SF2A 2010
S. Boissier, M. Heydari-Malayeri, R. Samadi and D. Valls-Gabaud (eds)

DWARF GALAXIES IN THE LOCAL GROUP: CORNERSTONES FOR STELLAR ASTROPHYSICS AND COSMOLOGY

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Abstract. Dwarf galaxies have been the crossroad of significant theoretical and observational efforts, but we still lack firm constraints concerning their formation and evolution. They are also fundamental laboratories to investigate the impact of the environment on star formation and on chemical evolution in stellar systems that are order of magnitudes smaller than giant galaxies. We present some recent results concerning the dwarf spheroidal Carina and the dwarf irregular IC10. In particular, we focus our attention on the evolutionary properties of their stellar populations using accurate and deep color-magnitude diagrams. We also briefly discuss the impact that the transition from old, low-mass (horizontal branch) to intermediate-age (red clump) helium burning stars has in constraining the star formation history of complex stellar systems.

Keywords: galaxies: individual (Carina, IC10), galaxies: stellar content, galaxies: dwarf, local group, galaxies: kinematics and dynamics, stars: evolution, stars: fundamental parameters

1 Introduction

Dwarf galaxies are ubiquitous stellar systems outnumbering giant systems in the Local Group (LG, Mateo 1998), in the Local Volume (up to 25 Mpc, Vaduvescu & McCall (2008)), and in the nearby Universe (Popesso et al. 2006; Gonzalez et al. 2007). According to the most widely accepted cosmological (Λ Cold Dark Matter) model, the density fluctuations typical of dwarf galaxies are the first to undergo dynamical instability and to collapse. However current models and observations do not allow us to satisfactorily constrain the epoch when these systems formed. Yet, according to the simulations, dark matter halos, after their formation, start to merge, thus forming larger structures (Navarro et al. 1997). In addition, it is not yet clear whether primordial dark matter halos already included a baryonic component. It has been suggested (Haardt & Madau 1996) that the accretion of baryons begins after the re-ionization era ($\sim$10 Ga ago). However current cosmological models

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predict a number of dwarfs significantly larger than that observed near giant spirals like the Milky Way and M31. This discrepancy is called the "missing satellite problem". It has not yet been established whether this discrepancy is due to the limits of theoretical models or to observational bias at the dark matter halos that were able to sustain star formation and chemical self enrichment at some epoch constitute the population of dwarf galaxies we observe today. Dwarfs display a huge variety in their gas content and star formation history, but have very similar structural properties and seems to obey to the same general scaling laws of giant galaxies. It is widely believed, and supported by state-of-the-art chemo/hydro/dynamical models, that gas-rich, star forming dwarf irregulars (dIs) and gas-poor quiescent dwarf spheroidals (dSphs) can simply represent different stages of a unique evolutionary path, driven by several internal and external factors.

However, we still lack firm constraints on galaxy formation and evolution (or transition) among different morphological types. Kormendy (1985, 1987), using high spatial resolution CCD images, found a well defined dichotomy between ellipticals (Es) and spheroidals (Sphs, Kormendy et al. 2009). In particular, early type galaxies are distributed along a sequence moving from cD (bright, low central surface brightness) to dwarf ellipticals (like M32, fainter, high central surface brightness). On the other hand, spheroidals are distributed along a different sequence that overlaps with spiral-galaxy disks and dwarf irregulars in which the faintest systems have a low central surface brightness (see Fig. 1 in Kormendy et al. 2009). On the basis of this clear empirical dichotomy it has been suggested that E and Sph galaxies are stellar systems that underwent different formation and evolution processes. In particular, Sphs might be either Spiral disks or Irregulars that lost their gas or transformed it into stars. The above findings are suggesting a galaxy formation scenario in which ellipticals only form via mergers, while spheroidals are defunct irregulars.

Several physical mechanisms have been suggested to support this scenario. The supernovae-driven energy feedback can remove a large amount of gas (Dekel & Silk 1986; Navarro et al. 1996; Veilleux et al. 2005). Tidal stripping and tidal stirring (Mayer et al. 2006), as well as ram pressure gas stripping (Chung 2007), UV flux from the host galaxy (Mayer et al. 2007) and galaxy harassment (Moore et al. 1998) can also remove both dark matter and baryons from dwarf galaxies and may induce star formation. However, the dichotomy between E and Sph galaxies has been questioned (Jerjen & Binggeli 1997; Gavazzi et al. 2005; Ferrarese et al. 2006). They suggest a smooth transition from Sphs to low-luminosity Es, since their intrinsic parameters are continuous. Moreover, the correlation between the shape of the brightness profile and the galaxy luminosity is continuous when moving from Es to Sphs.

The quoted arguments concerning galaxy formation and evolution are based on the integrated properties of complex systems. We can address the same problems more effectively using more quantitative information concerning the stellar and gas content of these systems. The disruption of dwarf galaxies and the ensuing formation of larger host galaxies can be traced back in time using kinematic properties, the metallicity distribution and the age distribution of their stellar populations (Grebel 2001; Gallart et al. 2005; Tolstoy et al. 2009). However, the details of the story are far from settled.

To address the quoted problems we decided to take into account two LG dwarf galaxies, namely Carina, the prototype of dwarf spheroidal galaxies with well defined multiple star formation episodes, and IC10, the prototype of dwarf irregular galaxies showing evidence of recent/ongoing star formation episodes.

2 The LG dwarf spheroidal Carina

Carina plays a key rôle among the LG dSph galaxies. The reasons are manifold: *i)* It is relatively close, and its central density is modest ($\log \rho = 0.17\ M_{\odot}\, pc^{-3}$, Mateo 1998). *ii)* Carina shows multiple, star formation episodes separated in time and in the amount of stellar mass involved (Dolphin 2002; Rizzi et al. 2003; Monelli et al. 2003). *iii)* Carina hosts a broad variety of variable stars ranging from low and intermediate-mass hydrogen burning dwarf Cepheids (δ Scuti, SX Phoenicis, Mateo et al. 1998) to low (RR Lyrae, Saha et al. 1986) and intermediate-mass helium burning stars (Anomalous Cepheids, Dall'Ora et al. 2003). *iv)* High-resolution spectra are available for less than a dozen of bright Red Giants (RGs). The mean metallicity is [Fe/H]=-1.69 dex, but the measurements show a spread of half dex (Koch et al. 2008). Independent measurements by Shetrone et al. (2003), using high-resolution spectra for five bright RGs, provided a mean metallicity of [Fe/H]=-1.64 and σ=0.2 dex. *v)* Calcium triplet measurements based on medium resolution spectra are also available for a large sample (437) of RG stars (Koch et al. 2006). Their metallicity distribution shows a peak at [Fe/H]=-1.72 ± 0.01 dex, but the metallicity distribution ranges from roughly -2.5 to -0.5 dex. By using the same spectra, but different selection criteria Helmi et al. (2006) found a metallicity distribution ranging from ~ -2.3 to ~ -1.3 dex.

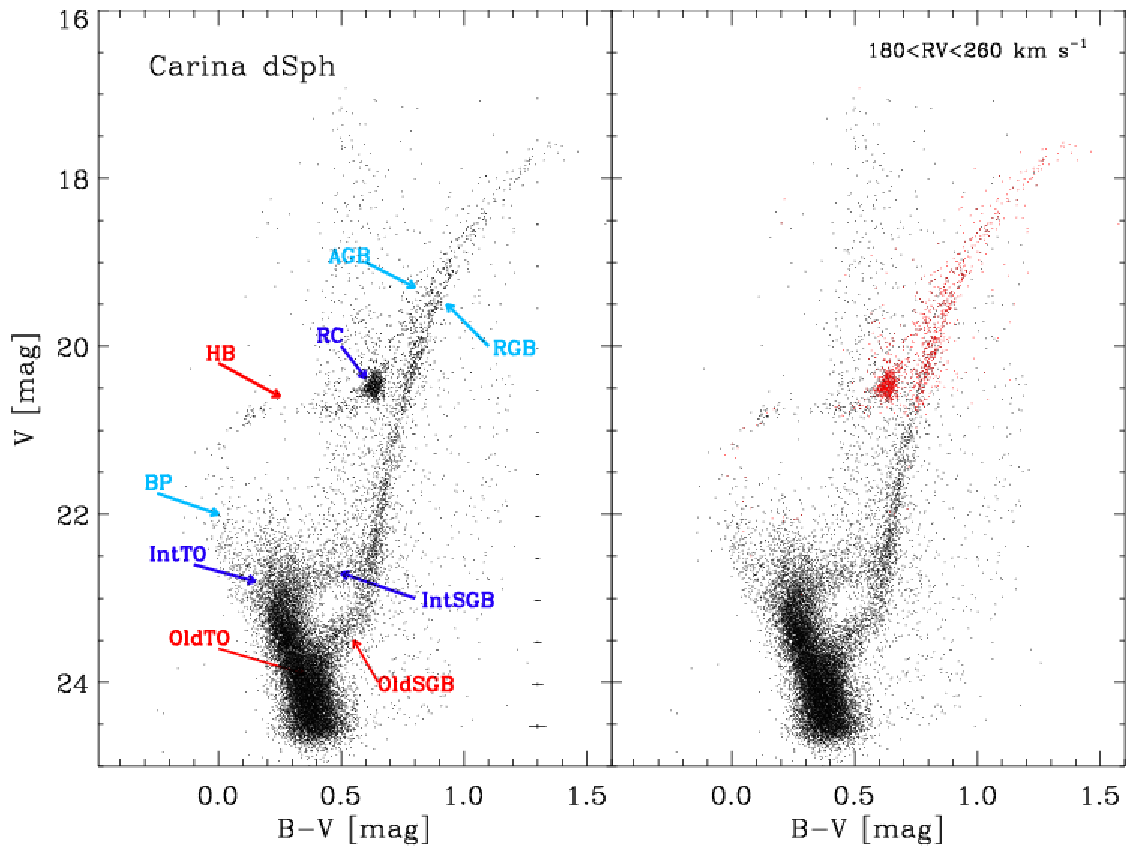

Fig. 1. *Left*: Optical V, $B-V$ Color Magnitude Diagram of the Carina dwarf spheroidal galaxy based on data collected with ground-based telescopes (Bono et al. 2010). Stars plotted are candidate Carina stars. The error bars on the right display intrinsic photometric errors both in magnitude and in color. The most relevant evolutionary phases of old (blue) and intermediate-mass (red) stars are labeled. In particular, MSTO (main sequence turn-off), BP (blue plume), SGB (sub giant branch), RGB (red giant branch), HB (horizontal branch), RC (red clump) and AGB (Asymptotic Giant Branch). *Right*: Same as the left, but the red dots display the distribution of evolved candidate Carina stars (1360 stars) selected using the radial velocity distribution ($180 \leq RV \leq 260$ km s^{-1}, 4σ).

However, we are facing a stark discrepancy between the spread in metallicity suggested by spectroscopic measurements and metallicity indicators such as the width in color of the red giant branch (RGB). Deep and accurate Color-Magnitude Diagrams (CMDs) of Carina indicate that the width in color of the RGB is quite limited (Monelli et al. 2003; Harbeck et al. 2001). This evidence was further supported in a recent investigation by Bono et al. (2010). They adopted more than 4000 multi-band (U, B, V, I) individual CCD images from three different ground-based telescopes covering the entire body of the galaxy. Moreover, to properly separate candidate Carina and field stars they performed an accurate selection using the $U-V$,$B-I$ color-color plane. They performed a detailed comparison with old (Galactic globular clusters) and intermediate-age (Small Magellanic Cloud open clusters) stellar systems and they found that the intrinsic spread in metallicity should be within 0.2 dex.

The left panel of Fig. 1 shows the V, $B-V$ CMD of candidate Carina stars based on the data collected by Bono et al. (2010). A glance at the data plotted in this CMD indicate that the quoted finding is supported by different photometric indicators. The spread in magnitude of old, low-mass helium burning stars (Horizontal Branch, HB) is only of the order of 0.15 mag, while a spread of 1.5 dex in metallicity would imply a spread in magnitude at least a factor of two larger (M_V(RR)≈0.18–0.36 mag/dex, Bono et al. 2003). The same outcome applies if we take into account intermediate-age helium burning stars (red clump, RC). By fitting the $B-V$ color distribution of RC stars, we found that the sigma is 0.12 mag, while a spread of 1.5 dex in metallicity would imply a spread in $B-V$ color that is a least a factor of two larger (see Fig. 6 in Bono et al. 2010). The above findings are minimally affected by the selection of candidate Carina stars, since HB stars are typically bluer than field stars. Moreover, the possible presence of field stars among the RC stars causes an increase in their spread in color.

To further constrain the mismatch between metallicity measurements and photometric indicators we decided to took advantage of an unprecedented sample of spectroscopic data of Carina stars (Fabrizio et al. 2010). We collected low-, medium- and high resolution spectra of evolved (old HB, intermediate-age RC, young blue plume, red giants) Carina stars using two different instruments available at the VLT, namely FORS2 (multi-object slit spectrograph) and GIRAFFE (multi-object fiber spectrograph). We ended up with a sample of ≈21,340 individual spectra of ≈2,000 stars covering the entire body of the galaxy. By using the radial velocity distribution, we selected more than 1,200 candidate Carina stars ($180 \leq RV \leq 260$ km s^{-1}, 4σ). These data were complemented with similar radial velocity measurements provided by Walker et al. (2007) and we ended up with a sample of 1,360 candidate Carina stars that is ≈75% larger than any previous Carina RV sample.

Data plotted in the right panel of Fig. 1 further support the photometric indicators concerning the spread in metallicity. The sample of RG, RC and HB stars kinematically selected cover limited ranges in color (RG, RC) and in magnitude (HB).

3 The LG dwarf irregular IC10

Among the dIs of the LG, IC10 is an interesting system, since it underwent a strong star-formation activity during the last half billion years. It is considered the only LG analog of starburst galaxies and a fundamental laboratory for the analysis of massive young stars and evolved intermediate-mass stars. Even though IC10 has been the cross-road of several investigations, its structural parameters and in particular its radial extent are poorly defined. Massey & Armandroff (1995) found that the major-axis of IC10 is $\sim 7'$. A similar diameter ($\sim 6'$) was found by Jarrett et al. (2003) using the isophotal radii from 2MASS near infra-red (NIR) images. More recently, Tikhonov & Galazutdinova (2009), using both ground-based and space images, suggested that the extent of the thick disk along the minor axis is $\approx 10'.5$. By using Asymptotic Giant Branch (AGB) and RGB stars as tracers of intermediate and old age stellar populations, Demers et al. (2004) suggested that IC10 should have a halo of $\sim 30'$diameter. The photometric method they adopted to pinpoint AGB and RGB stars relies on broad (R, I) and intermediate-band filters (TiO, CN). By using the 12k mosaic camera available on Canada-France-Hawaii Telescope (CFHT) they identified more than ≈ 600 AGB and ≈ 15000 RGB stars. The observational scenario becomes even more complicated if we consider the radio measurements by Huchtmeier (1979) indicating that IC10 has a huge envelope of neutral hydrogen extending over more than 1 square degree ($62' \times 80'$) across the galaxy.

The puzzling difference between the radial extent based on optical and on radio data was recently settled by Sanna et al. (2010). By using space (ACS and WFPC2 at HST) and ground-based (SuprimeCam at Subaru, Omega Cam at CFHT) images they found sizable samples of RG stars up to radial distances of $18'$-$23'$from the galactic center. Star counts also indicate the occurrence of IC10 stars at least at 3σ level up to $34'$-$42'$from the center. This evidence further supports the hypothesis that the huge HI cloud covering more than 1° across the galaxy is associated with IC10.

Data plotted in Fig. 2 also suggest that the stellar population characterized by different ages show relevant radial gradients. The CMD plotted in the top left corner shows a well defined blue main sequence of very young main sequence Turn-Off (TO) stars ($t \sim$30–200 Ma, $M(TO)/M_\odot \approx 8-3$). The dashed-dotted (30 Ma) and the dashed (200 Ma) isochrone plotted in this figure are based on scaled solar evolutionary models constructed by Pietrinferni et al. (2004)*, at fixed total metallicity ([M/H]=−0.66 dex). The same group of stars is marginally present in the CMD based on the WFPC2 and disappears at larger radial distances. On the other hand, the candidate AGB stars i.e. the tracers of intermediate-age stars with I-band magnitude similar to the stars located across the tip of the RGB ($I \sim$22 mag) and redder colors ($3 \leq V-I \leq 4.5$) are present both in the center and in the external regions. The same outcome applies to RG stars, i.e. to the tracers of old stars. The solid line shows an old α-enhanced isochrone (t=13 Ga) also constructed by (Pietrinferni et al. 2006) at the same fixed total metallicity of the young isochrones. These findings indicate that this galaxy might have experienced an ongoing star formation activity not only during the last few tens of Ma, but also during the last few hundreds of Ma. Current photometry does not allow us to constrain whether IC10 experienced a steady star formation activity on the time scale of Ga, but strongly supports the occurrence of an old stellar population (see Fig. 3 in Sanna et al. 2009).

*See also http://www.oa-teramo.inaf.it/BASTI

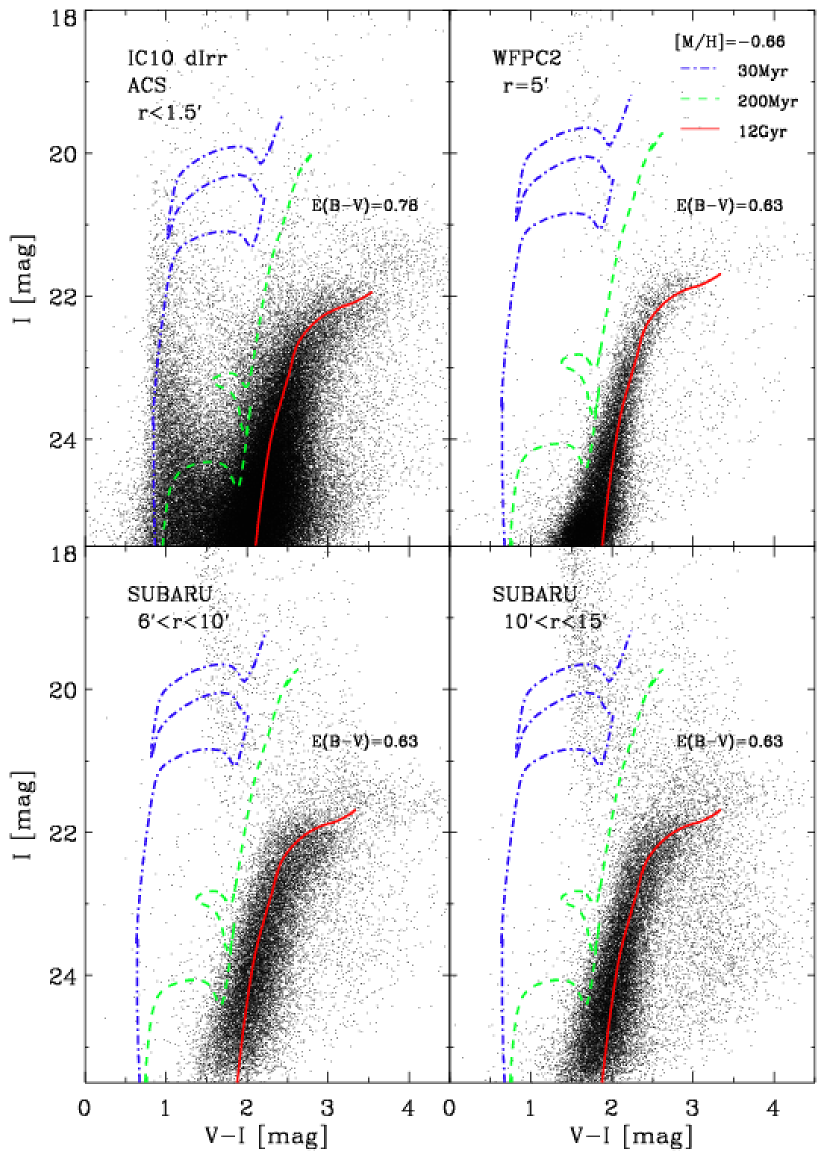

Fig. 2. *Top Left*: Optical I, $V-I$ CMD of the IC10 dwarf irregular galaxy based on data collected with ACS at HST and covering the central regions of galaxy (Sanna et al. 2009). The colored lines show three scaled solar isochrones (Pietrinferni et al. 2004, 2006) at fixed metal content ([M/H]=−0.66 dex) and different ages (see labeled values). The reddening and the distance modulus are also labeled. *Top Right*: Same as the left, but the CMD is based on images collected with the WFPC2 at HST. This pointing is located at 5′from the galaxy center (see Fig. 1 in Sanna et al. 2010). *Bottom Left*: Same as the top, but the CMD is based on images collected with the SuprimeCam at the Subaru telescope. The stars ploted in this CMD are located in an annulus around the galaxy center. *Bottom Right*: same as the left, but for stars in a more external annulus.

4 Conclusions

The scenario emerging from detailed photometric and spectroscopic investigations of Local Group dwarf galaxies is quite complex. A gas-poor system like Carina dSph galaxy according to current estimates is characterized by a large M/L ratio ranging from 30 (Mateo 1998) to 14 (Walker et al. 2009). This value agrees with similar estimates for LG dSphs and supports the view that they should be dark matter dominated. On the other hand, photometric indicators indicate that the chemical enrichment of both the old and the intermediate-age populations is quite limited and within 0.2 dex. This finding once supported by accurate measurements of iron and α-element abundances of RG stars can shed new lights on the chemical history of Carina stellar populations, and in turn firm constraints on the yields retained by this galaxy.

According to a recent estimate the IC10 dI has a M/L ratio that is one order of magnitude larger (Sanna et al. 2010, M/L∼10, [) than previous estimates (M/L∼1, Woo et al. 2008), thus suggesting that dIs might host a similar amount of dark matter than dSphs. The radial distribution of IC10 old- and intermediate-age stellar populations agrees quite well with the size of the huge neutral hydrogen cloud detected by Huchtmeier (1979) and Cohen (1979). This indicate that the stellar halo and the hydrogen cloud have, within the errors, similar radial extents (Tikhonov & Galazutdinova 2009). This evidence further supports numerical simulations suggesting that dwarf galaxies might have tidal radii significantly larger than empirical estimates (Hayashi et al. 2003; Kazantzidis et al. 2004). New and deeper data on this interesting system will allow us to constrain the possible occurrence of an old stellar population across the disc. This is a robust observable to constrain whether the formation of discs in dwarf galaxies follows the so-called down-sizing paradigm, i.e. massive discs formed before the low-mass ones (Cowie et al. 1996).

Finally, we mention that new theoretical and empirical insights are required to understand why dSphs and GCs do not seem to follow the Faber-Jackson relation (Chilingarian et al. 2010). The former systems appear to have, at fixed total luminosity, a radial velocity dispersion smaller than Ultra Compact Dwarfs (UCDs) and dwarf ellipticals. On the other hand, the latter systems show in this plane a steeper slope when compared with the other compact stellar systems. The empirical scenario becomes even more puzzling if we also account for their mean metallicity. The dSphs follow the same metallicity-luminosity relation of dwarf and giant ellipticals. However, the GCs and the UCDs cover a broad range in metallicity and do not show a clear correlation (see Fig. 8 in Chilingarian et al. 2010).

These open problems concerning the formation and evolution of dwarf galaxies, their chemical evolution and their stellar content are an excellent viaticum for those interested in addressing cosmological problems using nearby resolved stellar populations.

It is a real pleasure to thank the SOC of the workshop on Resolved Stellar Populations held in Marseille during the SF2A meeting, for inviting me to give a talk on dwarf galaxies in the Local Group. I would also like to thank young and less young collaborators with whom I am sharing the pleasure to understand the properties of these "fluffy" stellar systems.

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