Wolf-Rayet galaxies as probes of young stellar systems

Daniel Schaerer

Observatoire Midi-Pyrénées, 14, Av. E. Belin, F-31400, Toulouse, France (schaerer@obs-mip.fr)

Abstract. Wolf-Rayet (WR) galaxies provide detailed information on massive star populations in starbursts and thereby represent ideal objects to determine accurate ages for young systems, to measure the burst duration, and to probe the upper end of the IMF. WR galaxies play also a particular role in a variety of studies on star formation in Seyfert2/LINERS, dust production and local chemical enrichment, temperature fluctuations in HII regions, gas outflows and X-ray emission etc.

Different age indicators for young starbursts and WR galaxies are discussed. We summarise recent work on the burst properties of WR galaxies, massive star populations at different metallicities, and the use of WR galaxies as benchmarks for multi-wavelength models of starbursts and photoionisation models including IR fine structure lines.

1. Introduction

Among emission line galaxies, the so-called Wolf-Rayet (WR) galaxies are defined by the presence of one or several broad stellar emission lines in the optical (often called “WR bump”) attributed to WR stars (Conti 1991, Schaerer et al. 1999b). WR galaxies (or more accurately and independently of size, regions hosting detectable numbers of WR stars) are found among a large variety of objects including BCD, massive spirals, IRAS galaxies, Seyfert 2, and LINERs (Schaerer et al. 1999b).

Together with the UV P-Cygni lines (mostly Si iv, C iv, but also O vi; all originating in O stars) frequently observed in starbursts (e.g. Leitherer 1997, González Delgado et al. 1998), the WR lines are the most direct evidence of massive stars in these objects. Other lines, like e.g. H and He optical absorption lines due to O stars or UV photospheric metal lines from B stars, are generally weaker and/or more difficult to observe (cf. González Delgado et al. 1999, de Mello et al. 1999). All the above lines can be used to determine quantitatively the massive star populations (Wolf-Rayet, O, B) in the objects of interest. Compared to objects showing any of these spectral features, the main advantages of the more rare galaxies showing WR lines are the following: WR stars being the descendents of the most massive stars and a short-lived phase ($M_{\text{ini}} \gtrsim 25 M_\odot$),

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Given these basic considerations, WR galaxies are ideally used for studies on age datation of young systems, determinations of fundamental burst properties (IMF, SFR, etc.). They also allow to obtain constraints on stellar evolution models, e.g. at very low metallicities and serve as benchmarks for the modeling of UV-IR emission from starbursts. Results from such work is summarised in the present review.

In addition to these subjects, WR star populations play a particular role in a variety of other studies on:

- the importance of star formation in Seyfert 2 and LINERS (Heckman et al. 1997)
- dust production by WR stars (Williams 1995, Dwek 1998)
- local chemical enrichment by WR stars (Walsh & Roy 1987, Kobulnicky & Skillman 1996) and their possible influence on the primordial He abundance determination (Pagel et al. 1992, Esteban & Peimbert 1995)
- temperature fluctuations in HII regions (González-Delgado et al. 1994, Pérez 1996, Luridiana et al. 1999)
- the origin of optical–IR high excitation lines (Garnett et al. 1991, Schaerer 1996, Schaerer & Stasińska 1999)
- gas outflows and X-ray emission from starbursts (e.g. Stevens & Strickland 1998)

These issues will not, or only briefly, be discussed here. The reader is referred to the above selected references for more information. An overview of research on the WR phenomenon in stars and galaxies is found in the proceedings of the recent IAU Symposium 193 (van der Hucht et al. 1998).

2. Datation of young objects

A general review of the datation of young stars and stellar systems is presented by Leitherer (these proceedings). Here we focus on WR galaxies and the youngest objects.

**Age from the WR features:** The presence of WR stars indicates recent massive star formation. Stellar models (single stars) predict WR stars between ages of $\sim 2$ to $8$ Myr, the latter limit strongly depending on metallicity (cf. Maeder & Meynet 1994). The effect of rotation leading to additional mixing processes can also modify the lifetimes/ages of WR stars (cf. Meynet, these proceedings). Larger ages (up to $\sim 10$-30 Myr) can be obtained if WR stars form e.g. through Roche lobe overflow in massive close binary systems and possibly even from secondary mass gainer stars in such systems (see e.g. Vanbeveren et al. 1998, Mas-Hesse & Cerviño 1998). The exact binary scenarios and their frequency are not well established yet and fundamental tests e.g. on clusters remain
to be done. Assuming that the single star channel dominates the WR production at most metallicities (see e.g. Maeder & Meynet 1994) we thus conclude that the presence of the stellar features in WR galaxies indicates ages of 2-8 Myr for the bulk of this population. Including information on the metallicity, more refined age estimates can be made using evolutionary synthesis models (e.g. Schaerer & Vacca 1998, hereafter SV98).

Figure 1. Position of WR galaxies in metallicity (O/H) vs. H$\beta$ equivalent width (triangles, squares). Different greytones/colours indicate different samples. Solid lines denote the beginning/end of the WR-rich phase predicted by the SV98 models. Dashed lines indicate age steps of 1 Myr during the WR phase.

The $W(H\beta)$ age indicator: The H$\beta$ equivalent width provides another potential age indicator for young regions ionized by massive stars (cf. Copetti et al. 1986), which is commonly predicted by evolutionary synthesis models. In an instantaneous burst $W(H\beta)$ decreases rapidly with time. For obvious reasons the $W(H\beta)$–age relation is sensitive to the IMF slope and its upper mass cut-off, metallicity, the exact star formation history, and depends also on assumptions on the nebula (ionization boundedness etc.) Furthermore the measured $W(H\beta)$ can be reduced due to an underlying stellar population. Although this indicator is well known, even for HII regions no systematic comparisons have been undertaken to compare ages derived from $W(H\beta)$ to those derived from their stellar content. However, it is well known that regions with very large H$\beta$ equivalent widths such as predicted for populations of ages $\sim$ 0-1 Myr are not observed. The origin of this discrepancy is not understood yet.

A comparison of the observed and predicted $W(H\beta)$ for a large sample of WR galaxies is shown in Fig. 1 (see Schaerer 1998 for more details). Note that the bulk of the objects shown here represent star forming regions (e.g. giant HII regions etc.) in BCDs or spirals. The solid lines show the beginning and end of the WR phase for instantaneous burst models with a Salpeter IMF and $M_{up} = 120 M_\odot$. Fig. 1 shows that essentially all WR galaxies lie within the predicted
In the most populated metallicity range \((12 + \log(O/H) \sim 7.8 - 8.5)\) the observations also fully populate this domain. It can thus be concluded that on average the age and duration of the WR-rich phase predicted by the SV98 models for instantaneous bursts agree quite well with the observations. Despite the uncertainties mentioned above, the use of the \(W(H\beta)\) age indicator appears to work reasonably well for the known WR galaxies.

**Comparison with photometric indicators:** Devost (1999) has recently proposed the use of \((B-H)\) vs. \((H-K)\) color-color diagrams for the datation of young populations which allow to probe ages similar to those of WR galaxies. For unknown extinction his method allows the discrimination of regions younger and older than 4 Myr. With the availability of data on extinction, the time resolution is significantly improved. As shown by Devost (1999) for observations of Arp 299 the method yields a good agreement when compared with ages derived from the \(H\alpha\) equivalent width. This age indicator appears also to be confirmed by the spectroscopic detection of WR stars in knots B and C by Bill Vacca (see Schaerer et al. 1999b). Conversely BHK photometry could thus quite efficiently be used for a selection of regions hosting WR stars.

### 3. Stellar populations: burst properties and constraints on stellar models

In this Section we will summarise the main results on massive star populations in WR galaxies (see also Schaerer 1998 for a recent review).

**Burst properties of WR galaxies:** Two main conclusions could already be drawn from the early work of Arnault et al. (1989): 1) To reproduce the observed WR and O star populations bursts of very short duration ("instantaneous") are required. 2) The observed trend of increasing WRbump/\(H\beta\) intensities with metallicity is understood by the metallicity dependence of mass loss leading to an increased number of WR stars at high Z. These finding were largely confirmed by Vacca & Conti (1992) and all later studies.

More detailed studies of the massive star content of WR galaxies have been undertaken by Schaerer (1996), Schaerer et al. (1999a, hereafter SCK99), Huang et al. (1999), Mas-Hesse & Kunth (1999) and Guseva et al. (1999). The main results from the study of SCK99 are [where available comparison with other results given in parenthesis]: 1) Essentially instantaneous bursts \((\Delta t \lesssim 2-4\) Myr) are required to reproduce the observed WR line intensities. [Same as other authors.] 2) The majority of the observations can be reproduced with a Salpeter IMF. No clear case requiring a flatter IMF is found. [Similar result as Mas-Hesse & Kunth; cf. however Huang et al. 1999]. 3) The IMF in these regions must be populated up to large masses. For the case of I Zw 18, at \(Z \sim 1/50\) \(Z_\odot\), \(M_{\text{upp}}\) extending to 120-150 \(M_\odot\) is found (de Mello et al. 1998). 4) The relative populations of WN and WC stars detected clearly favour the high mass evolutionary models (cf. below).

The above results hold over a fairly wide range of metallicities \((1/50 \lesssim Z/Z_\odot \lesssim 1;\) cf. Schaerer 1998). The findings on the IMF slope and the upper mass cut-off are in agreement with several independent studies, e.g. stellar counts, UV line profile modeling of starbursts, photoionization models for HII galaxies etc. (references in Schaerer 1998). Interestingly, however, there are several studies
indicating the possibility of a lower value for $M_{up}$ at metallicities above solar (e.g. ULIRG, HII regions: Bresolin et al. 1999). A search for WR stars in metal rich regions will place direct constraints on the upper end of the IMF in such environments.

**Stellar evolution models at different metallicities:** The WR populations in starbursts are often found in clusters or super star clusters. In this case, and provided the bulk of the population has been formed coevally, the analysis of integrated spectra can thus provide powerful constraints on stellar evolution models. The case of mostly extra-galactic HII regions is summarised in the following.

SCK99 obtained high S/N spectra with sufficient resolution to resolve the main components of the WR bump (He II $\lambda$4686, N III $\lambda$4640+ C III $\lambda$4650, and others) and including the “red WR bump” (C IV $\lambda$5808) allowing the first detailed analysis of both the WN and WC star population in their objects. The distinction of WN and WC subtypes is of special interest since in particular their relative number is very sensitive the detailed evolutionary scenarios (mass loss, mixing; cf. Maeder & Meynet 1994, Meynet these proceedings, SV98). The analysis of SCK99 and de Mello et al. on I Zw 18 ($1/50 Z_\odot$) shows that stellar evolution models with high mass loss are clearly favoured, both to reproduce the observed WR and O populations and especially the WC/WN ratio. A similar study was undertaken more recently by Guseva et al. (1999) who analyse the WN, WC and O star content in a larger sample of WR galaxies. As above, good agreement is found with the high mass loss stellar models for the majority of objects. Guseva et al. (1999) find a possible underestimate of the WR population at very low metallicities ($\lesssim 1/10 Z_\odot$).

It is understood that part of the “requirement” for the high mass loss (cf. Schaerer 1998) may be compensated by additional mixing processes leading to a similar prolongation of the WR phase (cf. Meynet, these proceedings). In any case both the well known stellar census in the Local Group (cf. Maeder & Meynet 1994) and new data from integrated populations place important constraints on the evolutionary models. The new studies considerably extend the range of available metallicities to very low $Z$.

4. **WR galaxies as benchmarks for UV–IR modeling**

Since WR galaxies provide quite severe constraints on age and their massive star population they offer a special opportunity and testbed for starburst models, such as multi-wavelength evolutionary synthesis models, photoionisation models etc. A brief summary of such analysis undertaken recently shall be presented here.

**Multi-wavelength analysis:** A multi-wavelength study of 17 blue compact galaxies (BCD), the majority of them WR galaxies, was presented by Mas-Hesse & Kunth (1999). The results on the IMF slope and burst duration in the WR galaxies confirms those discussed above (e.g. SCK99). From UV–optical observations obtained through essentially identical apertures Mas-Hesse & Kunth (1999) find some objects with a non-negligible contribution from an older population to the optical light. They also confirm earlier findings showing a smaller extinction derived from the stellar continuum compared to Balmer emission lines.
Finally, the general agreement between predicted and observed far-IR emission suggests only a negligible fraction of hidden star formation in their objects. On the other hand, multi-λ observations of the prototypical starburst NGC 7714, also a known WR galaxy, reveal an important deficit of UV light compared the population observed in the IR (Goldader et al. 1999; see also Leitherer these proceedings).

**Photoionisation models:** Tailored photoionisation models of WR galaxies (or more precisely extra-galactic H\textsc{ii} regions hosting WR stars) have recently been constructed for NGC 2363 and I Zw 18 by Luridiana et al. (1999) and Stasińska & Schaerer (1999) respectively. Both studies make use of state-of-the-art evolutionary synthesis models including appropriate WR atmosphere models for the description of the radiation field. The presence of WR signatures and/or nebular He\textsc{ii} λ4686 emission attributed to these stars provides an important constraint in both studies.

Adopting the metallicity of NGC 2363 derived by standard methods, Luridiana et al. (1999) show that is not possible to reproduce the main optical emission line ratios considering a wide range of parameter space (IMF, age, and nebular parameters). From their failure the authors suggest a larger metallicity, which could be due to temperature fluctuations in the nebula.

Spectroscopic data and HST Hα images of I Zw 18 (NW region) providing information on its stellar content, nebular density distribution, and line emission were used by Stasińska & Schaerer (1999) to construct a detailed photoionisation model of this well known object. The main results from their study is that even taking strong deviations from the adopted ionizing radiation field and additional X-rays into account, photoionisation models underpredict [O\textsc{iii}] λ4363/5007, similarly to the case of NGC 2363 above, which indicates a missing energy source. This finding is of importance for elemental abundance determinations and our understanding of H\textsc{ii} regions in general. The origin of this discrepancy (shocks, conductive heating, ?) remains to be understood.

**Modeling IR emission lines:** To study the use of IR fine structure lines as potential indicators of star formation properties (IMF, \(M_{\text{up}}\), age, etc.; cf. Lutz et al. 1998, Colbert et al. 1999) in obscured systems we have recently constructed a combined evolutionary synthesis + photoionisation model for the WR galaxy NGC 5253 observed by ISO (Schaerer & Stasińska 1999, hereafter SS99). Modeling of this armorphous galaxy hosting two main ionizing clusters with a relatively well known stellar content should provide an ideal test-ground before stepping to more complex systems like M82, ULIRG etc.

As shown in SS99 the ionization structure of H, He, and O as revealed by the optical and IR emission lines is well reproduced. The presence of WR stars also explains the high excitation of this objects as indicated by the He\textsc{ii} λ4686 and O [iv] λ25.9 μm emission. Interestingly the IR line ratios of [Ne \textsc{iii}]/[Ne \textsc{ii}], [Ar \textsc{iii}]/[Ar \textsc{ii}], and [S \textsc{iv}]/[S \textsc{iii}] are predicted too strong for a single ionisation parameter fitting the above constraints. This implies that the use of these line ratios as diagnostics for the massive star population would lead to inconsistent results. The differences may be due to a more complex galaxy structure than assumed in the model, inadequacies in the ionizing spectrum, or erroneous atomic data (SS99). Work is in progress to establish how general this type of discrepancy is and to understand its origin. As this first test shows, caution needs to
be applied when interpreting IR fine structure lines in terms of star formation properties.

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