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We present a study of the radial distribution of RR Lyrae variables, which present a range of photometric and pulsational properties, 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. Therefore, the metallicity gradient must have appeared very early on in the history of this galaxy.

**Subject headings:** galaxies: dwarf — galaxies: individual (Tucana) — Local Group — stars: horizontal-branch — stars: variables: other

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1. INTRODUCTION

The oldest stellar populations in galaxies are of fundamental importance because they can constrain the epoch of onset of star formation in the universe. Unfortunately, the oldest main-sequence turn-offs (MSTO), which provide the most straightforward characterization of the old population, can only be reached in a handful of Milky Way satellite galaxies using current ground-based observing facilities. An alternative approach is the characterization of the RR Lyrae star populations. The fact that the properties of the RR Lyrae stars reflect the properties of the old population is crucial because the horizontal-branch (HB) stars are about 3 magnitudes brighter than their MSTO counterpart.

For example, it has long been suspected that the mean magnitude of the RR Lyrae variables, $M_v(RR)$, is a function of [Fe/H], in the sense that more metal-poor RR Lyrae stars are more luminous (Sandage 1958). The correlation between $M_v(RR)$ and [Fe/H] was later confirmed by stellar evolution models, but with the additional constraint that the morphology of the HB, i.e., the evolutionary status of the stellar population, must be taken into account (e.g., Cassisi et al. 2004). As the population gets older, the mass of the stars reaching the HB decreases, giving a bluer HB. In this case, the stars crossing the instability strip (IS) are therefore already evolving off the zero-age horizontal branch (ZAHB) and are more luminous than younger stars of the same metallicity.

In addition, observations of Galactic globular clusters suggested that the lower their metallicity, the longer the mean period of their RR Lyrae stars. This led to the various period-metallicity relations found in the literature (see, e.g., Catelan 1992; Sandage 1993; Sarajedini et al. 2006), or the more elaborate period-metallicity-amplitude relations (e.g., Alcock et al. 2000; Sandage 2004), providing a convenient way of estimating the metallicity of a stellar system based on distance- and reddening-free observables (namely, mean period $\langle P_\text{m} \rangle$ and visual amplitude $A_v$).

We note, though, that Clement & Shelton (1999) have argued that the period-amplitude (P-A) relation for RRab stars is not a function of metal abundance, but is instead related to the evolutionary status of the RR Lyrae stars. In the metal-poor, Oosterhoff type II clusters, the (blue) HB stars would have started to evolve away from the ZAHB, crossing the IS at higher luminosities, therefore following a different P-A relation from the ZAHB RR Lyrae stars.

However, theoretical (Bono et al. 2007) and observational (Wehlau et al. 1999; Kaluzny et al. 2000; Layden & Sarajedini 2000; Olesch et al. 2001; Borissova et al. 2001) evidence suggest that, while there is a clear correlation of Oosterhoff type with metallicity, there is an additional dependence of the period at a given amplitude on metallicity, with the more metal-rich stars having shorter periods.

An analysis of the variation of these observables as a function of the position within a galaxy can highlight the eventual radial trends across the studied galaxy. This, in turn, provides important clues to the formation mechanisms and the star formation history of the host galaxy. Hence, by providing information about the properties of the underlying population, variable star research procures a way to study the histories of these galaxies, independent of and complementary to the CMD analysis.

In this Letter we report, for the first time, the detection of stellar population gradients in a dwarf galaxy based solely on the periods and luminosities of its RR Lyrae stars. This was made possible by the large number of RR Lyrae variables discovered in the isolated Local Group dSph Tucana, based on Hubble Space Telescope (HST) ACS data covering the whole...
body of the galaxy, together with the high quality of the light curves. We present supporting evidence from the different evolutionary phases present in the CMD.

2. OBSERVATIONS AND DATA REDUCTION

The present analysis is based on observations obtained with the Advanced Camera for Surveys on board the HST as part of the major program LCID\textsuperscript{11} aiming at deriving detailed star formation histories for a sample of Local Group isolated dwarf galaxies (C. Gallart et al. 2008, in preparation). As the goal of these observations was to reach the oldest MTSO with good signal-to-noise ratio on the final stacked images, 32 orbits were devoted to the observations of Tucana. These were collected over about 5 consecutive days between 2006 April 25 and 30. As each orbit was devoted to one exposure in the F475W band and one in F814W, the observing sequence consisted of alternating \( \sim 1000 \) s exposures in F475W and F814W for an optimal sampling of the light curves. The DAOPHOT/ALLFRAME suite of programs (Stetson 1994) was used to obtain the instrumental photometry of the stars on the individual, nondrizzled images. A detailed description of the observations, data reduction, and calibration will be given in a forthcoming paper (M. Monelli et al. 2008, in preparation). To search for variable stars, the Welch-Stetson variability index (Welch & Stetson 1986) was used. From the list of candidates, 358 stars were identified as bona fide RR Lyrae stars, for which the period was searched through Fourier analysis following the prescription of Horne & Baliunas (1986). We identified 216 RR\textsubscript{ab}, 82 RR\textsubscript{c}, and 60 RR\textsubscript{d} stars based on their period and light-curve shape. Further details about the variable star content of Tucana and another isolated dSph, Cetus, will be presented in a future paper (E. Bernard et al. 2008, in preparation).

3. THE RR L YRAE POPULATION AND ITS SPATIAL GRADIENTS

Figure 1 (top) shows the CMD of Tucana centered on the HB. The (F475W + F814W)/2 \( \sim V \) filter combination was chosen for the ordinate axis so that the HB appears approximately horizontal. The RR Lyrae stars are overplotted with larger dots using their intensity-weighted magnitudes. One can see that Tucana harbors a rather complex 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 HBs of different luminosities. This is supported by the unusual width in luminosity of the HB inside the IS \( \sim 0.15 \) mag at F475W/F814W, even taking into account the evolution off the ZAHB.

We arbitrarily used the mean magnitude of the variables at (F475W + F814W)/2 \( \sim 25.2 \), shown with the horizontal line in the bottom panel of Figure 1, to split the RR\textsubscript{ab}, RR\textsubscript{c}, and RR\textsubscript{d} variables into bright and faint subsamples, each type of variable having approximately the same number of stars in each subsample. Different symbols have been used for each type and subsample. For the sake of clarity, RR\textsubscript{d} variables are not represented.

The RR Lyrae stars are plotted on P-A diagram in Figure 2. The symbols are as in the bottom panel of Fig. 1. Linear fits to each sample of RR\textsubscript{ab} are also represented.

\textsuperscript{11} Local Cosmology from Isolated Dwarfs, \url{http://www.iac.es/project/LCID/}
(KS) discrepancy of $D_{KS} = 0.4397$, implying a probability $P_{KS} < 10^{-3}\%$ that the bright and faint RRab subsamples were drawn from the same parent population. 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 RRc subtype: the “bell shape” distribution (Bono et al. 1997b) of the brighter RRc is shifted toward longer period with respect to the fainter RRc. The difference in mean period is $\sim 0.02$ days ($P_{KS} < 0.34\%$). The mean primary period of double-mode RR Lyrae stars presents a similar shift between the bright and faint subsamples ($P_{KS} < 2 \times 10^{-3}\%$).

Interestingly, the faint and bright subsamples of RRab variables have mean periods of 0.574 and 0.640 respectively, which is very reminiscent of the mean periods of the Oosterhoff types I and II (0.55 and 0.64, Oosterhoff 1939). This is also the case for the subsamples of RRc variables, having mean periods of 0.343 and 0.366, versus 0.32 and 0.37 for the OoI and OoII globular clusters of the Milky Way. On the other hand, the whole sets of RRab and RRc have mean periods of 0.604 and 0.353, respectively. These numbers would lead to the classification of Tucana as an Oosterhoff intermediate (Oo-Int), as is the case for most dSphs (Catelan 2004). In this particular case, however, there is the possibility that the Oo-Int status could be attributed to the mixture of OoI and OoII populations, as hinted by the two roughly parallel sequences in the P-A diagram of the RRab in Figure 2.

The presence of different populations in a galaxy, whether due to the details of its star formation history or to the accretion of an external stellar system, generally leads to gradients in the observable properties of its stars. Figure 3 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 variables are systematically more concentrated near the center of the galaxy, while the brighter RR Lyrae stars are spatially extended. The difference in spatial distribution is very significant as the radii containing half of the bright and faint RR Lyrae stars are 1.33′ and 1.09′, respectively, and a KS test gives a probability of $\leq 0.001$ for the bright and faint RR Lyrae stars to have the same radial distribution. The combination of different intrinsic properties of the individual stars with the different spatial distribution supports the hypothesis that they represent separate populations.

4. DISCUSSION

The difference in the mean period of the RRab 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 Figs. 16–17). However, the top panel of Figure 1 shows 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 hypothesis of a bimodal metallicity distribution is strengthened by the double “bell shape” of the RRc in the P-A diagram (Bono et al. 1997a) and the presence of two RGB bumps separated by $\sim 0.2$ mag in F814W (C. Gallart et al. 2008, in preparation). We use the luminosity of the theoretical ZAHB in Figure 1 to estimate this range. A firm upper limit for the metallicity of the old population is given by the ZAHB at $Z = 0.001$. While the $Z = 0.0001$ ZAHB seems to be slightly too luminous, the $Z = 0.0003$ tracks cannot produce the brightest RR Lyrae stars in our observations. We suggest $Z \sim 0.0002$ as an approximate lower limit to the metallicity of Tucana.

Although the range of metallicity is relatively wide for a dSph, it is supported by the color of the RGB of the inner and outer regions of Tucana presented in Figure 4. The isochrones show that the higher metallicity population visible in the central region, with
HB ratio (HBR) increases by about 0.5 over the radius sampled and the blue HB stars are present everywhere. Consequently, the only in the center of the galaxy, while the brighter stars of the IS HB. The faint RR Lyrae variables and the red HB stars show up sub-HB RGB. Note, also, the difference in the morphology of the lower than is needed to explain the blue side of the Z function of age and metallicity for artificial stars within the IS artificial HB computations: it represents the mean mass as a than the red HB stars. Figure 5 illustrates the results of our ing—do show that there is a slightly younger population in the regions of Tucana—which takes into account the effects of crowd- ing—do show that there is a slightly younger population in the center. However, the youngest stars within the IS are slightly older than the red HB stars. Figure 5 illustrates the results of our artificial HB computations: it represents the mean mass as a function of age and metallicity for artificial stars within the IS

\[^{12}\text{HBR} = (B - R)/(B + V + R),\text{ where } B, V, \text{ and } R \text{ are the numbers of stars to the blue, within, and to the red of the IS (Lee 1990).}\]

\[^{13}\text{See http://iac-star.iac.es/iac-star/}.\]

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