The Dwarf Spheroidal Galaxies in the Galactic Halo

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Abstract. In the first part of this contribution the observed velocity dispersions in Galactic halo dwarf spheroidal (dSph) galaxies are reviewed, and the consequences for dark matter content outlined. The results are suggestive of a dSph dark matter mass of $\sim 2 \times 10^7$ solar masses, independent of the luminosity of the dSph. Alternatives to the dark matter interpretation are also briefly discussed. In the second part of the contribution the emphasis is on the stellar populations of Galactic dSphs. Recent results for the ages of the oldest populations are presented. These data, together with similar recent results for Galactic halo and LMC globular clusters, indicate that regardless of the subsequent star formation history, the initial epoch of star formation was well synchronized throughout the entire proto-Galactic halo. The implications of the first high dispersion studies of element abundance ratios in Galactic dSph red giants are also discussed. For the Sagittarius dSph in particular, the observed abundance ratios show good agreement with expectations for an episodic star formation history, and such a history is in fact deduced from colour-magnitude diagram studies.

1. Introduction

At the present time, the Galaxy has nine identified dwarf spheroidal (dSph) galaxy companions: Sculptor, Fornax, Draco, Ursa Minor, Leo I, Leo II, Carina, Sextans and Sagittarius. These systems appear to be typical members of the dSph/dE class of low luminosity, small, low surface brightness galaxies. The wording “at the present time” is deliberately chosen because it is unclear whether the current population of Galactic dSph companions represents most, or only a small fraction, of the dSphs that existed in the halo at early times in the life of the Galaxy. For example, the Sgr dSph is currently undergoing a significant interaction with the Milky Way and, within the next billion years or so, it probably will no longer be recognizable as a distinct object, having merged into the Galactic halo. Thus, as other contributions in this volume will emphasize, the disruption of dSph galaxies might have contributed significantly to the make-up of the Galactic halo (see also Mateo 1996). In this review, however, I will concentrate on the properties of the current Galactic halo dSphs. Indeed, these galaxies are particularly relevant to the conference theme of “Bright Stars & Dark Matter”, since they are the only Galactic halo systems where both stars and dark matter are found together in bound systems.
In the first part of this contribution, then, the observed velocity dispersions of the Galactic dSphs and the implications for dark matter contents will be considered. This is followed in the second part by a discussion of some new results derived from characteristics of dSph stars.

2. Galactic Dwarf Spheroidal Velocity Dispersions

In 1983 the late Marc Aaronson published a paper (Aaronson 1983) that revolutionized our concept of the masses and dynamics of dSph galaxies. His paper indicated that the velocity dispersion of the Draco dSph, albeit based on only 5 observations of 4 stars, was at least $\sim 6.5 \text{ kms}^{-1}$ and that, as a consequence, the mass-to-light ratio of this dSph exceeded that of globular clusters by at least an order of magnitude. Since the stellar population of Draco is apparently similar to those of Galactic globular clusters, Aaronson’s result implied the existence of a substantial amount of dark matter in this dSph. Since the publication of that paper there have been a number of similar studies of Draco and of the other Galactic dSphs, with increasingly large samples of stars. Yet the basic result has remained the same. Indeed, with the publication of results for Leo I (Mateo et al. 1998), we can now say that all the Galactic dSphs appear to contain significant amounts of dark matter – see Mateo (1997) and Olszewski (1998) for recent reviews of this subject.

In this section the recent work on Leo I (Mateo et al. 1998) is first considered. Other than the large Galactocentric distance, which makes the target stars relatively faint (and therefore required use of the Keck telescope for the observations), the Mateo et al. (1998) study of the velocity dispersion of Leo I is typical of existing Galactic dSph velocity dispersion studies. It therefore provides an example with which to highlight the steps (and the potential pitfalls) in the process by which observations of individual radial velocities are transformed into a dSph mass-to-light ratio estimate. The dark matter content implications of these results, and those for other Galactic dSphs, are then presented. The section concludes with a brief discussion of an alternative interpretation of the large observed velocity dispersions – that the dSphs are undergoing tidal disruption and are thus not in virial equilibrium.

2.1. Leo I – A Case Study

The sample of Leo I stars observed by Mateo et al. (1998) consists of 33 red giants selected from a colour-magnitude study. These stars were observed at high dispersion ($R \approx 34,000$) but the resultant spectra have relatively low S/N ratio. Velocities are obtained by cross-correlating the spectra with high S/N spectra of radial velocity standards. The high systemic velocity of Leo I, $\sim 290 \text{ kms}^{-1}$, assures us of Leo I membership for all the candidates observed, though for some other Galactic dSphs this member/non-member discrimination is not as clear cut. A total of 40 individual measurements were made with the typical velocity error being $\sim 2.2 \text{ kms}^{-1}$ (the actual errors range from 1.4 to 4.8 kms$^{-1}$ depending on the S/N ratio of the spectrum). Then, based on a number of different techniques (e.g. weighted standard deviation, bi-weight estimator, maximum likelyhood), all of which produce similar values, the observed velocity dispersion for this sample of Leo I stars is $\sigma_{\text{obs}} = 8.8 \pm 1.3 \text{ kms}^{-1}$. Note that
the error associated with this dispersion comes principally from the “sampling error” arising from the finite size of the observed sample, and that the value applies to the core of Leo I, since all but one of the stars observed have (in projection at least) radial distances less than the core radius. Further, within this limited radial range, there is no indication of any change in \( \sigma_{\text{obs}} \) with location, nor is there any evidence for systematic rotation of Leo I, at least in the core region. These latter results are also commonly found for other Galactic dSph systems.

Mateo et al. (1998) then apply what is now standard formalism to calculate from the observed dispersion a central mass-to-light ratio \( (\rho_0/I_0, V) \), using the observed central surface brightness of Leo I, and a total mass-to-light ratio \( (M/L_{\text{total}, V}) \) from the total integrated magnitude of the dSph. Both these calculations require a length scale; the core radius derived from the observed surface brightness (or surface density) profile is usually used. These structural parameters are now (at least moderately) well known for all Galactic dSphs, though they are, of course, based on the stellar distribution which may not reflect the underlying mass distribution. The scale factors required in these calculations are usually taken as those for the King (1966) model which best fits the surface brightness/density profile. These models are appropriate for spherically symmetric systems with isotropic velocity distributions whereas the Galactic dSphs have significant flattening yet lack systematic rotation; consequently, they presumably have anisotropic velocity distributions. The use of King model parameters, however, is not regarded as crucial (e.g. Merritt 1988); much more fundamental (e.g. Pyror & Kormendy 1990, Pyror 1994) is the implicit assumption here that “mass follows light”, an assumption for which there is little justification at present.

Applying this formalism, Mateo et al. (1998) find \( \rho_0/I_0, V = 3.5 \pm 1.4 \) and \( M/L_{\text{total}, V} = 5.6 \pm 2.1 \) indicating that \( M/L_V \) for Leo I could lie anywhere between \(~2\) and \(~8\) in solar units. How then are we to interpret these values? Mateo et al. (1998) point out that data for low central concentration globular clusters (e.g. Pryor & Meylan 1993), which are the ones for which mass segregation effects should be minor, yield \( <(M/L_V)> = 1.5 \pm 0.1 \) when analyzed in the same way as the Leo I observations. At first sight a direct comparison of this mean value with the derived \( M/L \) values for Leo I doesn’t convincingly argue for the presence of a significant dark matter content in the dSph. However, we must keep in mind that the stellar population of Leo I is not that of a globular cluster (as is the case for many of the Galactic dSphs). In fact, Lee et al. (1993) have shown that the stellar population of Leo I is dominated by stars of intermediate-age (i.e. ages \(~2\) – \(~10\) Gyr) so that the “mean age” of Leo I is considerably younger than that of the globular clusters. Mateo et al. (1998) have constructed simple stellar population models to correct for this effect and have calculated that for a valid comparison with the Galactic globular clusters, the observed Leo I \( M/L_V \) value should be increased by a factor of approximately two. In other words, after compensating for stellar population differences, we have \( (M/L_V)_{\text{LeoI}} \approx 9 \) and \( (M/L_V)_{\text{glob cl}} \approx 1.5 \) – a clear indication that there is a significant dark matter component in Leo I.

One might question the strength of this conclusion on the basis that the Mateo et al. (1998) data, like the situation for many of the Galactic dSphs, are
essentially single epoch observations and that as a result, the presence of binary stars might have inflated the observed dispersion and caused the M/L ratio to be overestimated. The extensive work of Olszewski et al. (1996), however, has shown that this is not a valid objection. These authors have extensive repeat observations, extending over many years, of a large number of stars in the Galactic dSphs Draco and Ursa Minor. Indeed, despite the fact that the minimum possible binary period, given the radii of the red giants observed in these programs, is approximately six months, Olszewski et al. (1996) have sufficient data to investigate the binary frequency in these dSphs. Among the stars observed, they find six likely binaries, four in Ursa Minor and two in Draco. Then, via an exhaustive set of simulations, Olszewski et al. (1996) convert this observed binary frequency among red giants into an estimate of the overall binary star frequency in the dSphs. Surprisingly, they find that the binary frequency in Draco and Ursa Minor might be as much as three times higher than it is in Population I samples, and as much as five times higher than is the case for field Galactic halo samples. Discussion of this intriguing result is beyond the scope of this contribution. Nevertheless, the extensive simulations of Olszewski et al. (1996) show that even with such a high binary frequency, the effect of undetected binaries on the velocity dispersion determined from datasets similar to that of Mateo et al. (1998) for Leo I, is small and cannot be used as an explanation for the high mass-to-light ratio.

2.2. The Dark Matter Interpretation

The observed mass-to-light ratios for the Galactic dSph galaxies range from values in excess of 50 for the low luminosity systems Draco and Ursa Minor (e.g. Armandroff et al. 1995) to values of order 5 for the more luminous systems (e.g. Mateo 1998 and the references therein). As noted above, the star formation histories of the Galactic dSphs vary considerably from system to system and a proper comparison of M/L values must then take this into account. We follow the procedures of Mateo et al. (1998) and reduce the observed M/L values (taken from Mateo 1998) to those which would be expected if the dSphs were composed only of stars similar to those in globular clusters. The results of this process are shown in Fig. 1. As has been noted many times in the past (using uncorrected values), Fig. 1 reveals a general correlation with the least luminous systems showing the highest M/L values. The dashed curve in Fig. 1 is the relation (cf. Mateo et al. 1998) expected if the luminous stars in each dSph are embedded in a dark matter halo of constant mass, independent of the luminosity of the dSph. That is, the line is derived from the relation:

\[ (M/L)_{\text{total}, V, \text{corr}} = (M/L)_{V, \text{stars}} + M(\text{Dark Matter})/L_{\text{stars}, V, \text{corr}} \]

where, since we have corrected to a globular cluster like population, \((M/L)_{V, \text{stars}} = 1.5\) in solar units. For the curve shown in Fig. 1, \(M(\text{Dark Matter}) = 2 \times 10^7\) solar masses.

\(^1\)The Sgr dSph is excluded from the discussion here as the extent to which its obvious interaction with the Milky Way compromises the interpretation of the observed velocity dispersion measurements is unclear (but see also Ibata et al. 1997).
Figure 1. A plot of the logarithm of the total (as distinct from cen-
tral) visual mass-to-light ratio against absolute visual magnitude for
the Galactic dSphs. Both the M/L and M_V values, taken from Mateo
(1998), have been corrected for the stellar population differences be-
tween the dSphs, as outlined by Mateo et al. (1998). The Leo dSphs,
which have Galactocentric distances beyond 200 kpc, are plo-
ted as star-symbols, while the Sgr dSph, which appears to be strongly
perturbed by its interaction with the Milky Way, is plotted as an open
symbol. The dashed line is the relation M/L = 1.5 + M_{DM}/L with
M_{DM} = 2 \times 10^7 solar masses.

The constant dark matter mass line gives a reasonable representa-
tion of the Galactic dSph points in Fig. 1, but we should not take this concordance
too seriously. Recall that the mass estimates use scale factors from spherically
symmetric isotropic King (1966) models, which are unlikely to be appropriate
for real (flattened, anisotropic) dSphs. More significantly, the mass estimates
are based on the assumption that “mass follows light”. This latter assumption
can be investigated (e.g. Pyror 1994) if radial velocities are determined for large
samples (≥100 stars) of dSph stars in regions that extend well beyond the core
radius of the visible population. From such samples the observed velocity dis-
ersion profile can be constructed and compared to the predictions of models
which either retain or relax the “mass follows light” assumption. Such datasets
are just now becoming available. In all cases the observed velocity dispersion
profiles are flatter than the predictions based on the King model that best fits
the observed surface density profile (e.g. Fig. 1 of Mateo 1997), indicating a mass
distribution more extended than the light. This is an area where we can expect
to see interesting new developments in the near future, but it seems unlikely
that the new models and new data will remove the requirement for a significant
dark matter content in the Galactic dSph galaxies.

2.3. Alternatives to the Dark Matter Interpretation?
The oft-discussed alternative to the “significant dark matter content” inter-
pretation for the large observed velocity dispersions in Galactic dSphs is that the
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dSphs are, in fact, tidally disrupted remnants that are not in virial equilibrium (e.g. Kroupa 1997 and references therein). Consequently, the observed velocity dispersions cannot be true reflections of the actual dSph masses. There is insufficient space here to discuss this alternative view in detail. However, when considering its validity, at least two points should be kept in mind. First, the Galactic dSphs exhibit correlations between quantities such as luminosity, surface brightness, length scale and mean metal abundance. While Kroupa (1997) indicates how a surface brightness – absolute magnitude correlation might be expected among a set of tidally disrupted remnants, the corresponding absolute magnitude – mean abundance and surface brightness – mean abundance correlations among the Galactic dSphs have no explanation in this scenario. These correlations, which cover a luminosity range greater than a factor of 100, are also followed by the dSph companions to M31, by the isolated Local Group dSph Tucana, and even by dSphs beyond the Local Group (see, for example, Fig. 18 of Caldwell et al. 1998). The similarity of these relationships in different environments then argues rather strongly against the interpretation of the Galactic dSphs as nothing but a set of tidally disrupted remnants.

Second, the Galactic dSphs Leo I and Leo II have Galactocentric distances that exceed 200 kpc. Thus neither of these dSphs are subject to Galactic tides to anything like the same extent as the inner dSphs (R ≈ 65 – 90 kpc, excluding Sgr). Yet neither Leo I nor Leo II lies in a distinctly different location, relative to the other Galactic dSphs, in Fig. 1, for example. Further, both Leo systems have M/L values that imply the presence of dark matter. This lack of separation between the “near” and “far” Galactic dSphs is then a further argument against the tidally disrupted remnants interpretation for the Galactic dSphs.

Nevertheless, if the tidally disrupted scenario doesn’t apply to all Galactic dSphs, we can at least ask if there are any particular cases (other than the Sgr dSph, which is clearly being strongly affected by Galactic tides) where such a scenario might apply. The signatures of such a situation might well include large scale streaming motions, sub-structure and “extra-tidal” stars as well as appreciable line-of-sight depth. Given these potential signatures it is then interesting to consider recent results for the Galactic dSph Ursa Minor. This dSph is one of the closest of the Galaxy’s dSph companions and it has one of the largest apparent M/L values (M/L = 77 ± 13, Armandroff et al. 1995). With an ellipticity e = 0.55, Ursa Minor is also the flattest of the Galactic dSph companions.

The results of interest are as follows:

1. Kleyna et al. (1998) have used deep wide-field CCD imaging to confirm and establish the statistical significance of an asymmetry in the stellar distribution along the major axis of Ursa Minor. In a dynamically stable system such asymmetries should be erased on timescales that are of order at most a few crossing times, or ≤10⁹ years in Ursa Minor.

2. Kroupa (1997) has generated a tidally disrupted model for Ursa Minor in which he suggests that the true major axis of the dSph lies at a significant angle to the plane of the sky. This generates a line-of-sight depth which, for a core

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2Tidal disruption models, e.g. Piatek & Pryor (1995) and Oh et al. (1995), show that this process produces large scale ordered motions rather than large random motions.
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radius of $\sim 200$ pc, Kleyna et al. (1998) estimate as $\sim 0.04$ mag in size. These authors then searched for this effect by calculating the mean apparent magnitude of samples of horizontal branch stars along the major axis. They find that $\langle V \rangle_{SW} - \langle V \rangle_{NE} = 0.025 \pm 0.021$ mag and $\langle I \rangle_{SW} - \langle I \rangle_{NE} = 0.036 \pm 0.035$ mag, which is suggestive of the postulated effect but far from a convincing demonstration.

(3) Both Hargreaves et al. (1994) and Armandroff et al. (1995) have reported a velocity gradient approximately along the minor axis in Ursa Minor. Tidal disruption models generally have streaming motions that are revealed as apparent major-axis rotation, but, given the fact that of all the dSphs so far investigated, Ursa Minor is the only one to show any rotation signature (whether about the major or minor axis), it is not unreasonable to suggest that this observed motion is the consequence of a tidal effect. The size of these ordered motions ($\sim 3$ kms$^{-1}$ per 100 pc in projection), however, is considerably smaller than the observed dispersion ($\sim 9$ kms$^{-1}$). Thus it is unlikely that the observed M/L for Ursa Minor is significantly overestimated.

Then, given that Ursa Minor is seemingly the best object for which a tidal disruption model might be viable, yet such a model is not compellingly required, it seems reasonable to conclude that the Galactic dSph galaxies do indeed contain significant amounts of dark matter.

3. Galactic Dwarf Spheroidal Stellar Populations

One of the most interesting developments in the study of dSph galaxies in recent years has been the recognition that the star formation histories vary significantly from dSph to dSph (see, for example, the recent reviews of Da Costa 1997a, 1998, Mateo 1998, and the references therein). However, rather than consider the latest results on their evolutionary history (e.g. Stetson et al. 1998) two issues relevant to the conference theme will be considered. The first is the age of the oldest stars in the Galactic dSph companions as compared to the age of the oldest stars in other Galactic halo objects. The second is a discussion of how element abundance ratios in dSph red giants, recently determined for the first time, compare with similar data for field halo stars.

3.1. The Age of the Oldest Populations

All of the Galactic dSphs are known to contain RR Lyrae variable stars. Since such variables are also found in Galactic halo globular clusters, the occurrence of RR Lyraes in dSph galaxies has conventionally been taken as evidence for the presence of a stellar population in each dSph that has an age comparable to those of the Galactic globular clusters. The relative size of this old population varies from dSph to dSph, as does the subsequent star formation history. Nevertheless, the presence of this old population has led to the qualitative statement that star formation commenced in the Galactic halo dSph galaxies at an epoch similar to that for the formation of the Galactic halo globular clusters, regardless of the dSph’s location in the proto-Galactic halo. However, if we are to increase our understanding of the processes that occurred during the earliest stages of the evolution of the Galaxy’s halo, we need quantitative results. In particular, we seek a quantitative answer to the question “How similar in age are the “first
The advent of the WFPC2 camera onboard the Hubble Space Telescope has made attempting to answer this question feasible, and a number of relevant studies have recently appeared. For example, Grillmair et al. (1998) have used HST/WFPC2 observations of a field near the centre of the Draco dSph to produce a colour-magnitude (c-m) diagram that reaches well below the main sequence turnoff in this dSph. They then use these data to suggest that Draco is $1.6 \pm 2.5$ Gyr older than the metal-poor halo globular clusters M68 and M92. This result contrasts with previous expectations, based on Draco’s relatively red horizontal branch morphology, that this dSph would prove to be somewhat younger than Galactic halo globular clusters of comparable metallicity. It should be kept in mind, however, that the Grillmair et al. (1998) observations apply to a field region where the presence of significant abundance and possible age ranges complicate the interpretation. Less ambiguous results require studies of dSph star clusters, since star clusters are single age and abundance populations.

The two most luminous of the Galaxy’s dSph companions, Fornax and Sagittarius, possess their own globular cluster systems, and for both these dSphs there are new results on the ages of their star clusters. For example, Montegriffo et al. (1998) have shown that Terzan 8, the most metal-poor of the four globular clusters associated with Sagittarius, has the same age as the metal-poor Galactic halo clusters M55 and M68. The precision of this result, however, is limited to approximately $\pm 2 – 3$ Gyr by the uncertainties in their ground-based c-m diagram. For the Fornax dSph, Buonanno et al. (1998) have used WFPC2 images to produce c-m diagrams that reach below the main sequence turnoff for four of the five Fornax globular clusters. They find that these four Fornax globular clusters have identical ages to within $\pm 1$ Gyr. As for Draco, the similarity of these cluster ages contrasts rather strongly with the expected age range of $\sim 2$ Gyr based on the horizontal branch morphology differences shown by the Fornax cluster c-m diagrams and the assumption that age is the “second parameter”. As Buonanno et al. (1998) note, the result of closely similar ages for all four clusters suggests that either horizontal branch morphology is more sensitive to age than previously thought, or some other quantity besides age is responsible for the horizontal branch morphology differences. Buonanno et al. (1998) then go on to compare their Fornax cluster c-m diagrams with those for Galactic halo globular clusters. They find ages that are not significantly different, at the $1 – 2$ Gyr level, from those for the Galactic halo clusters M92 and M68.

Thus, to a precision of $\sim 1 – 2$ Gyr, we can conclude that Fornax, Sgr and Draco (and also probably Ursa Minor – see Olszewski & Aaronson 1985) did indeed commence forming stars at the same time as the metal-poor globular clusters were forming in the proto-Galactic halo. Other recent results allow this conclusion to be widened. In particular, Harris et al. (1997) have shown that the metal-poor globular cluster NGC 2419, which lies in the extreme outer halo at a Galactocentric distance of $\sim 90$ kpc, has an age that is indistinguishable from that of M92 to a precision of better than 1 Gyr. Similarly, Olsen et al. (1998) and Johnson et al. (1998) have obtained WFPC2 data for a total of eight globular clusters associated with the Large Magellanic Cloud. Their results show that, first, to within an upper limit of $\sim 1$ Gyr, there is no detectable age range...
among these LMC star clusters. Second, the clusters are indistinguishable in age, at the $\sim \pm 1$ Gyr level, from Galactic halo globular clusters of comparable metal abundance.

All these results then suggest that, regardless of the subsequent star formation histories, the initial epoch of star formation was well synchronized among all the components of the proto-Galactic halo, which may well have been distributed over a volume at least $\sim 100$ kpc in radius. In other words, despite the very different locations, masses, densities and dark matter contents of the proto-LMC, the proto-dSphs and the proto-NGC 2419 gas clouds, etc, in the proto-Galactic halo, the initial episode of star formation in all these components seems to have been well co-ordinated. An understanding of how this comes about would undoubtedly advance our knowledge of galaxy formation and of conditions in the early Universe.

3.2. Abundance Ratios in dSph Red Giants

The study of element abundance ratios, typically with respect to iron, in the atmospheres of the members of a stellar system is important because such ratios, and their variation with overall abundance, can provide significant information on the enrichment processes that occur during the evolution of the stellar system. In particular, abundance ratio studies of stars in dSph galaxies should be capable of providing direct constraints on their chemical evolution. It is also possible that such studies might provide a signature to mark those Galactic halo field stars that have come from disrupted dSph galaxies. The determination of abundance ratios for dSph stars is no easy task. Even the brightest red giants in the nearest dSphs are relatively faint and thus a large telescope is required. The results that are described below come from the Keck telescope and the HIRES spectrograph, but they should be regarded as precursors for what will undoubtedly be an extensive area of study once other large telescopes (e.g. HET, Gemini, VLT, Subaru, Magellan, etc) begin science operations.

The first such study is that of Shetrone et al. (1998) who have analyzed high dispersion spectra of four red giants in Draco. They find, firstly, that these stars show a substantial range in iron abundance: the [Fe/H] values are $-3.0$, $-2.4$, $-1.7$ and $-1.4$ dex, respectively, where in each case the uncertainty in the [Fe/H] value is $\sim 0.1$ dex. The existence of this large abundance range comes as no real surprise since we have known for some time that most, if not all, Galactic halo dSphs possess significant internal abundance ranges (e.g. Suntzeff 1993 and references therein). However, studies of large unbiased samples of red giants in dSphs from which to determine the abundance distribution functions are generally lacking at the present time.

The abundance ratios for these Draco red giants do, nevertheless, reveal some interesting differences from globular cluster and field halo red giants. These are illustrated in Fig. 2 where the Shetrone et al. (1998) results for Draco and for red giants in the globular clusters M92 ([Fe/H] $= -2.27$) and M3 ([Fe/H] $= -1.53$) are compared with the results of McWilliam et al. (1995) and McWilliam (1998) for metal-poor field halo stars. For the $\alpha$–element calcium, the [Ca/Fe] values for the globular cluster and field halo stars shown in the upper panel of Fig. 2 are consistent with the trends exhibited by larger samples of stars (see, e.g., Norris, these proceedings). However, the Draco stars, especially the two
more metal-poor objects, have \([\text{Ca}/\text{Fe}]\) values that are significantly lower than the overall trend. These two stars have \([\text{Ca}/\text{Fe}] \approx 0.1\) while the 24 field halo stars with \(-3.2 \leq [\text{Fe/H}] \leq -2.0\) in the McWilliam et al. (1995) sample have \(<[\text{Ca}/\text{Fe}] > = 0.42 \pm 0.02\) dex. On the other hand, as the middle panel of Fig. 2 shows, the results for magnesium, which is also an \(\alpha\)-element, show no such effect. The two metal-poor Draco red giants have \([\text{Mg}/\text{Fe}]\) values consistent with the field halo star and globular cluster red giant determinations. The low \([\text{Mg}/\text{Fe}]\) value for one of the more metal-rich Draco red giants will be discussed below.

The lower panel of Fig. 2 shows the results for the s-process element barium. The two more metal-rich Draco giants have \([\text{Ba}/\text{Fe}]\) values that are consistent with the results of McWilliam (1998) for a sample of metal-poor field halo stars. This is also true for the globular cluster red giants. However, as was found for \([\text{Ca}/\text{Fe}]\), the lower panel of Fig. 2 reveals that the two more metal-poor Draco red giants have significantly lower \([\text{Ba}/\text{Fe}]\) values than do field halo stars with similar \([\text{Fe/H}]\). For the Draco star D24 this difference in \([\text{Ba}/\text{Fe}]\) is \(\sim 1\) dex while for Draco star D119 the difference is indeterminate since there is only an upper limit on \([\text{Ba}/\text{Fe}]\) for this most metal-poor star. This upper limit though corresponds to the lowest measured values of \([\text{Ba}/\text{Fe}]\) in the McWilliam (1998) sample. What are we to make of these results? If they are substantiated by a larger sample of stars observed at higher S/N (the Shetrone et al. 1998 Draco spectra have S/N \(\approx 24-30\)), then they might well indicate that the IMF in the proto-Draco gas cloud was different from that in the Galactic halo.

One further point deserves comment. As the middle panel of Fig. 2 shows, the most metal-rich of the Draco red giants studied by Shetrone et al. (1998) exhibits a significant Mg depletion. As Shetrone et al. (1998) point out, this star also possesses an oxygen depletion and a modest enhancement of sodium. Together with a postulated enhancement of aluminium (Al was not observed), these abundance anomalies are reminiscent of the correlated CNO/NaMgAl abundance variations that are observed among the red giants in many globular clusters (e.g. Da Costa 1997b and references therein). The origin of these abundance anomalies remains uncertain but in this context we need only note that the phenomenon is restricted to globular cluster red giants; it is virtually unknown among field halo red giants. Consequently, if at least approximately 1 in 4 Draco red giants show these abundance anomalies, and if this fraction is typical for all Galactic dSphs, then the virtual complete absence of such anomalies in field halo red giants suggests that disrupted dSphs (or disrupted globular clusters for that matter) did not contribute significantly to the field halo population, contrary to the suggestions of some other contributions at this meeting. Clearly, a full accounting of the frequency of occurrence of CNO/NaMgAl abundance anomalies among dSph red giants is urgently needed.

A second high dispersion study of abundances and abundance ratios in Galactic dSph red giants is that of Smecker-Hane et al. (1998) for stars in the Sagittarius dSph. This dSph is known to have a large internal abundance range. For example, the most metal-poor of the four Sgr globular clusters, Ter 8, has \([\text{Fe}/\text{H}] \approx -2.0\) while the most metal-rich, Ter 7, has \([\text{Fe}/\text{H}] \approx -0.5\) (e.g. Da Costa & Armandroff 1995). The Smecker-Hane et al. (1998) results for individual Sgr red giants are based on Keck + HIRES spectra that have S/N \(\sim 80\). They find,
Figure 2. Abundance ratios as a function of $[\text{Fe}/\text{H}]$ for the $\alpha$-elements Ca (upper) and Mg (middle) and for the s-process element Ba (lower). In each panel filled symbols are field halo stars from McWilliam et al. (1995) and McWilliam (1998). The open circles are mean values for 5 red giants in the globular cluster M92 and 6 in M3, while star symbols represent individual red giants in the Draco dSph. These data come from Shetrone et al. (1998). In the lower panel the point for the most metal-poor Draco star is an upper limit, not a measurement. Other upper limits are shown by downward arrow symbols.
for the first three stars in their sample analyzed, [Fe/H] values of −1.30, −1.03 and +0.11 dex. This last value is remarkably high; for example, it is significantly larger than the present-day abundance, [Fe/H] ≈ −0.3, in the LMC! Yet, this star, once Sgr is fully disrupted, will become a “field” object in the Galactic halo.

Of particular interest here though are the abundance ratio results. For the Sgr red giant with [Fe/H] ≈ −1.30, the [α/Fe] ratios have values of ~0.3 dex, which are perfectly consistent with the ratios observed in globular cluster red giants and in field halo stars (cf. Fig. 2 and Norris, these proceedings). There is therefore nothing particularly remarkable about this Sgr red giant. For the Sgr red giant with [Fe/H] ≈ +0.11, however, the [α/Fe] ratios are indeed noteworthy. Smecker-Hane et al. (1998) find [O/Fe] ≈ −0.41, [Ca/Fe] ≈ −0.24, [Si/Fe] ≈ +0.06 and [Mg/Fe] ≈ +0.11 so that overall, [α/Fe] ≈ −0.12 dex. It is important to note that the low [O/Fe] in this star is not the result of the CNO/NaMgAl abundance anomaly effect seen in globular cluster red giants and in at least one Draco star. If the low [O/Fe] was due to this effect, then the abundances of sodium and aluminium should be significantly enhanced, and that is not observed in this Sgr star (Smecker-Hane et al. 1998). Instead, it seems reasonable to suggest that most of the iron in this star comes from Type Ia supernovae rather than Type II, and that consequently, since the timescale for SNIa exceeds that of SNII, this star is part of Sgr’s younger population. Further, as Gilmore & Wyse (1991) have shown, abundance ratios of this type are expected when the star formation is episodic rather than relatively continuous. In essence, the long intervals of quiescence between periods of star formation allow the iron abundance to build up via SNIa, while since there is no star formation in these intervals, no SNII occur to produce the α-elements. Consequently, while recognizing that these results come from a preliminary analysis for a single star, the element abundance ratios nevertheless suggest that Sgr has had an episodic star formation history. At least qualitatively, this result is remarkably consistent with those presented by Mighell et al. (these proceedings). Their HST/WFPC2 colour-magnitude diagram based study independently suggests that Sgr has indeed had an episodic star formation history. The concurrence of these results then indicates that we are moving towards a more complete understanding of the necessarily entwined star formation and chemical enrichment processes that occurred in this dwarf galaxy.

4. Summary

When considering the properties of the dSph galaxies present in the Galactic halo today, we must keep in mind that these galaxies have survived for a Hubble time. Consequently, if there was a large population of dSph-like objects early in the life of the Galaxy which has now been mostly disrupted, the dSph galaxies that we can observe at the present epoch may not have been “typical” members of this hypothesized early population. In particular, the current dSph galaxies may have orbits that make them less susceptible to tidal disruption, and/or perhaps they have more massive and/or denser dark matter halos. Consequently, we shouldn’t necessarily expect exact correspondence between halo properties and those of present-day dSphs even if the Galactic halo does have a substantial...
contribution from disrupted dSphs. Nevertheless, the present-day dSphs are intriguing objects for further study both: 

*dynamically*, since we are beginning to see the emergence of extensive observational datasets and more complex theoretical models of both the dSphs and their interaction with the Milky Way; and, from a *stellar populations* point-of-view, where increased knowledge of star formation histories, and abundance and abundance ratio distributions will tell us a lot about the evolution of these lowest luminosity galaxies.

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