Wolf-Rayet Stars
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Luminous Wolf-Rayet stars at low metallicity

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The evolution of massive stars in very low metallicity galaxies is less well observationally constrained than in environments more similar to the Milky Way, M33, or the LMC. We discuss in this contribution the current state of our program to search for and characterize Wolf-Rayet stars (and other massive emission line stars) in low metallicity galaxies in the Local Volume.

1 Resolved stellar populations

The evolution of massive stars is one of the key input parameters for understanding the formation and evolution of galaxies. The stars provide the ionizing and mechanical feedback into the ISM of their host galaxy and its circumgalactic environment. While these processes are hard to study directly during the epoch of galaxy formation and early evolution, we can use proxies at low redshift, which resemble in many ways the early universe objects. The proxies are the strongly starforming dwarf galaxies with very low metallicity. Using HST and high resolution ground-based imaging it is possible to study the resolved massive star content in such nearby galaxies (e.g. Dalcanton et al. 2009).

Recent progress in stellar evolution models of rotating massive single stars, (e.g. Meynet & Maeder 2005; Brott et al. 2011; Georgy et al. 2012) and binary stars (e.g. Vanbeveren et al. 2007; Eldridge et al. 2008) lead to a bewildering zoo of different evolutionary paths for massive stars and their end products. Testing these scenarios requires detailed observational tests, especially at very low metallicity, which hampers the measurements by, for example, decreasing the intensity of emission lines in the spectra of Wolf-Rayet stars (Crowther & Hadfield 2006). Another basic problem for observational tests is to find suitable, metal-poor galaxies with a significant number of massive stars, since these galaxies are low mass systems in virtue of the galaxy mass-metallicity relation (e.g. Skillman et al. 1989). Additionally, in the Local Volume the number of galaxies with metallicities of 1/10 solar and significantly below this is small, but fortunately far from zero (Bomans & Weis 2011).

2 Wolf-Rayet star searches

Wolf-Rayet stars have a clear signature, the blue and red Wolf-Rayet emission line blends (the WR bumps) (e.g. Brinchmann et al. 2008). The classical method to search for Wolf-Rayet stars uses narrow band filters centered on the optical blue Wolf-Rayet bump, the He II λ468.6 nm line, and/or the red Wolf-Rayet bump, or in the near IR on He I, He II, C IV and Br γ emission lines (Shara et al. 2009). Several recent and ongoing searches for Wolf-Rayet stars in massive galaxies use this method, e.g. the Milky Way using NIR filters with ground based telescopes (Shara et al. 2009, 2012), and M101 (Shara et al. 2013) using HST imaging in the optical. The LMC is target of a recent search also using the optical narrow band filter method (Massey et al. 2014, 2015), see also the contributions by Massey and Neugent et al., and for an alternative method by Becker et al. in this conference. The SMC was surveyed as well (Massey & Duffy 2001; Massey et al. 2003).

The Wolf-Rayet star content of low mass galaxies in the Local Volume was explored so far only for a relative small number of objects: IC 1613 and NGC 6822 (Armandroff & Massey 1985), IC 10 (Massey et al. 1992; Massey & Holmes 2002; Crowther et al. 2003), Gr 8, IC 2574, NGC 1569, and NGC 2366 (Drissen et al. 1993), IC 4662 (Crowther & Bibby 2009), and NGC 3125 (Hadfield & Crowther 2006). HST based analyses were carried out for NGC 1569 (Buckalew et al. 2000) and NGC 2366 (Drissen et al. 2000).

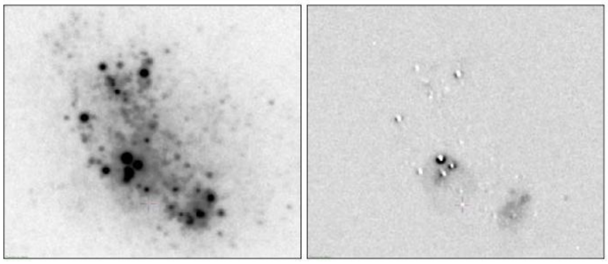

Fig. 1: Left: Broad band g image of the low metallicity dwarf galaxy Gr 8. Right: g band continuum subtracted He II image of the same field of view. The highest probability He II emitter candidate is located about halfway down below the center of the images and is marked with a crosshair. Note the dark (oversubtracted) nebular emission.

Of these galaxies only the SMC, Gr 8, IC 1613, and NGC 2366 have metallicities of 1/10 solar and below. The very low metallicity galaxy Mrk 178 was analyzed by use of IFU spectroscopy (Kehrig et al. 2013), a method we will discuss below in some more detail. With its large distance ($\sim$ 18 Mpc) I Zw 18 is a special case, where individual Wolf-Rayet stars could only be identified individually with HST imaging (de Mello et al. 1998). The presence of Wolf-Rayet stars at the extremely low metal abundance of I Zw 18 together with recent hints for the presence of massive stars similar to Pop III objects (Heap et al. 2015; Kehrig et al. 2015) supports the idea of using nearby low metallicity dwarfs as proxies for galaxies in the early universe.

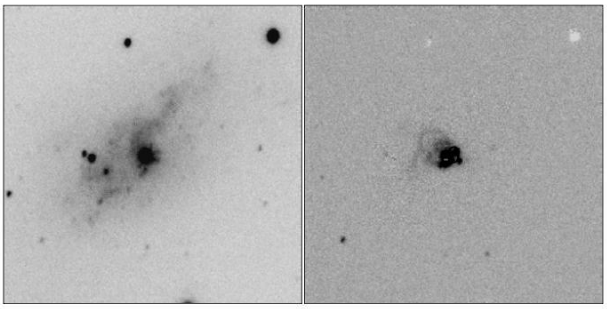

Fig. 2: Left: Broad band image (approximately Stömgren y band) of IC 4870 reconstructed from the data cube, right: continuum corrected He II image generated from the same data cube. Note the several He II point sources and the bright emission of the central cluster and the large diffuse He II emitting shell around the cluster.

3 Searching at low metallicity

IR color-color diagrams

This method is especially successful in highly reddened regions like the Milky Way disk, using the NIR and MIR excess created by the winds of the Wolf-Rayet stars (Hadfield et al. 2007). Since we discuss astro-informatics below, which shares the use of wide-band multi-color data, we did not try this method on low metallicity objects.

Astro-Informatics method

The starting point of the project was the successful application of new search methods for Wolf-Rayet stars in the LMC and SMC, described in more detail by Becker et al., this conference. In short, it uses the SED of known Wolf-Rayet stars and astro-informatics methods to identify candidates. As a test case we applied the method to HST data of Gr 8 and Sextans A. Unfortunately, the effect of the more uncertain distances to galaxies beyond the Magellanic Clouds turned out to have a unexpectedly significant effect on the precision of the candidates selection. We are currently refining the relative distances, adding more filter bands, especially in UV and NIR, and further improve our astro-informatics algorithms.

Narrow-band imaging applied to Gr 8

A proven, efficient method to search for Wolf-Rayet stars is imaging with a narrow band filter centered on the He II line at $\lambda 468.6nm$ and an adjacent (or broad) continuum filter. As discussed above, both ground-based and space-based telescopes can be used. We re-reduced data from the ING archive to search for He II emission objects in the very low luminosity ($M_B = -13.3$) dwarf galaxy Gr 8. At at metallicity of log (O/H) = 7.65 (van Zee et al. 2006) it is one of the most metal-poor starforming galaxy within 5 Mpc. A previous search by Drissen et al. (1993) yielded no He II emitter in this galaxy. In Fig.1 we show the g band image and the He II-continuum image. In the image 3 candidates are visible. The highest confidence candidate marked by a crosshair symbol. This object has no (or only a very weak) counterpart in the g band image and therefore a high flux excess in the He II filter. Several apparent He II peaks are subtraction artifacts of bright stars. The continuum corrected He II shows oversubtracted regions where nebular Hβ and [OIII] emission lines (inside the g filter band) are strong. Clearly, a careful PSF analysis has still to be performed to exclude residual images, filter ghosts, and false positives due to slight geometric mismatches.

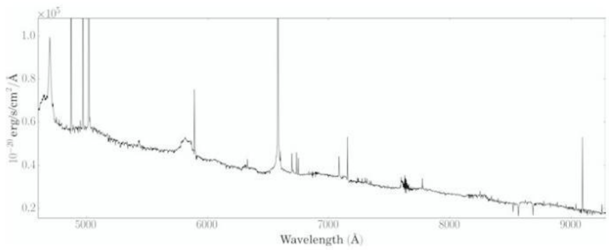

Fig. 3: Extracted spectrum of the central cluster of IC 4870.

IFU based search applied to IC 4870

Searches using IFU spectrographs have significant advantages over narrow band imaging. For each resolution element a full spectrum is available, allowing an improved continuum subtraction and better PSF and astrometric control. Most importantly, it immediately provides at least a classification spectrum of the detected stars. Up to now, this method was strongly hampered by either large spaxels or very small field of view, or both. The new ESO/VLT instrument MUSE delivers a significant progress with a $0.2''$ sampled field of view of $1' \times 1'$.

We present here a first look at the resolved stellar content of the irregular galaxy IC 4870 with about SMC metallicity and a distance of ~ 7 Mpc based on MUSE and HST data. As shown in Fig.2, the data cube allows the efficient detection of several sources in an image isolating the blue Wolf-Rayet bump. The line fluxes imply single stars (2 cases, see Fig.2 for one example) and compact groups of 2-3 Wolf-Rayet stars (2 other cases) as inferred from the strength of the Wolf-Rayet bump (Kleemann et al., in prep.). As with the narrow band filter method, Malmquist bias leads to the detection of only the intrinsically most luminous Wolf-Rayet stars or unresolved compact groups containing Wolf-Rayet stars.

The central star cluster shows extremely bright Wolf-Rayet features and therefore contains several 100 WN and WC stars (see Fig.3), shadowing even the huge Wolf-Rayet cluster in NGC 3125. Also interesting is the presence of the Ca II indicating the presence of red supergiants, which hints at a significant age spread (or 2 separated bursts of starformation) in the cluster.

4 Conclusions and outlook

Apparently, all presented search methods are capable of finding Wolf-Rayet stars in low metallicity systems. The narrow-band and the IFU methods share the problem of using the same PSF for the narrow and broad band images to achieve an as good as possible continuum subtraction. Obviously space based imaging is superior to ground-based (even with AO support) for more distant galaxies due to a more well behaved and stable PSF. Still, the classical ground based technique can efficiently expand the sample of low metallicity Wolf-Rayet star candidates for nearby objects. Clearly MUSE can be extremely promising as search engine even at a distance of 7 Mpc (and beyond), and immediately provides spectra suitable for further analysis.

Our astro-informatics method shows potential, but needs some fine-tuning still. The necessary accuracy of the relative distances of target galaxy and training sample galaxies can be reached e.g. with TRGB distances or Cepheids. The limiting factor is probably the intercalibration of the methods. Since Wolf-Rayet and other hot stars have significant structure in the SEDs in the UV and NIR/MIR, the use of the widest possible wavelength range and more that 5 filters will also help, as experience from the LMC data taught us already, see Bomans et al. (2015) and Becker et al., this conference. With the availability of the space mission archives (especially HST and SPITZER) and the ongoing and planned deep widefield surveys, there is already a rich data set available for using astro-informatics methods for us to investigate the hot and cool star content of a good number of low metallicity galaxies in the Local Volume.

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Jesús Toalá: How can you explain $\sim$ 500 WR stars at the center of your galaxy?

Dominik Bomans: The cluster in the center of the galaxy is indeed extreme, but not unique. A similar object is the somewhat more distant irregular galaxy NGC 3125, which was discussed e.g. by Hadfield & Crowther (2006) and Wofford et al. (2014).