DWARF SPHEROIDAL GALAXIES

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ABSTRACT. The properties of dwarf spheroidals are reviewed with emphasis on the newly discovered Sextans system, as well as on the star formation histories, the dark matter content and the abundance - luminosity relation of these galaxies. The relation of dwarf spheroidals to other dwarf galaxies is also discussed.

1. Introduction

The term *dwarf spheroidal* (hereafter dSph) is conventionally applied to the 8 low luminosity galaxies that are companions to the Milky Way (Carina, Draco, Fornax, Leo I, Leo II, Sculptor, Sextans and Ursa Minor) and to the 3 apparently similar systems that are companions to M31 (And I, And II and And III). Although often thought of in the past as merely large, low density globular clusters, detailed studies over the past ten years or so have revealed that the dSph galaxies possess a more diverse set of properties and contain more complex stellar populations than the globular cluster analogy would predict. Indeed an alternative definition of the term "dwarf spheroidal galaxy" might now be "*a low luminosity ($M_V > -14$) non-nucleated dwarf elliptical galaxy*" and as such, they are worthy of continued attention. In particular, since the individual stars in dSph galaxies can be resolved, their study has, and will continue to, contribute to the understanding of the origin and evolution of dwarf galaxies in general.

In the next section the properties of the recently discovered Sextans dSph are briefly discussed. Then follow sections dealing with the star formation histories, the mass-to-light ratios and the abundance-luminosity relation for dSph galaxies, while the final section contains some questions and speculations regarding the relation of dSphs to other dwarf galaxies.

2. Sextans

Unlike the discovery of the other 10 dSphs, the Sextans dSph was not found by visual inspection of photographic plates. Instead it was found as an excess of faint stellar images

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above the background on an APM scan of a UK Schmidt telescope plate. The discovery paper (Irwin *et al.* 1990) listed the following properties: an estimated distance of 85 kpc, an ellipticity of 0.4, and a density profile that fits a King model with a core radius of approximately 0.4 kpc and a limiting radius of ~2.2 kpc. Further, the photographic c-m diagram indicated a predominantly red horizontal branch but did not reveal any obvious population of bright very red stars. Subsequent to the discovery paper, two further studies have appeared, each based on observations made in the first season (1990) of Sextans observing. These are Da Costa *et al.* (1991) in which low signal-to-noise spectroscopy of a sample of 6 Sextans red giants was reported, and Mateo *et al.* (1991) which presented a CCD based c-m diagram. The former gave a first abundance estimate ([Fe/H] = -1.7 ± 0.25 dex) and a determination of the Sextans radial velocity (230 ± 6 km/s) while the latter, *inter alia*, confirmed the distance and the horizontal branch morphology suggested by the photographic results. The CCD c-m diagram also implied that Sextans was likely to be rich in RR Lyrae variables and based on deeper imaging of a smaller field, which revealed the main sequence turnoff, that the bulk of the stellar population of Sextans was comparable in age to the galactic globular clusters; *i.e.* no substantial younger component was present. However, the c-m diagram did identify the presence of a blue straggler population.

The second season of Sextans observing (1991) has now concluded and not surprisingly, the quality and scope of the studies of this dSph have improved significantly. For example, Mateo *et al.* (this volume) have used a CCD survey to establish the presence of a number of RR Lyrae variables as well as 3 anomalous cepheids in a single field near the center of the galaxy. Similarly, Suntzeff *et al.* (1991) have used fiber spectroscopy to observe a sample of approximately 30 Sextans red giant members. Based on a comparison of line strengths with those of globular cluster stars, these authors derive a mean abundance for Sextans of [Fe/H] = -2.05 ± 0.05 dex with a likely intrinsic abundance range of approximately -1.7 to -2.5 dex, corresponding to a σ([Fe/H] ≈ 0.15 dex. From the same set of observations Suntzeff *et al.* (1991) also estimate the velocity dispersion of Sextans as 5.6 ± 2.1 km/s. This value is lower than the 10 km/s dispersion found for Draco and Ursa Minor (see Pryor 1991 for a summary) but, given the low central density of Sextans, there is little doubt that this dispersion implies an M/L value that significantly exceeds the M/L for globular clusters. Hence it seems likely that Sextans also contains dark matter in the same way as do the other galactic dSphs studied in detail.

To summarize then, Sextans is a "conventional" dSph; *i.e.* its properties are very similar to those of the other galactic dSphs. The only unconfirmed characteristic at the present time is the identification of a small population of upper-AGB carbon stars, but given their presence in most if not all the galactic dSphs (see Azzopardi, this volume) and in And II (Aaronson *et al.* 1985), it would be surprising if Sextans lacked them.

3. Star Formation Histories

Perhaps the most interesting result to come from recent studies of dwarf spheroidal galaxies is the indication that all dSph show, to a greater or lesser extent, evidence for *star formation over extended periods*. This result was unexpected given that dSphs show no signs of current or recent star formation and have no detectable HI (*e.g.* Knapp *et al.* 1978, Mould *et al.* 1990). Nevertheless the stellar populations of dwarf spheroidals can be thought of as being made up of two basic components. These are an *old metal-poor population* similar to that of globular clusters, though in dSphs this old population invariably shows an intrinsic abundance range, and an *intermediate-age population*, *i.e.* a population of stars whose ages range from approximately 2 to 10 Gyr. The existence of this latter population is revealed by, for example, the presence of carbon stars on the AGB with luminosities above that of the first giant branch tip, and by the presence of main sequence stars whose luminosities exceed that of the turnoff for an old population. *The ratio of these two population types however, varies considerably from dSph to dSph.* For example, Ursa Minor consists almost completely of old stars (Olszewski & Aaronson 1985) while the stellar population of Carina is dominated by stars of intermediate-age (Mould & Aaronson 1983) with the old population being only a minor contributor to the total (Saha *et al.* 1986). It should also be noted that this characteristic of multiple age populations is not restricted to the galactic dSphs; the presence of upper-AGB carbon stars in And II (Aaronson *et al.* 1985) shows that this galaxy has an intermediate-age population also. The c-m diagram study of the giant branch of And I (Mould & Kristian 1990) however, did not reveal any candidate upper-AGB stars. These authors place a 2σ upper limit of 20% on the fraction of intermediate-age population in this dSph, but this limit is not inconsistent with the presence of a small intermediate-age component as found for example in Sculptor (Aaronson & Mould 1985).

The population mix in Carina has been recently placed on a more quantitative footing through the work of Mighell (Mighell 1990, Mighell & Butcher 1991). In these papers, estimates of the fraction of the old component comes from analysis of a deep color-magnitude diagram while estimates of the age and age-range come from a detailed luminosity function study. In the c-m diagram work (Mighell 1990), it is shown that the spread in V-R color fainter than $V \approx 23$ is significantly larger than that expected for a single age population. The cause of the color spread is identified as subgiants from an older population, which are redder than the dominant intermediate-age main sequence stars. Analysis of color distribution histograms then suggests that the old component comprises 17 ± 4 per cent of the total, a fraction in accord with earlier estimates (old ~ 30%) based on carbon star numbers (Aaronson & Mould 1985). In addition however, Mighell's analysis suggests that the old population was probably created in a single "burst " ($\tau < 3$ Gyr) and that the rate of star formation between the "bursts" that created the old (age > 13 Gyr) and intermediate-age (age ~ 7 Gyr) populations was probably negligible, otherwise the observed asymmetry in the color distribution histograms would not be as marked.

In the luminosity function study (Mighell & Butcher 1991), an observed luminosity function containing more than 2500 Carina stars with $1 < M_V < 5$, *i.e.* a magnitude interval ranging from just below the horizontal branch to somewhat fainter than the turnoff, was compared with the predictions of a number of theoretical models. The models were based on the luminosity functions contained in the Revised Yale Isochrones (Green *et al.* 1987) together with various assumptions for the initial epoch and duration of the star formation "burst" that produced the majority of Carina's stars. Despite a broad exploration of parameter space, only a small number of models gave acceptable fits to the observed luminosity function. These successful models all imply that the bulk of the star formation in Carina began approximately 9 Gyr ago, reached a peak between perhaps 6 and 8 Gyrs and had ceased by 5 Gyr.

As a consequence of this work Carina emerges as a dwarf galaxy which apparently has had the following star formation history: an initial epoch of star formation in which relatively few stars were formed, a significant quiescent interval, then a period of active star formation which lasted for at least 2 billion years, and then finally the cessation of all star formation approximately 5 Gyr ago. A star formation history of this type raises a number of questions! These include "What regulates the star formation?" or equivalently, "Why did Carina wait almost half the age of the Universe before forming significant numbers of stars?". A further point that should not be overlooked in this context is that the duration of the major episode of star formation in Carina was apparently much longer than the lifetime of massive stars. How then did Carina, a low density system, retain the gas necessary for such an extended period of star formation against the energy input from supernovae? This latter question is probably answered by noting that the rate of star formation implied is actually quite low (comparable to or less than the rate in the solar neighborhood, consequently the term "burst" does not apply here). Thus the rate of energy input from supernovae into what was presumably a large gas mass was no doubt insufficient to quench the star formation for a significant interval. The fact that Carina is "gas-free" at the present time however, indicates that the energy input did eventually become sufficient to drive the remaining gas from the system and stop the star formation.

This section can be summarized then by noting that the *star formation histories of dwarf spheroidal galaxies are clearly complex and varied.* The inevitable conclusion that follows from these results is that the star formation histories of the more luminous dE galaxies are therefore also likely to be complex and varied. Thus evidence for the existence of intermediate-age populations in dE galaxies (*e.g.* Gregg, this volume) should not come as a surprise.

4. Dark Matter

The subject of dark matter in dSph galaxies has recently been thoroughly reviewed by Pryor (1991) and his article contains the most up-to-date results for Draco and Ursa Minor. Both these systems have velocity dispersions of the order of 10 km/s and central M/L values of approximately 100 in solar units, indicating that they are dominated by dark matter. While work on these systems and others such as Carina and Sextans continues, recent new results on Sculptor and Fornax are of some interest. For both these systems, the samples of stars with accurate velocities are now sufficiently large that the form of the velocity dispersion profile, as distinct from just its central value, can now be investigated for the first time. The dispersion profile is a vital quantity if the distribution of the dark matter in these dSphs is to be constrained.

For Fornax, Mateo *et al.* (1991) have used the Las Campanas Observatory 2.5m echelle spectrograph to obtain accurate velocities for approximately 40 stars in two fields; one near the center and one situated approximately 1.5 core radii from the center, along the major axis. From these observations they find a central velocity dispersion of $\sim 10 \pm 2$ km/s (Paltoglou & Freeman 1991 report a similar number). This value however, is made rather more uncertain than it might otherwise be by the low systemic velocity of Fornax which makes it difficult to unambiguously assign membership to individual stars with velocities far from the mean; the low S/N of the high dispersion spectra prevent the application of any line strength based membership criterion. Nevertheless, combined with the most recent values for the structural parameters (Eskridge 1988b) this dispersion together with the observed central surface brightness leads to a central mass-to-(visual) light ratio of $\sim 11 \pm 5$ in solar units indicating a substantial dark matter component in this dSph. It should perhaps also be emphasized however, that, leaving aside questions concerning membership of individual stars and their effect on the observed dispersion, it is an unfortunate but true situation that the uncertainties in the distance of Fornax and in its central surface brightness and core length scale make a large contribution to the uncertainty in the M/L value. This is illustrated by the results of Paltoglou & Freeman (1991) who, although finding a similar velocity dispersion, derive a significantly lower central M/L value through the use of a different distance and different structural parameters.

Mateo *et al.* (1991) also find no evidence for any rotation about the minor axis in Fornax, a result consistent with Paltoglou & Freeman's determination of a rotation velocity of 3.5 ± 2.0 km/s at a radial distance of one core radius. Paltoglou & Freeman further demonstrate that this rotation velocity is inconsistent with the hypothesis that Fornax has evolved from a dwarf irregular (*i.e.* a system with a rotating disk). Perhaps more significantly though, the Mateo *et al.* results do not indicate any decrease in velocity dispersion outside the core; indeed within the error bars, the central and 1.5 core radius dispersions are the same. Further, the 1.5 core radius observed dispersion lies ~1.5σ above the prediction of the King model that best fits the surface density data. While these results are at most suggestive since, for example, the velocity dispersion profile of an isotropic King model is not likely to be a good representation of the dispersion profile of anisotropic flattened system even if the mass is distributed in the same way as the light, they may represent the first indication that the dark matter in this dSph has a more extended distribution than that of the stars.

The results of Armandroff & Da Costa (1992) for Sculptor are similar. Using velocities determined at CTIO for a sample of 32 stars spread from the center to radial distances of approximately two core radii, these authors find a central velocity dispersion of 7.0 ± 1.2 km/s and a central mass-to-light ratio of 8.2 ± 3.7 in solar units, using the most recent values for the structural parameters (Eskridge 1988a). As for Fornax, the largest contributor to the uncertainty in the M/L value is not the dispersion but is, in this case, uncertainty in the central surface brightness. The sample shows no evidence for rotation about the minor axis with an upper limit on the rotation velocity of this dSph being $V_{rot} < 2$ km/s at one core radius. Unlike Fornax however, as illustrated in Fig. 1 the velocity dispersion observations are consistent with either the flat dispersion profile expected if the dark matter is spatially much more extended than the stars, or the dispersion profile of the King model that fits best the stellar surface density profile.

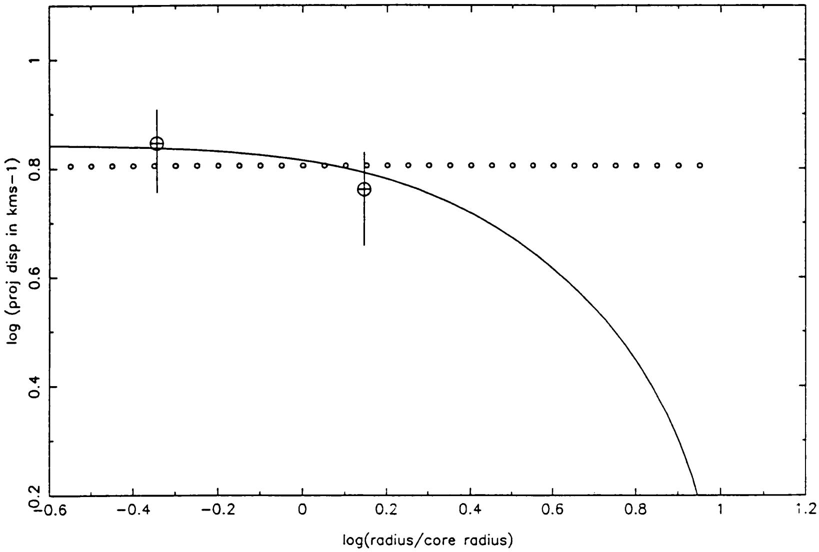

Figure 1. Velocity dispersion versus radius for the Sculptor dSph from Armandroff & Da Costa (1992). The open circles are the observed points with the inner sample comprising 18 stars and the outer 14 stars. The solid curve is the dispersion profile of the King (1966) model that fits the surface density data for this dSph. The dotted line is a schematic representation of what the dispersion profile might be if the dark matter is spatially much more extended than the stars.

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In both cases these first results on velocity dispersion profiles are tantalizing, but it is clear from Fig. 1 for example, that observations of stars still further from the centers of the galaxies are required before any meaningful constraints can be placed on the distribution of the dark matter. Fortunately, both Sculptor and Fornax are sufficiently rich that enough members with magnitudes brighter than the observational limit are likely to exist at large radial distances. Identifying such stars however, is a formidable task in itself even with the advent of fast CCD cameras capable of surveying large areas (square degrees!) of sky in relatively small amounts of telescope time.

5. Luminosity - Abundance Relation

Since this topic was last reviewed (*e.g.* Da Costa 1988), the publication of a number of new results necessitates a re-evaluation of the dSph luminosity - abundance relation. These new results include improved determinations of density profiles (*e.g.* Eskridge 1988a,b) that allow better (but still uncertain) estimates of absolute magnitudes, and additional abundance estimates from both spectroscopic (*e.g.* Armandroff & Da Costa 1991, Lenhert *et al.* 1992) and color-magnitude diagram studies (*e.g.* Reid & Mould 1991). Further, the addition of Sextans (see above) and And I (abundance from Mould & Kristian 1990, absolute magnitude from Caldwell *et al.* 1992) means that there are now 9 dSphs with both abundance and luminosity estimates. These data (see Caldwell *et al.* 1992 for a compilation of dSph abundance estimates and for new estimates of the absolute magnitudes of 5 of the 8 galactic dSphs as well as determinations of the luminosities of the three M31 companions; luminosities of the remaining 3 galactic dSphs come from Webbink 1985) reveal a relation that has more apparent scatter than earlier versions. Given the likely ±0.5 mag errors in the absolute magnitude estimates of most of the galactic dSphs (for which surface brightnesses are rarely directly measured, rather they are usually inferred from surface densities using a luminosity function) and the typical ±0.2 - 0.3 dex errors in the mean abundance values, it is difficult to estimate the size of any *intrinsic* dispersion in this relation. Plausible estimates are perhaps ±0.5 - 0.7 mag at constant [Fe/H] or ±0.2 dex at constant M_V. This is similar to what is seen for brighter dEs (*e.g.* Brodie & Huchra 1991). With the addition of the dE galaxies NGC 147 and NGC 205, whose abundances have been determined in the same way as for (at least some of) the dSph (Mould *et al.* 1983,1984), the relation becomes better defined. A unweighted least squares fit to these 11 dwarf galaxies yields the relation $Z \propto L^{0.36\pm0.07}$ or $L \propto Z^{2.8\pm0.5}$ which, coincidentally or not, is close to the relation predicted by the scaling law relations of Dekel & Silk (1986) in which dwarf galaxies form and lose gas inside a dominant extended dark matter halo.

The extent to which this dwarf galaxy abundance - luminosity relation matches the equivalent relation for the more luminous E galaxies is not easily assessed because of the uncertainty in converting measured line strength indices to abundance for high abundance objects (*e.g.* Sadler this volume; Faber *et al.* this volume). Nevertheless extrapolating the dwarf galaxy relation to higher luminosities yields solar abundance at $M_V \approx -22.5$ mag. In contrast, most calibrations of the line strengths of E galaxies indicate solar abundances for less luminous E galaxies. This difference would then appear to indicate that there is a steepening of the abundance luminosity relation in moving from dEs to ellipticals, but since the dEs appear to be morphologically different from the ellipticals and the lower luminosity compact ellipticals (*e.g.* Wirth & Gallagher 1984, Kormendy 1985), it may simply be evidence that the two types of galaxies follow intrinsically different luminosity - abundance relations. This point is also made by Caldwell *et al.* (1992); see also Bender (this volume). On the other hand, the dwarf galaxy luminosity - abundance relation is defined solely by Local Group galaxies and one may question its universality. However, the publication of abundances and absolute magnitudes for a large sample of dwarf galaxies outside the Local Group by Brodie & Huchra (1991) allows this question to be investigated. The Brodie & Huchra (1991) abundances have been derived from line strength indices calibrated using integrated spectra of globular clusters and should therefore be directly comparable with the available Local Group data. The results of this comparison are shown in Fig. 2; the M_B values listed by Brodie and Huchra (1991) have been converted to M_V by using the relation between $(B-V)_0$ and [Fe/H] defined by the galactic globular clusters. While the Brodie & Huchra (1991) data have large uncertainties, typically ~0.6 dex in abundance and ~0.5 mag in luminosity, resulting in a large apparent scatter, it is evident that these galaxies do generally follow the luminosity - abundance relation defined by the Local Group dwarfs. However, better data are required before the status of the few outliers, and thus the extent of intrinsic scatter in this relation, can be assessed.

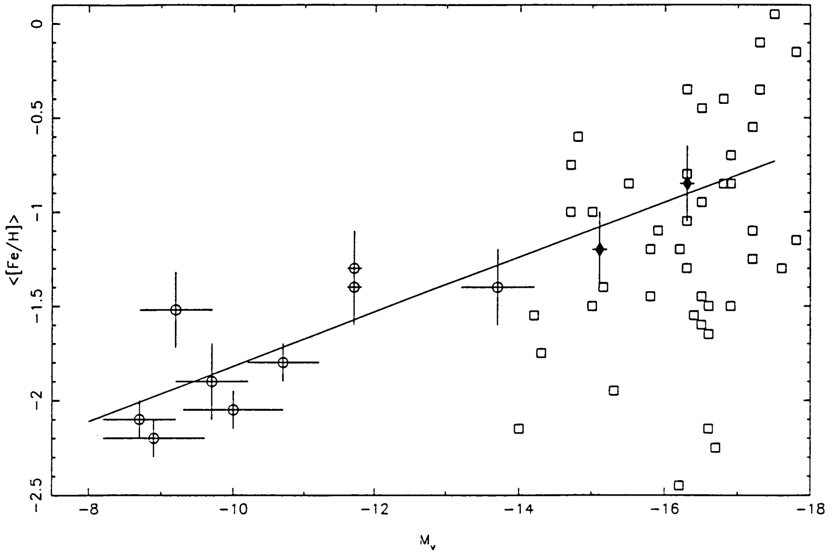

Figure 2. The abundance - luminosity relation for dSph and dE galaxies. The open circles with error bars are the dSph galaxies (8 Galactic dSph plus And I) while the filled diamonds are the dE galaxies NGC 147 and NGC 205. The open squares are dwarf galaxies from Brodie & Huchra (1991). The straight line is an unweighted least squares fit to the data for the 9 dSphs and NGC 147 and NGC 205.

6. Dwarf Spheroidals in the General Context of Dwarf Galaxies

Dwarf spheroidal galaxies are characterized by the absence of HI and by the presence of only old and intermediate-age stellar populations. Dwarf irregular galaxies, on the other hand, are characterized by the presence of large amounts of HI and by indications of current or recent star formation. Are these categories of dwarf galaxy disjoint or do transition objects exist? The recent results of van de Rydt *et al.* (1991), following on earlier work of Ortolani & Gratton (1988), suggest that the Phoenix dwarf galaxy may be such a transition object. This galaxy is a Local Group member that lies at a distance of some 400 kpc from the Milky Way. The van de Rydt *et al.* study shows that Phoenix consists mostly of an old metal-poor population which nevertheless possesses an intrinsic abundance dispersion. There is also a population of red stars with luminosities beyond the giant branch tip, one of which has been spectroscopically confirmed as a carbon star, thus indicating the presence of an intermediate-age population in this galaxy. These properties are all reminiscent of those of dSphs and in fact ,with $M_V \approx -10$ and $<[Fe/H]> \approx -2.0$ dex, Phoenix even lies on the abundance - luminosity relation of Fig. 2. However, Phoenix also contains an "association" of young blue stars whose age is estimated as less than 150 million years (van de Rydt *et al.* 1991) and further, HI was recently detected in this galaxy (Carignan *et al.* 1991). Both these latter properties are characteristic of a dwarf irregular. Thus it does appear that Phoenix is a dwarf galaxy whose properties span the gap between the dIrrs and the dSphs, the transition nature being further emphasized by the low (0.1) value of M_{HI}/L_v for Phoenix compared to typical values (~2) for dIrrs (Carignan *et al.* 1991). The Local Group member LGS3 may be a similar transition type dwarf since its properties are also similar to those of a dwarf spheroidal except for the presence of a moderate amount of HI (Cook & Olszewski 1989, Sargent & Lo 1985). It is then interesting to speculate as to what extent transition dwarfs like Phoenix and LGS3 have been able to retain modest amounts of HI gas because they lie far from any "large" galaxy such as M31 or the Milky Way; certainly with the exception of the Magellanic Clouds, all the companions to M31 and the Milky Way are gas poor (though the dEs NGC 185 and NGC 205 are not gas free).

The current catalog of dwarf spheroidals includes only objects that are companions to either our galaxy or to M31. Is this a selection effect or do isolated dwarf spheroidals exist? The recent discovery of a faint dwarf galaxy in the constellation of Tucana (Lavery 1990) may provide the first indication that isolated dwarf spheroidals exist. This galaxy presents a smooth appearance on optical images, *i.e.* there are no obvious HII regions or associations. It is noticeably flattened with $e \approx 0.5$ and has a diameter of approximately 1.2 kpc if its distance is of the order of 800 kpc (Lavery & Mighell 1991). It resolves into stars on deep images and the brightest stars are red. Preliminary color-magnitude diagrams (Lavery & Mighell 1991, Suntzeff & Seitzer 1991) suggest a distance modulus of approximately 24.5 making it a likely Local Group member with an absolute magnitude of approximately $M_V \approx -9.5$. No HI was detected in an initial search (Lavery & Mighell 1991). All these properties are reminiscent of the dSph companions to M31 and it thus seems quite probable that Tucana is indeed an isolated dSph galaxy. It is then of more than passing interest to note that Tucana was discovered entirely by chance(!) and to speculate how many similar galaxies are lurking both within the Local Group and at larger distances. The low surface brightness and small apparent size of such galaxies makes a directed search for such objects a daunting task!

7. Summary

The dwarf spheroidal companions to the Milky Way and M31, together with galaxies like Phoenix and Tucana are examples of what are probably the most common type of galaxy in the Universe. They differ from more luminous dEs only in intrinsic scale (mass,size); their properties are otherwise similar. Hence, because the individual stars can be studied in these galaxies, inferences can be made that are otherwise hard to draw when only integrated-light indices are available. For this reason dwarf spheroidals are worthy of continued attention. In particular, the following questions deserve serious study. *What governs the Star Formation History in dwarf spheroidal galaxies*, or equivalently, why does the ratio of old to intermediate-age populations vary so widely from dSph to dSph? *What role do the dark matter halos play in the evolution of dSphs? To what extent is proximity to a large "parent" galaxy important in the evolution of dSphs?* If these questions can be answered for the nearby dSph systems, then it will represent considerable progress towards answering similar questions for more distant and more luminous, but presumably otherwise quite similar, dwarf galaxies.

I would like to acknowledge the generosity of my colleagues, especially Dr. Nick Suntzeff, in supplying preprints and descriptions of work-in-progress that provided much of the material on which this review is based.

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DISCUSSION

Mateo: Just a comment. Sextans *has* been surveyed for variables as described in our poster. We find a total of 42 variables of which 3 are anomalous cepheids.

Da Costa: Obviously I was on the beach when I should have been looking at the posters. The written version will contain mention of your work.

Silk: The extended period of star formation in dwarf spheroidals such as Carina may be understood as follows. Depletion of the gas via a supernova-driven wind requires both that the energy input be sufficient to drive a wind, a condition easily satisfied, and that the radiative cooling timescale be longer than a dynamical timescale. The latter condition occurs only once the gas supply is sufficiently depleted by star formation. Hence the star formation efficiency determines the duration of the star formation phase, and so this can be long-lived.

Da Costa: This may be the case but remember that the metal abundance of the system is low (< 1/30 solar) - that may make the cooling less efficient. On the other hand, the rate of star formation implied is not high so perhaps you are right.

Gregg: Just as dSph galaxies are not the same kind of object as globular clusters, dSphs are also very different from the compact M32-like ellipticals. The existence of intermediate-age populations in dSphs and in some nucleated dEs should therefore *not* be interpreted as supporting evidence for intermediate-age populations in objects like M32.

Da Costa: I agree. Dwarf spheroidals and dwarf ellipticals form a different sequence from the compact ellipticals and so, yes, it is less certain that the results on the presence of intermediate-age populations can be applied to these galaxies.

Schommer: When I looked at the distributions of velocities in dSphs, I found all of them consistent with a gaussian except your earlier Sculptor data. These velocities show a minor skew. Have you looked at the actual distribution with your new data?

Da Costa: The distribution of the 32 velocities in the current sample is consistent with a gaussian.