Dark Galaxies and Lost Baryons
Proceedings IAU Symposium No. 244, 2007
J. I. Davies & M. J. Disney, eds.

doi:10.1017/S1743921307014135

Baryonic Properties of the Darkest Galaxies

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Abstract. The faintest and darkest galaxies that we know of today are the dwarf spheroidal (dSph) galaxies. They appear to be plausible counterparts of cosmologically predicted small subhalos though their numbers do not (yet?) suffice to resolve the substructure crisis. Their mass-to-light ratios may go up to 1000 for the faintest objects, and their total masses are of the order of a few 10^6 to 10^7 $M_\odot$. Though most dSphs are dominated by old populations, they all show extended and presumably slow star formation histories with considerable enrichment. While environment has certainly affected their evolution, as evidenced by the morphology-gas-distance relations, intrinsic properties such as their (initial) baryon content may also have played a major role. The complexity and diversity of their star formation histories is surprising, and there are no obvious evolutionary connections to dwarf irregulars.

Keywords. Local Group, galaxies: dwarf, galaxies: abundances, galaxies: evolution, galaxies: stellar content, galaxies: structure, stars: Population II, stars: kinematics

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1. Introduction

Galaxies are generally believed to contain a substantial fraction of dark matter. Observational evidence for this comes from a variety of different techniques such as stellar or gas dynamics and gravitational lensing. Yet the fraction of dark matter in galaxies varies, i.e., the mass-to-light ratios in different galaxy types cover a wide range of values.

Here I will concentrate on the least massive, least luminous galaxies known, the dwarf spheroidal (dSph) galaxies. These small objects (with diameters of typically a few hundred pc) appear to be the most dark-matter-dominated galaxies known. DSphs are fainter than $M_V = -14$, have V-band surface brightnesses fainter than 23 mag arcsec^{-2}, and typical masses of a few times 10^7 $M_\odot$. They appear to be pressure-supported and have not been found to show measurable rotation. Almost all of them are devoid of gas and thus do no longer show star formation (one of the properties distinguishing them from low-mass dwarf irregular galaxies). While dSphs are typically more metal-poor than [Fe/H] = −1.2 dex, spectroscopy has revealed large abundance spreads exceeding 1 dex, indicative of long-lasting star formation (e.g., Shetrone *et al.* 2001; Ikuta & Arimoto 2002; Grebel *et al.* 2003, Lanfranchi & Matteucci 2004; Grebel & Gallagher 2004; Helmi *et al.* 2006; Koch *et al.* 2006, 2007a, 2007b. For a detailed discussion of the properties and possible origin of dSphs, see Grebel *et al.* (2003).

In this review the following questions will be considered: What are the baryonic properties of these galaxies, and what do they tell us about their dark matter content? How does star formation and chemical evolution in these kinds of galaxies proceed? Are these galaxies the observable counterparts to the large number of small dark matter halos predicted in cosmological models?

Since we can obtain the required detailed information only for the closest galaxies, I concentrate here on dSphs in the Local Group, mainly companions of the Milky Way.

2. The substructure problem and the Local Group galaxy census

2.1. *The substructure problem*

The substructure problem or the missing satellite problem refers to the unresolved discrepancy between the observed number of low-mass dwarf galaxies and the much larger predicted number of small dark matter halos. In the Local Group about one order of magnitude fewer satellites are observed than the number of expected dark matter substructures (Moore *et al.* 2006).

Many solutions have been proposed for the substructure problem, including (early) merging (e.g., Bullock *et al.* 2001), dark matter halos whose mass has been underestimated because they only contain baryons in the form of gas (Blitz *et al.* 1999, Braun & Burton 1999), and the existence of pure dark matter halos that do not contain baryons (anymore) (e.g., Moore *et al.* 2006). Observationally, searches for the missing satellites have employed a variety of techniques. These include searches for merger remnants in the Galactic halo (e.g., Vivas *et al.* 2001; Newberg *et al.* 2002, 2003; Yanny *et al.* 2003; Juric *et al.* 2005; Duffau *et al.* 2005; Belokurov *et al.* 2005, 2007; Grillmair 2006; Wyse *et al.* 2006; Vivas & Zinn 2006) and searches for new satellites (e.g., Karachentsev & Karachentseva 1998; Armandroff *et al.* 1998, 1999; Grebel & Guhathakurta 1999; Whiting *et al.* 1999; Zucker *et al.* 2004a, 2004b, 2006a, 2006b, 2007; Willman *et al.* 2005; Martin *et al.* 2006; Sakamoto & Hasegawa 2006; Grillmair 2006; Liu *et al.* 2006; Belokurov *et al.* 2006a, 2007; Walsh *et al.* 2007; Ibata *et al.* 2007; Majewski *et al.* 2007).

2.2. *Observations of Galactic substructure*

Searches for substructure in the Galactic halo have benefitted tremendously from the availability of the Sloan Digital Sky Survey (SDSS), which covers approximately one quarter of the sky with five-color optical photometry and spectroscopy (Stoughton *et al.* 2002), and from the infrared all-sky survey 2MASS (Skrutskie *et al.* 2006). Moreover, stellar variability has been very successfully exploited, e.g., in the Quasar Equatorial Survey Team (QUEST) RR Lyrae survey (Vivas *et al.* 2001). Following the pioneering discovery of the Sagittarius dwarf galaxy (Ibata *et al.* 1994), which is currently merging with the Milky Way, the above surveys have lead to the detection of new stellar streams and are allowing us to trace existing ones over larger regions (e.g., Majewski *et al.* 2003).

Complementary clues come from spectroscopic (or mixed photometric and spectroscopic) surveys including the SDSS, the Century Survey Galactic Halo Project (Brown *et al.* 2003) and the Radial Velocity Experiment (RAVE, Steinmetz *et al.* 2005), which have the potential of providing phase-space and chemical information (e.g., Nordström *et al.* 2004; Wyse *et al.* 2006; Carollo *et al.* 2007). These kinds of surveys also provide constraints on the amount of mass in the Milky Way, on the shape of the Galactic halo and on the potential merger origin of the Galactic thick disk (e.g., Newberg *et al.* 2002; Helmi *et al.* 2003; Brown *et al.* 2003; Peñarrubia *et al.* 2005; Smith *et al.* 2007).

We note in passing that not all of the detected substructure comes from external accretion events. Some of it is caused by the disruption of Galactic globular clusters (e.g., Odenkirchen *et al.* 2001, 2003; Rockosi *et al.* 2002; Belokurov *et al.* 2006b, Grillmair & Johnson 2006). Other structures may be caused by the internal dynamics of the Milky Way such as resonances (Famaey *et al.* 2007). The extragalactic origin of other overdensities in the Milky Way (such as Canis Major and Monoceros) remains under debate (see, e.g., Newberg *et al.* 2002; Conn *et al.* 2005); Martin *et al.* 2005; Momany *et al.* 2006).

Overall, these studies are revealing that the Galactic halo is highly substructured (see references in the previous subsections), but they do not yet allow us to constrain the overall number, magnitude, nature, and times of the former merger events.

https://doi.org/10.1017/S1743921307014135 Published online by Cambridge University Press

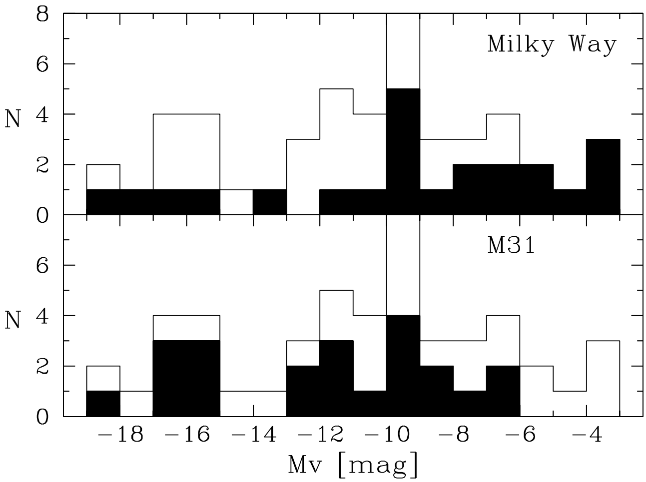

Figure 1. Luminosity function of the Local Group, subdivided in galaxies around the Milky Way (upper panel, black histograms) and galaxies around M31 (lower panel, black histograms). Most of the recent additions are galaxies fainter than $M_V = -8$ mag. The white histogram includes also Local Group galaxies that are not obviously satellites of the Galaxy or M31.

2.3. *Searches for the missing satellites*

Searches for new satellites have seen considerable progress in recent years, largely thanks to the SDSS. The new satellites discovered around the Milky Way and M31 are all very faint objects with low total and low surface brightnesses (see references at the beginning of Section 2). While a decade ago the Local Group luminosity function ended at $M_V \sim -8$ (see Grebel 1997 for a review), the recent discoveries have now extended it down to $M_V \sim -3$ (Fig. 1). In fact, such extremely faint satellites have so far only been found around the Milky Way; for M31 the luminosity function includes objects only as faint as ~ -6 mag. It would seem reasonable to expect that the existing surveys are not yet sensitive enough to permit one to detect even fainter satellites around M31, and that the satellite census for the Milky Way remains incomplete because of the available area coverage, sensitivity, and foreground extinction along the Galactic plane. Forthcoming surveys such as the Panoramic Survey Telescope and Rapid Response System (Pan-STARRS, Kaiser *et al.* 2002) and the Australian Skymapper (Keller *et al.* 2006) may be expected to yield further progress.

Overall, the luminosity function of the Local Group still looks fairly flat (with perhaps a mild indication of a rise around M_V -10 to -9; Fig. 1). If we do a simple by-eye estimate of the faint galaxy numbers that might result if we had a more complete area coverage for the Milky Way and more sensitive surveys of M31's surroundings, we might expect a perhaps three- to fivefold increase at the faint end of the galaxy luminosity function, i.e., a gentle rise in the slope. This is not yet enough to resolve the missing satellite problem, but helps to reduce it (cf. Simon & Geha 2007).

It is unknown at present whether there may be even fainter galaxies out there yet to be discovered. We may even ask whether there is a lower limit in luminosity or baryon content for such objects, and indeed a lower limit as to what we can call a galaxy. Are we now at the point where we have uncovered a continuum of objects with decreasing baryon content but substantial dark matter; objects that are the observational counterparts of the elusive, theoretically predicted low-mass dark matter halos? (Evidence for dark matter in these satellites will be discussed in Section 3.)

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2.4. *The galaxy census of the Local Group*

Kinematic evidence suggests that the Local Group has an approximate radius of ~ 1 Mpc (e.g., Karachentsev *et al.* 2002a), so to first order we may consider all objects within this putative sphere to be bound members of the Local Group. Exceptions would include objects with high relative velocities. Of course, since most of the mass of the Local Group is concentrated at the locations of the Milky Way and M31, the zero-velocity surface of the Local Group cannot be spherical. Disregarding these caveats, we currently know of 54 galaxies within 1 Mpc. These include the three large spirals M31, Milky Way, and M33, and a large variety of dwarf and satellite galaxies (see Grebel *et al.* (2003) for a listing of all Local Group members known by 2003). The 51 currently known dwarf and satellite galaxies do not include the progenitors of merger events such as the giant stellar stream around M31 (Ibata *et al.* 2001; Ferguson *et al.* 2002).

The Local Group contains one compact and three dwarf elliptical galaxies, all of which orbit M31. There are eight irregular and dwarf irregular (dIrr) galaxies, most of which are found at larger distances from the massive spirals. Four galaxies are so-called transition-type galaxies whose stellar populations and low luminosities resemble dSphs, but that also contain gas and show evidence for low-level recent star formation like dIrrs. The remaining 35 galaxies are dSphs. For a more detailed definition and a summary of the properties of the different types of dwarfs, see Grebel (2001).

Within the last decade, the census of dSphs in the Local Group has seen a more than 2.5-fold increase, and pending new surveys it may well continue to grow. Moreover, once we have the full six-dimensional phase space information for significant numbers of stars in our Milky Way, we may be able to place firm constraints on the number of past, already accreted satellites and their contribution to the Galaxy.

The dSphs are the most numerous type of galaxy in the Local Group and probably also in other nearby groups of galaxies (as may be inferred from, e.g., Karachentsev *et al.* 2002b, 2002c). We have little knowledge of the census and fraction of dSphs in galaxy clusters, since their low surface brightnesses, small angular extent, and the much larger distances to the nearest clusters make it difficult to detect dSphs there. Yet also in clusters a rise in the luminosity function is observed toward the faint end (e.g., Binggeli & Cameron 1999; Hilker *et al.* 2003; Lisker *et al.* 2007; Roberts *et al.* 2007). The contribution of dSphs to the overall luminosity and mass of their parent galaxy group is negligible, since with typical total masses of the order of a few 10^7 $M_\odot$ (e.g., Wilkinson *et al.* 2004; Koch *et al.* 2007a, 2007b; Gilmore *et al.* 2007; Walker *et al.* 2007) they are up to five orders of magnitude less massive than the dominant galaxies in their parent groups.

2.5. *Morphological segregation and gas content*

The dSphs are found to be clustered around massive galaxies. In the Local Group, most of them are found within 300 kpc from either the Milky Way or M31 (see Fig. 3 in Grebel 1999 and Fig. 1 in Grebel 2000). The same holds for the dwarf elliptical galaxies around M31. In contrast, the gas-rich, early-type dwarfs are mainly found at larger distances and also in the surrounding field. (The Magellanic Clouds are an exception from this trend. Presumably they are sufficiently massive to have been able to survive in close proximity to the Milky Way.) This morphological segregation is also observed in other nearby galaxy groups (see Fig. 1 in Grebel 2005) and can also be seen in galaxy clusters (e.g., Lisker *et al.* 2006a, 2006b, 2007, and references therein).

As one would then expect the morphological segregation is also reflected in the HI content of the dwarf galaxies (see Fig. 3 in Grebel *et al.* 2003; and Einasto *et al.* 1994 for very early work): Low-mass satellites within 300 kpc of massive galaxies tend to be devoid of gas, at least within the sensitivity limits of presently available telescopes. The upper HI mass limits are typically below 10^5 $M_\odot$ in dSphs, whereas the HI masses of low-mass dIrr galaxies start at 10^7 $M_\odot$. Some dwarf ellipticals do contain measurable amounts of gas of the order of a few times 10^5 $M_\odot$. The low-mass, so-called dIrr/dSph transition-type galaxies tend to be found at larger distances and typically also have HI masses of a few times 10^5 or 10^6 $M_\odot$.

What makes the low gas content of dSphs surprising is that the observationally derived upper limits for their neutral gas masses are even below the amount of gas expected from the normal evolutionary gas loss of their numerous red giants (e.g., Knapp *et al.* 1978). Hence there must either be efficient mechanisms at work that continue to remove the gas, or we may be missing it for other reasons – for instance, it may be ionized. Thus far searches for ionized gas, however, have again only yielded upper limits and no detections (Gallagher *et al.* 2003 and references therein).

3. Radial velocity dispersion profiles and dark matter

In the absence of gas and rotation, the stars in dSphs are the most suitable means to infer their total masses. Traditionally, these kinds of measurements were done by obtaining the central velocity dispersions of nearby dSphs, often based on relatively few stars owing to the faintness of the targets. The early work is reviewed by Mateo (1997). A common finding of these studies was that the velocity dispersions of all dSphs are fairly similar (of the order of 10 km s^{-1}), and that most dSphs have relatively high mass-to-light ratios. For the few objects in which larger numbers of stars had been measured, relatively flat velocity dispersion profiles out to the tidal radii were found, along with lack of evidence for pronounced rotation.

3.1. *Radial velocity measurements across the full angular extent of nearby dSphs*

The last few years have seen a substantial increase in kinematic data for dSphs, largely thanks to large optical telescopes such as ESO's Very Large Telescope (VLT), Keck, Gemini, and Magellan. Programs such as our VLT Large Programme Wilkinson *et al.* 2006; Koch *et al.* 2006b) concentrated on obtaining radial velocity dispersion profiles for as many stars as possible out to the optical boundaries of the target dSphs. Results of our program are also described in the contribution by Wyse & Gilmore in these proceedings.

In all dSphs that we have analyzed to date – Ursa Minor, Draco, Sextans, Carina, Leo I, Leo II – we find flat velocity dispersion profiles out to the outermost radii of our targets (Wilkinson *et al.* 2004; Koch *et al.* 2007b, 2007c; Gilmore *et al.* 2007). Only then a fall-off is seen. As the surface brightness profiles of the dSphs roughly follow an exponential, mass clearly does not follow light. Jeans mass modelling assuming spherical symmetry and isotropic velocities leads to very similar total masses for a range of dSphs of different luminosities – approximately $4 \cdot 10^7$ $M_\odot$ across at least eight magnitudes.

Kinematic analyses done by other researchers confirmed the flat velocity dispersion profiles and dark-matter dominance in dSphs, e.g., Walker *et al.* (2006, 2007). However, there are also alternative explanations (e.g., Muñoz *et al.* 2005; Sohn *et al.* 2077) favoring tidal disruption and low mass-to-light ratios. In the case of the distant Galactic dSph satellite Leo II curious stellar overdensities have been found at larger distances whose nature is not yet understood (Komiyama *et al.* 2007; Coleman *et al.* 2007), and the nearby dSph Ursa Minor may experience tidal disruption as indicated by its elongated, S-shaped stellar density distribution (e.g., Palma *et al.* 2003).

Simon & Geha (2007) measured velocity dispersions in eight of the newly discovered extremely faint dwarfs. With the exception of two dSphs that may be undergoing

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tidal disruption, they found these galaxies with $M_V < -4$ to be strongly dark-matter-dominated with mass-to-light ratios reaching as much as 1000 $M_\odot/L_{\odot,V}$. These galaxies deviate from the apparent trend of constant mass and and lie the range of a few times 10^6 $M_\odot$. Whether there may be galaxies with even lower masses remains unknown.

3.2. *Cores versus cusps*

Our measurements indicate shallow mass density profiles with a slight preference for a cored distribution (as compared to a cuspy distribution). The resulting mass-to-light ratios range from > 10 to < 300 km s^{-1} (e.g., Wilkinson *et al.* 2006; Koch *et al.* 2007c). The average dark matter density within two half-light radii is 0.1 $M_\odot$ pc^{-3} for cored profiles under the above assumptions, while cusped models result in a maximum mass density of 60 $M_\odot$ pc^{-3} within the inner 10 pc (Gilmore *et al.* 2007).

An independent argument favoring cores in dSphs comes from the detection of cold substructure in some of them. For instance, in Fornax, five globular clusters are known, but only one of them reside close to the center of Fornax. It is unclear why the globular clusters would not simply all have merged in the center due to dynamical friction. One possibility is that Fornax was tidally heated (Oh *et al.* 2000). The detection of shell features in Fornax may even be indicative of a past merger event (e.g., Coleman *et al.* 2005). Alternatively, the globular clusters would have survived in a galaxy with a cored mass distribution (Goerdt *et al.* 2006; Strigari *et al.* 2006).

3.3. *Baryonic (stellar) density distributions favoring dark matter*

Finally, we mention two arguments favoring the presence of substantial amounts of dark matter in dSphs using Draco as an example. These arguments are not based on kinematic measurements. Draco, one of the closest dSphs at a distance of $\sim$ 80 kpc, shows very smooth and regular stellar isopleths out to its outermost radii (Odenkirchen *et al.* 2001, Ségall *et al.* 2007). In this respect it differs substantially from the similarly nearby dSph UMi (see above). The smoothness and symmetry of Draco's contours is interpreted as evidence of absence of tidal disruption in spite of its proximity to the Milky Way and hence a high dark matter content in this galaxy.

It has also been suggested that dSphs may not be dark-matter-dominated at all, but that they are unbound tidal remnants with a large depth extent along the line of sight (e.g., Klessen & Kroupa 1998), which in turn can be observationally tested using the width of the horizontal branch. Klessen *et al.* (2003) carried out this test for Draco and found no evidence for a widening of the horizontal branch; not even across a 6.25 deg^2 area well beyond the limiting radius of Draco.

4. Star formation histories of the darkest galaxies

Even the faintest, least luminous, least massive galaxies known, the dSph galaxies, exhibit a surprising variety of star formation histories. No two galaxies are alike (Grebel 1997). They vary in the intensity and duration of their star formation, in the relative fractions of different subpopulations, and in the amount of enrichment. In spite of these differences, common properties are found as well. For instance, just like other galaxies dSphs follow a metallicity-luminosity relation. Interestingly, their metallicity-luminosity relation is offset from that of dwarf irregulars (e.g., Richer *et al.* 1998), even when considering the same metallicity tracers in the same populations (i.e., old populations – see Grebel *et al.* 2003). The offset is such that dSphs are too metal-rich for their luminosity, making it difficult to turn dIrrs into dSphs by mere fading. The low-mass transition-type dwarfs, on the other hand, are indeed plausible dSph progenitors (Grebel *et al.* 2003).

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4.1. *The oldest measurable epoch of star formation*

Nearby dwarf galaxies permit us to observe stars even well below the oldest main-sequence turn-offs (MSTO), a key requirement for accurate age determinations. Of course, MSTO age dating only works for populations that are sufficiently numerous to have produced an observable MSTO – they cannot be applied to individual stars. For old field populations, MSTO methods measure the mean ages of Population II stars. For a canonical, single-age globular cluster they give us the age of its coeval simple stellar population. The highest accuracy can be reached for relative age dating techniques, more specifically, it allows us to quantify how much older or younger an extragalactic population is as compared to the oldest Galactic globular clusters of comparable chemical composition.

Applying relative and absolute MSTO age dating techniques to globular clusters and field populations in nearby galaxies, we found that (1) all of these galaxies contain old populations (although their fractions may vary), and that (2) all of these galaxies experienced their first substantial Population II star formation at the same time within the measurement accuracy (Grebel & Gallagher 2004). Hence there is evidence for a common early epoch of star formation in nearby dwarf and giant galaxies alike. For most of the more distant Local Group galaxies, we do not yet have sufficiently deep data for MSTO dating; yet the detection of horizontal branches and/or RR Lyrae stars provides irrefutable evidence for the existence of old populations (> 10 Gyr) in these objects even though we cannot constrain the times more accurately (Grebel & Gallagher 2004).

At present, we do not know of any galaxies in the Local Group and its immediate surroundings that started to form stars only at more recent times. In particular, all of the dSphs exhibit old populations even though in some objects intermediate-age populations are dominant. We also do not find evidence for cessation of star formation caused by re-ionization in these low-mass objects (Grebel & Gallagher 2004).

4.2. *Spatial variations in age and metallicity*

In all Local Group galaxies studied in detail so far large metallicity spreads have been found, even in dSphs dominated by old populations (e.g., Grebel *et al.* 2003; Simon & Geha 2007). In none of the dSphs evidence for just one single starburst has been found; in essentially all cases there appear to have been extended episodes of star formation (even in Carina with its unique, episodic star formation; see Section 4.4). The enrichment observed in dSphs typically covers 1 dex in [Fe/H] or more. We note that these extended star formation histories impose additional constraints on the total masses (and the dark matter content) of the dSphs – they must be sufficiently massive to not just expel all of their gas once the first supernovae go off.

Moreover, we find spatial variations in star formation even in dSphs dominated primarily by old populations, providing further support for extended star formation episodes. These spatial variations are such that the somewhat younger and/or somewhat more metal-rich populations are more centrally concentrated (Grebel 1997; Stetson *et al.* 1998; Hurley-Keller *et al.* 1999; Harbeck *et al.* 2001; Tolstoy *et al.* 2004; Koch *et al.* 2006a), indicating longer-lasting star formation in the central regions of these galaxies' potential wells. As one would expect, these gradients are visible photometrically as well as in spectroscopical metallicity and kinematics studies. The younger and/or more metal-rich populations tend to have lower velocity dispersions.

4.3. *Detailed chemical abundances*

For a growing number of stars in nearby dSphs detailed individual element abundance ratios are becoming available from high-resolution spectroscopy with 8 to 10m-class

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telescopes. These measurements show a general trend of lower [α/Fe] ratios at a given [Fe/H] than what is found in Galactic halo stars of comparable metallicity (e.g., Shetrone *et al.* 2001; Fulbright 2002; Tolstoy *et al.* 2003; Sadakane *et al.* 2004; Geisler *et al.* 2005; Monaco *et al.* 2005; Sbordone *et al.* 2007, Koch *et al.* 2007d). Moreover, there is a lack of extremely metal-poor stars in all dSphs studied in detail so far, i.e., very few stars more metal-poor than [Fe/H] $= -2.5$ dex have been found (Helmi *et al.* 2006; Koch *et al.* 2007a). We note that the mass functions and the inferred initial mass functions in dSphs seem to be normal, globular-cluster-like (e.g., Grillmair *et al.* 1998; Feltzing *et al.* 1999).

Both of these differences seem to indicate that the present-day dSphs cannot have been the dominant contributors to the build-up of the Galactic halo (see references in the preceding paragraph). The difference in α elements has been attributed to lower star formation rates with little contribution from massive supernovae of type II, to a significant loss of metals, and/or to a larger contribution from supernovae of type Ia (e.g., Shetrone *et al.* 2001). The apparent absence of metal-poor stars in dSphs, however, may also be a statistical effect (Koch *et al.* 2007a).

4.4. *Environmental effects*

The apparent distance dependences suggests that the evolution of the dwarfs is likely affected by their environment. A number of interaction mechanisms have been proposed, e.g., photoevaporation by star-forming events in the massive galaxy that the satellites are orbiting, ram pressure, and tidal stripping, or possibly the combination of several effects (for more details, see, e.g., van den Bergh 1994; Mayer *et al.* 2001, 2006; Grebel *et al.* 2003; and references therein). Any viable mechanism has to be able to account for the puzzling existence of seemingly isolated, distant dSphs in the Local Group (Tucana and Cetus) and for the wide variety of star formation histories found in the dSphs (see later sections). Tucana and Cetus have distances of ~ 680 and 870 kpc from the closest spiral and no other recognizable neighbors. Yet they are "normal" dSphs in every other respect (e.g., Harbeck *et al.* 2001; Sarajedini *et al.* 2002), revealing long-lasting early star formation. It is unclear how they could have lost their gas.

Another "exceptional" dSph is the Galactic companion Carina, the only dSph known to have experienced clearly episodic star formation interrupted by periods of quiescence (e.g., Smecker-Hane *et al.* 1994; Monelli *et al.* 2003; Koch *et al.* 2006). It is not understood what lead to the pauses and the repeated onset of star formation. Carina's still unknown orbit may shed light on its unusual history. Yet another unusual galaxy is the Fornax dSph, which ended its star formation activity only 200–300 Myr ago and yet does not show any measurable traces of gas (Grebel & Stetson 1999; Young 1999). Based on Fornax' proper motion, Dinescu *et al.* (2004) suggest that it may have been stripped of its gas when it crossed the Magellanic Stream.

While environment certainly does play a role, as is also evidenced by the ongoing disruption events and possibly even by the seemingly non-random distribution of the satellites in preferred polar planes (e.g., Kunkel *et al.* 1979; Lynden-Bell 1982; Majewski 1994; Fusi Pecci 1995; Kroupa *et al.* 2005, Koch & Grebel 2006), it is unclear to what extent it has affected the evolutionary histories of dSphs. Van den Bergh (1994) and Grebel (1997) noticed the trend of increasingly younger populations in dSphs with increasing distance from the Milky Way. This trend is, however, not visible in the newly discovered, extremely faint Galactic dSphs nor in the M31 companions. Intrinsic properties such as a dSph's initial baryon content may play a prominent role in shaping their evolution.

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