models (Salpeter IMF, instantaneous burst, single star evolution), while the right panels include massive close binary stars (cf. Sect. 4). The lower left Figure shows the relative WR and populations as a function of the age of the burst. The WR-rich phase lasts from $\sim 2.5$ to 5.5 Myr. WC stars evolving from the most massive stars dominate the WR population from about $3 - 4$ Myr, while WNL stars are more numerous from $4 - 5.5$ Myr. Thus, the models predict a WC-rich phase shortly after the first appearance of WR stars. For an instantaneous burst the last period of the WR-rich phase is always dominated by WNL stars, as these objects represent the descendents of the least massive stars which barely manage to peel off their outer layers revealing the processed material resulting from H-burning.
Figure 1: Left panels: Time evolution of the equivalent width of the strongest WR lines (upper left) and WR/O star ratios including subtypes (lower left) at Z=0.004 for standard evolutionary models. Right panels: Models including massive close binaries for $f=0.2$. Upper right: same as upper left. Lower right: evolution of the relative He II/Hβ line intensities as a function of the Hβ equivalent width (solid line). The dashed line shows the contribution from single stars. The two “epochs” where WR stars are formed from single stars and by the binary channel are well separated in this diagram.

The upper left panel shows the corresponding evolution of the equivalent widths of the most important WR lines. The He II and N IV 4640 emission predicted before the WR rich phase is due to the (relatively large) contribution adopted for OIf stars. Broad He II 4686 emission usually dominates the optical spectrum except during the short ($\sim 1$ Myr) WC-rich phase, during which C III/IV 4650 dominates the broad classical “WR bump” and the presence of WC stars can be unambiguously deduced from the strong C IV 5808 feature. Although the predicted strength of N IV 4640 is relatively uncertain, its is always lower than that of He II 4686 except at solar or higher metallicities. This is an immediate consequence of the abundance effect pointed out by Smith et al. (1996). As expected, C III 5696 is very weak at $Z=0.004$; this feature is strong only in late WC stars, which are not found at low metallicities.

4 The frequency of WR-rich starbursts

The predictions illustrated above can be used to determine the WR content in individual starbursts and allow us to determine separately the WN and WC populations. In addition to the study of individual objects, however, a statistical analysis of a set of starburst galaxies also provides a test of the models, as recently stressed by Meynet (1995). Although large samples adequate for such statistical studies are not yet available, we would like to point out briefly some interesting results from the low metallicity samples of Izotov et al. (1994, 1996a) and Pagel et al. (1992), which have been obtained as part of a systematic determination of the primordial He abundance. Since the major goal of these studies is to obtain as many low metallicity objects as possible these samples are suited for statistical studies of starbursts over a low, and clearly specified metallicity interval.
The Izotov sample contains 33 objects with Z between ∼ 0.001 and 0.004, of which 14 exhibit WR features, including 4 WC with signatures. Thus ∼ 40 % of the objects show evidence of WR stars, and ∼ 30 % of those include WC stars. Similar, or even larger, percentages of WR detections are found in the Pagel et al. sample over a similar metallicity range. Interestingly these numbers are fairly close to the percentages of starbursts containing WR stars predicted from evolutionary models (Meynet 1995)[1]. The expected percentage is between ∼ 18 and 40 % for Z between 0.001 and 0.004; the duration of WC-rich phase is predicted to be ∼ 1/3 of the WR phase (see Fig. 1). An observational bias is introduced by the requirement that the [O III] 4363 line can be detected and reliably measured. This requirement favours inclusion of objects with the youngest bursts and could therefore lead to an overestimate of the percentage of WR-rich objects as compared to the definition used by Meynet (1995). This might be responsible for the apparent difference with the model predictions at low Z.

The approximate agreement between models and observations regarding the statistical number of WR-rich objects is very encouraging although admittedly the present samples are fairly small. In particular the detection of a significant fraction of WC stars at low metallicities gives strong support to the adopted high-mass-loss evolutionary models. In this context it is also interesting to note that to date no WR features have been detected in objects with metallicities below O/H ≤ 7.7–7.8 (Pagel et al. 1992; Izotov et al. 1996), corresponding to an absolute metal abundance of Z ≤ 0.0012–0.0015, or about 0.06Z⊙. Although no formal low metallicity cut-off for the presence of WR stars is expected from evolutionary models, this observed limit seems to be in fair agreement with the predicted sharp decrease in the duration of the WR phase between Z = 0.004 and 0.001 (cf. Meynet 1995).

5 The role of massive close binaries in young starbursts

Recent studies have begun to explore the importance of the formation of WR stars in massive close binaries (MCB’s) on massive star populations in starbursts (Cerviño & Mas-Hesse 1996; Vanbeveren et al. 1996). Here we briefly discuss some basic considerations, which are useful to estimate those circumstances in which binary stars may be of relevance for the WR populations in starbursts. An important property of binary models is that, because the high mass loss rate prevents a large increase in the stellar radius, primaries with initial masses M₁ > 40-50 M⊙ should, in general, avoid Roche lobe overflow (cf. Vanbeveren 1995); for those stars that do experience Roche lobe overflow, their evolution is nearly indistinguishable from that of single stars (Langer 1995). Therefore, in instantaneous bursts with ages ≤ 5 Myr the stellar population is unaltered by the formation of WR stars through the binary channel.

Do WR galaxies contain a significant population of WR stars formed through the binary channel? The observed Hβ equivalent width in the spectrum of an H II region exhibits a monotonic decrease with time can be used as a good indicator of the age of a starburst (e.g., Leitherer & Heckman 1995). Bursts with ages τ ≥ 5 Myr are predicted to have W(Hβ) < 60 Å for Z ∼ 0.001, while at larger metallicity the upper limit for W(Hβ) is even lower. An inspection of the compilation of WR galaxies given Conti (1991) reveals that most objects have large Hβ equivalent widths: 12 out of 37 objects have W(Hβ) < 60 Å, and only 3 show W(Hβ) < 30 Å. In fact, because of various physical effects which serve to artificially reduce the observed W(Hβ), these fractions are actually upper limits to the true number of WR galaxies with low equivalent widths. Therefore, most WR galaxies experienced bursts of star formation

[1]The values for the high mass loss models at Z = 0.004 in Table 1 of Meynet (1995) are erroneous. Furthermore the duration of the WC-rich phase given by Meynet is overestimated. This accounts for the difference between our results in Fig. 1, and those in Fig. 3 of Meynet (1995).
less than 5 Myr ago. If star-formation has taken place on such a short timescale compared to the lifetime of massive stars (“instantaneous burst”) roughly 70 to 90 % of the burst populations in WR galaxies are too young to be affected by WR formation through the binary channel and therefore they should be well described by single star models.

The link between population synthesis models and observable quantities. In recent studies Cerviño & Mas-Hesse (1996) and Vanbeveren et al. (1996) have included massive close binaries (MCB’s) in population synthesis models. They find that (1) the WR-rich phase of a starburst lasts much longer (up to 12-20 Myr) when MCBs are taken into account, (2) WR/O number ratios can be larger than those predicted by synthesis models including only single stars, and (3) even with a “standard” IMF the observed WNL/O ratios are well reproduced by their models (Vanbeveren et al. 1996). These findings require some remarks.

As shown above, in the vast majority of the observed WR galaxies the bursts are very young and therefore, in general, their WR population has probably not been formed through the binary channel. Older objects with a possibly large WR population remain to be found; however most searches are biased against finding such objects. Given the young age of the known WR galaxies, the “observed” WNL/O star ratios of Vacca & Conti (1992) cannot be compared to the large values obtained by Vanbeveren et al. (1996) in the “binary rich” WR phase. Moreover, as shown by Schaerer (1996) the observed WR/O population can be explained with single star models and a “standard” Salpeter IMF.

To allow for a direct comparison between synthesized stellar populations and observations the relevant observable quantities (line fluxes, equivalent widths etc.) need to be modeled (see Sects. 2 and 3). Predictions from exploratory calculations which also include binary stars are shown in Fig. 1 (right panel). The behaviour of the equivalent widths of the most important broad WR lines (upper right) nicely illustrates the prolonged WR phase. The lower right panel shows that, compared to the flux in Hβ, a relatively large flux in the broad He ii 4686 line can be obtained if binaries are included. However, as mentioned before, such behaviour can be obtained only at ages τ > 5 Myr corresponding roughly to W(Hβ) < 30–60 Å.

Massive X-ray binaries as the origin of nebular HeII emission? Based on the same age considerations we would like to mention several arguments regarding the role of high-mass X-ray binaries (HMXRB) in the origin of nebular He II emission in extragalactic H II regions (see Garnett et al. 1991; Schaerer 1996). There are several lines of evidence that indicate that HMXRBs are not the source of the nebular He II emission: (1) All the objects from the samples of Campbell et al. (1986) and Izotov et al. (1994, 1996ab) have large Hβ equivalent widths, corresponding to burst ages of less than ∼ 5 Myr. If nebular He II emission is due to HMXRB these systems must have had primaries with very large masses (M1 ≥ 40–50 M⊙) necessary to form neutron star remnants. Such a scenario for the formation of HMXRB seems to be very unlikely (van den Heuvel 1994). The age argument was also put forward by Motch et al. (1994). (2) Given the short duration of the X-ray emitting phase (∼ 5 × 10^4 yr, van den Heuvel 1994), it is very difficult to produce HMXRB in large numbers (e.g. comparable to the number of equivalent O7 stars in SBS 0335-052 according to Izotov et al. 1996b). (3) It is not clear why the spatial distribution of nebular He II should preferentially follow the continuum instead of the remaining emission lines as found by (Izotov et al. 1996b). (4) Motch et al. (1994) find that the He II emission and the X-ray emission are not spatially coincident, as would be expected if HMXRB are the source of the He II emission.

The above results render the MXRB hypothesis rather unlikely. In many objects WR stars appear to be a very likely source of the high energy photons needed to ionize He II (Motch et al. 1994; Schaerer 1996) although peculiar O stars close to the Eddington limit (Gabler et al. 1992) cannot be excluded. We also note that out of the 38 objects from Campbell et al. and
Izotov et al. (1994, 1996a) which have a definite measurement of He II, only 7 objects are found at very low metallicities (O/H < 7.72), for which WR features have never been detected.

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References

Arnault Ph., Kunth D., & Schild H., 1989, A&A 224, 73
Campbell A., Terlevich R., & Melnick J., 1986, MNRAS 223, 811
Cerviño M., & Mas Hesse J.M., 1994, A&A 284, 749
Cerviño M., & Mas Hesse J.M., 1996, ASP Conf. Series, Vol. 98, p. 174
Conti P.S., 1991, ApJ 377, 115
Contini T., Davoust E., & Considère S., 1995, A&A 303, 440
de Loore C., & Vanbeveren D., 1994, A&A 292, 463
Gabler R., Gabler A., Kudritzki R.P., Méndez R.H., 1992, A&A 265, 656
Garnett D.R., Kennicutt R.C., Chu Y.-H., & Skillman E.D., 1991, ApJ 373, 458
González-Delgado R.M., et al., 1994, ApJ 437, 239
Heckman T., et al., 1996, ApJ, submitted
Izotov Y.I., Thuan T.X., & Lipovetsky V.A., 1994, ApJ 435, 647
Izotov Y.I., Thuan T.X., & Lipovetsky V.A., 1996a, ApJ, submitted
Izotov Y.I., et al., 1996b, ApJ, submitted
Kunth D., & Joubert M., 1985, A&A 142, 411
Krüger H., Fritze-v. Alvensleben U., Fricke K.J., Loose H.-H., 1992, A&A 259, L73
Langer N., 1995, in “Wolf-Rayet Stars: Binaries, Colliding Winds, Evolution”, IAU Symp. 163, Eds. K.A. van der Hucht, P.M. Williams, Kluwer, Dordrecht, p. 15
Leitherer, C. & Heckman, T. M. 1995, ApJS 96, 9
Meynet G., 1995, A&A 298, 767
Motch C., Pakull M. W., & Pietsch W. 1994, in “Violent Star Formation, From 30 Doradus to QSOs”, Ed. G. Tenorio-Tagle, Cambridge University Press, p. 208
Pagel B.E.J., Simonson E.A., Terlevich R.J., & Edmunds M.G., 1992, MNRAS 255, 325
Schaefer D., 1996, ApJ 467, L17
Schaefer D., de Koter A., Schmutz W., & Maeder A., 1996a, A&A 310, 837
Schaefer D., de Koter A., Schmutz W., & Maeder A., 1996b, A&A 312, 475
Schaefer D., & Vacca W.D., 1996, ApJ, in preparation
Schaller G., Schaefer D., Meynet G., & Maeder A., 1992, A&AS 96, 269
Schmutz W., Leitherer C., & Gruenwald R., 1992, PASP 104, 1164
Smith L.F., & Maeder A., 1991, A&A 241, 77
Smith L.F., Shara M.M., & Moffat A.F.J., 1990a, ApJ 348, 471
Smith L.F., Shara M.M., & Moffat A.F.J., 1990b, ApJ 358, 229
Smith L.F., Shara M.M., & Moffat A.F.J., 1996, MNRAS 281, 163
Vacca W.D., & Conti P.S., 1992, ApJ 401, 543
Vanbeveren D., 1995, A&A 294, 107
Vanbeveren D., Van Bever J., & De Donder E., 1996, A&A, in press
van den Heuvel E.P.J., 1994, in “Interacting Binaries”, Saas-Fee Advanced Course 22, Eds. H. Nussbaumer, A. Orr, Springer, p. 263