Wolf-Rayet Stars in Starburst Galaxies

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Abstract

Wolf-Rayet stars have been detected in a large number of galaxies experiencing intense bursts of star formation. All stars initially more massive than a certain, metallicity-dependent, value are believed to experience the Wolf-Rayet phase at the end of their evolution, just before collapsing in supernova explosion. The detection of Wolf-Rayet stars puts therefore important constraints on the evolutionary status of starbursts, the properties of their Initial Mass Functions and their star formation regime. In this contribution we review the properties of galaxies hosting Wolf-Rayet stars, with special emphasis on the factors that determine their presence and evolution, as well as their impact on the surrounding medium.

Key words: Wolf-Rayet stars; starburst galaxies; initial mass function.

1 Introduction

In the last 20 years, Wolf-Rayet stars have been detected in several extragalactic objects. Allen et al. (1976) [1] identified for the first time the characteristic He II $\lambda$4686 broad atmospheric emission line in He 2-10. Conti (1991) [5] listed already 37 objects showing WR features, a number which was increased

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to more than 130 in Schaerer and Vacca (1999) [15], and which is continuously increasing. The WR features are broad, but generally weak, so that they can be detected only in spectra with high signal to noise in the continuum. This explains why they were not identified in the first years of emission line galaxies spectroscopy. The detectors narrow dynamical range prevented having good signal to noise simultaneously on the bright emission lines and in the weak continuum of these galaxies. More careful searches in the last years have allowed to also identify the broad feature around CIV $\lambda5808$ attributed to WC stars, a subtype of WR stars characterized by strong and broad C emission lines. We show in Fig. 1 the optical spectrum of IZw 18, with the identification of some typical WR lines.

Wolf-Rayet stars have been found in very different extragalactic environments: Giant HII regions, Blue Compact galaxies, generic emission line galaxies, IRAS galaxies, Seyfert galaxies,..., in general, always in regions experiencing a strong episode of massive star formation. This fact provided in the 80’s a definitive support to the so-called “Conti scenario”, according to which WR stars were the descendants of massive stars, experiencing this short evolutionary phase (around 500,000 years) just before collapsing into a supernova
explosion. Conti (1991) [5] successfully proposed the term “Wolf-Rayet galaxies” to group all the galaxies hosting WR stars. Given the very different kind of objects in which WRs have been identified and the fact that their detection depends in most cases just on the observational strategy, this term has to be taken with care. I Zw 18 could be a prototype for that. Being the most metal deficient galaxy known, it has been observed for years aiming to measure in detail the intensities of the different emission lines, with no WR feature being detected at all. However, long integrations on big telescopes allowed two independent groups to identify in 1997 the WR features around H\(\text{e}\)II and CIV, adding this object to the WR galaxy list (Izotov et al. 1997 [6], Legrand et al. 1997 [8]).

In this contribution we will review the parameters that control the presence of Wolf-Rayet stars in star-forming environments, as well as their effects on the surrounding medium. Our goal will be to summarize what the detection of Wolf-Rayet stars can tell us about the properties of massive star-formation episodes in different environments.

2 What can we learn from the presence of WR’s?

The detection and quantification of the number (and type!) of Wolf-Rayet stars, and their ratio to OB stars, provide a bulk of information about the intrinsic properties of the different star formation episodes, like Initial Mass Function slope and limits, star formation regime, and so on. Let’s summarize first which factors drive the formation of WR’s in star-forming environments.

2.1 What controls the formation of WR’S?

As predicted by present stellar evolutionary tracks, there are mainly three parameters controlling the formation of WR’s:

- Metallicity.
- Initial Mass Function (IMF) limits.
- Properties of binary systems.

The Wolf-Rayet phase is characterized by the ejection via strong stellar winds of the outer layers of evolved massive stars. The efficiency in powering these winds is clearly a function of the metallicity, so that the lower the metallicity, the higher the initial mass required for a star to become a WR. The precise values for this mass limit depends also on the mass loss rate prescriptions and the rotation properties of a given star. Following a conservative mass loss rate
scenario, Mas-Hesse and Kunth 1991 [10] and Cerviño and Mas-Hesse 1994 [2] estimated the lower mass limit for WR formation at solar metallicity to be 32 $M_{\odot}$. Lower and more realistic mass limits are reached if the mass loss rate are somewhat enhanced, as discussed in (Schaerer and Vacca 1998 [15]). In general we can say that a star will become a WR if its initial mass is above 20 $M_{\odot}$ for solar metallicity, and above 80 $M_{\odot}$ at $Z = Z_{\odot}/10$. Therefore, the detection of a significant number of WR stars in low metallicity environments, as in IZw 18, directly implies that the upper mass limit of the IMF has to be close to 100 $M_{\odot}$.

The evolution of massive stars in binary systems can also lead to the formation of WR’s. Around 50% of massive stars are believed to form in binary systems, out of which around 5% are expected to evolve as massive close binaries. Such close binaries experience different processes of mass transfer during their evolution, which can lead to the formation of WR stars at ages where no WRs would exist according to the evolution of single stars (Cerviño 1998 [3], Vanbeveren 1998 [17] and references therein, Cerviño et al. 1999 [4]). First, a star can lose completely its outer envelope at the end of the H burning phase, with a naked core emerging which could have very similar properties to single WR stars. Second, accretion of mass would allow a star of initial medium/low mass to evolve as an initially massive star, becoming a WR at late evolutionary stages of the starburst. Summarizing, while the standard Conti scenario predicts the presence of WR stars only between 2 and 6 Myr after the onset of the burst (only 3 to 4 Myr at low metallicities!), the binary channel predicts a rather constant amount of WR stars between 5 and around 20-30 Myr, as shown in Figs. 2 and 3.

2.2 WR features detectability

In the previous section we have summarized the parameters affecting the presence of WR stars at a given time during a star formation episode. But even if they are present, their detection and quantification is furthermore affected by some additional questions:

- Star formation regime.
- Underlying stellar population.
- Differential reddening.

It has been well established that the present star formation rates showed by several starbursting galaxies can not have been maintained over long periods of time without exhausting the estimated original amounts of gas. It seems that massive star formation proceeds in these objects as (maybe repeated) short-lived, very intense episodes. The question now is how short are really
Fig. 2. Predicted number of WR stars as a function of the abundance of binary systems. All WRs appearing after 6 Myr are formed by mass transfer processes in massive close binaries. More details are given in Cerviño et al. (1999) [4].

Fig. 3. Predicted population of Wolf-Rayet stars as a function of metallicity, assuming 50% of binary systems and Salpeter’s IMF.

these episodes: almost instantaneous or extended over tens of million years? Several arguments point towards almost coeval star formation, i.e., all stars (at least, all massive stars) would have been formed almost simultaneously, or in any case within few million years. The ignition of hundreds or thousands of massive stars within relatively small volumes and within relatively short times would probably inhibit the further formation of stars, at least for several
million years, until the most massive stars start to fade out.

The detection of Wolf-Rayet stars provides important constraints on this issue. In extended star formation scenarios massive stars would be continuously formed during tens of million stars. Since the WR phase lasts for only around 500,000 years, the net effect is that the expected $L(WR)/L(H\beta)$ ratio would be significantly smaller than for coeval starbursts. We show in Fig. 4 the predictions for this ratio at different metallicities and assuming different IMF slopes, both for an instantaneous burst and for an extended star formation episode. We have plotted on the figures the mean values compiled by Mas-Hesse and Kunth (1999) [11]. It can be seen that, first, the distribution of observed values fall rather well within the predictions of coeval models, while, second, the observations are barely consistent, at most, with the predictions of extended star formation episodes. We can conclude, therefore, that the formation of massive stars in Wolf-Rayet galaxies proceeds almost coevally, in any case within few million years.

Another factor strongly affecting the detectability of the WR features on the stellar continuum spectra is the presence of an underlying, older stellar population. Up to now, WR stars have been generally detected in galaxies whose optical continuum is mostly dominated by the newly formed, massive stars, with older stars contributing less than 50% to the total continuum at around 5000 Å (see the examples in Mas-Hesse and Kunth 1999 [11]). But if a star-

Fig. 4. Predicted $L(WR)/L(H\beta)$ ratio for different metallicities and two extreme IMF slopes. The data points correspond to the compilation of Mas-Hesse and Kunth (1999) [11].
burst takes place in a galaxy with an important older stellar population, the WR features would be diluted within the optical continuum, and would be harder to be detected.

Finally, two additional factors can lead to significant errors in the quantification of the relative WR vs. OB stars population as derived from the observed $L(WR)/L(H\beta)$ ratio. First, it has to be taken into account that the $L(H\beta)$ emission is spread over a relatively large area ionized by the cluster of young, massive stars. On the other hand, the WR features are associated to the stellar population, and are therefore spatially restricted within a much smaller region. Therefore, if $L(WR)/L(H\beta)$ is derived from single narrow slit observations, the ratio can be severely overestimated, since it would have been contributed by most WR stars in the region, but only a fraction of the total H\beta flux. Mas-Hesse and Kunth (1999) [11] have estimated that this problem can distort the derived ratios by even an order of magnitude, making them useless for comparison with theoretical predictions. And second, it has been established in the last years that the extinction affecting the stellar continuum (and therefore the WR features) might be in some cases significantly smaller than the extinction affecting the Balmer emission lines (Schaefer and Vacca 1998 [15]). Maíz-Apellániz et al. (1999) [13] showed the spatial decoupling of stars, gas and dust in the star-forming regions of NGC 4214, which are rich in WR stars. It seems that the stellar winds can be very efficient in some cases in blowing away both the nebular gas and the dust grains, leaving the massive stellar cluster within relatively dust-free volumes. On the other hand, dust particles were detected mixed with the nebular gas, yielding relatively large extinctions on the Balmer emission lines. Maíz-Apellániz et al. (1999) [13] estimated that this effect could yield to an overestimation of the observed $L(WR)/L(H\beta)$ ratio by a factor between 2 and 5.

We conclude therefore that the quantification of the relative number of WR over OB stars in star-forming regions can be severely overestimated by different effects. Therefore, reliable constraints on the properties of the star formation episodes can only be derived when different observational parameters are analyzed simultaneously, including $L(WR)/L(H\beta)$, $W(H\beta)$, $EW(WR)$,... as discussed in more detail by Mas-Hesse and Kunth (1999) [11].

2.3 Effects of Wolf-Rayet stars on the surrounding medium

As we have commented above, WR stars appear as the effect of strong stellar winds blowing out the outer atmospheric layers of evolved massive stars. The detection of WR’s traces therefore the presence of clusters rich in very massive stars, which are significantly affecting their surrounding interstellar medium in many ways:
Large amounts of mechanical energy are being injected into the medium, even before the production of the first supernova explosions after the onset of the burst. Leitherer et al. (1995) [9] and more recently Cerviño et al. (1999) [4] have evaluated the amount of mechanical energy released by these powerful winds. It would be enough to blow out the surrounding nebular gas, leading to an empty cavity free of gas and dust. Kunth et al. (1998) [7] detected outflowing gas apparently powered by the central starburst in a number of galaxies. Fig. 5 shows the profile of the Ly\(\alpha\) emission line, clearly absorbed at the blue wing by neutral gas moving at several hundreds of km/s. The mechanical energy released would imply that the chemical enrichment associated to a new generation of stars wouldn’t become evident immediately, since the enriched gas could be thrown away to relatively large distances by these gas outflows, as proposed by different authors in the last years (see the contribution from G. Tenorio-Tagle in this volume).

When a star enters the Wolf-Rayet phase, its naked He core at a very high effective temperature (around 100,000 K) can become visible, producing so a source of rather hard ionizing radiation, much harder than the ionizing flux associated to Main Sequence OB stars (below 50,000 K in any case). This hard ionizing flux can produce a number of emission lines not usually found in HII regions. Schaerer (1996) [14] proposed that some kind of WR stars could provide enough hard ionizing photons to explain the narrow HeII $\lambda_{4686}$ detected in some, but not in all, starburst galaxies.
3 Summary and conclusions

The identification of Wolf-rayet stars in starburst environments in the last 20 years has helped to place strong constraints on the properties of these massive star formation episodes. We know presently that these starbursts are apparently short-lived (all massive stars are essentially coeval), that the Initial Mass Function in these regions is almost always close to Salpeter’s one (with slope $\alpha = 2.35$), with stars of initial masses around $100 \, M_\odot$ at least. Most of these starbursts formed their massive stars less than around 6 Myr ago, but this is probably a selection effect, since after this age the ionizing flux fades rapidly and the objects do not look like “emission line galaxies” any longer. There are nevertheless a number of questions still open:

- The starbursts in which WR stars have been detected seem to have been generally very short-lived. But, can we extrapolate this conclusion to all starbursts, including those in which no WR stars have been (yet) detected?
- What are the constraints that can be derived from the WN/WC ratios observed in different galaxies?
- How does rotation affect the predictions of the synthesis models used up to now? A. Maeder provides in this volume a summary of the state of the art evolutionary tracks including stellar rotation.
- Are there really Wolf-Rayet stars at evolved stages of the cluster, when the emission line strengths are very small, as predicted by the models including the evolution of binary systems? Would these WR’s show the same features as WR stars formed along the Conti scenario?

Let’s continue searching for Wolf-Rayet stars in different environments in order to help solve these open questions in the near future.

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