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The stellar populations of dSph galaxies in nearby groups

G.S. Da Costa

Research School of Astronomy & Astrophysics, The Australian National University
email: gdc@mso.anu.edu.au

Abstract. In this contribution initial results are presented from a program to study in detail the stellar populations of dwarf Spheriodal (dSph) galaxies in three nearby groups. The long-term aim of the program is to assess the influence of environment in governing the evolution of these low-luminosity systems. Specific results described here include the detection and measurement of intermediate-age upper-AGB populations in dSphs in the M81 and Cen A groups, and the discovery that four of the five low-luminosity early-type dwarfs in the low density Sculptor group contain modest amounts of neutral hydrogen gas.

Keywords. galaxies:dwarf, galaxies:stellar content, galaxies: evolution, stars: AGB

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1. Introduction

We have known for more than two decades that the dwarf Spheroidal (dSph) companion galaxies to the Milky Way show a variety of star formation histories. These range from essentially a single old stellar population (e.g. Ursa Minor, Olszewski & Aaronson 1985, Carrera *et al.* 2002) through to the complex star formation histories of dSphs such as Carina (e.g. Monelli *et al.* 2003), Fornax (e.g. Saviane *et al.* 2000) and Leo I (e.g. Gallart *et al.* 1999), which contain stars as young as ∼1 Gyr, or perhaps even younger. The derivation of these star formation histories is now based on deep colour-magnitude (c-m) diagrams that reach below the main sequence turnoff for the oldest populations, but it is important to recall that the first evidence for the existence of intermediate-age (i.e. age between ∼1 and 10 Gyr) populations in dSphs came from the observation that some systems contain upper-AGB stars (cf. Aaronson & Mould 1980). Upper-AGB stars are stars with sufficient mass that they evolve to luminosities well above the tip of the red giant branch in the c-m diagram. Provided the underlying population is relatively metal-poor ($<$[Fe/H]$>$ $\leqslant -1.0$, approximately), the presence of upper-AGB stars, which are frequently seen as carbon stars, in a stellar population is an unambiguous signature of the existence of an intermediate-age population, and the luminosity of the brightest upper-AGB stars is a measure of the age of the youngest intermediate-age population present.

With advent of HST it has also become possible to determine c-m diagrams that reach below the level of the horizontal branch for the dSph† companions to M31 (e.g. Da Costa *et al.* 2002), and thus gain some first-order information on their star formation histories. All the systems studied contain RR Lyrae variables, indicating that they contain at least some stars with ages comparable to that of the Milky Way globular clusters (this is also true of the Milky Way dSph companions). Nevertheless, the ubiquitous red horizontal branches in the c-m diagrams argue for extended epochs of star formation and "mean ages" younger than that of the Galactic globular clusters (much like the Galactic dSph Leo II – see Mighell & Rich 1996). However, the M31 dSph companions appear to lack the

† Throughout this contribution the term 'dSph' is synomous with 'low luminosity dE'.

substantial intermediate-age upper-AGB populations seen in many of the Milky Way's dSph companions. Confirmed populations of upper-AGB stars are known only in some of the M31 dSph companions, such as And II and And VII (Cas) (see Harbeck *et al.* 2004 and Harbeck, these proceedings), but the luminosities of these stars suggest ages of perhaps 6–9 Gyr, in contrast to the younger (and more luminous) stars seen in Carina, Leo I and Fornax (cf. Da Costa *et al.* 2000).

Within the Local Group there are a further four known low-luminosity early-type dwarf galaxies. These are the transition-type (dIrr/dE) systems Phoenix and LGS 3, that are outlying companions of the Milky Way and M31, respectively, and the relatively isolated dSph systems Tucana and Cetus. Both Phoenix and LGS 3 have modest populations of young stars, contain small amounts of HI gas, and clearly have had star formation from the distant past to the present (cf. Holtzman *et al.* 2000, Miller *et al.* 2001). The somewhat limited data for Cetus shows that this dSph has a red horizontal branch morphology (Sarajedini *et al.* 2002), and that it lacks any obvious upper-AGB population (Harbek *et al.* 2004). It is apparently broadly analogous to the M31 dSph companions. The isolated dSph Tucana, however, shows a relatively strong blue horizontal branch morphology in its c-m diagram (cf. Da Costa 1998); indeed other than the Galactic dSph companion Ursa Minor, the horizontal branch morphology of Tucana is the bluest known of the Local Group dSphs, suggesting a relatively brief star formation epoch in the distant past. A recent determination of the radial velocity of Tucana (Tolstoy, personal communication) has removed any possibility of an association between this dSph and an HI cloud that lies nearby on the sky (cf. Osterloo *et al.* 1996). Given this result, the Oosterloo *et al.* (1996) upper limit of $M_{HI}/L_B \approx 10^{-2}$ in solar units indicates that the Tucana dSph is similar to the Galactic dSphs in lacking neutral gas.

Do we understand what causes this variety of star formation histories in early-type low-luminosity galaxies? In general the answer is 'no' but it is clear from the existing results that 'environment', represented by, for example, proximity to a luminous galaxy, and the type of that galaxy, plays a role in influencing the star formation histories of these systems. Van den Bergh (1994) noted that for the Galaxy's dSph companions, there is a tendency for the systems with larger intermediate-age component to lie at larger galactocentric distances. The same trend may also apply for the M31 dSphs, as the two systems with likely intermediate-age populations, And II and And VII (Cas), are among the most distant from M31. Further, the difference in relative frequency of intermediate-age populations between the Galactic and M31 dSph systems may have its origin in the different 'parent' galaxy types: M31 has a much larger bulge than the Galaxy.

Clearly if we wish to understand the role of environment in influencing the evolution of these low luminosity systems, we need to study the stellar populations of dSphs in groups beyond the Local Group. Fortunately, the nearest groups provide a variety of different environments. The Sculptor group is a loose aggregation of galaxies ranging in distance from $\sim$1.5 to $\sim$4 Mpc. It contains half a dozen or so early-type low-luminosity systems though the group contains mainly late-type galaxies. In contrast, the M81 and Cen A groups are relatively dense, compact groups that lie at distances of $\sim$3.5 to $\sim$4 Mpc. Both groups contain at least a dozen or more low-luminosity early-type galaxies. In all three groups the dSphs cover a range of internal (absolute magnitude, size, etc) and external (distance from nearest large galaxy, local galaxy density) properties.

Together with my collaborators I am involved in a number of programs aimed at studying in detail the stellar populations of the dSphs in these groups. We are using HST ACS/WFC and existing 'snapshot' data to determine distances and metal abundances, Gemini-North NIRI and VLT ISAAC near-infrared images to study upper-AGB populations, and, for the two southern groups, Australia Telescope Compact Array and Parkes radiotelescope observations to determine, or place limits on, neutral gas contents. In this contribution I present initial results for some of the dSphs in these groups.

2. M81 Group

The first investigation of the stellar populations of dSph galaxies in this group was that of Caldwell *et al.* (1998), who used multi-orbit HST/WFPC2 V and I imaging to determine c-m diagrams for two M81 group dSphs, F8D1 and BK 5N. The latter system has $M_V \approx -11.3$ and lies approximately 70kpc from M81 and ~30kpc from NGC 3077 (in projection). The Caldwell *et al.* (1998) c-m diagram clearly shows that an upper-AGB population is present in this galaxy, indicating on-going star formation. Caldwell *et al.* (1998) estimate the upper-AGB termination luminosity as $M_{bol} \approx -4.3$, which suggests that stars formed in this dSph until ~8 Gyr ago. F8D1, on the other hand, is a luminous ($M_V \approx -14.2$) low surface brightness dSph that lies ~120kpc from M81 and approximately 35kpc from the spiral galaxy NGC 2976 (in projection). The c-m diagram shows a strong upper-AGB population, which remains even when allowance is made for the likely presence of 47 Tuc-like long period variables, i.e. stars that lie above the red giant branch tip, but which are not of intermediate-age. Such stars can occur whenever the mean metallicity of a system exceeds [Fe/H] ≈ –1.0 dex. Caldwell *et al.* (1998) indicate that the most luminous of the upper-AGB stars in F8D1 have $M_{bol} \approx -5.0$. This dSph has also been observed in the near-infrared using NIRI on the Gemini-N telescope. The observations (see Da Costa 2004 for a full discussion) yield very similar results to those of Caldwell *et al.* (1998): the most luminous stars again have $M_{bol} \approx -5.0$ and the luminosity functions for the upper-AGB stars calculated from the I-band and K-band data agree well (Da Costa 2004). Comparisons with LMC and SMC cluster data, and with near-IR data for the Galactic dSph companion Leo I (cf. Menzies *et al.* 2002), suggest that F8D1 contains stars as young as 1–2 Gyr.

Gemini-N NIRI imaging has now also been analysed for an additional M81 group dSph, known as kkh57 (Da Costa *et al.*, in preparation). This dSph is a small, low luminosity ($M_V \approx -10.9$) system, that lies in a rather isolated location in the group, approximately 370kpc in projection from M81. The c-m diagram for kkh57 clearly shows the presence of upper-AGB stars, indicating on-going star formation in this dSph as well. The brightest of the upper-AGB stars have $M_{bol} \approx -4.3$ to –4.6, somewhat more luminous than for BK 5N yet fainter than for F8D1. This would appear to be prima facie evidence that the diversity of star formation histories seen among the Local Group dSphs is also present in the dSphs of the M81 group.

3. Cen A Group

In this group we have recently obtained VLT ISAAC near-IR imaging of 14 dwarf systems (see Rejkuba *et al.*, these proceedings). Analysis of this dataset continues but I present here initial results for AM1343-452 (kk217), a dSph with absolute visual magnitude $M_V \approx -11.5$ that lies approximately 290 kpc in projection from Cen A. Karachentsev *et al.* (2002) classify it as a Cen A companion. The left panel of Fig. 1 shows an optical c-m diagram derived from the HST snapshot data for this galaxy. *The stars plotted are only those that are measured on both the HST and the VLT ISAAC data.* The tip of the red giant branch is clearly visible at $I \approx 23.9 \pm 0.1$. Overplotted are standard globular cluster giant branches which suggest a mean metallicity for the dSph of $<$[Fe/H]$> \approx -1.55 \pm 0.3$ dex. The field contamination is substantial, given the comparatively low

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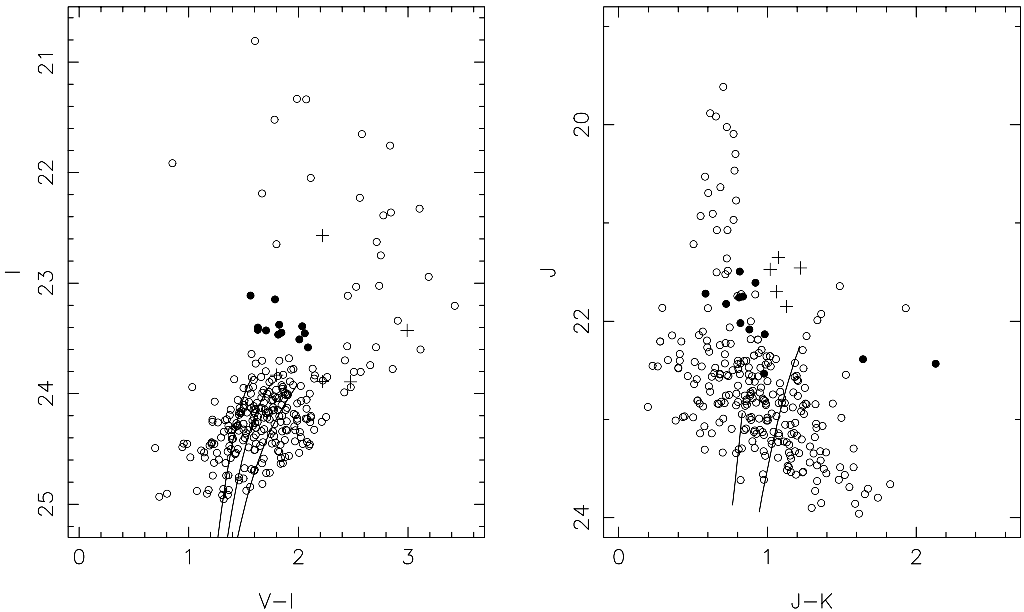

Figure 1. Colour-magnitude diagrams for the Cen A group dSph AM1343-452 (kk217). The left panel shows V, I photometry derived from HST snapshot images. Shown also are the red giant branches (RGBs) of the Galactic globular clusters M15 ([Fe/H]=–2.12), M2 (–1.62) and NGC 1851 (–1.22) shifted to the distance modulus and reddening of the dSph. The right panel shows J, K photometry derived from VLT ISAAC images together with the RGBs for the globular clusters M92 (–2.28) and 47 Tuc (–0.76). In both panels the stars plotted are those measured on both sets of data. A number of potential upper-AGB stars are plotted as filled symbols, for those selected in the left panel, and as plus-signs, for those selected in the right panel. The same symbol is used to show the location of these stars in the corresponding diagram.

galactic latitude, but nevertheless there is some indication of a population of stars that lie above the red giant branch tip. A sample of such potential upper-AGB stars, selected using the c-m diagram of BK 5N of Caldwell *et al.* (1998) as a guide, are plotted as filled symbols in this panel.

The right panel of Fig. 1 shows the near-IR colour magnitude diagram derived from the ISAAC data. Plotted in this panel are the red giant branches of the Galactic globular clusters M92 and 47 Tuc, using the same AM1343-452 reddening and distance modulus as for the left panel. In this c-m diagram most of the Galactic field stars have colours of $J - K \approx 0.7$, and so form a vertical sequence in the c-m diagram. Five possible upper-AGB stars are plotted as plus symbols in this panel: the left panel shows that these stars also fall at or above the RGB tip in the optical c-m diagram. Similarly, while some of the upper-AGB candidates selected in the left panel fall in the field star sequence in the near-IR c-m diagram, the majority are above the RGB tip and two have quite red near-IR colours. These two stars may well be carbon stars.

Regardless of the actual status of individual stars, these data suggest that AM1343-452 does contain a population of upper-AGB stars. This interpretation confirmed by an analysis of the field-subtracted J-band luminosity function (see Rejkuba *et al.*, these proceedings), which reveals a clear excess of stars brighter than the RGB tip. The most luminous of these stars have M_{bol} values in the range of –4.5 to –4.8, corresponding to ages of a few Gyr. Clearly there has been on-going star formation in this particular Cen A group dSph.

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While the complete data set remains to be analysed in detail, it appears that a sizeable fraction (perhaps as much as 50%) of the Cen A group dwarfs observed in the near-IR show evidence for upper-AGB populations, and thus on-going star formation. Nevertheless, there are clearly some dSphs in our sample that apparently lack such populations. Further modelling of the image completeness as a function of magnitude and colour is required to be certain of this result, but it is likely that some of the dSphs in this group lack intermediate-age populations. These would be dSphs in which essentially all the stars are older than 8–10 Gyr, making them Cen A group analogues to Local Group systems such as Sculptor and And I. When the full analysis is complete it will be interesting to see where these particular dwarfs lie in the group, as compared to the locations of the dSphs with intermediate-age populations.

4. Sculptor Group

In this group there are five low-luminosity early-type galaxies with confirmed group membership. Four of these five have been classified by Jerjen *et al.* (2000) on the basis of their morphology: three are classed as transition types while the fourth is classed as a dwarf elliptical. The fifth system is classified as a dSph by Karachentsev *et al.* (2000). We do not as yet have any near-IR imaging data for these systems, though HST snapshot imaging is available for all five. These data, together with existing ground-based optical imaging data for ESO 540–032, reveal the presence of blue stars in the central regions of at least two of the dwarfs (cf. Karachentsev *et al.* 2000, Jerjen & Rejkuba 2001), suggesting that they have had modest levels of relatively recent star formation.

We have observed all five systems with the Parkes radio telescope to determine, or place limits on, their neutral hydrogen contents. The results are described in more detail in Bouchard *et al.* (these preceedings) but in summary, four of the five systems, including all three classified as transition types, and including both of the systems with central blue stars, were detected in HI. The M_{HI}/L_B values range from 0.08 to 0.19 in solar units for the detections, comparable to those for the Local Group transition systems LGS 3 and Phoenix, while the 3σ upper limit for the non-detection corresponds to $M_{HI}/L_B <$ 0.08 in solar units. For three of these four systems, knowledge of the HI radial velocity has allowed the generation of HI maps from data available in the Australia Telescope Compact Array archive. These maps show that for two systems, the center of the HI distribution is offset from that of the optical image, while in the third, the HI, which is apparently quite extended, peaks near the center of the optical image (Bouchard *et al.*, in preparation). Again these situations are reminiscent of that for the Local Group transition objects Phoenix and LGS 3, but considerably more information than is currently available is required before we can attempt to connect the gas dynamics with the recent star formation histories (cf. Gallart *et al.* 2001).

5. Conclusions

Although the sample of objects analysed so far is not large, it does seem clear that in the M81 and Cen A groups a substantial fraction of the dSphs have had on-going star formation, and that like the Local Group, there is considerable diversity in the extent and duration of this phenomenon. On the other hand, in the Scl group, which is a less dense environment, the low-luminosity early-type galaxies are predominantly of the transition type, possessing modest amounts of neutral gas and showing indications of relatively recent star formation. This would appear to be a direct observational confirmation of the premise of Grebel *et al.* (2003), who suggested that "transition-type dwarfs ... should replace dSphs in isolated locations where stripping is ineffective".

In a more general sense these results support the idea that 'environmental conditions' do play an important role in governing the evolution of low-luminosity early-type systems. Specificially, the majority of the Scl group objects have apparently evolved in a relatively independent fashion, generating a star formation history that extends to the present epoch. The M81 and Cen A group objects, on the other hand, have apparently been influenced to a greater or lesser extent by external factors depending on their orbits and location within the group. It will be interesting to see the extent to which these conclusions remain valid once the full sample of dSph observations is analysed.

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Discussion

KARACHENSTEV: There are two peripheric companions to M31: the Cass dSph and the Cetus dSph. Why do you use for Cetus its original name (given by its discovers), but in the case of Cassiopeia you ignore the original name?

Da Costa: Cetus is relatively isolated Local Group dSph, and as far as I am aware, is not associated with M31. There is therefore no reason to refer to it by any other designation. However, for the confirmed dSph companions of M31, I prefer to follow the convention initiated by Sidney van den Bergh of referring to these systems as And ♯♯, where ♯♯ is a roman numeral. It is important, however, to also include other designations where these exist: specifically And VI is also referred to as the Pegasus dSph (as distinct from the Pegasus dwarf irregular DDO 216) and And VII, discovered by Karachentsev & Karachentseva (1999, A&A, 341, 355) is also referred to as the Cas dSph.

Gallagher: Are there any obvious trends in the overall mix of dwarf galaxy types between the M81 and Cen A groups, where recent interactions are important, as compared with the Local and Sculptor groups which are quiescent?

Da Costa: There does exist, of course, the well established morphology-density relation in which early-type dwarfs are more commonly found in higher density environments than late-type dwarfs. However, comparing specific groups in this context is somewhat difficult because of completeness concerns. Fig. 1 of Karachentsev el al. (2002, A&A, 383, 125) shows there are approximately equal numbers of 'Sph' and 'Irr' dwarfs within the M81 group, with the 'Sph' galaxies on average somewhat closer to M81 than the 'Irr' dwarfs. To a comparable magnitude limit, the Local Group also has roughly equal numbers of early- and late-type dwarfs, with the early-type dwarfs notably clustered around the Milky Way and M31. Similarly, judging from Table 2 of Karachentsev *et al.* (2002, A&A, 385, 21) or Fig. 2 of Jerjen *et al.* (2000, AJ, 119, 593), in the Cen A group there are about one-third more late-type dwarfs than early-types, though again the early-type dwarfs are generally closer to Cen A. The Sculptor group though is clearly different in this respect as it has roughly three times as many late-type dwarfs as early-types, as judged from Fig. 2 of Jerjen *et al.* (2000). Our program, however, is endeavouring to go beyond these morphological relations in attempting to assess more quantitatively possible relations between star formation histories and environment.

Caldwell: You find that a larger number of dE and transition dwarfs in Sculptor have been unperturbed over time when compared to those in the M81 and Cen A groups. Given that there are more early-type dwarfs in the latter two groups, could the observed difference in Sculptor be a small number statistics problem?

Da Costa: It is true that the analysis so far is based on relatively small numbers of objects, both in terms of the number of objects analysed in detail in the M81 and Cen A groups, and in terms of the fact that there are only 5 low-luminosity early-type systems in the Sculptor group. Nevertheless I would be surprised if, for example, our HI observations of the dE and dE/Irr systems in the Cen A group produced the same high relative fraction of detections as was found in the Sculptor group.