ON THE STELLAR CONTENT OF THE STARBURST GALAXY IC10

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ABSTRACT

We investigate the stellar content of the starburst dwarf galaxy IC10 using accurate and deep optical data collected with the Advanced Camera for Surveys and with the Wide Field Planetary Camera 2 onboard the Hubble Space Telescope. The comparison between theory and observations indicates a clear change in age distribution when moving from the center toward the external regions. Moreover, empirical calibrators and evolutionary predictions suggest the presence of a spread in heavy element abundance of the order of one-half dex. The comparison between old and intermediate-age core He-burning models with a well defined overdensity in the color–magnitude diagram indicates the presence of both intermediate-age, red clump stars and of old, red horizontal branch stars.

Key words: galaxies: individual (IC10) – galaxies: stellar content – Local Group – stars: evolution

1. INTRODUCTION

Dwarf galaxies are ubiquitous stellar systems outnumbering giant systems in the Local Group (LG, Mateo 1998), in the Local Volume (d ≤ 10 Mpc, Vadussc2 & McCall 2008) and in the nearby Universe (Popesso et al. 2006; Milne et al. 2007). Recent evidence indicates that the Local Group includes at least 62 dwarfs and among them 26 ± 5% are dwarf irregulars (dIrrs; Grebel et al. 2003; McConnachie et al. 2008). However, we still lack firm criteria discriminating between dIrrs and blue compact galaxies (BCDs). According to Thuan (1985) and to van den Bergh (1999) the BCDs are dIrrs that are experiencing a significant burst of star formation. On the other hand, Richer & McCall (1995) found that the metal abundance of BCDs is more similar to dwarf spheroidals than to dIrrs, and Papaderos et al. (1996) pointed out the lack of an evolutionary link among BCDs, dIrrs, and dwarf ellipticals (dEs). This key issue is far from being settled, and indeed in a recent detailed photometric and spectroscopic investigation Vadussc2 & McCall (2008) suggested that BCDs, dIrrs, and dEs define the same fundamental plane.

Dwarf irregulars also play a key role in constraining the impact that structural parameters and intrinsic properties have on the evolution (initial mass function, star formation history) of complex systems (Massey et al. 2007). Moreover, they are fundamental laboratories for investigating the evolution of massive stars in systems that are undergoing significant bursts of star formation (Crowther 2007).

Among the nearby dIrrs IC10 is an interesting system, since it is one of the most massive (log M/M⊙ = 8.49, Vadussc2 et al. 2007), and the comparison between the Hα and the B-band luminosity indicates that it is experiencing a starburst phase (Hunter et al. 1993). Moreover, it has been suggested that IC10 harbors a large number of young Wolf–Rayet stars (Massey & Holmes 2002) and intermediate-age carbon stars (Demers et al. 2004). However, we still lack detailed knowledge of the stellar content of IC10. In particular, Vacc et al. (2007), using deep optical and near-infrared data, proposed that the isochrone fit to IC10—at fixed distance and metal content—would require different reddening values for main-sequence (MS) and red giant branch (RGB) stars.

In a previous investigation (Sanna et al. 2008), we provided a new estimate of the distance modulus (μ = 24.60 ± 0.15 mag) based on a new calibration of the tip of the RGB, and of the reddening (E(F555W–F814W) = 1.16 ± 0.06 mag) based on empirical calibrators. Here we address the galaxy’s stellar content.

2. RESULTS AND DISCUSSION

The photometric catalog we adopt is based on archival optical images from the Advanced Camera for Surveys (ACS) and the Wide Field Planetary Camera 2 (WFPC2; see top panel of Figure 1 and Sanna et al. 2008). The final catalog includes ~720,000 stars with at least one measurement in each of two different bands. The ACS data in the F555W and F814W bands were placed on the VEGAMAG system following Sirianni et al. (2005). The F606W-band images collected with the ACS were transformed into the F555W band using local standards, and the same approach was adopted to transform the F555W and the F814W images collected with WFPC2 into the corresponding ACS bands. On average the star-to-star precision of the above transformations is better than 0.02 mag (N. Sanna et al. 2009, in preparation). The final catalog was split into two different regions: region (C) covers the galaxy center and includes both ACS and WFPC2 data, while region (E) lies at a radial distance greater
scaled-solar isochrones (BaSTI) at fixed chemical composition and different 
0.4 (Pietrinferni et al. 2006). The data plotted in the bottom 
right corner show the shift in color and in magnitude caused by the possible
for the IC10 external regions. The cross (\( \text{TO} \)) of three young isochrones. Bottom right: same as the left, but
http://www.oa-teramo.inaf.it/BASTI

than 2 arcminutes and only includes ACS data (see the blue and red polygons in the top panel of Figure 1 and Sanna et al. 2008).

Spectroscopic estimates of IC10’s metallicity, based on \( \text{H} \) ii regions, indicate a metal content (\( \text{[Fe/H]} \approx -0.71 \pm 0.14 \); Lee et al. 2003) similar to the Small Magellanic Cloud (SMC, \( \text{[Fe/H]} \approx -0.7 \); Zaritsky et al. 1994 also based on \( \text{H} \) ii regions or \( \text{[Fe/H]} \approx -0.75 \pm 0.08 \); Romaniello et al. 2008, based on Cepheids). To characterize the stellar content of IC10 we adopted different sets of both scaled-solar (young and intermediate ages) and \( \alpha \)-enhanced (old ages) isochrones from the BaSTI database\(^{12} \) plus a few young isochrones specifically computed for this project. In particular, we adopted isochrones based on evolutionary tracks accounting for mass loss (\( \eta = 0.4 \), neglecting both convective overshooting during the core H-burning phases and atomic diffusion (Pietrinferni et al. 2004, 2006). We have assumed a true distance modulus of \( \mu = 24.60 \) and a reddening \( E(F555W-F814W) = 1.16 \) mag. Data plotted in the bottom left panel of Figure 1 show that young scaled-solar isochrones (red lines) at fixed metal and helium content (\( \text{[M/H]} = -0.66, \text{Y} = 0.251 \)), and ages ranging from 6 Myr (\( \text{M(Turn-off)} = 0.7 \text{[TO]} \)) to 100 Myr (\( \text{M(TO)} = 4.3 \)) properly fit young MS stars in IC10. The same conclusion applies to the fit of RGB stars with the old \( \alpha \)-enhanced isochrone (\( t \approx 14 \) Gyr). Note that the global metallicity of this isochrone is \( \text{[M/H]} = -0.66 \) with \( \text{[Fe/H]} = -1.01 \) and \( \text{[\alpha/Fe]} \approx 0.4 \) (Pietrinferni et al. 2006). The data plotted in the bottom panel of Figure 1 were selected according to photometric error (\( \sigma_{\text{F814W}} = \sigma_{\text{F555W}} \lesssim 0.1 \), separation (\( \text{sep} \gtrsim 4 \)), and

\(^{12} \text{http://www.oa-teramo.inaf.it/BASTI} \)

\( \text{sharpness} (|\text{sha}| \lesssim 0.3) \). The \textit{separation index} quantifies the degree of crowding (Stetson et al. 2003). The current value corresponds to stars that have required a correction of less than a few percent for light contributed by known neighbors. The \textit{sharpness index} quantifies the similarity between the shape of the measured objects and of the point-spread function (PSF). It is the quadrature difference between the one-sigma-half-width of the measured object and the one-sigma-half-width of the core of the PSF (Stetson & Harris 1988). The bottom right panel of Figure 1 shows that the CMD of the external regions is deeper, since these regions are less affected by crowding. The comparison with the central regions indicates a significant change in age distribution, and indeed, massive MS stars almost disappear when moving toward the external regions. The MS stars are well fitted by isochrones with ages ranging from 12 Myr (\( \text{M(TO)} = 14.2 \)) to 350 Myr (\( \text{M(TO)} = 2.5 \)). These findings and the continuous stellar distribution along the MS indicate that IC10 experienced ongoing star formation during \( \approx \) the last half Gyr. Figure 1 also indicates that IC10’s stellar populations show a spread in metal content. The width in color of RGB stars is well fitted by isochrones with a single age (14 Gyr) and metal contents ranging from \( \text{[M/H]} \sim -0.96 \) (\( \text{Y} = 0.248 \), green line) to \( \text{[M/H]} \sim -0.35 \) (\( Y = 0.256 \), blue line). The above comparison between theory and observations has to be considered as a preliminary guideline. These estimates of age and metal content are affected by empirical (distance modulus, reddening, photometric zero points) and theoretical (mixing length, color–temperature relations) uncertainties. Firm constraints on these parameters require deep and accurate photometry down to the TO of the old population. Note that the possible presence of differential reddening amounting to \( \pm 10\% \) would not account for the observed spread in color (see the arrows in the right panel of Figure 1 and Sanna et al. 2008). However, IC10 has an extended \( \text{H} \) i envelope, a large number of \( \text{H} \) ii regions (Hidalgo-Gamez 2005) and molecular clouds (Leroy et al. 2006). This means that internal spatial variations of the reddening are quite probable. To partially overcome this problem, we adopted as representative of the IC10 stellar content the stars located in a small external region (E, see the red polygon in the top panel of Figure 1).

To further characterize the stellar content of IC10 we also adopted empirical tracers. Figure 2 shows the comparison between field (E) of IC10 and the ACS photometry of an SMC field provided by Sabbi et al. (2007; red dots). Note that in this figure we plotted a number of IC10 stars, randomly selected, similar to the number of stars present in the SMC field. The SMC sample

\begin{figure}
\centering
\includegraphics[width=\textwidth]{figure1.png}
\caption{Figure 1. Top: the coverage of the \textit{HST} data sets collected with the ACS and with the WFCPC2 (black lines). The blue and red polygons, superimposed onto IC10, mark fields (C) and (E), respectively. The background is a MegaCam@CFHT image of 6x7 arcmin. North is up and east is to the left. Bottom left: F814W, F555W–F814W CMD of IC10 central regions. Red lines display scaled-solar isochrones (BaSTI) at fixed chemical composition and different ages (see the labeled values). The circle (\( \text{M(TO)}/M_\odot = 30.5 \)), the diamond (\( \text{M(TO)}/M_\odot = 7.7 \)), and the triangle (\( \text{M(TO)}/M_\odot = 4.3 \)) mark the Turn-Off (TO) of three young isochrones. Bottom right: same as the left, but for the IC10 external regions. The cross (\( \text{M(TO)}/M_\odot = 14.2 \)), the asterisk (\( \text{M(TO)}/M_\odot = 5.0 \)), and the square (\( \text{M(TO)}/M_\odot = 2.5 \)) mark the TO of three young intermediate-age isochrones. The green and the blue lines show two old (\( t = 14 \) Gyr) isochrones at different metal contents. The arrows in the top right corner show the shift in color and magnitude caused by the possible occurrence of a differential reddening of \( \pm 10\% \).
}
\end{figure}

\begin{figure}
\centering
\includegraphics[width=\textwidth]{figure2.png}
\caption{Figure 2. F814W, F555W–F814W CMD of IC10 external regions (black dots) compared with an SMC field (red dots) and with the GC NGC 6362 (green dots). The number of IC10 stars plotted in this figure is similar to the number of stars in the SMC field. See the text and Table 1 for more details concerning the true distance moduli and the reddenings adopted for these systems.
}
\end{figure}
Figure we plotted a number of IC10 stars, randomly selected, blue HB and extreme HB stars, NGC 2808). Note that in this listed in Table 1) and HB morphologies (only red HB stars, with three GCs with different metal contents ([M/H]).

To further constrain its horizontal-branch (HB) morphology is characterized by both red and blue stars. To investigate the properties of He-burning stars we adopted RGs in IC10 cover at least one-half dex in metal content.

Intrinsic Parameters of the GCs Adopted as Empirical Calibrators

| ID       | μ^a     | E(B − V)^b | [Fe/H]_{spec} | [Fe/H]_{ZW}^d | [Fe/H]_{CG} | [M/H] | RGB bump^f |
|----------|---------|------------|---------------|---------------|------------|-------|------------|
| 47 Tuc   | 13.32 ± 0.09^6 | 0.04 ± 0.02^a | −0.76 ± 0.04^4 | −0.71 ± 0.05 | −0.78 ± 0.02 | −0.47 | 13.49 ± 0.10 |
| NGC6362  | 14.43 ± 0.05^i | 0.08 ± 0.02 | −1.04 ± 0.06^3 | −1.18 ± 0.06 | −0.99 ± 0.03 | −0.75 | 14.45 ± 0.10 |
| NGC2808  | 15.23 ± 0.10^d | 0.18 ± 0.01^m | −1.14 ± 0.10^9 | −1.36 ± 0.05 | −1.11 ± 0.03 | −0.85 | 15.10 ± 0.10 |
| NGC1851  | 15.44 ± 0.20^p | 0.02 ± 0.02^b | −1.22 ± 0.03^3 | −1.23 ± 0.11 | −1.03 ± 0.06 | −0.93 | 15.16 ± 0.10 |

Notes.

^a Cluster true distance modulus (mag). ^b Cluster reddening (mag). ^c High-resolution spectroscopic iron abundances. ^d Iron abundances based on Ca triplet measurements provided by Rutledge et al. (1997) in the Zinn & West (1984) and in the Carretta & Gratton (1997) metallicity scale. ^e Global metallicity based on spectroscopic iron abundances and assuming [α/Fe] = 0.4 (Salaris et al. 1993). ^f The Johnson–Cousins magnitudes of the RGB bump provided by A. Di Cecco et al. (2009, in preparation) were transformed into the ACS F814W-band (VEGAMAG) following Sirianni et al. (2005). ^g Bono et al. (2008). ^h Salaris et al. (2007). ^i Koch & McWilliam (2008). ^j Brocato et al. (1999). ^k Gratton (1987). ^l Castellani et al. (2006). ^m Bedin et al. (2000). ^n Carretta (2006). ^o Saviane et al. (1998). ^p Yong et al. (2009).

was plotted by assuming for the SMC a true distance modulus of μ = 18.9 and a reddening of E(B − V) = 0.08 mag. The ages of the main stellar components in this SMC field range from a few tens of Myr (bright MS) to a few Gyr (red clump, RC). To investigate the possible presence of an old stellar population we also compared IC10 to the globular cluster NGC 6362. The V, I-band photometry (Stetson 2000) for this cluster was transformed into the ACS photometric system using the transformations by Sirianni et al. (2005). NGC 6362 is an almost metal-rich cluster ([Fe/H] = −1.04 ± 0.06, [M/H] ~ −0.75, see Table 1) and its horizontal-branch (HB) morphology is characterized by both red and blue stars (Brocato et al. 1999). Data plotted in this figure, in particular in the helium burning region (i.e., RC and red HB stars, 25.8 < F814W < 25.2, 1.7 < F555W − F814W < 2.1), indicate that IC10 hosts both intermediate-mass stars (RC) and candidate old low-mass (red HB) stars. To further constrain these key points, Figure 3 shows the comparison of the same field with three GCs with different metal contents ([M/H] ~ −0.47, 47 Tuc; −0.85, NGC 2808; −0.93, NGC 1851, see references listed in Table 1) and HB morphologies (only red HB stars, 47 Tuc; red, blue HB and RR Lyrae stars, NGC 1851; red, blue HB and extreme HB stars, NGC 2808). Note that in this figure we plotted a number of IC10 stars, randomly selected, similar to the number of stars present in the GC NGC 2808. Data in Figure 3 further support the evidence (see Figure 1) that RGs in IC10 cover at least one-half dex in metal content (−0.4 < [M/H] < −1). Moreover, a fraction of the stars located near F814W ≈ 26 and 1.5 < F555W − F814W < 1.8 appear to be candidate RR Lyrae stars. Finally, we note that the comparison with empirical calibrators indicates that both metal-intermediate and metal-rich candidate RGB bump stars (see Table 1) should be systematically fainter than our current limiting magnitude at the color typical of RGB bump stars (F555W − F814W ≈ 2.1–2.2 mag, see the arrows in Figure 3).

To investigate the properties of He-burning stars we adopted different sets of evolutionary models constructed assuming both old and intermediate-age progenitors. The top panel of Figure 4 shows α-enhanced Zero-Age-Horizontal-Branch (ZAHB, solid line) models together with the He-exhaustion locus (dashed, 10% of central He still available) at a fixed metal and helium content (M/H] = −0.66, Y = 0.251) for an old (~14 Gyr) progenitor (Mpr = 0.80 M⊙). To cover the age range of IC10 stars we also adopted core He-burning (solid) and He-exhaustion (dashed, 10% of He left) models for a set of intermediate-age (160 Myr ≤ t ≤ 6.6 Gyr) progenitors (1.0 ≤ Mpr ≤ 3.5 M⊙). The evolutionary properties of He-burning, low-to-intermediate mass stars have been thoroughly investigated in the literature (Sweigart et al. 1990; Castellani et al. 2000; Pietrinferni et al. 2004, 2006; Bertelli et al. 2008). Here we note that the ratio between He- and H-burning lifetimes is quite constant (tHe/tH = 0.006) when moving from M(HB) = 0.60 to 0.80 M⊙ (old progenitor). On the other hand, the same ratio changes from tHe/tH = 0.11 (M(RC) = 1.83 M⊙) to 0.39 (M(RC) = 2.18 M⊙) and to 0.34 (M(RC) = 2.78 M⊙) for scaled-solar, intermediate-mass progenitors (see top panel of Figure 4). This stark difference is caused by the fact that when moving from 0.8 to 2.2 M/M⊙ the core He-ignition takes place in structures that are less and less affected by electron degeneracy. This means that the He core mass at He-ignition, and in turn the luminosity during core He-burning, decreases from MHe/M⊙ = 0.485 (Mpr = 0.80 M⊙, MHe/F814W = −0.35 mag, tHe ≈ 14 Gyr) to MHe/M⊙ = 0.467 (Mpr = 2.2 M⊙, MHe/F814W = −0.05 mag, tHe = 750 Myr). More massive structures are characterized by a convective core during H-burning phases and a further increase in stellar mass causes a steady increase in the He core mass and in luminosity (Mpr = 2.80 M⊙, MHe/M⊙ = 0.370 M⊙, MHe/F814W = −1.02 mag, tHe = 280 Myr). The above difference implies that the expected star count ratio between MS and He-burning structures increases by 1–2 orders of magnitude when moving from old to intermediate-mass stars.

Therefore, we decided to perform a more detailed comparison between theory and observations. We selected stars in the external regions using severe criteria (σF814W = σF555W ≤ 0.07 mag, sep ≥ 6, |sha| ≤ 0.2). Data plotted in the bottom panel...
of Figure 4 show that the well defined overdensity centered on $F814W \sim 25.72$ and $F555W - F814W \sim 1.90$ agrees quite well with the expected position of old, red HB stars and of intermediate-age red clump stars. The solid lines display the ZAHBs for two different metal contents ($[M/H] = -0.96$, $Y = 0.248$; $[M/H] = -0.35$, $Y = 0.256$) and for old and intermediate-age progenitors. The stellar masses and the ages of the progenitors are quite similar to the models plotted in the top panel. Note that the spread in magnitude and color of the He-burning region is larger than the typical photometric errors (see error bars). The range in color covered by the stellar overdensity is also systematically bluer and larger than the color range covered by typical low-mass RGB bump stars. The RGB bump in a metal-rich (47Tuc) and in a metal-intermediate (NGC 1851) globular cluster is, indeed, fainter and redder (see the arrows in Figure 3). This comparison also supports the hypothesis that the stars with $F814W \sim 26$ and $F555W - F814W \sim 1.7$ are candidate RR Lyrae stars. Note that corrections for completeness of the current photometry would go in the direction of increasing the number of candidate old HB stars.

The photometric accuracy in the region around the peak does not allow us to distinguish RC from old HB stars. However, the occurrence of warm HB stars, once confirmed by independent experiments, will provide a robust identification of the so-called Baade’s red sheet, i.e., evidence for an old stellar population (Baade 1963) in a starburst galaxy. Current circumstantial evidence is, indeed, based on intermediate-age (RC) He-burning stars (Aparicio et al. 1997; Schulte-Ladbeck et al. 1998). Moreover, the identification of massive MS stars, old (HB), and intermediate age (RC) helium burning stars indicates that IC10 underwent several star formation episodes during its life. A CMD couple of magnitudes deeper and with a stronger temperature sensitivity could provide firm constraints on whether the star formation activity of this interesting system has been continuous or sporadic.

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Figure 4. Top: color–magnitude diagram for predicted He-burning structures at fixed global metallicity ($[M/H] = -0.66$). The fainter solid and dashed lines show the α-enhanced ZAHB and the He-exhaustion (10% of He core still available) for an old progenitor ($t_f = 14$ Gyr, $M_{pr} = 0.80 M_\odot$). The brighter solid and dashed lines show the core He-burning and the He exhaustion for intermediate-age progenitors. The mass of the progenitors, the mass at core He-burning, and the ratio between He and H lifetimes for selected structures is also systematically bluer and larger than the color range covered by typical low-mass RGB bump stars. The RGB bump in a metal-rich (47Tuc) and in a metal-intermediate (NGC 1851) globular cluster is, indeed, fainter and redder (see the arrows in Figure 3). This comparison also supports the hypothesis that the stars with $F814W \sim 26$ and $F555W - F814W \sim 1.7$ are candidate RR Lyrae stars. Note that corrections for completeness of the current photometry would go in the direction of increasing the number of candidate old HB stars.