DWARF SPHEROIDAL GALAXIES AND GLOBULAR CLUSTERS

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ABSTRACT: Recent observational results for dwarf spheroidal galaxies are reviewed and discussed. In particular, the differences in stellar populations between dwarf spheroidal galaxies and globular clusters are highlighted. It seems most probable that the origin and evolution of dwarf spheroidal galaxies was very different from that of globular clusters.

1. INTRODUCTION

In 1938 Shapley (1938a) announced the discovery of "A Stellar System of a New Type" in the constellation of Sculptor. The collection of faint images just visible at the limit of a 3 hour Bruce telescope plate was at first thought to be an extended cluster of galaxies, but subsequent 60-inch plates revealed the individual member objects to be faint stars, not galaxies. This system was novel in that it had the smooth density profile of a low central concentration globular cluster, yet if its brightest stars were assumed to have the same absolute magnitude as those in globular clusters, the Sculptor system had to be much larger and much more distant than any galactic globular cluster known at that time. Of course, this system is now known as the Sculptor dwarf spheroidal (dSph) galaxy.

Some months later Shapley (1938b) reported the existence of a second such system in the constellation of Fornax. However, an examination of over 150 small scale plates taken in South Africa, which covered more than 15,000 sq. degrees of sky at galactic latitudes above 20°, revealed no additional systems (Shapley 1939). In fact, discovery of additional systems had to await the Palomar survey of the northern sky; two systems in Leo were announced by Harrington and Wilson (1950) and a further two, Draco and Ursa Minor, were listed by Wilson (1955). A single additional southern object, Carina, was added by the SRC southern sky survey (Cannon, Hawarden and Tritton 1977) and except for the obscured regions at low galactic latitudes, the census of dSph galaxies associated with the Galaxy is considered complete. Three dSph galaxies associated with M31 are also

J. E. Grindlay and A. G. Davis Philip (eds.),
The Harlow-Shapley Symposium on Globular Cluster Systems in Galaxies, 217–236.

known (van den Bergh 1972a,b; 1974).

In his original article Shapley (1938a) argued that the most appropriate description for the Sculptor system was as "a super-cluster of the globular type" and this view, that dSph galaxies are simply very low density analogues of globular clusters, has prevailed for many years. However, in recent years evidence has accumulated which indicates that this view is too simple, and that in fact, dSph galaxies and globular clusters have as many differences as they do similarities. In this review then, it is these differences that will be the focus.

2. VARIABLE STARS

The variable star content of dSph galaxies has been reviewed recently by Zinn (1980, 1985) and so only new results will be discussed here.

2.1 RR Lyrae Variables

Large samples of RR Lyrae variables have been discovered in the Draco, Sculptor, Ursa Minor and Leo II galaxies (Baade and Swope 1961; van Agt 1967, 1973, 1978; Swope 1967) which until recently was all the dSph galaxies in which adequate searches have been made. To this list we can now add Carina since Saha, Monet and Seitzer (1986) have just published detailed photometry for 53 variables, mostly RR Lyrae stars, that are believed to be members of this dSph galaxy. As has been found for Draco and Leo II (see for example Zinn 1980), the mean period of the ab-type variables in Carina (0.62 days) is intermediate between Oosterhoff type I ($<P_{ab}>$ = 0.55d) and type II ($<P_{ab}>$ = 0.65d), though as noted by Sandage (1982), the Oosterhoff types for galactic globular clusters in reality form a "bimodal continuum" rather than a strict dichotomy.

In this context it is worth mentioning the work of Nemec (1985) who, by analyzing the photographic photometry of Baade and Swope (1961), identified and studied 10 double mode RR Lyrae variables in Draco. From their period ratios, he found that nine of these stars have masses near 0.65 M_o and were indistinguishable from the double mode variables in the Oosterhoff type II cluster M15. The tenth star however, has a derived mass of 0.55 M_o and is indistinguishable from the double mode variables in the type I cluster M3. In the period-amplitude diagram, this star also shows a shift from the fiducial M3 relation that is smaller than that of the other double mode stars by an amount equal to, within the uncertainties, the period shift between M3 and M15. Thus, in addition to being 0.1 M_o less massive, this star probably has an abundance larger than the mean of the others by about 0.5 dex, the difference in [Fe/H] between M3 and M15. Indeed both the period-amplitude diagram and the period-rise time diagram for the entire sample of variables (Nemec 1985) offer strong support for the existence of an abundance range in Draco, a result that will be discussed further below.

2.2 Anomalous Cepheids

The first indication of a difference in stellar populations between globular clusters in dSph galaxies came with the recognition of a new class of variable stars in Draco (Baade and Swope 1961). These stars are known as anomalous Cepheids because they fail to obey the period-luminosity relations for either Type I or Type II Cepheids. Anomalous Cepheids are relatively much more common in dSphs than in globular clusters; at least 25 such stars are known in the Draco, Ursa Minor, Sculptor, Leo I and Leo II systems (Zinn and Searle 1976, van Agt 1967, Swope 1968, Kunkel and Demers 1977, Hodge and Wright 1978), whereas the globular clusters contain but a single example, V19 in NGC 5466 (Zinn and Dahn 1976). Anomalous Cepheids are also found in the Small Magellanic Cloud but not in the LMC.

Both theoretical (Demarque and Hirshfeld 1975, Hirshfeld 1980) and observational analyses (Norris and Zinn 1975, Zinn and Searle 1976, Zinn and King 1982, Smith and Stryker 1986) indicate that these variables have masses in the range of 1 - 2 $M_{\odot}$. Further, in order that they evolve into the instability strip, they are also required to be quite metal-poor ([Fe/H] < -1.3 approximately). Explanations for the larger masses are that either the stars result from a population of 1-3 billion year old stars, or they are the result of mass transfer in a binary system of old stars (Renzini, Mengel and Sweigart 1977). At present there seems no obvious way to select between these competing hypotheses for the dSph anomalous Cepheids. However, the discovery of a large number of blue stragglers in NGC 5466 (Nemec and Harris 1986) suggests the binary mass transfer hypotheses is appropriate for NGC 5466 V19 while, following the discussion of Smith and Stryker (1986), the "young metal-poor stars" explanation seems reasonable for the SMC variables.

An anomalous Cepheid has now been discovered in Fornax also by Light, Armandroff and Zinn (1986). Though this star lies near one of the Fornax globular clusters, it is most likely a member of the field population of this galaxy. Undoubtedly more extensive searches will reveal additional such stars. This leaves Carina as the one remaining dSph in which no anomalous cepheids have yet been identified. However, given that every other dSph contains at least one, it seems highly unlikely that Carina would lack them. Indeed it is quite possible that such stars have already been identified. The variable star survey of Saha et al. (1986) contains 8 short period variables that are 0.5 to 1.5 mag brighter than the Carina RR Lyraes. If these stars are assumed to be halo field variables, then their density is 2 orders of magnitude greater than that expected (Saha et al. 1986). However, despite this discrepancy, Saha et al. did not explore in any detail the possibility that these stars are Carina anomalous Cepheids. In Fig. 1a, the data for these stars, taken from Saha et al. (1986), are plotted in the (log P, $<M_B>$) plane on the assumption that they are members of Carina, along with equivalent data for the anomalous Cepheids in other dSph galaxies taken from the sources cited above. Fig. 1b shows the same stars in the (log P, A_B) plane. At least 4 of the Carina variables (nos. 1, 29, 33 and 129)

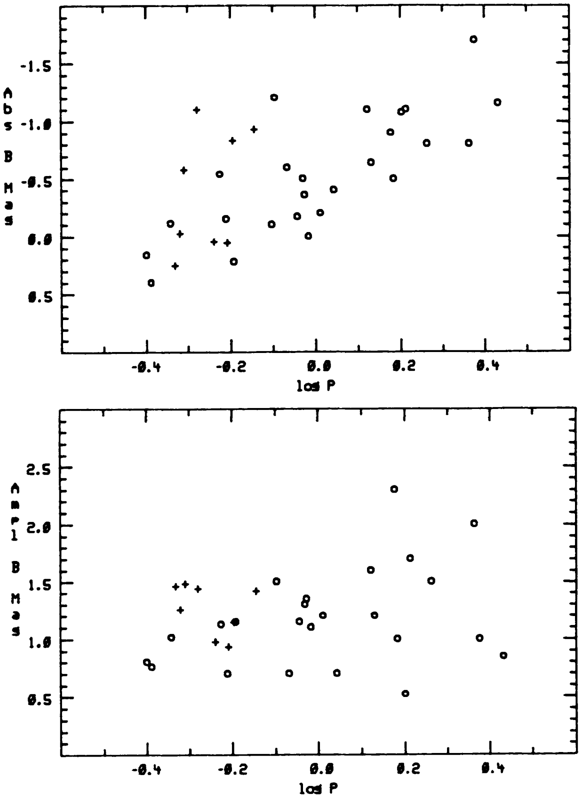

Fig. 1. (a) Upper panel: Period-Luminosity relation for all known anomalous cepheids in dSph galaxies (open symbols) and for the "bright" RR Lyraes in the Carina field (plus signs) plotted as if they are members of the Carina system. (b) lower panel: Period-Amplitude diagram. The symbols are the same as for Fig. 1a.

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fall within the scatter outlined by the known anomalous cepheids in both diagrams and thus deserve to be considered as likely candidates for anomalous Cepheids in this dSph galaxy. In this context it is also worth noting that since the plates used by Saha et al. (1986) were taken in a single 4 night run, their probability of defining light curves and periods for variables with periods longer than about 0.9d is rather low. Hence it is quite possible that additional longer period anomalous cepheids are also present.

2.3 Type II cepheids

The paper of Light et al. (1986) also reports the discovery of the first Type II Cepheidsin a dSph galaxy. Such stars are found only in galactic globular clusters with blue horizontal branches (Harris 1985) so it is reassuring that the variable discussed by Light et al. appears to be a member of Fornax globular cluster 2, which Buonanno et al. (1985) have shown to have a blue horizontal branch. The lack of such stars in the other dSph systems is consistent with their generally red horizontal branches except of course for Ursa Minor. In this situation it is possible to argue, as is done for the globulars with blue horizontal branches that also lack Type II Cepheids, that the observed absence of such stars is due to statistical fluctuations caused by the short evolutionary lifetime of such stars.

3. ABUNDANCE VARIATIONS

With the well established exception of ω Centauri and the possible exception of M22, all galactic globular clusters are chemically homogeneous with respect to heavy element abundances. The available results for dSph galaxies however, suggest that in general they are not chemically homogeneous, possessing instead substantial abundance ranges.

Evidence to suggest abundance ranges is usually found from one of two distinct methods which, given the controversy that has at times enveloped this subject, are worth describing here. The simplest method seeks to test whether the observed color widths of principal features in c-m diagrams are greater than that expected from the photometric errors alone. In principal this method has the advantage of allowing use of a large sample of stars, but in practice its application is complicated by: (a) uncertain knowledge of the true photometric errors, (b) the probable inclusion of AGB stars if the sample being investigated is at magnitudes above that of the horizontal branch, and (c) by the relatively low sensitivity of broad band colors to abundance variations at low abundances. While (b) can be corrected by using stars fainter than the horizontal branch, effects (a) and (c) remain.

The second method is spectraphotometry of individual red giant stars in the dSph galaxy. Here the principal difficulty, aside from those inherent in measuring features in low S/N spectra of cool luminous stars, is simply gathering a sufficiently large sample of stars for meaningful analysis. This method should yield more precise abundance measures, especially for low abundances, than photometry. A variant of this method is the application of the ΔS method to the variables in dSph galaxies. While this technique has seen little use because of the faintness of the stars involved, it is known to give reliable results for galactic globular clusters (Smith 1984) and the coming new generation of large aperture telescopes may make it practical for dSph stars. At present, this kind of analysis has been employed only for anomalous Cepheids in Sculptor (Smith and Stryker 1986).

3.1 Draco

This dSph galaxy was the first for which a claim of a substantial abundance range was made (Zinn 1978). Since Zinn's work there has been a succession of papers (e.g. Kinman, Kraft and Suntzeff 1981; Smith 1984; Stetson 1984; Aaronson and Mould 1985) all of which have argued for a real abundance spread in this dSph galaxy, with estimates of the total abundance range present reaching as high as 1 dex ($-2.7 < [Fe/H] < -1.7$, approximately). Bell (1985) however, has contested this result, arguing principally from Stetson's data that the apparent abundance spread in Draco is the result of underestimated observational errors.

This issue is further complicated by the recent photometry of Carney and Seitzer (1986). These authors claim that in the c-m diagram, the giant branch in the magnitude interval $20.5 < V < 21.5$ (equivalent to $+1.0 < M_V < +2.0$; i.e. below the horizontal branch) shows an intrinsic total range of 0.19 mag in (B-V). This corresponds to an abundance range of approximately 0.8 dex if the Zinn and West (1985) calibration of $(B-V)_{o,g}$ is assumed to apply, and in particular remain linear, at abundances less than that of M92, to which the mean Draco lower giant branch color corresponds. However, it appears these authors have underestimated their photometric errors. Using the 20 stars in common between their fields 1 and 2 in the magnitude interval $20.5 < V < 22.0$, the (B-V) single observation 1σ error is calculated as 0.057 mag. The standard deviation of the (B-V) colors for the 54 giants in the interval $20.5 < V < 21.5$, selected as described in Carney and Seitzer (1986), is 0.058 mag; thus contrary to the claims of Carney and Seitzer (1986), their photometry analyzed in this fashion provides no evidence to support the existence of an abundance spread in Draco. However, as reported elsewhere in this volume, a reanalysis using the error estimate calculated above but with a larger sample of stars ($20.5 < V < 22.0$ instead of $20.5 < V < 21.5$) and with a ridge line defined by the giant branch itself rather assuming a fixed (B-V) color, indicates that the lower giant branch in Draco does have an intrinsic width.

Further support for the existence of an abundance spread in Draco is the correlation found by Aaronson and Mould (1985) between the $(J-K)_o$ and $(V-K)_o$ color residuals from the M92 giant branch at constant luminosity, and the spectroscopically determined residuals at constant color from the M92 ridge line in the (m_{HK}, $(B-V)_o$) diagram of Kinman, Kraft and Suntzeff (1981).

3.2 Ursa Minor

The majority of the authors cited above have also observed stars in Ursa Minor, but the largest sample of spectroscopically observed stars is that of Suntzeff et al. (1986). Aside from one very metal-poor ([Fe/H] = -3.5 dex) star, the spread in abundance sensitive parameters in this sample is consistent with the observational errors alone; certainly there is no compelling evidence for any abundance spread similar in size to that claimed for Draco. This result is supported by the photometry: neither the lower giant branch data of Olszewski and Aaronson (1985) nor the new upper giant branch photometry of Cudworth, Olszewski and Schommer (1986) indicate any substantial color width in excess of the errors.

3.3 Fornax

The Fornax dSph is unique among the galactic dSph galaxies in that it has 5, possibly 6, globular clusters associated with it (Hodge 1961, 1969). These clusters appear in all respects to be comparable to galactic globular clusters (see Buonanno et al. 1985 and the references therein). In particular, these clusters cover a considerable range in abundance, from approximately [Fe/H] = -2.2 (cluster 3) to [Fe/H] = -1.2 dex (cluster 4; Zinn and Persson 1981).

Buonanno et al. (1985) have also produced c-m diagrams for two field regions in this dSph galaxy. In these diagrams the giant branch is quite broad, as first noted by Demers et al. (1979). After consideration of their photometric errors, Buonanno et al. (1985) conclude first, that the mean abundance of the stars in these fields is [Fe/H] = -1.4 dex, and second, that there is an intrinsic abundance spread. The abundance spread is characterized by a standard deviation $\sigma([Fe/H]) = 0.3$ dex and an apparent total abundance spread of approximately $-2.0 < [Fe/H] < -0.9$, though given that these values are drawn from a c-m diagram, it is possible that more metal poor stars exist in this dSph galaxy. Interestingly, the mean abundance of the field population is approximately 0.4 dex more metal rich than the mean abundance of the globular clusters. See also the paper of Light and Seitzer in this volume.

3.4 Sculptor

The suggestion of an abundance range in this dSph galaxy was first put forward by Norris and Bessell (1978). These authors, based on their own analysis of the giant branch photometry of Kunkel and Demers (1977) and on spectra of 2 giants, concluded that there was an abundance range of perhaps 0.6 dex in this dSph galaxy. A range of Ca II H and K lines strengths among Sculptor giants was confirmed by the narrow band imaging of Smith and Dopita (1983) but unfortunately these authors gave no actual estimate of the abundance spread implied by their results. The CCD photometry of Da Costa (1984) also supported the results of Norris and Bessell (1978) but the number of stars in the appropriate part of the c-m diagram was not large. Yet more support is provided by the ΔS results of Smith and Stryker (1986); the 3 anomalous cepheids studied show an abundance range of 0.4 dex.

In Fig. 2 preliminary results from a new study of the abundance range in Sculptor are presented (Armandroff, Da Costa and Zinn 1986). The upper panel shows the location of 16 radial velocity members of Sculptor in the M_I, $(V-I)_o$ plane along with equivalent photometry for a number of giants in the well-studied galactic clusters M15, M2, NGC 1851 and 47 Tuc. The photometry of all stars was obtained at CTIO with the CCD detector. The middle panel shows a plot of the sum of

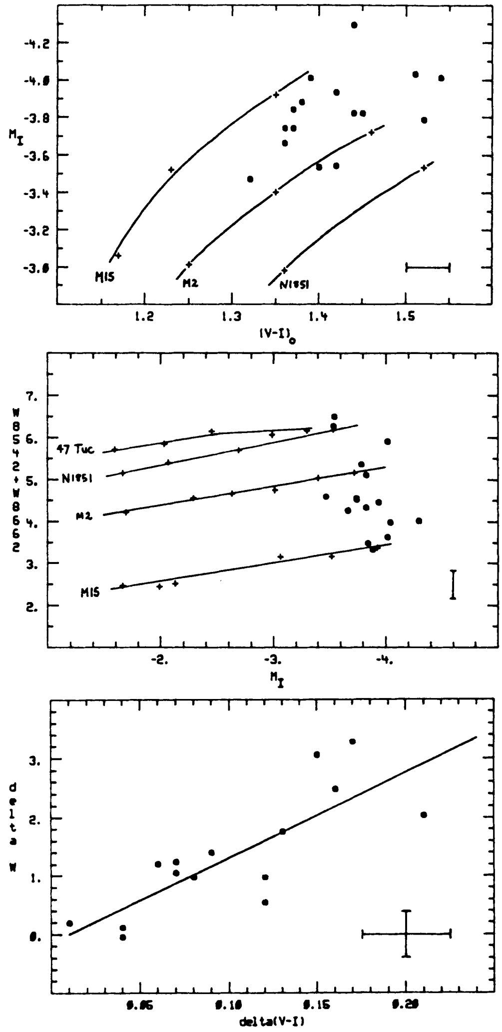

Fig. 2. Upper panel: M_I,$(V-I)_o$ color-magnitude diagram for 16 radial velocity members of the Sculptor dSph galaxy. Also shown are the giant branches of three galactic globular clusters. Middle panel: the total equivalent width (A) of the CaII IR-triplet lines at λ8542 and λ8662 plotted against M_I for the Sculptor stars. Constant abundance lines are defined by the galactic globular cluster stars. Lower panel: the deviation in equivalent width from the M15 ridge line in the middle panel, at constant M_I, plotted against the deviation in $(V-I)_o$ color from the M15 giant branch in the upper panel, again at constant M_I. The correlation coefficient is 0.80.

the equivalent widths of the Ca II infrared triplet lines at λ8542 and λ8662 against M_I for both the globular cluster and Sculptor stars. Again the data were obtained at CTIO. Finally the bottom panel shows a plot of residual equivalent width, measured at constant M_I from the M15 fiducial line, against residual $(V-I)_o$ color, from the M15 giant branch, for the Sculptor stars.

A number of points can be made from these diagrams. These include: (a) the Sculptor star (H264) with $M_I = -4.3$ has, using the $(M_{bol}, (V-I)_o)$ relation of Mould, Kristian and Da Costa (1984), $M_{bol} = -3.75$ and thus is an upper-AGB star. (b) Both the photometry and the spectroscopy indicate that the mean abundance of the Sculptor stars is [Fe/H] = -1.8 ± 0.05 dex if the Zinn and West (1985) abundance values are adopted for the calibrating clusters. (c) The good correlation between the equivalent width and color residuals indicates that the scatter shown by the Sculptor stars in both the upper and middle panels is not due to observational errors alone. Although the effect of different gravities, temperatures and abundances combine to produce ambiguity in the interpretation of the abundances of the most metal rich Sculptor stars in the middle panel, the combined data are consistent with a total abundance range of approximately 0.6 dex, from [Fe/H] = -2.1 to [Fe/H] = -1.5 dex. The dispersion σ([Fe/H]) is approximately 0.2 dex.

3.5 Comment

It has been established for sometime now that the mean metal abundances of the dSph galaxies are tightly correlated with their luminosities. The dwarf elliptical companions of M31 studied by Mould, Kristian and Da Costa (1983, 1984), namely NGC 147 and NGC 205, also fall on this relation which is shown in Fig. 3. The galactic globular clusters however, show no such relation and this difference is yet another clue that the origins of globular clusters and dSph galaxies were different. Interestingly, it also appears likely that the abundance dispersions in these galaxies are correlated with their mean abundance (or luminosity). The data are presented in Fig. 4. For NGC 205 and NGC 147, the values are taken from Mould et al. (1983, 1984); note that the value for NGC 205 is a lower limit since this galaxy contains stars more metal rich than 47 Tuc, the most metal rich cluster is used in their calibration. For Fornax, the results of Buonanno et al. (1985) are used, while the results described above are used for Sculptor. For Draco the value is the mean of the dispersions calculated from Zinn (1978), 0.16 dex, which is probably an underestimate if the abundances of the most metal poor stars have been overestimated, and that, 0.30 dex, from Kinman, Kraft and Suntzeff (1981), calculated without any attempt to correct for abundance errors. The Ursa Minor value is an attempt to allow for one very metal poor star in a sample with an otherwise small dispersion (Suntzeff et al. 1986). The mean metal abundances are typically determined to 0.2 dex or better; the errors in the dispersions are poorly known but probably do not exceed ±0.1 dex.

Naively such a correlation is perhaps expected; more generations

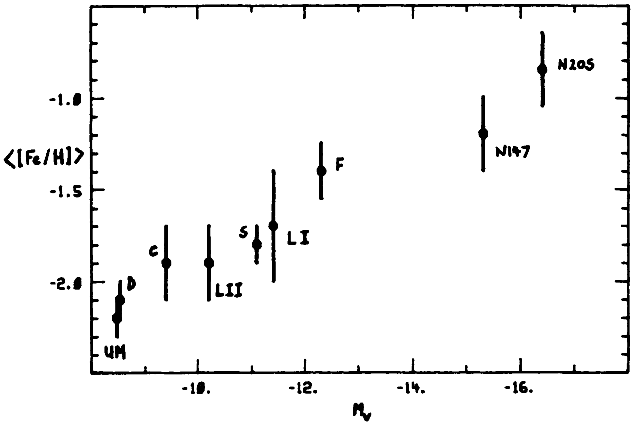

Fig. 3. The mean metal abundances of the 7 galactic dSph galaxies and of the M31 dE companions NGC147 and NGC205 plotted against the absolute visual magnitudes of these systems.

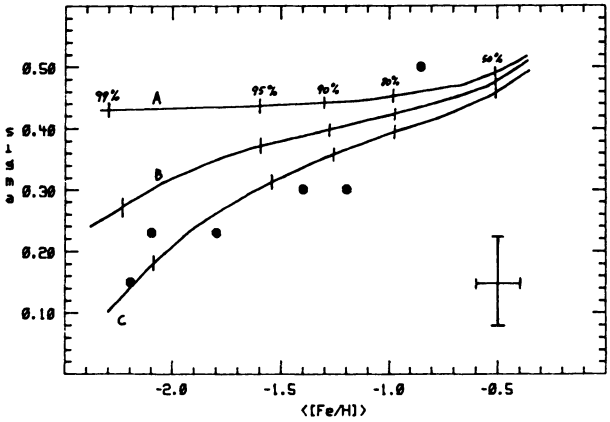

Fig. 4. The abundance dispersion σ([Fe/H] plotted against mean abundance <[Fe/H]>. In order of increasing abundance, the filled symbols are for Ursa Minor, Draco, Sculptor, Fornax, NGC147 and NGC205. Typical errors for both quantities are indicated. The solid curves are predictions of the simple model of chemical evolution assuming a yield equal to the solar abundance. Curve A: initial abundance z_o = 0.0; Curve B: z_o = 2 x 10^{-5}; Curve C: z_o = 6 x 10^{-5}. The vertical bars indicate the amount of initial mass lost from the system.

of stellar processing meaning not only a higher mean abundance but also a larger abundance dispersion. In an attempt to quantify this statement, Fig. 4 also shows the results of some crude calculations. The simple "closed box" model of chemical evolution was employed with the addition that evolution was assumed to halt when the stellar abundance reached a predetermined Z_{max}. As noted by Zinn (1978), in such models, assuming a yield equal to the solar abundance (as done here) requires that the evolution cease when only a small fraction of the original mass of gas has been turned into stars if the metal abundance is to be low. The curves, labeled A, B, and C were calculated assuming "primordial" abundances of 0.0, 0.001 Z_{sun} and 0.003 Z_{sun}, respectively. The fractions of original mass lost, which are generally large, are also indicated. With the possible exception of curve C, none of these models give a good representation of the observations. This is undoubtedly the result of the unrealistic assumptions (e.g. instantaneous recycling) that underlie the simple model of chemical evolution. However, like the (M_V, <[Fe/H]>) relation, the data of Fig. 4, and future more precise versions, can be used to provide constraints on more detailed models of the chemical evolution of dSph galaxies.

4. AGE AND AGE VARIATIONS

It is clear from the many very accurate main sequence c-m diagrams for globular clusters now available, that the range of age present among the stars in any one cluster must be very small. That does not seem to be the case for dSph galaxies. Following the discovery of upper-AGB, and therefore intermediate age, carbon stars in the Fornax dSph (Aaronson and Mould 1980), there have been a plethora of papers concerning the ages, age ranges and carbon star content of dSph galaxies. The situation regarding carbon stars has been thoroughly discussed recently by Aaronson and Mould (1985) and little can be added to their conclusions: five of the seven galactic dSph galaxies have extended giant branches and therefore contain stars younger than the globular clusters. This appears also to be the case for at least one of the M31 dSph companions (Aaronson et al. 1985). Only Draco and Ursa Minor lack stars at luminosities above that of the first giant branch tip. Since these are also the lowest luminosity systems, and since the evolutionary lifetime of upper-AGB stars is short, it is by no means inconceivable that this apparent lack of upper-AGB stars is simply a statistical effect. This point will be discussed further below.

4.1 Main Sequence Color-Magnitude Diagrams

Color-Magnitude diagrams that reach the main sequence are currently available for 5 dSph galaxies and the results from each of these data will now be examined. The least ambiguous result is that for Ursa Minor (Olszewski and Aaronson 1985) which, it will be recalled, is the only dSph known to have a blue horizontal branch.

The c-m diagram is well fit by the ridge lines of the old metal poor globular cluster M92 and there is little, if any, indication of the presence of a substantial younger population. An age of 16 ± 2 billion years is derived from isochrone fits. The c-m diagram however, does contain a small number of blue stragglers which will be discussed further below.

The results for Draco, a dSph galaxy with a red horizontal branch, are however, less clear cut. Stetson, VandenBerg and McClure (1985) conclude from a rather small sample of stars that Draco is not measurably younger than the galactic globular clusters or Ursa Minor. The precision of their data however, is rather low. However, photometry of a much larger sample of Draco stars, with somewhat better accuracy, is presented by Carney and Seitzer (1986). These authors conclude from both a c-m diagram and a luminosity function comparison with M92, as well as from isochrone fits, that Draco may in fact contain a sizeable population of stars that is perhaps a few billion years younger than the globular clusters of similar abundance (and Ursa Minor). The existence of this population will of course go some way towards explaining the horizontal branch difference with Ursa Minor, but not the whole way since there is evidence that a significant old population is also present. Once again there is evidence for a sizeable blue straggler population.

For Sculptor, Da Costa (1984) has argued from both a comparison with the M92 ridge lines in the (V,B-V) plane and from isochrone fits in the (R,B-R) plane, which reduces the sensitivity to photometric color errors, that the bulk of the stars in this dSph galaxy are 2 - 3 billion years younger than the globular clusters. An age difference of this size is quite capable of explaining the predominantly red horizontal branch of this system. Further, although an older population is certainly not ruled out by these data, it is not likely to be dominant. As for Draco and Ursa Minor, there is also a notable blue straggler population in this dSph galaxy.

The IR-photometry of carbon stars in Carina (Mould et al. 1982) suggested that this dSph galaxy had a substantial intermediate age population. This was confirmed by the CCD photometry of Mould and Aaronson (1983) who derived a turnoff age of only 7 billion years for the majority of the stars in their c-m diagram. Further, comparison with theoretical luminosity functions apparently left little room for any older population. However, the discovery of RR Lyrae variables in this dSph galaxy (Saha et al. 1986) shows that a population of stars with ages in excess of 10 billion years must be present. The relative importance of this older population however, is apparently not large. Depending on the number of RR Lyraes produced per old giant progenitor, the fraction of old stars could be as low as 2%; a direct comparison with Draco suggests a 15% contribution in line with estimates from the carbon star numbers of approximately 70% intermediate age population.

As noted above, the Fornax globular clusters appear to be indistinguishable from their galactic counterparts, even to the existence of blue horizontal branches in their c-m diagrams (Buonanno et al. 1985). This would appear to be *prima facie* evidence that

Fornax contains very old stars. Yet this dSph galaxy also contains a large number of carbon stars whose luminosities are the brightest of any known in the dSph galaxies, indicating ages as young as 3 billion years or less (e.g. Aaronson 1986). The main sequence progenitors of these stars are seen in the deepest c-m diagrams of Buonanno et al. (1985); hence it seems inescapable that star formation has proceeded in Fornax over most of its life. Based again on the numbers of carbon stars, the fraction of this younger (i.e. age < 10 billion years) population is estimated as 15 - 25 percent of the total (Aaronson 1986). Similar fractions apparently also apply for the Leo I and Leo II systems (Aaronson 1986).

In summary then, it appears that the degree of on-going star formation in dSph galaxies, by which is meant the formation of stars younger than 10 billion years, is highly variable, ranging from negligible or non-existent in Ursa Minor, Draco and Sculptor, to significant for Leo I, Leo II and Fornax, to dominant for Carina. In a similar sense, as typified by the sequence Ursa Minor, Sculptor, Carina, it is also clear that the epoch of formation for the bulk of the stars varies from dSph to dSph.

4.2 Blue Stragglers: Binaries or Young Stars?

As noted above, the main sequence c-m diagrams of the Ursa Minor, Draco and Sculptor dSph galaxies all show a population of blue stragglers and it is of interest to inquire into the origin of these stars. Are they, for example, intermediate age main sequence stars, which would indicate on-going star formation at very low levels in these dSph galaxies, or are they the result of mass transfer in old binary systems? Since blue stragglers are known to occur in at least some globular clusters, the existence of similar stars in the dSph galaxies does not of itself require them to be of intermediate age. However, by investigating the consequences, the validity of the assumption that they are intermediate age stars may be investigated.

The stars in question, if interpreted as normal main sequence stars, would appear to have ages from 1 to 3 billion years upwards. The subsequent evolution of such stars should produce (a) upper AGB carbon stars and (b) at least for the more massive progenitors, anomalous cepheids since the abundances in these dSph galaxies are sufficiently metal poor. Turning first to the upper AGB stars and noting that (a) the total population of possible main sequence progenitors, assumed to be all stars with indicated ages less than 10 billion years, is approximately 300, 700 and 1400 stars in Ursa Minor, Draco and Sculptor (Olszewski and Aaronson 1985, Carney and Seitzer 1986, Da Costa 1984); and (b) that the number of upper AGB stars is somewhere between 1/500 and 1/2000 times the number of main sequence progenitors (Da Costa 1984; Olszewski and Aaronson 1985). The predicted numbers of upper AGB carbon stars are then approximately 0.4, 0.6 and 2 stars, respectively. The observed numbers are 0, 0, and at least 1 (Aaronson and Mould 1985). Hence there is no obvious conflict here.

Second, if following Carney and Seitzer (1986), blue stragglers brighter than about $M_V \simeq +2.5$ are assumed to have sufficient mass to become anomalous Cepheids, and if anomalous Cepheids are assumed to have an evolutionary lifetime of approximately 50 million years (Hirshfeld 1980), then the number of anomalous cepheids should be approximately 1/40 the number of main sequence progenitors. The total numbers of bright blue stragglers in these dSph galaxies is approximately 45, 70 and 200 leading to predicted numbers of anomalous cepheids of 1, 2 and 5 stars. The observed numbers are 3, 5 and 3 stars. Hence once again, despite the obvious large uncertainties in these estimates, there is no conflict with the hypothesis that the blue stragglers observed in the Ursa Minor, Draco and Sculptor dSph galaxies are young single stars.

In summary then, while there is no evidence against the old binary mass transfer scenario, it is also true that there is no evidence that rules out the competing hypothesis, namely that the blue stragglers are single intermediate age main sequence stars. Certainly for Sculptor, where the existence of upper AGB (intermediate age) carbon stars is confirmed, it seems likely that this second hypothesis is correct, and that therefore, this dSph galaxy continued to form stars at a very low rate long after the major epoch of star formation.

5. DARK MATTER

The globular clusters of our Galaxy have typical visual mass-to-light ratios of the order of 2 to 3 in solar units. These M/L values can be adequately explained without the need to postulate the existence of any additional "dark matter" other than the remnants of evolved stars (e.g. Illingworth 1975, Gunn and Griffin 1979; Lupton, Gunn and Griffin 1985). On the other hand, perhaps *the* most intriguing new result for dSph galaxies is the suggestion that the M/L values, for at least some dSph galaxies, maybe an order of magnitude or more higher. This would suggest that dSph galaxies contain substantial amounts of dark matter in an analogous fashion to the halos of spiral galaxies. Such a result has a number of important astrophysical applications aside from the obvious ones for the formation and evolution of dSph galaxies. For example, the dark matter almost certainly could not be "hot", i.e. in the form of massive neutrinos, if it can be confined on scales the size of dSph galaxies (Tremaine and Gunn 1979; Lin and Faber 1983).

Since Aaronson's (1983) original measurement of an unexpectedly large velocity dispersion for Draco, a number of further studies have been published. These are summarized in Table I, which gives velocity dispersion measurements for 5 dSph galaxies; the samples on which the entries are based are described in the notes. Also listed in the Table are the corresponding central mass-to-light ratios which, with the exception of the recent studies of Armandroff and Da Costa (1986) and Aaronson and Olszewski (1986b), have been taken directly from Kormendy (1986). As discussed by Kormendy (1986), central M/L values are to be preferred to "global" values in order to minimize the impact of assumptions regarding the internal dynamics of dSph galaxies.

Further, use of central M/L values also minimizes the effect of errors in the limiting radii of these systems, which are often poorly determined.

Table I
Dwarf Spheroidal Velocity Dispersions

dSph	Reference	$<v^2>^{1/2}$ (km/s)	$(M/L)_V$	Notes
Draco	A086a	9 ± 2	37 ± 11	1
Ursa Minor	A086a	11 ± 3	100 ± 40	2
Carina	SF85	6 ± 2	10 ± 6	3
Sculptor	SF85	6 ± 3	6 ± 3	4
	AD86	6.2 ± 1.2	6.0 ± 2	5
Fornax	SF85	6 ± 2	1 ± 0.5	6
	A086b	8 ± 3	2 ± 1	7

References: A086a, A086b = Aaronson and Olszewski (1986a, 1986b); SF85 = Seitzer and Frogel (1985); AD86 = Armandroff and Da Costa (1986).

Notes:

1. Multiple epoch observations; 3 Carbon stars and 8 K-giants; 2 velocity variables (1 Carbon star, 1 K-giant).
2. Multiple epoch observations; 2 Carbon stars and 8 K-giants; 3 velocity variables (2 carbon stars, 1 K-giant)
3. Single epoch; 6 Carbon stars
4. Single epoch; 3 Carbon stars
5. Single epoch; 16 K-giants
6. Single epoch; 5 Carbon stars
7. 3 Fornax globular clusters.

Table I also lists the uncertainty in the velocity dispersion measures. In most instances this uncertainty stems entirely from the small numbers of stars observed. Uncertainties are also given for the central M/L values. In this case, again following Kormendy (1986), the listed uncertainties reflect only the velocity dispersion errors and do not include the effects of uncertainties in the central surface brightnesses or in the core radii of these systems. These latter quantities however, especially the central surface brightnesses, are difficult to establish observationally and they are therefore also subject to large uncertainties. Consequently, the M/L errors listed in Table I are very much lower limits; for example, Armandroff and Da Costa (1986) have shown that the uncertainty in the central M/L value for Sculptor, a relatively well-studied system, increases by almost 50 percent when uncertainties in all quantities, not just in the velocity dispersion, are considered.

It is also worth emphasizing that the central M/L values in Table I have been calculated using the observed velocity dispersions; no corrections for the expected decrease in velocity dispersion with distance from the galaxy center or for projection effects have been applied, since to do so would require the adoption of a (possibly incorrect) model for the dynamics. Fortunately, since the stars observed are generally within 1 or 2 core radii of the center, these corrections are probably not large. Nevertheless it must be kept in mind that the M/L values listed in Table I are actually lower limits to the true central values.

Given all these caveats, can any reliable conclusions be drawn from these results? The answer is undoubtedly yes and the implications have been extensively discussed by Kormendy (1986). Briefly, despite the large uncertainties, the conclusion that both Draco and Ursa Minor contain large amounts of dark matter seems difficult to avoid. This is less obviously the case for Sculptor and Carina, while for Fornax, there is no requirement to invoke the presence of dark matter at this time. The result for Carina however, deserves some further attention since this dSph galaxy is dominated by a population that is less than half the age of the bulk of the stars in the other systems. Simple calculations show that Carina's M/L value should be increased by a factor of 1.5 to 2 to compensate for this age difference when comparing it with those for the other dSph galaxies. Thus if its measured velocity dispersion is confirmed by further observations, Carina will join Draco and Ursa Minor as a dSph galaxy apparently containing a substantial amount of dark matter.

Regarding Sculptor and in particular Fornax, it is important to remember that the tabulated values are central M/L values. If the core radius of the dark matter exceeds the core radius of the visible stars, or equivalently, if the central density of dark matter is significantly less than that of the stars, as seems likely in Fornax (Kormendy 1986), then it is difficult to learn much about the presence of dark matter from this type of observation. What is required in these cases is a measurement of the velocity dispersion at large r/r(core), a difficult but not impossible observational task.

6. SUMMARY

It should be clear from the preceeding discussion that in fact dSph galaxies do not have much in common with globular clusters. They share only the common properties of similar density profiles, at least for the lowest central concentration globular clusters, a lack of gas and current star formation, and of course, the general characteristic of a basically "old" stellar population. Instead it appears more appropriate to consider dSph galaxies in the same context as dwarf ellipticals and dwarf irregulars, for as shown by Kormendy (1985) for example, all these systems follow the same correlations between absolute magnitude, central surface brightness and core radius (see also Dekel and Silk 1986). The observations in dSph galaxies of ongoing star formation over a substantial fraction of a Hubble time, albeit at variable rates, of large internal abundance ranges, the clear correlation between mean metal abundance and absolute magnitude, and the possibility of dark matter halos all add further support to this idea. In this respect, it is perhaps appropriate to end by once again quoting from Shapley's 1938a paper announcing the discovery of Sculptor. In it Shapley offers as an alternative to his preferred description of Sculptor as a "super cluster of the globular type" the following: "or...a Magellanic Cloud [i.e. a dwarf irregular galaxy] devoid of its characteristic bright stars, clusters and luminous diffuse nebulosity". These latter remarks may well be close to the truth.

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DISCUSSION

NEMEC: You failed to mention the important structural differences in the central characteristics as summarized by Kormendy (1985).

DA COSTA: The (M/L) values were central (M/L) values calculated following Kormendy's precepts. For Draco, Ursa Minor and Carina, the values were taken directly from his paper.

COHEN: How do you know Draco and Ursa Minor, the least luminous dwarf spheroidal galaxies, are not currently being torn apart?

DA COSTA: Perhaps Ed Olszewski would like to comment.

OLSZEWSKI: If Draco and Ursa are being ripped apart, the stars with high velocity move very far in 10^9 yr. We would have to catch both Draco and Ursa in a unique part of their life, a necessarily small part of their life (since at 10km/s the crossing time is 10^8 years), which seems unlikely.

CAYREL: Could you say something about the globular clusters associated to the dwarf spherical galaxies?

DA COSTA: The only galactic dwarf spheroidal galaxy containing globular clusters is Fornax. The clusters show an abundance range of about 1 dex and have CM diagrams that show blue horizontal-branch stars. Essentially they appear identical to galactic globular clusters.

CARNEY: The proper way to compare the spread in Draco's (B-V) giant colors due to observational errors versus due to a metallicity spread is to derive σ's in the same magnitude range, unlike what we did and you showed. When it is done rigorously, as in our poster paper, the metallicity spread seems real.

DA COSTA: If the giant branch width is calculated exactly as outlined in your published paper, then there is no evidence for any intrinsic width. If however, you increase the sample, by going 0.5 mag fainter, calculate relative to a ridge line, etc., I agree you will find that an intrinsic width probably is present. The calculation is however rather sensitive to which outlying stars are included.

CARNEY: Comparing anomalous Cepheids in low density dwarf spheroidal galaxies vs. high density globular clusters is not quite fair. Perhaps one should instead compare to the low density halo field. There is at least one known local field anomalous Cepheid. Does Hugh Harris know of any more?

DA COSTA: I think it must be rather difficult to identify anomalous Cepheids in the galactic halo since you generally lack distance information. Especially for shorter period stars, anomalous Cepheids are not easily distinguished from RR Lyrae stars.

HARRIS, H.: XZ Ceti may be a field anomalous Cepheid, but its distance and luminosity have not yet been determined. Many other field Type II Cepheids could be anomalous, but we have distance estimates for only a few.

INAGAKI: What do you think about Saito's (1980? PASJ) formation picture of dwarf spheroidal galaxies? He considered that dwarf spheroidal galaxies were more massive before (10 to 100 times) and lost mass. So dwarf spheroidal galaxies were nearer to dwarf Es than to globular clusters.

DA COSTA: I think its generally agreed that dwarf spheroidal galaxies have lost a lot mass during their formation; this seems a reasonable way to account for their low density.

WEBBINK: It seems to me that all of the evidence cited in favor of an age spread within individual dwarf spheroidal galaxies might as well be explained by supposing they have some initial population of binaries. Can you give an argument to rebut this hypothesis?

DA COSTA: The strongest evidence in support of an age range is the existence of luminous carbon stars in 5 of 7 galactic dwarf spheroidal galaxies (and 1 M 31 companion). These stars appear indistinguishable from similar stars in intermediate-age Magellanic Cloud clusters.

VAN DEN BERGH: In thinking about dwarf spheroidal galaxies it is, perhaps, a good idea to remark that NGC 147, NGC 185 and NGC 205 probably belong to the same "form family".