The Ages of Stars
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The ACS LCID project: Variable stars as tracers of population gradients

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Abstract. We present a few highlights concerning the search for short-period variable stars in four galaxies, namely IC 1613, LGS 3, Cetus and Tucana, based on very deep, multi-epoch HST/ACS photometry. These are discussed in the context of the star formation histories obtained from our very deep color-magnitude diagrams. In particular, we show how the pulsational properties of the RR Lyrae stars, which represent the vast majority of the observed variables, can trace subtle differences in the age and metallicity of the old population. For example, in the dwarf spheroidal galaxy Tucana we find that the fainter RR Lyrae stars, having a shorter period, are more centrally concentrated than the more luminous, longer period RR Lyrae variables. Through comparison with the predictions of theoretical models of stellar evolution and stellar pulsation, we interpret the fainter RR Lyrae stars as a more metal-rich subsample. In addition, we show that they must be older than about 10 Gyr, indicating that the metallicity gradient must have appeared very early on in the history of this galaxy. We also compare the populations of Cepheids in the galaxies of our sample based on their period-Wesenheit diagram. We tentatively classify them as classical short-period Cepheids in the two gas-rich galaxies (IC 1613 & LGS 3), and as anomalous Cepheids in the dwarf spheroidals.

Keywords. stars: horizontal-branch, stars: oscillations, stars: Population II, stars: variables: other, galaxies: dwarf, galaxies: evolution, Local Group

1. Introduction

Pulsating variable stars play a major role in the study of stellar populations and in cosmology, as their pulsational properties are traditionally used to determine distances and to put constraints on stellar physical properties. Because the pulsations occur at a particular phase of their evolution depending on the star mass, variable stars trace the spatial distribution of stellar populations of given ages, therefore highlighting the eventual radial trends across the studied galaxy (e.g., Gallart *et al.* 2004).

This, in turn, provides important clues to the formation mechanisms and the star formation history (SFH) of the host galaxy. Therefore, by providing information about the properties of the underlying population, variable star research procures a way to study the histories of these galaxies, independent and complementary to the color-magnitude diagram (CMD) analysis.

With the goal of understanding these processes, we are carrying out a large project (LCID) aiming at reconstructing the full SFH of a sample of isolated dwarf galaxies of the Local Group (LG), based on very deep, multi-epoch *Hubble Space Telescope* (*HST*) ACS data (see Monelli *et al.*, these proceedings). The sample includes representatives of the three main dwarf galaxy morphological types—irregular (dIrr), spheroidal (dSph) and so-called transition dIrr/dSph—located further than about two virial radii from both

† Local Cosmology from Isolated Dwarfs: http://www.iac.es/project/LCID/.

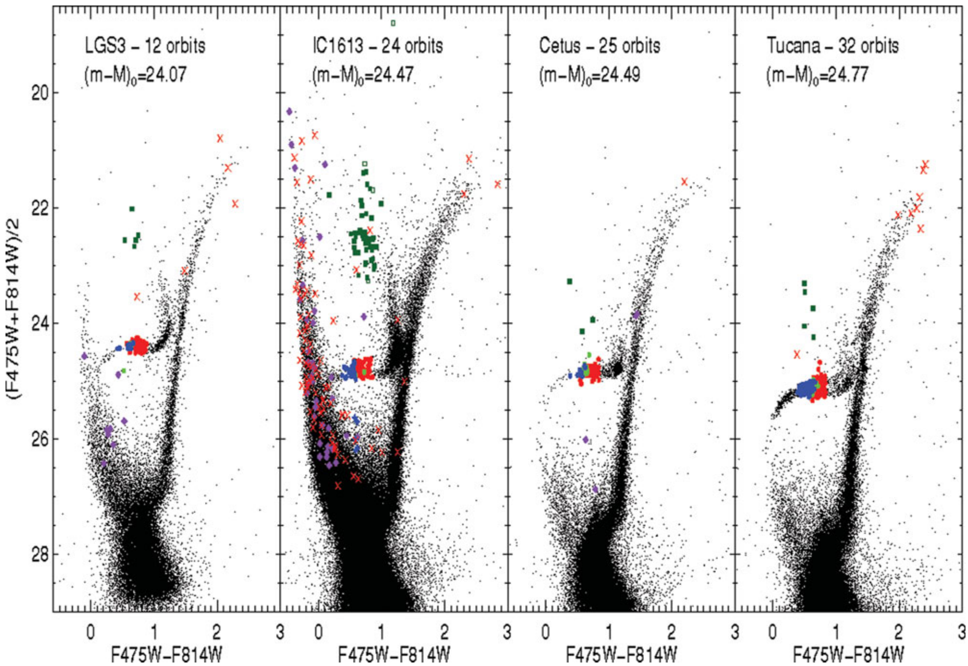

Figure 1. Color-magnitude diagrams of four of the galaxies of our sample, where the variables have been overplotted: Cepheids (*squares*), RR Lyrae stars (*circles*), eclipsing binaries (*diamonds*), and other candidates (*crosses*).

the Milky Way (MW) and M31. The project will be described in detail in a forthcoming paper (Gallart *et al.* 2009, in preparation), and the first results concerning the SFH of Leo A were presented in Cole *et al.* (2007).

Figure 1 shows the CMDs of the four galaxies that have been searched for variable stars to date: LGS3, IC1613, Cetus and Tucana. The number of orbits devoted to each galaxy, which also corresponds to the number of datapoints per band (F475W and F814W), is also indicated in the panels. In total, we found more than 900 variables in these galaxies. The vast majority (~700) are of the RR Lyrae type. The other classified variables include about 60 Cepheids—both classical and anomalous (see below)—and 50 eclipsing binaries. For LGS3, Cetus and Tucana, these are also the first confirmed variable stars. The remaining candidates are mainly located on the main sequence of IC1613 and, while most of them are probably eclipsing binaries, some of the brightest stars exhibit low-amplitude, pulsating-like variation. The variables in the dSphs Cetus and Tucana are presented in Bernard *et al.* (2009a). We will describe the variables in IC1613 in a forthcoming paper (E. Bernard *et al.* 2009b, in preparation). Here, we present a few highlights of the project, namely the use of RR Lyrae stars as tracers of old population gradients, and the relationship between the SFH and the type of Cepheid present in a galaxy.

2. RR Lyrae stars in Tucana

In Fig. 1, one can see that Tucana harbors a rather complex horizontal-branch (HB), which is well populated on both sides of the IS. The red side also presents a small gap in magnitude, suggesting the combination of two HB of different luminosities. This is supported by the unusual width in luminosity of the HB inside the IS (~0.3 mag at

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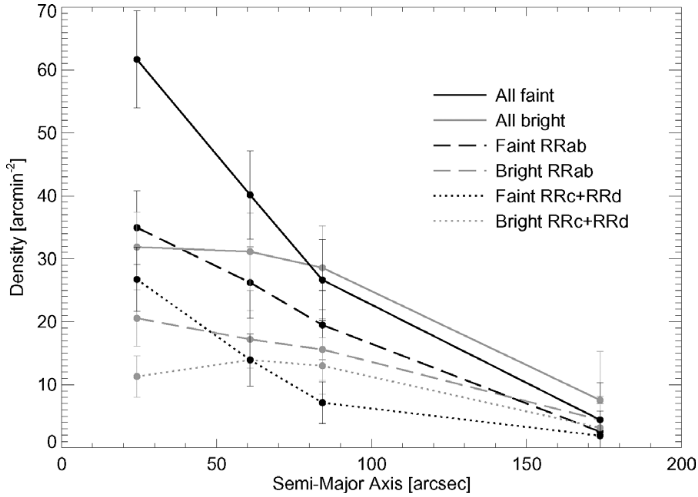

Figure 2. Radial distribution of the different subsamples of RR Lyrae stars in Tucana, showing how the fainter RR Lyrae stars are systematically more concentrated in the center of the galaxy than the brighter variables.

F475W-F814W=0.7, excluding the few bright and faint outliers), which is larger than expected from the evolutionary tracks, even taking into account the evolution off the zero-age HB (ZAHB).

We arbitrarily used the mean magnitude of the variables to split the RR*ab*, RR*c* and RR*d* variables into bright and faint subsamples, each type of variable having approximately the same number of stars in each subsample.

On a period-amplitude (PA) diagram, two distinct RR*ab* sequences are clearly identified, characterized by different mean periods (0.574 vs. 0.640 days) and dispersions around the fit. As predicted by nonlinear pulsation models (Bono *et al.* 1997b), the mean period is a function of luminosity, in the sense that the more luminous variables tend to have a larger period. The period difference also shows up in the RR*c* and RR*d* subtypes, and is of the order of 0.02 days.

The difference in the mean period of the RR Lyrae stars of each sample could be attributed to both a difference in metallicity (from the period-metallicity correlation) or a difference in the evolutionary status of the individual stars, the stars in the redward evolution off the ZAHB having a longer period (Bono *et al.* 1997b, their Fig. 16-17). However, stellar evolution models indicate that evolution off the ZAHB alone cannot account for the range of luminosity spanned by the RR Lyrae stars. Hence, it is necessary to invoke a range of metallicity to reproduce the distribution of stars within the IS, the more metal-rich stars being fainter. The hypothesis of a bimodal metallicity distribution is strengthened by the double "bell-shape" of the RR*c* in the PA diagram (Bono et al. 1997a) and the presence of two RGB bumps separated by $\sim$0.2 mag in F814W.

The presence of different populations in a galaxy, whether due to the details of its SFH or to the accretion of an external stellar system, generally leads to gradients in the observable properties of its stars. Figure 2 presents the radial profile for each subsample of RR Lyrae stars. The radii were chosen so that each concentric region contains the same number of variables. It shows that, for each type of RR Lyrae stars, the fainter, more metal-rich variables are systematically more concentrated near the center of the galaxy,

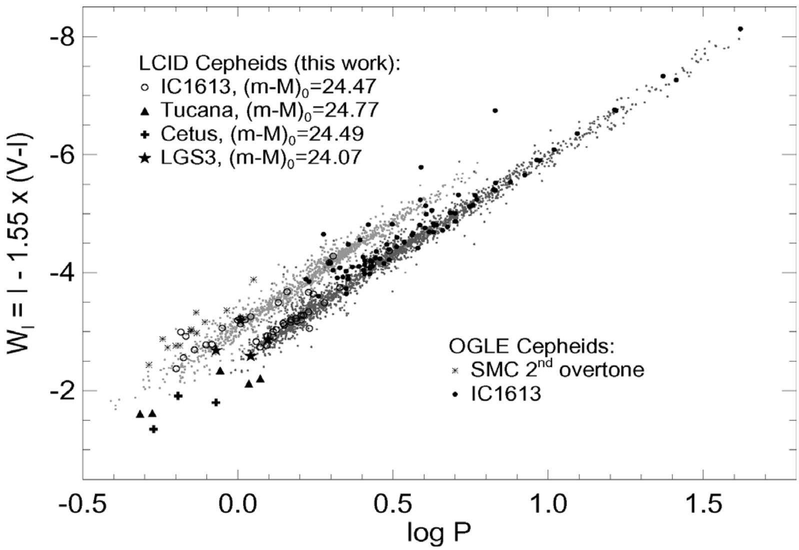

Figure 3. Period-Wesenheit diagram of the Cepheids in the galaxies of our sample (*see inset*), overplotted on the OGLE Cepheids (F: *dark gray*, FO: *light gray*).

while the brighter, metal-poor RR Lyrae stars are spatially extended. The combination of different intrinsic properties of the individual stars with the different spatial distribution supports the hypothesis that they represent separate populations.

In addition, our artificial HB computations indicate that the faintest, highest metallicity ($Z>0.0006$) RR Lyrae variables of Tucana must be >10 Gyr old. Therefore, under the reasonable assumption that chemical enrichment follows age in star forming galaxies, the presence of gradients in the RR Lyrae populations shows that these metallicity gradients appeared very early on in the history of this galaxy.

3. Cepheids

As shown in Fig. 1, Cepheids were detected in all four galaxies. However, their mean luminosities are very different between the gas-rich galaxies, LGS3 and IC1613, and the dSphs. This is also apparent in Fig. 3, where we plot the Cepheids found in the four galaxies of our sample in the period-Wesenheit diagram. The use of the Wesenheit, or reddening-free, index instead of the luminosity reduces the scatter due to interstellar reddening. The Johnson magnitudes for our Cepheids were obtained as described in Bernard et al. (2009a). They are shown overplotted on the classical Cepheids of the Large and Small Magellanic Clouds (LMC & SMC; fundamental mode: *dark gray*, first overtone: *light gray*) and of IC 1613 from the OGLE collaboration (Udalski *et al.* 2001, and references therein). The apparent magnitudes were converted to absolute magnitude assuming a distance modulus of 18.54 to the LMC (which is the value we adopted to calculate the distance of the LCID galaxies), and a distance offset of 0.51 of the SMC relative to the LMC (Udalski *et al.* 1999). The distances for the galaxies of our sample were calculated from the properties of the RR Lyrae stars (see Bernard *et al.* 2009a) and are shown in the inset.

It shows that the Cepheids in the gas-rich galaxies fit very well on the PL relations, while those in the dSphs fall significantly below. Note that the uncertainty on the

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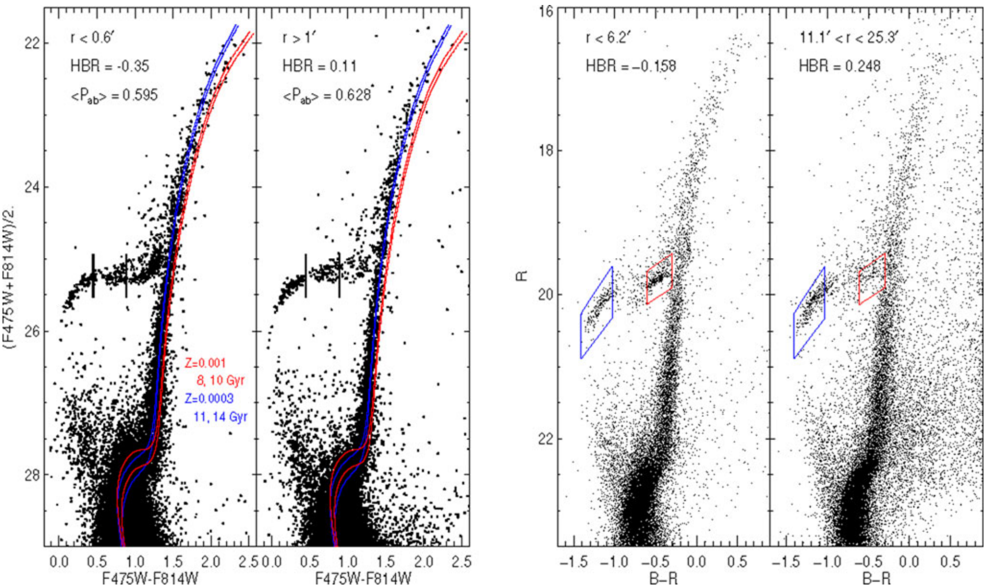

Figure 4. CMDs of Tucana (*left*, from Bernard *et al.* 2008) and Sculptor (*right*, in instrumental magnitude, from WFI@ESO 2.2-m data; Giuffrida *et al.* 2006) for two galactocentric distances. Note the similarity between the two galaxies in terms of slope of the upper RGB, horizontal-branch morphology and turnoff stars, both in the inner and outer regions.

distance estimates for the LCID Cepheids is about 0.1, which is insufficient to explain the magnitude shift. Their position with respect to the PL relations is similar to that of the anomalous Cepheids found in the dwarf galaxy Phoenix (Gallart *et al.* 2004). The difference between anomalous and classical Cepheids, from a theoretical point of view, is that the former initiated the core He burning under degenerate conditions while the latter are massive enough to burn He in non-degenerate conditions. Given that the dSphs did not form stars in the past few Gyrs, the only stars that can cross the instability strip above the HB have relatively low mass. On the other hand, the gas-rich galaxies have current star formation, at least residual in the case of LGS3, and therefore still have massive stars producing luminous, short-period classical Cepheids.

4. Isolated vs. Satellite Dwarf Spheroidals

As stated in the previous section, we found that the pulsational properties of the RR Lyrae stars in Tucana trace metallicity gradients, and that these gradients must have appeared very early on. This was the first time spatial variations of these properties were observed in a dwarf galaxy, thanks to the large spatial coverage and number of discovered variables. Is Tucana unique in this respect, or can we expect the same to occur in other dSphs?

In the Local Group (LG), the gas-deficient dSph galaxies are preferentially found as satellites to the MW or M31, while the gas-rich dwarfs are usually isolated. This suggests that environmental factors must play a fundamental role in the formation and evolution of these dwarf galaxies. However, our very deep HST photometry of Tucana, which is one of only two *really isolated* dSphs in the LG—at 870 kpc from the MW and 1340 kpc from M31—showed that its stellar population is disturbingly similar to that of the nearby satellite dSph Sculptor: their deep CMD are basically indistinguishable (see Fig. 4) and present similar gradients in their HB morphology and main-sequence turnoff as a function of galactocentric distance.

Given its location in the LG, Tucana might have experienced *at most* one close encounter with the MW in its lifetime. Sculptor, on the other hand, with its apogalacticon of 122 kpc and orbital period of 2.2 Gyr (Piatek *et al.* 2006), spent most of its lifetime within the halo of the MW. In these conditions, theoretical investigations indicate that tidal stripping and stirring and ram pressure stripping (Blitz & Robishaw 2000, Mayer *et al.* 2006), and the local UV radiation from the primary galaxy (Mayer *et al.* 2007) all act to remove dark matter and/or baryons from the dwarf, implying that it was likely ten times more massive in the past (Kravtsov *et al.* 2004). Even so, Sculptor is still much more massive than Tucana at the present time ($M_V = -11.1$ versus -9.6 for Tucana).

However, to date the only CCD-based search for variable stars in Sculptor is that of Kaluzny *et al.* (1995, in the V-band only), which identified 226 RR Lyrae stars in a field of only 15'x15', while the galaxy's tidal radius is at least of 80' (Westfall *et al.* 2006) and $\sim$1050 variables are expected (van Agt 1978). The fact that Tucana and Sculptor have important differences in mass and in interaction history makes of them an interesting pair to compare in detail their evolutionary histories in order to shed light on possible mechanisms shaping up the early evolution of galaxies. For these reasons, as a parallel project we recently obtained deep, multi-epoch photometry of a 1.7 square degree field centered on Sculptor using the MOSAIC-II camera mounted on the CTIO-4m Blanco telescope, specifically to study the gradients in the properties of the variable stars and the star formation histories, and to compare the results with those of Tucana.

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Discussion

A. Pipino: Can you give an estimate of the metallicity gradient on the basis of the RR Lyrae analysis alone? Is the method accurate enough?

E.J. Bernard: We did not try to quantify the gradients from the RR Lyrae stars since their location in the CMD is also a function of their evolutionary status, and the populations are mixed in the center of the galaxy.

A rough estimate based on the difference of average RR Lyrae luminosity between the inner—where the populations are mixed—and outer—mostly metal-poor—fields ($\sim$0.05 mag) and the slope of the luminosity-metallicity relation (ΔM_V(RR)/Δ[Fe/H]=0.214; Clementini *et al.* 2003, AJ, 125, 1309) gives a 0.2 dex difference over the sampled radius. Assuming the bright and faint subsamples are *bona fide* metal-poor and metal-rich populations, that is, ignoring the evolutionary effects on the luminosity of individual stars and the fact that the HB is not precisely horizontal, their difference in luminosity of 0.1 mag implies a difference in metallicity of $\sim$0.5 dex.

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