A Universe of Dwarf Galaxies
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DWARF GALAXIES BEYOND OUR DOORSTEP: THE CENTAURUS A GROUP

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Abstract. The study of dwarf galaxies in groups is a powerful tool for investigating galaxy evolution, chemical enrichment and environmental effects on these objects. Here we present results obtained for dwarf galaxies in the Centaurus A complex, a dense nearby (∼4 Mpc) group that contains two giant galaxies and about 60 dwarf companions of different morphologies and stellar contents. We use archival optical (HST/ACS) and near-infrared (VLT/ISAAC) data to derive physical properties and evolutionary histories from the resolved stellar populations of these dwarf galaxies. In particular, for early-type dwarfs we are able to construct metallicity distribution functions, find population gradients and quantify the intermediate-age star formation episodes. For late-type dwarfs, we compute recent (∼1 Gyr) star formation histories and study their stellar distribution. We then compare these results with properties of the dwarfs in our Milky Way and in other groups. Our work will ultimately lead to a better understanding of the evolution of dwarf galaxies.

1 Introduction

If the taste of a cake depends primarily on its ingredients, then the study of dwarf galaxies deserves a very careful attention. These objects are indeed believed to

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be the smallest baryonic counterparts to the dark matter constituent blocks in our Universe. It is established that dwarf galaxies are by far the most numerous galactic population, and they come in diverse flavours (ranging from the predominantly old and neutral gas-free early-type dwarfs, to the actively star-forming and gas-rich late-type dwarfs, see *e.g.* Grebel 2001).

The most detailed information we have about dwarf galaxies comes directly from our closest neighbourhood, the Local Group (LG, *e.g.*, Mateo 1998; Tolstoy *et al.* 2009). In the last few years, many studies have also started to look beyond the borders of the LG and have analyzed the properties of dwarf galaxies in nearby groups (*e.g.*, Karachentsev *et al.* 2002; Sharina *et al.* 2008; Bouchard *et al.* 2009; Dalcanton *et al.* 2009). We are particularly interested in the resolved stellar populations of these objects, since stars provide the record of a galaxy's past evolution and thus constitute a powerful tool to constrain its physical properties. Moreover, as mentioned before, dwarf galaxies are numerous and heterogeneous systems, and in environments different to that of the LG, we can learn more about which factors shape their evolution.

The CenA/M 83 group is believed to be a denser and maybe more dynamically evolved system than the LG (see, *e.g.*, Jerjen *et al.* 2000), thus making it a very appealing target for dwarf galaxy evolutionary studies and possible environmental effects. In this contribution we present the first results about the study of this group's dwarf members. We analyze archival Hubble Space Telescope (HST) data taken with the Advanced Camera for Surveys (ACS) instrument. We use data for six early-type dwarfs (companions of CenA) and ten late-type dwarfs (five companions of the elliptical CenA and five of the spiral M 83). For three of our early-type dwarf targets, near-infrared (NIR) data have been additionally obtained at the Very Large Telescope (VLT) with the Infrared Spectrometer And Array Camera (ISAAC).

2 Early-type dwarfs

As can be seen from the example in Figure 1, the color-magnitude diagrams (CMDs) of our early-type dwarf targets show a prominent red giant branch (RGB), composed of old populations. Although this evolutionary stage suffers from the well known age-metallicity degeneracy, the CMDs show very few luminous asymptotic giant branch (AGB) stars (indicative of an intermediate-age population, IAP, with ages in the range ∼1–9 Gyr). We can thus make the simplified assumption that the stars in our target galaxies are old, and assume that the width of their RGBs is entirely due to a range of metallicities (see, *e.g.*, Rejkuba *et al.* 2005). We adopt isochrones from the Dartmouth stellar evolutionary models (Dotter *et al.* 2008), with fixed age and varying metallicities, and derive photometric metallicity distribution functions (MDFs) from the RGB stars (an example is shown in Fig. 1). All of our targets have a metal-poor stellar content, and we also compute the internal spreads in metallicity for the target dwarfs, after subtraction of the observational errors. Our results and the possible uncertainties of this method are discussed in detail in Crnojević *et al.* (2010a). We also find weak

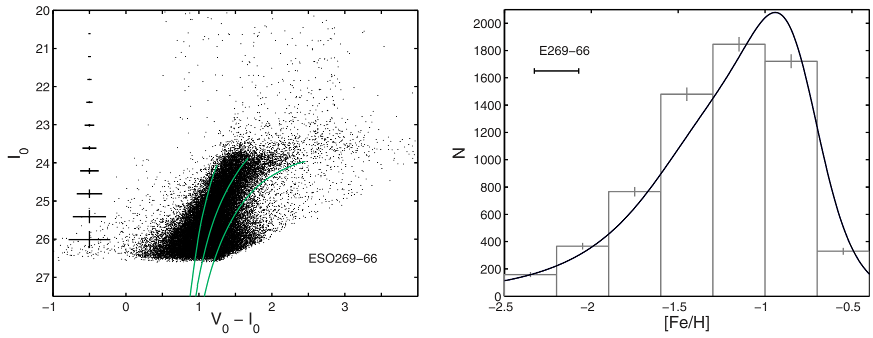

Fig. 1. *Left panel*: optical (dereddened) CMD for one of the target early-type dwarfs. The dominant feature of the CMD is a prominent RGB, with a small presence of luminous AGB stars above the tip of the RGB. Representative photometric errorbars are plotted on the left side of the CMD. The green lines are stellar isochrones with a fixed age of 10 Gyr, and metallicity values of [Fe/H] = −2.5, −1.2 and −0.4. *Right panel*: MDF for the same galaxy, derived via interpolation of isochrones at a fixed age (10 Gyr) and with varying metallicity. Overlaid (black line) is the MDF convolved with the observational errors. Also plotted in the upper left corner is the median error on the individual values of [Fe/H].

metallicity gradient as a function of galactic radius in some of our objects. Moreover, we arbitrarily divide the stellar samples into metal-poor and metal-rich (with respect to the median metallicity values), and find that for two of our targets the metal-rich stars are significantly more centrally concentrated than the metal-poor ones.

We further investigate the possible presence of IAPs in our targets and estimate the latest epoch when star formation took place there. Luminous AGB stars are more luminous at NIR wavelenghts and, most importantly, in a NIR CMD the Galactic foreground is clearly confined to a vertical sequence, well distinguishable from the dwarf galaxy's stars (the CenA group lies at a galactic latitude of $b \sim 20°$ and is thus affected by Galactic stellar foreground). We thus have a powerful tool, when combining the deep and extremely well resolved optical HST images with the NIR data, to firmly identify candidate luminous AGB stars (for details, see Crnojević *et al.* 2010b). We can apply this technique to three of our target early-type dwarfs since we have NIR imaging data for them.

We compare the derived ratio of luminous AGB stars to RGB stars to theoretical stellar evolutionary models, and estimate the IAP fractions for our targets. The resulting fractions are very low, between 5% and 15%, and are likely to be lower limits to the true ones (given our observational uncertainties and also the uncertainties in the stellar evolutionary models, see *e.g.*, Melbourne *et al.* 2010). We do not find any obvious correlation between metallicity or IAP fraction and the position of the dwarfs within the group, but this result could be biased by the small size of our sample.

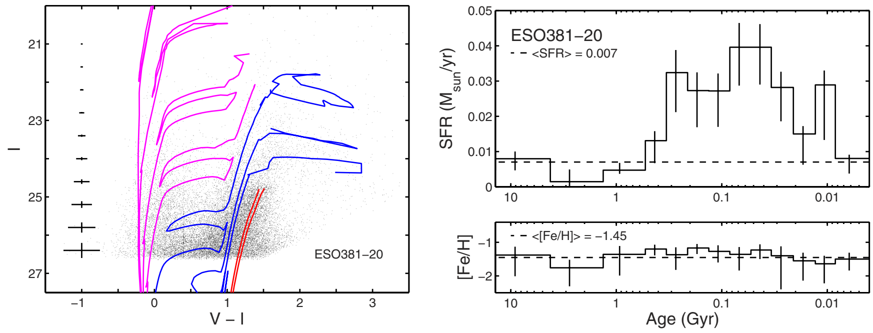

Fig. 2. *Left panel*: optical CMD for one of the target late-type dwarfs. We overlay Padova isochrones with a fixed metallicity of [Fe/H] $=-1.4$ and varying ages (respectively: 4, 12, 35 and 80 Myr for the magenta lines, 200, 550 Myr, and 1 Gyr for the blue ones, and 7 and 1 Gyr for the red lines). We also report typical 1σ photometric uncertainties on the left side of the CMD. *Right panel*: SFR as a function of time derived for the same galaxy (the oldest age being on the left side and the most recent time bin on the right edge of the logarithmic horizontal axis). The size of the time bins is variable, due to the different amount of information obtainable for different stellar evolutionary stages. We also show the derived metallicity as a function of time (with the same axis convention as above). The black dashed lines indicate the mean SFR and the mean metallicity over the galaxy's lifetime, respectively.

3 Late-type dwarfs

Unlike the early-type dwarfs considered in the previous Section, the late-type dwarfs of our sample show additional structure on the blue side of their CMDs (see Fig. 2 as an example), thus giving us the possibility to extract more information about their past histories. We analyze our late-type dwarfs with the synthetic CMD modeling technique (see, *e.g.*, Cole *et al.* 2007 and references therein). Starting from Padova stellar isochrones (Marigo *et al.* 2008), we quantify the amount of stars produced by the galaxy in each different evolutionary stage, which corresponds to a specific age (for more details, see Crnojević *et al.* 2010c). The young, massive main sequence and helium-burning stars, and the intermediate-age luminous AGB stars allow us to accurately reconstruct the star formation rate (SFR) in the past 1–2 Gyr, while for ages older than that the time resolution is poorer. We also derive a mean metallicity estimate for the studied objects (although its evolution with time is extremely uncertain). We show an example of a resulting star formation history (SFH, *i.e.*, SFR as a function of time) in Figure 2. The derived SFHs for our sample of galaxies show considerable diversity in their main features (for more details, see Crnojević *et al.* 2010c; Crnojević *et al.* 2010d). Overall, the general trend seen in all the SFHs is the presence of long quiescent periods, interrupted by more or less extended (few tens to several hundreds Myr) episodes of enhanced star formation.

We divide the stellar content of each galaxy into subsamples with different ages and produce density maps for each of them. The youngest stars always tend to be concentrated in clumps close to the central regions of the galaxies, while the oldest stars are uniformely distributed all over their bodies. This stems from the fact that the young stars still have the imprint position of their birthplaces, while the old ones have had the time to migrate and redistribute within the galaxy (see *e.g.*, Dohm-Palmer *et al.* 1997). We can furthermore trace the spatially resolved SFH of a galaxy by considering stellar maps of blue helium-burning stars with different ages (in this evolutionary stage, stars with different ages are very well separated in the CMD). We find that star forming complexes have diameters of ∼100 pc and timescales of >100 Myr, and we confirm that global bursts in a galaxy are long-lived (several hundreds of Myr) events, within which smaller, localized star forming regions form and dissolve (see also McQuinn *et al.* 2009).

We also look for possible relations between the physical properties of our dwarfs and their environment. There is no clear correlation between the lifetime average SFR with the position of the galaxies in the group. This is a reasonable result, if we consider that average properties depend on the whole galaxy's history, and we only have information about the current position of the objects within the group because their orbits are unknown. However, if we compute the ratio of the SFR in the last ∼500 Myr to the lifetime average value, we do find that dwarfs that are closest to the dominant group galaxy, and found in a denser environment, have a lower such ratio with respect to the more isolated objects (see also Bouchard *et al.* 2009). Finally, we find that dwarfs located in denser regions will consume their HI gas content much faster than isolated ones, provided they continue to form stars at their lifetime average SFR.

4 Discussion and conclusions

We have studied a sample of dwarf galaxies in the nearby CenA/M 83 group, an environment similar to the LG but denser (in terms of number of galaxies) and possibly more evolved.

In terms of metallicity content of their old populations, the early-type dwarfs studied are similar to the LG dwarf companions (metal-poor content, metallicity spreads, MDF's shape, luminosity-metallicity relation, statistically distinct stellar subpopulations). However, a careful analysis of the luminous AGB stars tells us that, intriguingly, the IAP fractions in CenA companions are smaller than what is found for Milky Way dwarf spheroidal companions and for M 31 dwarf elliptical companions (the relative differences are not affected by model uncertainties). Our results are more similar to what is seen for dwarf spheroidal companions of M 31. This is one of the first studies where IAPs for dwarfs in nearby groups are investigated from their resolved stellar populations. Although our sample is still too small to draw firm conclusions, our results suggest that the CenA environment could somehow have played a role in the suppression of its companions' star formation. This is a very interesting result which certainly deserves more observational evidence.

The late-type dwarfs considered in our study all show complex and varied SFHs. If we compare the resulting average SFRs to the values found for LG dwarf galaxies in the same luminosity range, we find that the CenA/M 83 dwarfs have slightly higher values, comparable to what is found for the M 81 group (a highly interacting nearby group) late-type dwarfs (see Weisz *et al.* 2008). The global enhancements in SFR that we are able to resolve from the recent SFHs of our targets last for several hundreds of Myr, with smaller and localized star forming regions. We conclude that star formation in these objects is a stochastic process. Finally, also among late-type dwarfs we find a hint for environmental effects, in the sense that dwarfs in denser environments and closer to the dominant galaxy have had lower SFRs in the last $\sim$500 Myr, and are consuming their gas reservoirs faster than the isolated ones.

The CenA/M 83 group has proved to be a very promising target, in which the resolved stellar populations of the dwarf companions can be analyzed to better understand the details of galactic evolution. The study presented in this contribution should thus be an appetizer, and stimulate the curiosity for the work that has started to be done for nearby groups of galaxies.

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