Dwarf Galaxies: From the Deep Universe to the Present
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Synergies between Massive Stars and Metal-poor Dwarf Irregular Galaxies

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Abstract. The community of massive stars is working intensively on Local Group dwarf irregular galaxies (dIrr). They are a reservoir of metal-poor massive stars that serve to understand the physics of their higher redshift siblings and population III stars, interpret the farthest, most energetic SNe and GRBs, and compute feedback through Cosmic History. Along the way, we became interested in the recent star-formation history and initial mass-function of the host dIrr's, their chemical evolution, and gas and dust content. Our team is working to unveil and characterize with spectroscopy the OB-stars in IC 1613, Sextans A and SagDIG, that form a sequence of decreasing metal content. We showcase some results to stimulate synergies between both communities.

Keywords. stars: early-type, galaxies: irregular, galaxies: Local Group

1. Introduction

Massive stars are active agents shaping galaxies and the Universe. Their evolution is a succession of stages, some of them very hot ($\gtrsim$20000 K), all of them with smooth or episodic mass outflows, that makes them key suppliers of kinetic and ionizing energy into the interstellar medium. In single or binary systems they are also progenitors of very disruptive events, type Ib,c,II supernovae (SNe) and long γ-ray burst (GRBs), and sources of gravitational waves within the age of the Universe. A proper understanding of the different stages experienced by massive stars with well constrained physical properties (effective temperatures, luminosities, wind mass loss rates) is thus crucial to interpret a number of observables and to inform the simulations of the evolution of galaxies.

Libraries of homogeneous observations and analyses have been produced in the Milky Way and the Magellanic Clouds (e.g., Simón-Díaz *et al.* 2011, Evans *et al.* 2011). However, these are not representative of massive stars at medium and high redshifts: even the Small Magellanic Cloud (SMC), with $\sim$0.2 $Z_\odot$ metallicity, is far from the chemical composition at the peak of star formation of the Universe (Madau & Dickinson 2014).

Multi-object spectrographs on 8m and 10m telescopes enabled the observations of resolved massive stars in dIrr's of the Local Group (LG), thus surpassing the double

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frontier of distance and low-metallicity set by the SMC. Teams around the world set out to produce a large enough sample as to provide constraints to existing models of evolution and winds at the metal-poor regime (e.g. Szécsi *et al.* 2015; Kudritzki 2002). The sub-SMC metallicity targeted galaxies include IC 1613, NGC 3109, WLM and Sextans A (e.g. Garcia & Herrero 2013, Tramper *et al.* 2014, Bouret *et al.* 2015, Camacho *et al.* 2016).

Our team is using intensively the 10m *Gran Telescopio Canarias* to unveil the population of massive stars in IC 1613 ($1/5\,O_\odot$), Sextans A ($1/10\,O_\odot$) and the Sagittarius Dwarf Irregular (SagDIG, $1/20\,O_\odot$). The symbiosis of our project with studies of the host galaxies soon became evident. Knowledge of the host, in terms of UV sources and the distribution of neutral and ionized gas, results in better targeted searches of massive stars. On the other hand, massive stars confirmed by spectroscopy pinpoint the *loci* of star formation (see below) and enable an accurate reconstruction of the initial mass function IMF (Schneider *et al.* 2018). This paper summarizes some of our results and the implications for the host galaxy, to stimulate future collaborations between both fields.

2. Precision-dating star formation

With H-burning stages of $\lesssim 30\ Myr$ (e.g. Massey 2013) main sequence massive stars pinpoint star formation (SF) both in space and time, but their use as SF-tracers is not straightforward. At their high effective temperature (25000-45000 K, corresponding to O to $\sim$ B1 spectral types, Martins *et al.* 2005) the spectral energy distribution in the optical range is well within the Rayleigh-Jeans regime, and their optical colors are degenerated. In addition, the youngest stars are often located in gas- and dust-rich regions prone to enhanced and differential extinction. For these reasons they can neither be identified nor characterized from their location in the color-magnitude diagram (CMD) only, and spectroscopy is needed.

The additional observational effort, however, pays off. The analysis of the spectra with the state-of-the-art FASTWIND or CMFGEN codes (Puls *et al.* 2005; Hillier & Miller 1998) provides accurate effective temperatures (and luminosities, since distance is known to their host galaxy). When the spectral quality is poor, these parameters can be taken from modern calibrations (e.g. Berlanas *et al.* 2018, Fig. 6) as long as a spectral type can be assigned. With this information we can build the Hertzsprung-Russell diagram and date star forming regions with $< 10\ Myr$ precision (see e.g. Camacho *et al.* 2016).

The intrinsic colors tabulated for the assigned spectral types also enable a more accurate reddening correction. Fig. 1 shows the location of 4 O-stars we recently discovered in Sextans A (Garcia et al. in prep.) in the galactic CMD. Two of the stars are located in the red edge of the blue plume and they would have been likely discarded as candidate blue massive stars by classical color-cuts. However, the *spectroscopic* reddening correction reveals them as intrinsically very blue stars and the brightest among the sample. We have similarly found that the correction by the foreground value may be insufficient in SagDIG, and that an additional component renders a more consistent location of the reported OB-type stars in the CMD (Garcia 2018).

These results indicate that **internal extinction is significant in dIrr galaxies**, contrary to the usual assumption. Stellar masses calculated from CMD's can be severely underestimated if only the foreground value is used. Whether the impact on the computed total barionic mass of the galaxy is significant will need to be carefully assessed.

3. Young massive stars and neutral Hydrogen

The location of OB-type stars in dIrr galaxies is apparently random. We detected young OB-associations in the outskirts of IC 1613, far from the giant HII shells and the optical center of the galaxy (Garcia *et al.* 2010). The massive stars so far reported in SagDIG

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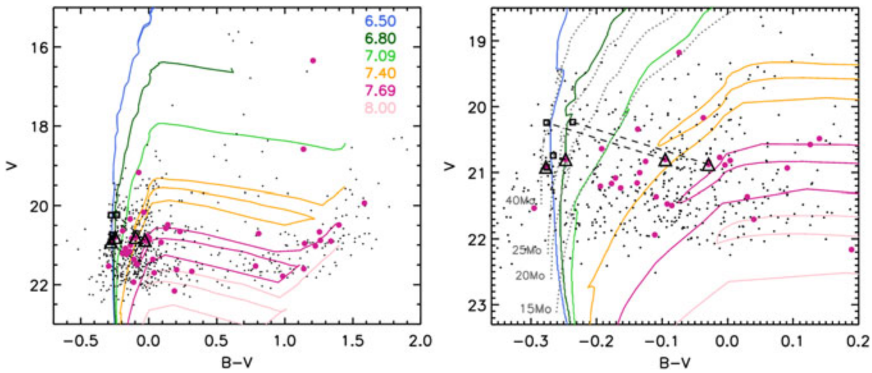

Figure 1. Left: Sextans A, CMD made with Massey *et al.* 2007's catalog (dots). The stars in the new region of star formation reported by Garcia et al. (in prep) are highlighted by filled violet circles. The figure also includes Lejeune & Schaerer 2001's Z=0.001 isochrones shifted to account for the distance modulus and foreground extinction of Sextans A (DM=25.63, $E\,(B-V)_{fg}$=0.044, Tammann *et al.* 2011). Their color-coded $log\,(age)$ is indicated in the legend. The observed magnitudes of the confirmed O-stars are marked with triangles. A dashed line links this position and their reddening-corrected location, which is marked with squares. **Right:** Zoom into the blue plume, now also including evolutionary tracks. The four stars have masses in the 25-40 $M_\odot$ range. Had we only corrected for foreground extinction, the most reddened stars would have been assigned $\sim 10\,M_\odot$.

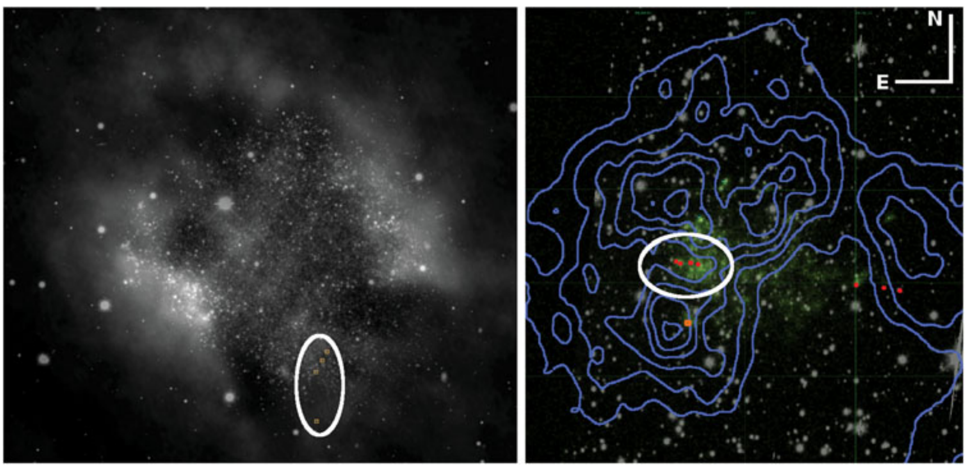

Figure 2. Left: Sextans A: the LITTLE THINGS neutral hydrogen map is overlaid on a V-band image. The ellipse encircles the O-stars recently discovered by Garcia et al. There is neutral hydrogen at their location, but the gas density is lower than at the East and West concentrations. **Right:** V-band image of SagDIG (white), with far-UV emission overlaid in green and neutral hydrogen density represented by the contours. The ellipse encloses the massive stars reported by Garcia (2018), which are located within two overdensities of HI.

dwell at an inconspicuous location (Garcia 2018), and the O-type stars we recently found in Sextans A are far from the traditionally considered regions of star formation.

Nonetheless all pieces fit together when the distribution of neutral hydrogen is considered. The youngest massive stars always overlap with HI clouds or are located at the ridges of the HI distribution (see Fig. 2; see also Fig. 11 from Garcia *et al.* 2010).

It is interesting to note that the associated clouds of neutral hydrogen show a variety of densities. Sextans A's giant HII shells and their ionizing population overlap with the

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highest concentration ($N_{HI} = 6.1 \times 10^{21}\ cm^{-2}$, Ott *et al.* 2012), but the youngest O-stars reported so far are located in a very low density region ($N_{HI} \sim 0.5 - 1 \times 10^{21}\ cm^{-2}$) that barely reaches the alleged threshold for star formation ($1 \times 10^{21}\ cm^{-2}$, Skillman 1987).

Our results in Sextans A therefore provide **spatially-resolved, spectroscopic confirmation of recent findings suggesting that star formation can occur in dIrr galaxies despite their low gas density** (Holwerda *et al.* 2013, Hunter *et al.* 2016). Moreover, two of the most massive stars are apparently isolated (Garcia et al. in prep), which suggests that the IMF is populated randomly at this location. The stochastic sampling of the IMF has been proposed to explain the apparent break-down of the Kennicutt-Schmidt law found in low surface density galaxies if star formation rates are estimated from the far-UV (Teich *et al.* 2016).

We continue working to complete our spectroscopic census of massive stars in IC 1613, Sextans A and SagDIG. The quantitative analysis of the resulting database will constrain the properties of massive stars in the very metal-poor regime and take us one step closer to the physics of the first, very massive stars of the Universe. The census will also trace on-going star formation at the host and the derived stellar masses will be used to study the IMF. Uniting efforts, researches from both fields can tackle pressing questions such as how star formation is triggered in dwarf galaxies, what the role of neutral hydrogen is and whether these translate into specific mechanisms of massive star formation.

Acknowledgments

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