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Local Dwarf Spheroidal Galaxies and their Histories

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Abstract. In the first part of this review, an assessment of the possible contribution of disrupted dwarf Spheroidal (dSph) galaxies to the formation the Galactic halo is presented. The discovery of a major difference between the [α/Fe] ratios for red giants in the Draco, Ursa Minor and Sextans dSphs and for field halo stars is highlighted. This difference suggests that the disruption of dSphs similar to those studied did not contribute significantly to the halo. The lack of intermediate-age stars in the halo field also argues against a significant contribution from the disruption of dSph systems similar to Fornax, except at the earliest times. The properties of the M31 dSph companions are then presented and compared with those of the Milky Way. Considerable similarities are found but an apparent real difference exists in the comparative lack of ~1–6 Gyr intermediate-age populations in the M31 systems. In the third part, recent results for dSphs beyond the Local Group are discussed. The contribution then concludes with speculation as to whether any underlying trends can be discerned from these data that might aid in explaining the surprising diversity of star formation histories among these supposedly simple systems.

1. Introduction

Dwarf Spheroidal (dSph) galaxies, which can equally be referred to as low luminosity dwarf Elliptical (dE) galaxies, are probably the most common type of galaxy in the Universe. For example, approximately 60% of the known Local Group population are dSph or dE galaxies, with new examples continuing to be discovered (e.g. Armandroff et al. 1998, 1999). Indeed, galaxies of this type, or objects like them, may have been the building blocks from which most larger galaxies were made. In this contribution I will focus on three aspects of dwarf Spheroidal galaxy research. These are: (i) the extent to which the properties of the current population of dSph companions to the Galaxy do (or don't) support the idea (cf. Morrison, these proceedings) that the Galactic halo is largely made up of stars from disrupted dSphs; (ii) the extent of the similarities (or differences) between the dSph companions to M31 and those to our Galaxy; and, (iii) the properties of dSph galaxies beyond the Local Group. As regards this latter aspect of dSph research, it is the *Hubble Space Telescope* and now large ground-based telescopes that have opened up the study of dSphs beyond the

Local Group. This allows us to investigate the extent to which "environment" influences the evolution of dSph galaxies.

2. The Galaxy's dSph Companions

There have been a large number of recent results concerning the Milky Way's dSph companions based on both HST and ground-based observations. It is not possible to review them all here, so in this section I will concentrate on those results that bear on the question of the extent to which the present Galactic halo has been formed, or significantly modified, through the disruption of dSph-like galaxies.

Obviously, if the Galactic halo was built up from the disruption of many dSph-like galaxies, then the few (9, shortly to be 8 when the disruption of Sagittarius is completed) that remain should most definitely be regarded as "survivors". This may mean that they have "special properties", such as particular orbits, that distinguish them from the mean properties of any now-disrupted large initial population of dSph-like galaxies; we should always keep this possibility in mind.

I will concentrate on recent results in two particular areas, *abundance ratios* and *the age range in the Galactic halo.* As regards the first topic, the natural assumption is that the chemical enrichment processes in the surviving dSphs should have resulted in element abundance ratios that are very similar to those of the field halo. In terms of the second topic, it is worth noting that most of the Galaxy's dSph companions have significant, even dominant, intermediate-age (i.e. age $\lesssim$ 10 Gyr) populations. Consequently, unless the merging/disrupting processes occurred predominantly at early times, the Galactic halo field should contain a notable population of intermediate-age stars.

2.1. Galactic dSph Abundance Ratios

Because of the generally large distances involved, the red giants in the Galactic dSph companions are faint. Thus it is only with the availability of 8-10m class telescopes that high dispersion spectroscopic studies of individual dSph red giants have become possible. The number of such studies, however, remains small and I will concentrate on the recents results of Shetrone et al. (2001). These authors have analyzed Keck+HIRES spectra for 17 dSph red giants: 6 in Draco, 6 in Ursa Minor and 5 in Sextans. It is perhaps worth noting that these three dSphs are all relatively low luminosity, low mean abundance systems that *lack* any sizeable intermediate-age populations. In particular, Ursa Minor has a blue horizontal branch (HB) morphology and is likely to be the same age as metal-poor halo globular clusters such as M92. Draco and Sextans, on the other hand, have red HB morphologies and may be ~2–3 Gyr younger than the majority of halo globular clusters.

The results of the Shetrone et al. (2001) study can be summarized as follows. First, there is a large abundance range in each dSph. This result is not too surprising given that an internal abundance range is one of the established characteristics of dSph galaxies. What is somewhat surprising however, is the size of the abundance ranges, particularly in Draco and Sextans where the total range observed is approximately 1.5 dex in both dSphs, and stars with abun-

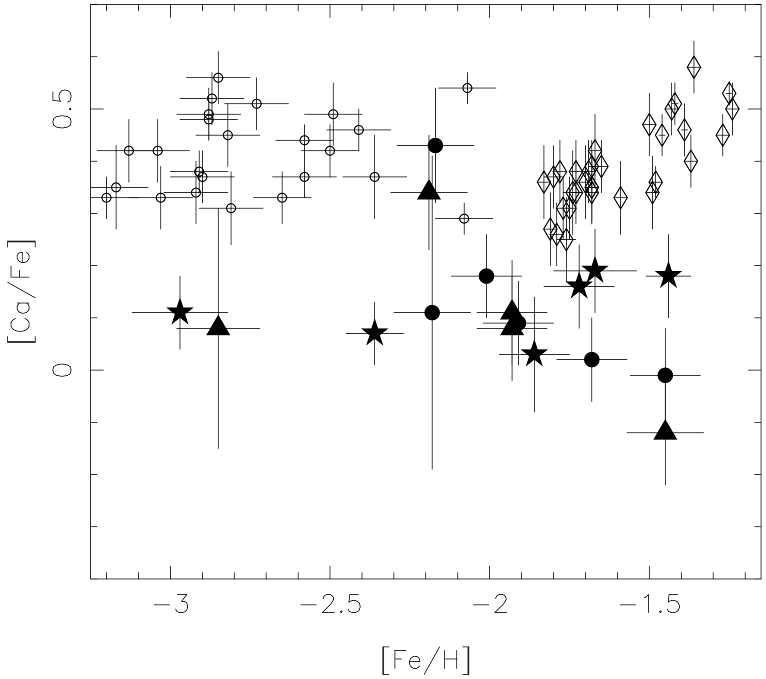

Figure 1. A comparison of [Ca/Fe] ratios for red giants in the dSphs Draco (filled star symbols), Ursa Minor (filled circles) and Sextans (filled triangles), from Shetrone et al. (2001), with [Ca/Fe] ratios for metal-poor field halo stars (open circles), from McWilliam et al. (1995) and ω Cen red giants (open diamonds) from Norris & Da Costa (1995). Note that the majority of the dSph stars have lower [Ca/Fe] values than the halo stars.

dances as low as [Fe/H] ≈ –3.0 are found. Consequently, if Draco and Sextans were disrupted today, some notably metal-poor stars would be added to the halo. This contrasts with the disruption of globular clusters where the lowest abundance stars have [Fe/H] ≈ –2.2 only. Second, the abundance ratio patterns are quite similar from dSph to dSph. This indicates that the nucleosynthetic histories of these dSphs were probably quite similar and in turn, this presumably implies that their initial mass functions were also similar. Third, comparison of element-to-iron abundance ratios in the dSph red giants with those for field halo stars reveals some interesting results. For example, the iron-peak element ratios resemble those of the field halo. In particular, the [Cr/Fe] and [Co/Fe] ratios show the same trend with decreasing [Fe/H] as do the field halo stars (cf. Fig. 5, Shetrone et al. 2001). Similarly, the heavy element ratios are also like those for field halo stars in that they are *r*-process dominated.

The surprise, however, lies in the even-Z or "alpha" elements. These appear to show quite significant differences from the field halo. Halo (field and globular cluster) stars typically have [α/Fe] ≈ +0.3 over the abundance range exhibited by the dSph red giants (cf. Norris, these proceedings). However, Shetrone et al. (2001) find [α/Fe] = 0.09 ± 0.02 for Draco, 0.13 ± 0.04 for Ursa Minor and

0.02 ± 0.07 for Sextans, values that are significantly lower than the halo value. These results are illustrated in Fig. 1 where the Shetrone et al. (2001) results for [Ca/Fe] are shown together with data for other halo stars.

In this context it's perhaps worth recalling that low [α/Fe] values can result from: (a) the failure to retain and to incorporate into the subsequent generation of stars the ejecta of massive star supernovae, or (b) an unusual IMF that results in a comparative lack of massive stars and therefore of Type II supernovae, or (c) a chemical evolution and star formation history that permits Type Ia supernovae to contribute relatively large quantities of the iron-peak elements. As regards the last of these possibilities it's important to remember that none of these three dSphs shows much evidence for having had an extended epoch of star formation; Ursa Minor, in particular, with its blue horizontal branch, looks like a purely old population.

Regardless of the origin of these differences in the [α/Fe] ratios, it is apparent that the dSph stars differ significantly from stars in the general field halo population. This difference has an immediate implication: *if Draco, Ursa Minor and Sextans are typical objects, then the disruption of Draco, Ursa Minor and Sextans-like objects didn't contribute significantly to the Galactic halo field.* While halo stars with low [α/Fe] ratios such as those seen in these dSphs are known (e.g. Norris et al. 2001; Norris, these proceedings) such stars are relatively rare. Consequently, to address this apparent conundrum we urgently require abundance ratio data for red giants in the more luminous dSphs such as Fornax, since these systems may be more typical of the disrupted systems that supposedly made major contributions to the populations of the Galactic halo. Such studies would be interesting in an additional sense, since it should be possible to follow chemical enrichment processes in those dSphs with extended epochs of star-formation. For example, will the metal-poor giants in Fornax show higher [α/Fe] ratios that the more metal-rich, and presumably younger, stars?

2.2. Age Range in the Galactic Halo

In 1996, Unavane, Wyse & Gilmore published a paper in which they drew attention to two salient points. First, that stars bluer than the turnoff of an old metal-poor population are relatively *rare* in the field halo, and second, that stars bluer than the turnoff of an old metal-poor population are relatively *common* in the Galactic dSphs, especially in systems like Leo I, Carina and Fornax. These dSphs have strong intermediate-age (~1–10 Gyr) populations. This disparity naturally limits the number of merger events involving Leo I/Carina/Fornax-like systems that could have occurred within the past 10 Gyr or so. Indeed Unavane et al. (1996) conclude that $\leq$6 Fornax-like dSphs could have been accreted into the halo within the last ~10 Gyr.

Recent results have served only to strengthen the Unavane et al. (1996) conclusions. In particular, new colour-magnitude (c-m) diagrams for Fornax (e.g. Stetson et al. 1998, Saviane et al. 2000) and Leo I (e.g. Gallart et al. 1999) emphasise how frequent stars bluer than an old main sequence turnoff are in these dSphs. Perhaps more significant though, are new results that suggest the number of intermediate-age field halo stars may be considerably less than previously assumed.

The class of objects referred to as "Blue Metal-Poor", or BMP stars, have [Fe/H] $\leq$ –1, main sequence gravities, $0.15 \leq (B-V)_0 \leq 0.35$ (i.e. bluer than an old metal-poor main sequence turnoff) and kinematics intermediate between the halo and the thick disk (Preston et al. 1994, and references therein). The conventional interpretation of these stars has been that they are metal-poor intermediate-age stars accreted from dwarf spheroidal satellites of the Milky Way within the past 10 Gyr. However, recent work by Preston & Sneden (2000) has seriously questioned this interpretation. Based on a study of 62 BMP stars over 7 years, they found a high fraction of binaries in the sample ($f_{BMP} \approx 0.6$). They went on to suggest that the vast majority of the BMP stars are actually blue stragglers, formed by mass transfer in binary stars, and not intermediate-age main sequence stars. Carney et al. (2001, see also these proceedings) reached similar conclusions. Consequently, these results require a major downward revision (by a factor of ~5) of the fraction of BMP stars that might be accreted intermediate-age main sequence stars from disrupted dSphs. Indeed, it is possible that all BMP stars are (old) blue stragglers.

An alternative approach to this question is that adopted by Hernandez et al. (2000), who investigated the (luminosity-weighted) combined star formation history for the dSphs Leo I, Carina, Leo II and Ursa Minor. This combined star formation history predicts that the halo should contain a sizeable number of intermediate-age blue metal-poor stars, if dSphs like these had been merged into the halo relatively recently.

Taken together, these new data strengthen the Unavane et al. (1996) conclusions that in the past 10 Gyr or so, there have not been more than a few, at most, mergers into the Galactic halo of substantial (i.e. Fornax-like) dSphs that possess substantial intermediate-age populations. Of course, any number of dSphs that lack intermediate-age populations could have merged into the halo over this time. Such systems, however, are not common, at least among the current "surviving" dSphs.

3. The dSph Companions of M31

For many years M31 was thought to have only three dSph companions in addition to the dE companions NGC 147, NGC 185, NGC 205 and M32. The dSph companions, known as And I, II and III, were discovered by van den Bergh in the early 1970s from visual searches of Palomar Schmidt plates (van den Bergh 1972, 1974). Recent work, however, has revealed the existence of three more dSph companions, known as And V, VI (Pegasus) and And VII (Cas). The first two were found by automated search techniques applied to digital sky survey images (Armandroff et al. 1998, 1999), while the third was found via visual searching of the second generation sky survey plates (Karachentsev & Karachentseva 1999). In most respects, the M31 dSphs appear to be similar to the Milky Way's companions. In particular, using $\langle$[Fe/H]$\rangle$ values from mean giant branch colours, the M31 dSph systems generally follow the same $\langle$[Fe/H]$\rangle$, M_V relations as the Milky Way dSphs. Similarly, the M31 dSphs exhibit the same range of flattenings, sizes and surface brightness as the Galaxy's companions. They also show a similar range of galactocentric distances.

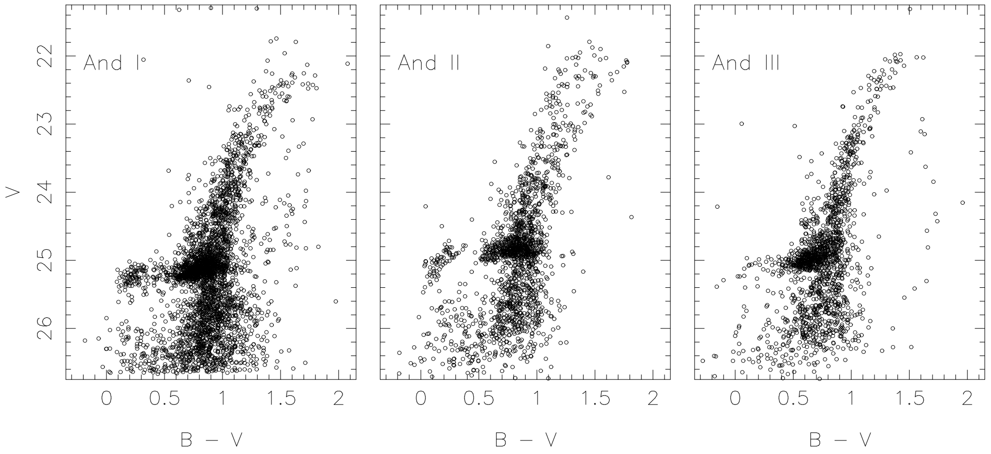

Figure 2. Color-magnitude diagrams for the M31 dSph companions And I, II and III based on the HST/WFPC2 data of Da Costa et al. (2000, 2002).

These similarities also extend to horizontal branch (HB) morphologies, which can be studied in the M31 companions with HST/WFPC2: eight of nine Galactic dSph companions have red HBs, as do all four of the M31 systems studied so far. This is illustrated in Fig. 2, which shows HST/WFPC2-based c-m diagrams for And I, II and III (Da Costa et al. 2000, 2002). As for the Galaxy's companions, the most likely explanation of the red HB morphologies is that the bulk of the stars in the M31 dSphs are somewhat younger than the age of the majority of the Galactic halo globular clusters.

The HST/WFPC2 studies of the red giant branches in the M31 dSphs have sufficient internal precision that the intrinsic internal abundance spreads can be inferred. Perhaps the most surprising result in this area has been the discovery of significant differences between And I and And II. Both dSphs have similar luminosities and similar mean abundances, so that they lie at similar locations in the $\langle[\mathrm{Fe/H}]\rangle$, M_V relation. However, as is apparent in Fig. 2, the intrinsic giant branch width, and by inference the intrinsic internal abundance dispersion, is considerably larger in And II than it is in And I (Da Costa et al. 2000). Evidently, the two dSphs have had quite different enrichment histories, yet the mean abundances have in each case come out at the 'right' value. Clearly there are multiple routes to the same endpoint.

There does exist, however, one major difference between the Galactic dSphs and the M31 dSph companions. Based on existing observational material (which is admittedly in need of enhancement), it appears that none of the M31 dSph companions show any significant indications of strong intermediate-age populations like those seen in some of the Galactic dSphs. For Galactic dSphs such as Fornax, Carina and Leo I, c-m diagrams that reach below the main sequence turnoff have revealed significant populations of stars as young as ~1–3 Gyr. The existence of the intermediate-age populations was first revealed by the presence of upper-AGB (carbon) stars in these dSphs. Such stars, which are also found in the intermediate-age clusters of the Magellanic Clouds, are a characteristic signature of the presence of an intermediate-age population: old (age $\gtrsim$ 10 Gyr) stars have insufficient mass to evolve to luminosities on the AGB significantly above that of the red giant branch tip. In Fornax, Carina and Leo I, the upper-AGB carbon stars reach luminosities as bright as $M_{bol} \approx -5.5$, consistent with the relatively young intermediate-age populations. However, among the M31 dSphs, upper-AGB stars have been positively identified only in And II. Even in this case, the luminosities of the upper-AGB stars are comparatively faint, $M_{bol} \approx -4.1$ (Da Costa et al. 2000), suggesting an age of only ~6–9 Gyr. This difference in the "strength of intermediate-age populations" between the Galactic and M31 dSph companions suggests a role for environmental influences in the evolution of these galaxies.

Returning to the question of the disruption of dSph satellites and their possible contribution to the make-up of galactic halos, it is interesting to note that Ibata et al. (2001) have recently reported the discovery of what is apparently a large tidal stream in the halo of M31. The metallicity of this feature, determined from the red giant branch colours, is surprisingly high – somewhat higher than that of the Galactic globular cluster 47 Tuc ([Fe/H] = –0.7). This abundance, together with the (mean abundance, luminosity) relation followed by dSphs and dEs, then suggests that this stream must have come from the disruption of a relatively luminous (and therefore massive) dwarf. Ibata et al. (2001) mention both NGC 205 and M32 in this context, noting that both have mean abundances consistent with that for the stream. Moreover, the outer isophotes of NGC 205 are clearly distorted, presumably as the result of a tidal interaction with M31, and M32 has long been regarded as "tidally truncated" object. Indeed, Bekki et al. (2001) have recently suggested that M32 is the remnant bulge of a low luminosity spiral that has been "shredded and threshed" by M31's tidal field. It is of course also possible that the system responsible for the stream has been completely disrupted. Intriguingly, the M31 dSph And I also lies in the general vicinity of the Ibata et al. (2001) stream. The large difference in mean abundance between that of And I ([Fe/H] ≈ –1.5) and that of the stream ([Fe/H] ≈ –0.6), however, argues against any direct connection. Nevertheless, regardless of the origin of this stream, it does appear to be an M31 halo analogue to the tidal disruption of the Sagittarius dSph in the halo of our own galaxy.

4. dSph Galaxies Beyond the Local Group

Dwarf Spheroidal galaxies are ubiquitous – they are found in all environments from loose groups through to galaxy clusters such as Virgo. With facilities such as HST/WFPC2 and the new generation of large aperture telescopes, we can begin to investigate the stellar populations of dSphs that lie beyond the Local Group by directly resolving and measuring the magnitudes and colours of the brighter red giants in these galaxies. This allows us to gain additional insight into the possible role of environment in governing the evolution of these systems. In this section I will briefly describe recent results for the stellar populations of dSphs in two nearby groups, the M81 group and the Sculptor group.

The *M81 group* is relatively compact (at least compared to the Local Group) and contains more than a dozen dSphs. This group has a clear history of interactions between its members (e.g. Yun et al. 1994), and so it has provided a

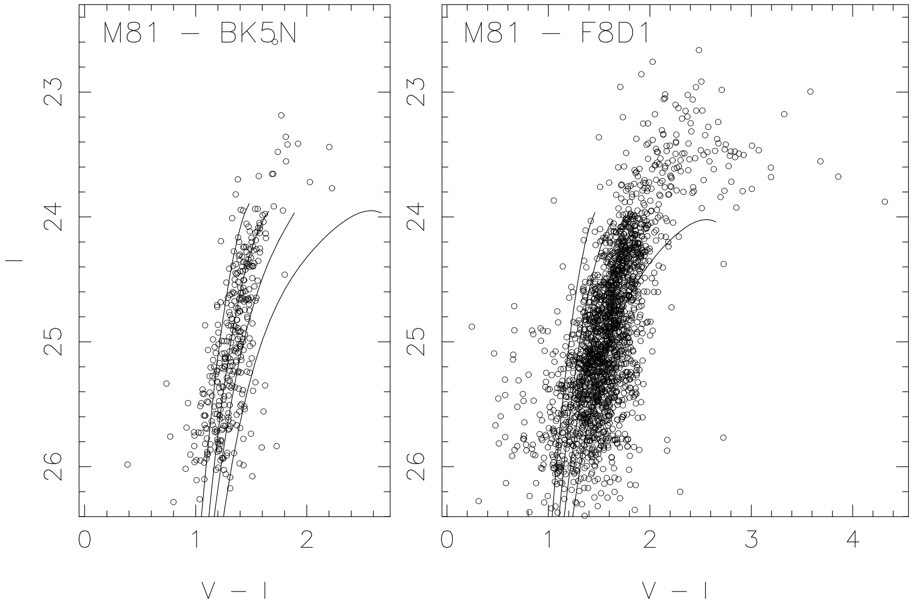

Figure 3. Color-magnitude diagrams for the M81 group dSphs BK 5N and F8D1 based on the HST/WFPC2 data of Caldwell et al. (1998). The solid lines are the giant branches for standard Galactic globular clusters.

notably different environment for its dSph members. Further, given the compact nature, it is not straightforward to describe any of the dSphs as satellites of the larger group galaxies, such as M81. The *Sculptor group* on the other hand, is a loose, low-density aggregation of galaxies strung-out along the line-of-sight. Consequently, without relatively precise distance information, it is once again not possible to classify any of the group-member dSphs as satellites of the larger group galaxies.

The first HST/WFPC2 study of M81 group dSphs was that of Caldwell et al. (1998) who studied two dSphs in detail: F8D1, a large low surface brightness dSph with $M_V \approx -14$, and BK 5N, a Milky Way dSph analogue with $M_V \approx -11.3$. The multi-orbit HST/WFPC2 data enabled Caldwell et al. to construct relatively precise c-m diagrams that revealed the first few magnitudes of the red giant branch. Both galaxies have mean abundances, derived from the mean colours of the red giant branches, that are consistent with the $\langle[\mathrm{Fe/H}]\rangle$, M_V relation defined by the Local Group dSphs. As is evident in Fig. 3, both dSphs also have obvious intermediate-age populations revealed by the presence of significant numbers of upper-AGB stars. Indeed, Caldwell et al. (1998) suggest that F8D1 contains stars as young as 3–4 Gyr, while in BK 5N stars as young as ∼8 Gyr are present. Neither c-m diagram, however, shows any evidence for blue (young) stars.

Other HST/WFPC2 studies of M81 group dSphs come from the "snapshot" survey of potential nearby galaxies. With only 600 sec *V* and *I* exposures, the quality of the resulting c-m diagrams are much lower than those of Caldwell et al. (1998). Nevertheless, it is possible to confirm, from the magnitude of the red giant branch tip, that the dSphs are M81 group members. It is also possible to determine, at least qualitatively, the existence of any intermediate-age population from the number and luminosity of any upper-AGB stars present. Karachentsev et al. (2000a, 2001) have presented c-m diagrams, based on snapshot survey observations, for 8 M81 group dSphs. Using the c-m diagrams of F8D1 and BK 5N as a guide, it is then possible to make a qualitative assessment of the upper-AGB populations of these dSphs: two have strong upper-AGB populations (like F8D1), four have modest upper-AGB populations (like BK 5N) and two lack, or have weak, upper-AGB populations. None of these dSphs have been detected in HI (see Karachentsev et al. 2000a, 2002), although the complex and extensive distribution of HI in the M81 group (see Yun et al. 1994) makes it difficult to be certain. Interestingly, the otherwise apparently unremarkable dSph Kar 61 contains a small HII region (Johnson et al. 1997), and the small number of blue stars in the Karachentsev c-m diagram for this dwarf lie, not surprisingly, in the vicinity of the HII region.

As regards the Sculptor group, two dSphs are have been studied – one with HST/WFPC2 as part of the snapshot survey (Karachentsev et al. 2000b) and the other using observations obtained from the ground with the VLT and the FORS1 imager (Jerjen & Rejkuba 2001). If the qualitative upper-AGB content classification used for the M81 group dSphs is also applied to these dwarfs, then one is "modest" and one is "weak-none". However, it is intriguing that both dSphs show evidence for the presence of younger populations – the c-m diagrams reveal populations of blue stars that have ages of perhaps 100 to 150 Myr. In this respect these Sculptor group systems resemble the Local Group dwarfs Phoenix and LGS 3, both of which also contain populations of younger stars (e.g. Holtzman et al. 2000, Miller et al. 2001).

5. Nature or Nurture?

Given this set of observations, it's of interest to inquire whether any general inferences can be made regarding the respective roles of environment (nurture) and intrinsic properties (nature) in governing the evolution of dSph galaxies. The situation can be summarized as follows. In the relatively compact M81 group, of 10 dSphs studied (qualitatively) three show strong upper-AGB populations, five have modest populations and two have weak or none. One object has a weak population of younger/blue stars with ages $\lesssim$ 500 Myr. The Milky Way subgroup of the Local Group has three of eight (the relative frequency of upper-AGB stars in Sagittarius is difficult to establish) dSphs with strong upper-AGB populations, two with modest populations and three with weak or none. One system, Fornax, has a weak population of younger/blue stars (e.g. Stetson et al. 1998). We should also not overlook the Phoenix dwarf, which is a distant companion of the Milky Way with an identifiable population of younger stars (e.g. Holtzman et al. 2000). For the M31 subgroup, of six dSphs none have a strong population of upper-AGB stars, one has a modest population and the others all have weak or none. Further, none of these systems shows any population of younger/blue stars. On the other hand, LGS 3 is a distant M31 companion and, like Phoenix, it does have a distinct population of younger stars. The Local Group also contains the

Tucana system, which can be classified as "weak or none" as regards upper-AGB populations. Finally, we have two dSphs in the Sculptor group, one with a modest upper-AGB population and one with weak or none, but with both possessing younger/blue stars in their c-m diagrams. Both these dSphs are relatively isolated.

Can any conclusions be drawn from this, other than the general comment that "environment probably does play a role and it's a complex one"? Perhaps. The M31 dSph companions certainly seem to have lost their gas earlier than the other systems – perhaps this is the influence of a "big bulge" parent where strong supernova driven winds and/or a high uv-flux and/or ram pressure stripping in a relatively dense halo led to the relatively early and complete removal of any dSph gas remaining after the initial epoch of star formation. The M81 dSphs and the Milky Way's would then form the next class – these dSphs are constantly "harrassed" with the degree of harrassment depending on the actual orbit of the dSph. This interpretation is much along the lines of the recent work of Mayer et al. (2001), who showed that model dIrr galaxies can be converted into dSphs under the influence of the Milky Way's halo, with the gas both being lost and consumed in episodes of star formation. Finally, in the less dense environment of the Sculptor Group, the dSphs evolve in a more independent manner giving rise to a more constant star formation rate analgous to the situation for the distant companions Phoenix and LGS 3.

However, while all this sounds plausible, it is very difficult to see how Tucana fits into such a scenario. Tucana is an isolated Local Group dSph whose c-m diagrams (e.g. Da Costa 1998; Saviane et al. 1996) show very little evidence for star formation beyond that of the initial episode. Even the horizontal branch morphology of Tucana is relatively blue – the bluest of those known among dSphs with the exception of Ursa Minor. If Tucana has always lived an un-harrassed life, then it should at least resemble systems like Phoenix or LGS 3 or the Sculptor group dSphs. Indeed, it ought to be a dIrr like the other comparatively isolated dwarf galaxies in the Local Group. However, this is evidently not the case and so we must conclude that we are still some way from understanding what drives the evolution of these supposedly simple systems.

Acknowledgments. I'd like to place on record my indebtness to Ken for his mentorship over the years. Indeed, it was his advice to include "something other than more of your thesis" in research proposals for my first job applications that initiated my interest in dwarf Spheroidal galaxies.

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Discussion

Quinn: There are very strong dynamical selection effects that act on satellites with respect to their binding energies, orbital sense and orbital inclination. This introduces strong selection effects into the current surviving satellite population with respect to the already dissolved satellites in the stellar halo.

Da Costa: I agree, but I don't see how this could readily generate surviving-satellite to dissolved-satellite abundance ratio differences.

Carney: In my opinion, dynamical and chemical data favor a merger origin for the moderate metallicity (and very old) thick disk. Its mass is a siginificant fraction of the stellar halo, so it should (possibly) be added to the summary of merger events.

Da Costa: Again I agree, but the current "hot topic" is the possiblity of star streams in the halo, not the origin of the thick disk.

Morrison: The Unavane et al. constraints on the percentage of intermediate-age populations in the halo is a LOCAL measure; we need some good deep halo colour-magnitude diagrams to make a similar measurement in the outer halo.

Carney, to Morrison: That is not necessarily correct: we have studied local stars whose orbits take them into the outer halo.

Harding, to Carney: But if the halo is not well mixed, then we may not be able to take the solar neighbourhood as representative. Further, Helmi et al. (1999, Nature, 402, 53) argue that ~10% of the local halo comes from a single disrupted structure.