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The Stellar Populations of dE Galaxies in Nearby Groups*,†

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Abstract: In this contribution Gemini-North NIRI *J*, *K*-observations are used to investigate the upper-Asymptotic Giant Branch (AGB) intermediate-age population in the M81 Group dwarf elliptical (dE) F8D1. Hubble Space Telescope (*HST*) 'snapshot' *V*, *I*-observations are also analysed to investigate the upper-AGB populations in two other M81 Group dEs, DDO 71 and kk077. In all three dEs, significant intermediate-age populations are found. Further, there are sizeable dE-to-dE differences in these populations: F8D1 contains relatively more, and relatively more luminous, upper-AGB stars. These results are compared with existing information for Local Group and Sculptor group dwarfs. It is suggested that 'environmental harrassment' plays an important role in governing dwarf galaxy evolution.

Keywords: galaxies: dwarf — galaxies: evolution — galaxies: stellar content — stars: Population II

1 Introduction

We have known for some time now that the dwarf Spheroidal[1] (dSph) companions to the Milky Way galaxy show a variety of star formation histories. These range from basically a single old stellar population (e.g. Ursa Minor) through to systems such as Carina, Fornax, and Leo I which have had complex star formation histories and which contain stars as young as ∼1 Gyr, or even less in the case of Fornax (see the review articles of Da Costa 1998, Mateo 1998, and Grebel 1999, 2001 and references therein).

While our information on the star formation histories of these nearby dwarf galaxies now comes from observations that reach well below the main-sequence turnoff (e.g. Hurley-Keller et al. 1998), it is important to recall that the first clues to the existence of extended star formation in the Milky Way's dSph satellites came from the discovery that these systems contain upper-AGB carbon stars (e.g. Mould et al. 1982). These are stars with sufficient mass to evolve to luminosities well above the red giant branch (RGB) tip, and their presence is an unambiguous indicator of the existence of an intermediate-age (≈2–10 Gyr) population in the dwarf galaxy.

The existence of complex star formation histories is not restricted to the Galaxy's dSph companions. Recent work with the WFPC2 camera on *HST* has revealed that M31's dSph companions have also had extended epochs of star formation. For example, Da Costa et al. (2000, 2002) have interpreted the observed horizontal branch morphologies as suggesting that the M31 companions And I, II, and III have stellar populations with an age range of at least a few Gyr, but with the oldest population still comparable in age to the Galactic globular clusters. In particular, all the M31 dSph systems studied so far (see Pritzl et al. 2004 and references therein) contain populations of RR Lyrae variable stars, indicating the presence of a population comparable in age to that of the Galactic globular clusters. Nevertheless, the ubiquitous red horizontal branches in these systems argue for extended epochs of star formation and 'mean ages' younger than that of the Milky Way's globular clusters (see Da Costa et al. 2000, 2002 for the justification of these conclusions). However, there is one notable difference between the dSph companions to M31 and those of the Galaxy — all the M31 systems lack intermediate-age populations with ages less than ∼5 Gyr (e.g. Da Costa et al. 2000), while such stars are relatively common among at least some of the Galaxy's dSph companions. A confirmed population of upper-AGB stars is known only in And II (but see Harbeck et al. 2004 for new results). In this dSph the most luminous stars have $M_{\rm bol} \approx -4.1$ corresponding to an age of perhaps 7–9 Gyr, in marked contrast to the more luminous and younger stars seen in Carina, Leo I, and Fornax (Da Costa et al. 2000).

Do we understand what causes this variety of star formation histories? In general the answer is 'no', but there are some clues available. For example, van den Bergh (1994) noted that, for the Milky Way's dSph companions, there is a tendency for the relative importance of the

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[1]Note that dwarf Spheroidal galaxies are not a separate type, they are just low luminosity dwarf Ellipticals (dE).

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intermediate-age populations to increase with increasing galactocentric distance, although what is really required to substantiate such a trend are orbital parameters for the dSph companions. These are now becoming available (e.g. Piatek et al. 2002, 2003). Such a trend may also be present for the M31 dSphs — And II, the only system with an established upper-AGB population, is one of the most distant of the M31 dSph satellites. Such trends clearly hint at a role for the 'parent' galaxy in influencing the star formation histories of the low mass companions. Similarly, the difference in intermediate-age populations between the Milky Way and M31 dSphs hints at a role for parent galaxy type; recall that M31 has a much larger bulge than the Milky Way. Physical processes that could influence the star formation histories of satellite systems include gravitational tidal effects, ram pressure stripping of interstellar material by a hot gaseous corona or a supernovae-driven galactic wind, or a high UV and/or X-ray flux from the parent galaxy (e.g. Grebel et al. 2003). Indeed the simulations by Mayer et al. (2001) have shown how a dIrr galaxy on an initial 'plunging' orbit in the Milky Way halo can be converted into a dSph satellite by such processes.

This trend of more extended star formation histories with increasing distance from a parent is further supported by considering the 'transition type' (dE/dIrr) dwarfs Phoenix and LGS3. These galaxies are distant outlying satellites of the Galaxy and M31, respectively. They have both formed stars in the recent past and both contain modest amounts of neutral hydrogen, yet their stellar populations are dominated by intermediate-age and old populations (e.g. Holtzman et al. 2000; Miller et al. 2001). In this sense it is also notable that the vast majority of isolated dwarfs in the Local Group are dIrrs, i.e. systems with active star formation and substantial amounts of gas. Among the lower luminosity systems, the one definite exception to this *morphology–density relation* is the Local Group dE Tucana[2]. This system lies in an isolated location and it is not obviously associated with any large galaxy. Yet WFPC2 observations (e.g. Da Costa 1998) reveal little indication of *any* extended star formation. Indeed, using horizontal branch morphology as an indicator of the mean age of the stellar population, Tucana is the second-oldest Local Group dE known, despite its isolated low density location. Consequently, unless it is postulated that Tucana was once close to the Milky Way or M31, the lack of extended star formation in this dwarf shows that parent galaxy influence cannot be the only factor governing the star formation history.

There are no other dE systems in the Local Group. Therefore, in order to make any progress in understanding the physical processes that govern their evolution, we must study dEs beyond the Local Group. The nearest group to the Local Group is the Sculptor (Scl) Group. This is a loose aggregration of mostly late-type galaxies that is enlongated along the line-of-sight. The nearest galaxies are at ∼1.5 Mpc while the most distant are at ∼4 Mpc (e.g. Karachentsev et al. 2003). In addition to an established population of ∼15 dwarf irregulars, the Scl group contains six dwarf systems that are variously classified as dE, dE/Im, or dSph (e.g. Jerjen et al. 2000). The lack of dominant galaxies and the low density implies that the Scl group is a rather benign environment for its members. In contrast, the Cen A and M81 groups, which lie at distances of ∼3.5–4 Mpc, are considerably denser and more compact than the Local Group. As the name implies, the dominant galaxy of the Cen A group is the giant elliptical Cen A (NGC 5128) and the group contains at least 50 galaxies, including over 30 dIrrs and 13 dEs (Jerjen et al. 2000). The M81 group, on the other hand, shows clear indications of strong interactions between group members (e.g. Yun et al. 1994); it also contains about a dozen dEs and perhaps two dozen dIrrs (e.g. Karachentsev et al. 2002). In these three groups it is then possible to define a sample of dEs for study that covers a wide range of internal (e.g. absolute magnitude, scale length, surface brightness) and external (distance from nearest large galaxy, local galaxy density) properties.

We have begun a program to study the stellar populations of the galaxies in this sample using *HST* ACS/WFC and existing 'snapshot' optical data for distances and metal abundances, Gemini-North NIRI and ESO VLT ISAAC near-infrared data for intermediate-age populations, and radio facilities (ATCA, Parkes) to study neutral hydrogen contents. In this contribution we present first some initial results for three dEs in the M81 group. The subsequent section discusses some existing results for dEs in the Scl group, while the final section draws some preliminary conclusions.

2 M81 Group

The three M81 group dEs to be discussed in this section are F8D1, a relatively luminous ($M_V \approx -14.2$) but low density dE (see Caldwell et al. 1998), and DDO 71 and kk077, both of which have $M_V \approx -13$. These three galaxies are respectively 115, 160, and 100 kpc in projection from M81. Their locations are then comparable to the Galactocentric and M31-centric distance of systems such as Carina, Fornax (but not Leo I), And I, and And III (but not And II).

F8D1 has been observed in J- and K-bands with the NIRI imager on the Gemini-North telescope (proposal GN-2002A-Q10). The images on the final combined frames have FWHM $\approx 0.7''$ and, since the data only just reach the tip of the RGB, the frames are relatively uncrowded. The frames were reduced using DAOPHOT and the resulting colour–magnitude (c-m) diagram is shown in Figure 1. Artificial star tests have been used to determine the 50% completion limits for both J and K and these are shown on the Figure. At this completeness level and brighter, the artificial star tests also show there are no systematic errors in the photometry. The Figure also shows the red giant branches for the Galactic globular clusters

[2]The Galaxy's relatively luminous companions the LMC and the SMC are also obvious exceptions.

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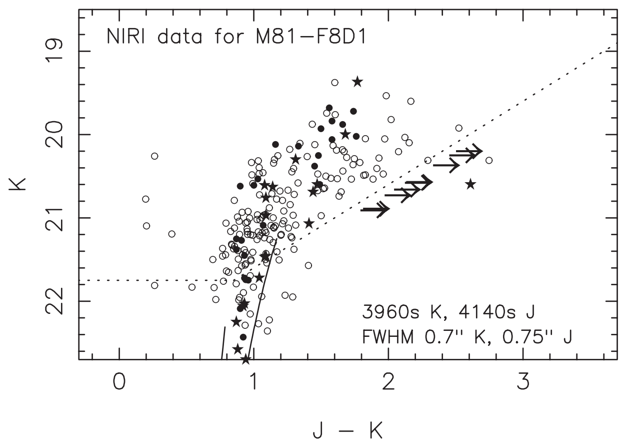

Figure 1 A colour–magnitude diagram for the M81 group dE F8D1 based on observations taken with NIRI on the Gemini-North telescope. F8D1 stars are plotted as open circles. The stars with $J - K \approx 0.3$ are probably field stars. Dotted lines indicate 50% completeness limits at $J = 22.6$ and $K = 21.75$. A number of stars are readily detected on the K-frames but are absent on the J-frames. These are plotted at their K-magnitudes, and at a lower limit on their colour, as arrow symbols. Stars in the SMC cluster NGC 419 (filled circles) and in the LMC cluster NGC 1978 (filled stars) are also shown, shifted to the distance modulus and reddening of F8D1. The solid lines are the red giant branches of the Galactic globular clusters M92 and 47 Tuc, also shifted to the distance and reddening of F8D1.

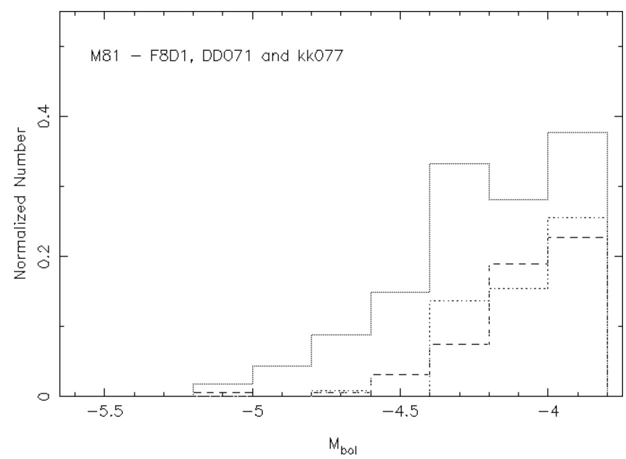

Figure 2 Normalised bolometric Luminosity Functions for the M81 Group dEs F8D1 (solid line), DDO 71 (dotted) and kk077 (dashed). In each case the number of upper-AGB stars has been normalised by the number of RGB stars between the RGB tip and 0.2 mag fainter than the RGB tip. As for Local Group systems, there are evidently real differences in intermediate-age populations between the dEs.

M92 and 47 Tuc. It is evident from Figure 1 that there is a significant population of stars above the RGB tip in this dE. F8D1 has a mean metallicity $\langle[\mathrm{Fe/H}]\rangle \approx -1.0$ and a notable abundance dispersion (Caldwell et al. 1998). Consequently, it is conceivable that some fraction of the stars above the RGB tip are not intermediate-age stars but come instead from a 47 Tuc-like (i.e. old) Mira variable population. However, as detailed in Caldwell et al. (1998), such a population is likely to represent no more than ~20% of the total. Further, such stars are also likely to found at $K \geq 20.8$, fainter than a significant number of the F8D1 stars in Figure 1. The inescapable conclusion then is that this M81 group dE contains a substantial intermediate-age population, in line with the earlier results of Caldwell et al. (1998).

Modelling the evolution of upper-AGB stars is no easy task, so the best approach to determine the ages of the F8D1 upper-AGB stars is an empirical one, in which the F8D1 data are compared with equivalent data for systems of known age. Nevertheless, theoretical models can provide some guidance. For example, the isochrone set of Girardi et al. (2000) shows that for the abundance range of interest here, there is a ~0.6 mag increase in M_{bol} (AGB tip) from 1 to 3 Gyr, independent of Z. Similarly, at fixed age in the 1–3 Gyr range, changing Z from 0.001 to 0.008 results in an increase in M_{bol} (AGB tip) of ~0.3 mag.

Figure 1 shows a comparison of the F8D1 photometry with the J- and K-photometry for upper-AGB and RGB stars in the SMC cluster NGC 419 and in the LMC cluster NGC 1978 from Frogel et al. (1990), shifted to the distance and reddening of F8D1. NGC 419 has a metal abundance of $[\mathrm{Fe/H}] \approx -0.65$ and an age of approximately 1.2 Gyr, while NGC 1978 is ~2 Gyr in age and has an abundance of $[\mathrm{Fe/H}] \approx -0.55$ dex. The Magellanic Cloud cluster photometry overlays that of F8D1 in terms of both colour and magnitude, indicating that the upper-AGB stars in F8D1 are likely to have ages of 1–2 Gyr. Further, the very red objects in seen F8D1 have counterparts in the J, K-photometry of upper-AGB stars in Leo I presented by Menzies et al. (2002), who interpret these stars as circumstellar dust-obscured objects. When the different distances are allowed for, the brightest stars in the Menzies et al. (2002) photometry of Leo I also have comparable colours and magnitudes to those in F8D1. This again supports an age of 1–2 Gyr for the brightest F8D1 stars as Gallart et al. (1999) have shown, based on *HST* data that reaches below the main sequence turnoff, that Leo I has had substantial star formation from ~7 Gyr to ~1 Gyr ago.

The J- and K-photometry allows the bolometric magnitude to be calculated for each F8D1 upper-AGB star, and thus a bolometric luminosity function can be constructed. This is shown in Figure 2, where it is apparent that the brightest F8D1 stars have $M_{\mathrm{bol}} \approx -5$, again suggesting an age of ~2 Gyr (cf. Girardi et al. 2000). This luminosity function (LF), which agrees well with that calculated from the I-band data of Caldwell et al. (1998), shows a sharp rise at $M_{\mathrm{bol}} \approx -4.4$. It is tempting to associate this rise with an increased star formation rate at an age of ~5–6 Gyr, but without propering modelling of the LF expected for different star formation histories, such inferences remain speculative.

For the M81 Group dEs DDO 71 and kk077, the data analysed are the *HST* 'snapshot' data: 600-s exposures with the WFPC2 camera and V, I-filters. Given the relatively short exposures (cf. Caldwell et al. 1998), the resulting colour–magnitude diagrams do not reach much

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more than a magnitude below the RGB tip. Nevertheless, the data have proved sufficient to analyse the properties of the stars that lie above the RGB tip. The c-m diagrams indicate the presence of such stars, and we have carried out an extensive series of artificial star tests to confirm that these are real populations above the RGB tip, and not an artifact of the photometry process.

The results of this analysis are also shown in Figure 2. Here for DDO 71 and kk077, the bolometric magnitudes have been calculated from the V- and I-photometry, and for all three dEs the number of stars above the RGB tip have been normalised by the number of RGB stars between the tip and 0.2 mag fainter than the tip[3]. Figure 2 shows that real differences in intermediate-age populations exist between the three dEs: F8D1 has relatively more upper-AGB stars which reach higher luminosities; DDO 71 has a sharp cutoff at $M_{\rm bol} \approx -4.4$ (age ~ 5–6 Gyr); while kk077 has a few somewhat brighter (younger) stars compared to DDO 71, although the overall number of upper-AGB stars is about the same. It is evident from these data that not only do M81 group dEs contain significant intermediate-age populations, but also, like the Local Groups systems, there are substantial dE to dE variations in the size and 'age' of these populations. However, the c-m diagrams of DDO 71 and kk077 do not show any indications of the presence luminous blue (young) stars. This suggests no significant star formation could have occurred in these systems for at least the past ~200 Myr (cf. Caldwell et al. 1998).

3 Sculptor Group

Colour–magnitude diagrams based on *HST* 'snapshot' data have been constructed for five of the six early-type dwarfs in this group. Based on the magnitude of the RGB tip in the c-m diagrams, all five systems are members of the Scl group. The results for two of these systems are particularly interesting, in that their stellar populations apparently show a marked resemblence to those of the distant M31 and Milky Way satellites LGS 3 and Phoenix. The first Scl object is ESO 410-005 for which a c-m diagram has been published by Karachentsev et al. (2000). This dE lies at a distance of ~1.9 Mpc and it is not obviously associated with any of the more luminous Scl group galaxies. The c-m diagram reveals a centrally concentrated population of probable upper-AGB stars (i.e. a population of intermediate-age) but most interestingly, there is also a centrally concentrated population of *blue* stars with ages of perhaps ~200–500 Myr. Extensive artifical star tests (Karachentsev et al. 2000) indicate that these upper-AGB and blue star populations are unlikely to result from crowded-field photometric errors.

[3]While it would have been preferable to normalise by a larger number of RGB stars, the artificial star tests show that the completeness of the *HST* 'snapshot' data drops rapidly from >90% for magnitudes fainter than 0.2 mag below the RGB tip. Brighter than this limit there are no incompleteness concerns nor is crowding a significant influence on the photometry.

The second dwarf of interest is ESO 540-032, which lies at a distance of ~3.2 Mpc, and which is also not obviously associated with any of the more luminous Scl group galaxies. Colour–magnitude diagrams have been published for this dwarf by Jerjen & Rejkuba (2001), based on ground-based imaging, and by Karachentsev et al. (2003) based on *HST* 'snapshot' images. Both c-m diagrams indicate that, like ESO 410-005, ESO 540-032 contains a modest population of blue stars concentrated to the central regions, with ages of order ~150–500 Myr. However, there is no clear evidence for any upper-AGB intermediate-age stars in this galaxy. Whether these observations indicate a recent 'rebirth' of star formation in this system after a significant period of inactivity is a question that can only be answered by detailed modelling of a c-m diagram that reaches considerably fainter magnitudes.

4 Conclusions

On the basis of the available data, it is clear that in the M81 Group, at least some, perhaps all, of the dEs have had extended star formation. Further, like the Local Group, there is evidently considerable diversity in the properties of this extended star formation. Nevertheless, like the Local Group, the M81 group dEs studied so far lack young stars, although a HII region has been identified in the M81 Group dE Kar 61 — see Johnson et al. (1997). On the other hand, in the less dense environment of the Scl group, at least two of the dEs show populations of young stars. These results would seem to support the idea that '*environmental harrassment*' does play an important role in determining dwarf galaxy evolution. The sense would be that the Scl group objects have evolved in a more independent manner, giving rise to a more constant star formation rate, while the M81 (and Local Group) systems have been 'harrassed' to varying degress depending on their orbits within the group. Whether these conclusions will still be valid, once a larger sample of dEs has been studied, remains to be seen.

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