Wolf-Rayet Stars
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The Wolf-Rayet Population and ISM Interaction in Nearby Starbursts

J. R. Walsh[1], **A. Monreal-Ibero**[2], **J. M. Vílchez**[3], **E. Pérez-Montero**[3], **J. Iglesias-Páramo**[3], **C. Sandin**[4], **M. Relaño**[5] **& R. Amorín**[5]
[1]*European Southern Observatory, Garching, Germany*
[2]*GEPI, Observatoire de Paris, Meudon, France*
[3]*Instituto de Astrofísica de Andalucía – CSIC, Granada, Spain*
[4]*Leibniz-Institut für Astrophysik Potsdam, Germany*
[5]*Departamento de Física Teórica y del Cosmos, Universidad de Granada, Spain*
[6]*INAF-Osservatorio Astronomico di Roma, Italy*

The interaction between massive star formation and gas is a key ingredient in galaxy evolution. Given the level of observational detail currently achievable in nearby starbursts, they constitute ideal laboratories to study interaction process that contribute to global evolution in all types of galaxies. Wolf-Rayet (WR) stars, as an observational marker of high mass star formation, play a pivotal role and their winds can strongly influence the surrounding gas. Imaging spectroscopy of two nearby (<4 Mpc) starbursts, both of which show multiple regions with WR stars, are discussed. The relation between the WR content and the physical and chemical properties of the surrounding ionized gas is explored.

1 Local starbursts as WR laboratories

Nearby blue compact galaxies (BCGs) are the nearest examples of actively starbursting galaxies. They display more vigorous star formation rates and higher gas and stellar mass than the Magellanic Clouds and provide the opportunity to study star formation in low and very low Z environments, comparable to younger, and more active, galaxies at high z. Some of these galaxies display Wolf-Rayet (WR) star features, such as the blue bump around 4650 Å or red bump around 5800 Å, in their integrated spectra and have been named *WR galaxies*. But this is not really a type, but rather a selection effect of viewing a starburst at the time when the high mass stellar content of a single strong starburst is evolving through the H and He burning phases.

Surveys of starburst galaxies to search for WR features in integrated spectra, such as the massive study of SDSS emission line galaxies with EW (Hβ) $\geq$ 2 Å by Brinchmann et al. (2008), show that a small fraction of the emission line galaxies (around 0.2%) exhibit WR features in their integrated spectra. Our approach is to select a few nearby starburst galaxies and study in detail with integral field spectroscopy the interplay between massive star formation and the surrounding gas, the spectral properties of their WR stars and the relation to the general stellar population.

2 Mapping gas and stars in BCGs

Three integral field units (IFUs) have been employed for this study: on the VLT the FLAMES Argus and VIMOS IFU, and on Gemini GMOS. All have subarcsecond spaxel size and fields of view well-matched to map nearby BCGs. Use of an IFU avoids slit biasing resulting from preselection based on surface brightness morphology in line or continuum. Nearby BCGs allow single clusters or super star clusters (SSCs) to be distinguished. From the datacubes, regions can be flexibly delimited based on various parameters, such as line ratios, stellar colour, WR feature, etc. By comparing WR star and emission line properties to resolved stellar photometry, such as from HST imaging in optical and UV, the luminosity, ionizing flux, age and stellar content (WR/O ratio) can be assessed. Studies of two starburst galaxies at <4Mpc, NGC 5253 and NGC 625, are highlighted.

2.1 NGC 5253

NGC 5253 was among the first blue compact galaxies to have a WR feature (blue bump) identified, after He2-10 (Campbell et al. 1986; Walsh & Roy 1987). It is an irregular, low Z (0.5 $Z_\odot$) starburst H II galaxy in Centaurus, at ∼3.8Mpc with many young stellar clusters, including two SSCs (masses $\sim 10^6$ $M_\odot$) in its embedded core. Infrared images show a nucleus with central starburst, a spiral dust feature, a disk of star forming regions and a warped rotating gas disk (observed in H I, H II and CO). It has been suggested that the current starburst activity was initiated by an interacting H I plume from nearby M83 (Kobulnicky & Skillman 2008).

It is still the best observed example of an extended enhanced N region (Walsh & Roy 1989), which is centred on the central SSC. However the other elements, O, He, Ar, S, etc display uniform abundance distribution. With FLAMES Argus (R∼12000) and GMOS IFU (R∼8000), the optical spectra (3500–7300 Å) were observed and lines fluxes and velocities, stellar continuum and line ratios over 12×8″

fields (∼210×130pc) were studied and extinction, electron density (N_e), temperature (T_e) and abundance maps derived (Monreal-Ibero et al. 2010). Fifteen regions were defined based on various criteria, such as blue bump (He II+N III), presence of narrow (nebular) He II line, and young star clusters resolved by HST (Harris et al. 2004), and intercompared (Monreal-Ibero et al. 2012). The occurrence of the red bump was studied with the GMOS IFU data (Westmoquette et al. 2013). An extensive study of ionized He in NGC 5253 (Monreal-Ibero et al. 2013) did not reveal an enhancement of He corresponding to the N enrichment.

The SSC in NGC 5253 presents both blue bump (predominantly WN) and red bump (WC) features, extended N^+/H^+, higher N_e and broad line profiles, the latter suggesting outflow. A second N enriched region was detected in an older (10 Myr) cluster (#3) with no WN signature (but narrow He II emission; the WR red bump has not yet been observed, but the presence of WC stars is predicted). Many regions with distinct WN and or WC features, such as at the position of a UV cluster, and three other regions (W-R 1, 4 and 5) were identified. Figs. 3 and 4 of Westmoquette et al. (2013) and Fig. 10 of Monreal-Ibero et al. (2010) show the location of all identified regions. From the size of the N-enriched region on the SSC (80×35 pc) and the emission line velocities, a timescale for N enrichment of $\leq$ 1 Myr is estimated.

Four other distinct regions with narrow (nebular?) He II but no clear evidence of very young clusters or blue bump emission were identified (see Fig. 12 in Monreal-Ibero et al. 2010). GMOS observations showed, however, how one of them (He II-1) was spatially associated to red bump emission. After a re-inspection of the FLAMES data, it was noticed that the relatively older cluster #3 presented He II nebular emission (see Fig. 1). This has not been reported so far. Interestingly enough, this region is spatially coincident with the secondary area of N enrichment in this galaxy. In a scenario where this enrichment is caused by WR stars, given both the age of the cluster and the extra amount of N in the region, this cluster is a candidate to host evolved/older versions of WR stars (i.e., WC, or even WO, stars). However, the cluster was not observed with GMOS and further spectroscopic observations would be needed to test this hypothesis.

2.2 NGC 625

The Sculptor group dwarf SB galaxy NGC 625 (∼3.9 Mpc), has a similar metallity to NGC 5253 but slightly higher mass $\sim 10^{8.3}$ $M_\odot$, with a central extended starburst. It has a more prominent underlying stellar disk and well-defined (old) radial population gradient. IFU spectroscopy with VIMOS in two fields (R ∼ 3000) reveals five compact regions with WR N III/He II signature (and one with only C IV) without general correspondence with blue stellar continuum peaks.

Data reduction and processing will be presented in a forthcoming contribution (Monreal-Ibero et al., in prep.). A first inspection of the distribution of the WR emission (see Fig. 2) shows that: i) WR emission in this galaxy is extended and shows peaks of emission in multiple locations; ii) the peaks for the *blue bump* emission may or may not coincide with those of the *red bump* emission; iii) in general, these blue/red WR peaks do not necessarily coincide with features in the overall general stellar distribution. The stellar distribution presents several independent peaks of emission. The most important one is associated with the peak of emission in Hα and with the strongest peak of the *blue bump* emission. Additionally, the overall stellar distribution presents some peaks which are associated to a plethora of young (i.e., <20 Myr) stars identified by means of HST broad-band imaging (Cannon et al. 2003; McQuinn et al. 2012). However, no WR emission is found in any of these peaks. In general, the *blue bump* emission is more concentrated and centralized that the *red bump* emission. Indeed the only WR emission detected in region #2 is the red bump; this region is situated at a distance of about 400 pc from the peak of emission in Hα. These results are in accord with the spatially resolved star formation history for the galaxy (McQuinn et al. 2012).

3 General deductions

Nearby starburst galaxies, although few in number, allow a privileged view on the earliest stages of clustered high mass star formation. Although this work is only based on two galaxies, the results refer to 22 WR regions. Monreal-Ibero et al. (2012) summarize the diversity of WR pollution in nearby starburst galaxies. Four cases can be distinguished:

i) No WN or WC stars and no N enrichment (default scenario);

ii) WN and WC stars and N enrichment (NGC 5253, SSC);

iii) WN and/or WC stars and marginal N enrichment (normal scenario; NGC 5253 cluster and possibly NGC 625);

iv) N enrichment and no detectable WN presence, but candidate for WC presence (NGC 5253 cluster #3).

It appears that WR stars can provide N enrichment in special circumstances, but witnessing the process of pollution itself requires fine tuning of conditions, age, confinement, etc.

The presence of narrow He II 4686Å emission also provides several test cases:

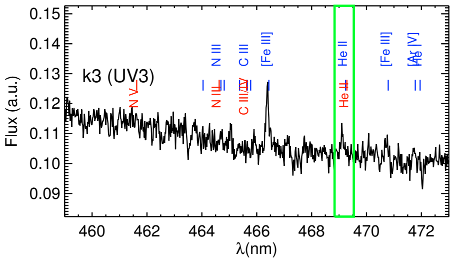

Fig. 1: Spectrum showing nebular He II in the NGC 5253 cluster ♯3. The positions of the nebular emission lines are indicated with blue ticks and labels, while those corresponding to Wolf-Rayet features appear in red. The green rectangle marks the position of the He II nebular emission line.

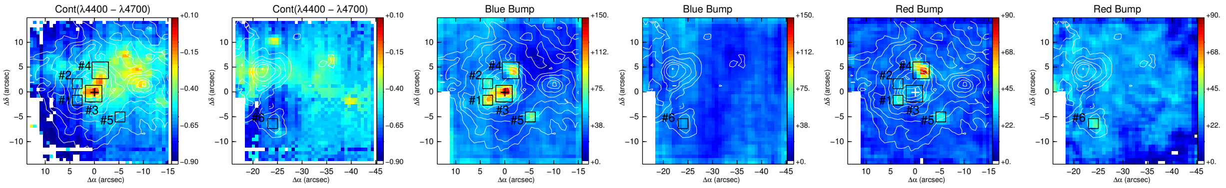

Fig. 2: Maps showing the location of the Wolf-Rayet features with respect to the overall stellar population in NGC 625 (Monreal-Ibero et al. in prep). *Two left maps:* Emission line free stellar continuum. *Two central maps:* WR blue bump emission. *Two right maps:* WR red bump emission. Every map displays contours tracing the observed Hα flux in steps of 0.3 dex as derived from Gaussian fitting. Square apertures used to extract spectra at the locations presenting WR emission are shown and numbered in black and the cross marks the peak of Hα emission. Orientation is north up, east to the left.

i) High EW (Hα) emission, no He II, no WR stars (default scenario);
ii) High EW(Hα) emission, no He II, WN and or WC stars;
iii) He II emission, no WN or WC star broad line signatures;
iv) He II emission, WR and/or WC star presence.

In the absence of other indicators (high velocity shocks, high mass X-ray binaries or clusters with many low mass X-ray binaries), very young massive O stars, or hot late-type WR stars, such as WC and WO, may explain the narrow He II 4686Å emission.

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Carolina Kehrig: Regarding the origin of nebular He II emission, you might be interested in having a look at the paper Kehrig et al. (2015).

Jeremy Walsh: Thank you. This galaxy has much lower metallicity than NGC 5253 and NGC 625 starbursts. I was considering, but a very important datum for exploring the effects of metallicity on WR and ISM interaction.

John Eldridge: I'm going to say binaries again but in this case this is close enough that if you check in HST you might see the source in an image. And that would be the first detection of one of these low mass helium stars.

Jeremy Walsh: At this distance the cluster may be too mesh and difficult to see individual stars.

Yes, true. I'm just thinking of the SN progenitor detections where we can see the progenitors at these distances.