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THE PROGENITORS OF DWARF SPHEROIDAL GALAXIES

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ABSTRACT

The gas-deficient dwarf spheroidal (dSph) galaxies present an evolutionary puzzle that we explore in 40 early-type and late-type dwarfs in the Local Group and nearby field. Although dSph's experienced star formation over extended time spans in their youths, today all but one are completely free of detectable interstellar material, even in the Fornax dSph, where stars formed in the last 100 Myr. Combining photometric and spectroscopic stellar metallicity estimates for red giant branches with high-sensitivity H I 21 cm line data from the literature, we show that the well-established offset in luminosity-metallicity relationships for dSph's and dwarf irregular (dIrr) galaxies exists also when confining the comparison to their old stellar populations: dSph's have higher mean stellar metallicities for a fixed optical luminosity. Evidently star formation in younger dSph's was more vigorous than in the youthful dIrr's, leading to more efficient enrichment. Dwarf galaxies, whose locus in the luminosity-metallicity diagram is consistent with that of dSph's, even when baryonic luminosities are considered, are the "transition-type dwarfs" Phoenix, DDO 210, LGS 3, Antlia, and KKR 25. These dwarfs have mixed dIrr/dSph morphologies, low stellar masses, low angular momentum, and H I contents of at most a few $10^6\ M_\odot$. Unlike dIrr's many transition-type dwarfs would closely resemble dSph's if their gas were removed, as required to become a dSph; they are likely dSph progenitors. As gas removal is the key factor for such a transition, we consider the empirical evidence in favor and against various gas removal processes. We suggest that internal gas removal mechanisms are inadequate and favor ram-pressure stripping to clean the bulk of interstellar matter from galaxies to make dSph's. A combination of initial conditions and environment seems to support the formation of dSph's: nearby dSph's appear to form from small galaxies with active early star formation, whose evolution halts due to externally induced gas loss. Transition-type dwarfs, then, are dSph's that kept their interstellar medium and therefore should replace dSph's in isolated locations where stripping is ineffective.

Key words: galaxies: abundances — galaxies: dwarf — galaxies: evolution — galaxies: stellar content — intergalactic medium

1. INTRODUCTION

Dwarf spheroidal (dSph) galaxies are the least luminous, least massive galaxies known. They are defined morphologically in terms of their low surface brightnesses, elliptical shapes, and relatively smooth distributions of stars. In galaxy groups the dSph galaxies are most frequently found within ~300 kpc of more massive galaxies, while most of the numerous dSph's in galaxy clusters are not associated with specific giant systems. They have total masses as low as $\sim 10^7\ M_\odot$, $M_V \gtrsim -14$ mag, $\mu_V \gtrsim 22$ mag arcsec^{-2}, and diameters (from tidal radii) of ~2 to ~6 kpc. Their projected radial light profiles are shallow and can be fitted by a range of different profile types, including exponentials. Dwarf spheroidal galaxies are usually devoid of gas and dominated by old and intermediate-age stars, although some have experienced small amounts of recent star formation. Even though dSph's can appear to be quite flattened, the Galactic dSph satellites are known not to be rotationally supported, a trend that extends to many, but not all (e.g., Pedraz et al. 2002), members of the structurally similar, more massive dwarf elliptical (dE) family. Whether lack of rotational support is a general characteristic of dSph's is not yet known. For reviews of dSph properties see, e.g., Gallagher & Wyse (1994), Grebel (1997, 1999, 2000), Da Costa (1998), Mateo (1998), and van den Bergh (1999a, 2000). Properties of dE's are reviewed by Ferguson & Binggeli (1994).

The dSph's are fascinating galaxies. They combine low densities of luminous matter, predilections for locations in dense cosmic environments, in some cases high apparent total mass densities, and recently recognized complex star formation histories. Three general classes of models have been suggested for the origins of dSph galaxies: tidal interactions that transform field disk galaxies into spheroidal systems (e.g., Sofue 1994; Mayer et al. 2001a, 2001b), processes associated with the birth of small systems, especially in the cold dark matter (CDM) model (Dekel & Silk 1986), and fragments liberated during collisions between larger galaxies (Gerola, Carnevali, & Salpeter 1983). These models are not necessarily independent of one another; e.g., dwarfs may form via the collapse of CDM and then evolve through tidal interactions. While this paper does not study the formation or early evolution of galaxies that may become dSph's, we will discuss whether multiple evolutionary paths might have dSph's as their end points.

Unfortunately, these perspectives on the origins of dSph's face well-known difficulties. For example, standard CDM models overpredict the fraction of dwarfs that should be dSph's; the issue in this case is why we do not see even more examples of this class of galaxy (e.g., Klypin et al. 1999; Moore et al. 1999; Bullock, Kravtsov, & Weinberg 2000). Simple gas loss or passive evolution to gas exhaustion cannot make a rotating dwarf irregular (dIrr) galaxy into a nonrotating dSph (e.g., Binggeli 1986). While the tidal model allows angular momentum to be lost, it offers neither a ready explanation for the existence of isolated dSph's, such as the Tucana or Cetus dwarfs, nor a simple physical basis for the dSph mass-metallicity correlation (see § 3). More generally, if passive evolution leads to gas exhaustion, we wonder why so few dwarf galaxies exist with a combination of old stars and neutral gas, as might be expected if star formation stops at some critical gas density threshold (Phillipps, Edmunds, & Davies 1990).

While dSph's and dIrr's show similar trends of global properties with luminosity, the dSph's are more metal-rich than dIrr's at the same optical luminosity. This difference is observed both for abundances in planetary nebulae and for stellar metal abundances, which we denote as "[Fe/H]" (e.g., Skillman & Bender 1995; Richer, McCall, & Stasinska 1998; Mateo 1998, and references therein), and stands as an argument against evolution from dIrr's to dSph's. Low-mass galaxies, including dIrr's and dSph's, show similar exponential radial brightness profiles (Lin & Faber 1983; Kormendy 1985), which has been interpreted as an indication that these could be different versions of the same basic type of galaxy. In this case another mechanism, such as tides, is required to produce spheroidal systems from objects that formed as disk galaxies. Tidal fragment models for dSph's face different types of difficulties, including explaining the apparent lack of extratidal stars, the highly symmetric structure, and the high dark matter content of some dSph systems, such as Draco (e.g., Odenkirchen et al. 2001; see also Kleyna et al. 2002 for arguments based on a kinematic study). Note that another very nearby dSph, Ursa Minor (Table 1) shows considerable indications of ongoing tidal disruption (e.g., Martínez-Delgado et al. 2001), showing that at least some dSph's do experience this.

Another key aspect of dSph's is how they achieve their present gas-poor states (e.g., Skillman & Bender 1995). In order to have formed stars, all dSph's must once have contained significant amounts of gas. However, it is unclear what their progenitors were and how the transformation from gas-rich to gas-free galaxies proceeded. One possibility is that the gas-deficient nature of dSph's is closely associated with their births, e.g., as a result of special effects associated with their rapid early collapse, as predicted by CDM galaxy formation models (e.g., Chiu, Gnedin, & Ostriker 2001). Alternatively, dSph's could result from the transformation of low-mass galaxies, as predicted by models invoking tidal distortion and ram-pressure stripping of objects orbiting near giant systems (Einasto et al. 1974; Mayer et al. 2001a).

In this paper we explore the implications of mean stellar population metal abundances and H I gas contents of nearby low-mass dwarf galaxies, although we include more massive dwarfs when considering trends in physical properties. We pay particular attention to the "transition-type dwarf galaxies," the dIrr/dSph's. These objects combine properties associated with dSph's (such as low luminosities and prominent old stellar populations) with those of dIrr's (such as H I gas). The dIrr/dSph's, therefore, may hold clues to the nature of relationships between these two galaxy classes. In particular, we explore whether dIrr/dSph systems could be hybrid objects that merely combine features of dIrr and dSph galaxies or whether they might be in an evolutionary transition from dIrr types toward dSph's (or possibly the reverse; see Silk, Wyse, & Shields 1987).

In § 2 we describe observational and derived data on mean stellar chemical abundances and H I gas masses of dwarf galaxies in the Local Group and its surroundings, which form the basis of our analysis. In § 3 the luminosity-metallicity relation for gas-rich dIrr, transition-type dIrr/dSph, and gas-free dSph galaxies is discussed. Properties of individual transition-type galaxies and selected dSph's are discussed in § 4, which describes their similarities with respect to lack of rotation and star formation histories. Section 5 briefly reviews mechanisms that can remove gas from dwarf galaxies, an essential precondition for producing dSph's. In § 6 we present our conclusions.

2. THE NEARBY DWARF GALAXY SAMPLE

For this investigation we compiled a sample of nearby dwarf galaxies, whose resolved stellar populations were studied through deep ground-based observations or through *Hubble Space Telescope* (*HST*) imaging. We adopted a generous definition for dwarfs, and consider galaxies with $M_V \lesssim -18$ mag to be potential members of this structural class (Gallagher 1998; Grebel 1999). We included all known and suspected Local Group members that lie within a zero-velocity radius of 1.2 Mpc (Courteau & van den Bergh 1999) around the barycenter of the Local Group, which yields 33 dwarf and satellite galaxies, in addition to the three Local Group spirals. The four possible members of the small, nearby Sextans-Antlia group (van den Bergh 1999b) were added as well. If Sextans-Antlia is indeed a physical group, then it is extremely poor, consisting only of dwarf galaxies. Furthermore, we added three isolated dwarfs in the nearby field. In total, our sample of dwarf galaxies in and around the Local Group contains 40 objects, and includes the Magellanic Clouds, dIrr's, transition-class dIrr/dSph's, dSph's, and dE's.

Table 1 lists some optical and H I properties of this sample. Horizontal lines separate spatially defined galaxy subgroups: the first set of galaxies are possible or likely companions of the Milky Way, the second companions of M31, the third more distant possible Local Group members, the fourth possible members of the Sextans-Antlia group, and the fifth are seemingly isolated galaxies in the nearby field. Column (1) gives the dwarf galaxy names, column (2) their types (see table comments for details), columns (3) and (4) their J2000.0 coordinates, column (5) heliocentric distances based largely on the tip of the red giant branch, column (6) the distance to the nearest "parent" galaxy (omitted for Milky Way satellites) or to the barycenter (subscript "bary") of the Local Group. Column (7) specifies absolute *V*-band magnitudes, column (8) central *V*-band surface brightnesses, column (9) mean metallicity and metallicity spread (not uncertainty), column (10) the H I mass, and column (11) the *V*-band luminosity. Literature references are given in the table comments.

TABLE 1
PROPERTIES OF NEARBY DWARF GALAXIES

Name (1)	Type (2)	α (3)	δ (4)	$D_{\odot}$ (kpc) (5)	$D_{\rm near}$ (Mpc) (6)	M_V (mag) (7)	μ_V (mag arcsec^{-2}) (8)	[Fe/H] (dex) (9)	$M_{\rm H\,I}$ ($10^6\ M_{\odot}$) (10)	L_V ($10^6\ L_{\odot}$) (11)
Sgr	dSph, t, N?	18 55 03	−30 28 42	28 ± 3		−15.0	25.4 ± 0.2	−0.5 ± 0.8	<0.01:	80.1
LMC	Irr III–IV	05 23 35	−69 45 22	50 ± 2		−18.5	20.7 ± 0.1	−0.6 ± 0.5	500.0	1995.0
SMC	Irr IV/IV–V	00 52 49	−72 49 43	63 ± 10		−17.1	22.1 ± 0.1	−1.2 ± 0.4	420.0	550.0
UMi	dSph	15 09 10	+67 12 52	69 ± 4		−8.9	25.5 ± 0.5	−1.9 ± 0.7	<0.007	0.3
Dra	dSph	17 20 12	+57 54 55	79 ± 4		−9.4	24.4 ± 0.5	−2.0 ± 0.7	<0.008	0.47
Sex	dSph	10 13 03	−01 36 53	86 ± 6		−9.5	26.2 ± 0.5	−1.9 ± 0.4	<0.03	0.5
Scl	dSph	01 00 09	−33 42 33	88 ± 4		−9.8	23.7 ± 0.4	−1.5 ± 0.5	>0.09:	2.2
Car	dSph	06 41 37	−50 57 58	94 ± 5		−9.4	25.5 ± 0.4	−1.8 ± 0.3	<0.001	0.4
For	dSph	02 39 59	−34 26 57	138 ± 8		−13.1	23.4 ± 0.3	−1.2 ± 0.5	<0.7	15.5
Leo II	dSph	11 13 29	+22 09 17	205 ± 12		−10.1	24.0 ± 0.3	−1.6 ± 0.5	<0.03	0.6
Leo I	dSph	10 08 27	+12 18 27	270 ± 10		−11.9	22.4 ± 0.3	−1.4 ± 0.5	<0.009	4.8
Phe	dIrr/dSph	01 51 06	−44 26 41	405 ± 15		−9.8	. . .	−1.9 ± 0.4	0.17?	0.9
NGC 6822	dIrr IV–V	19 44 56	−14 52 11	500 ± 20		−16.0	21.4 ± 0.2	−1.2 ± 0.4	140.0	94.4
M32	dE2, N	00 42 42	+40 51 55	770 ± 40	$\sim 0.0_{\rm M31}$	−16.5	11.5 ± 0.5	−1.1 ± 0.6	<2.5	383.0
NGC 205	dE5p, N	00 40 22	+41 41 07	830 ± 35	$0.06_{\rm M31}$	−16.4	20.4 ± 0.4	−0.5 ± 0.5	0.39	366.0
And I	dSph	00 45 40	+38 02 28	790 ± 30	$0.05_{\rm M31}$	−11.8	24.9 ± 0.1	−1.4 ± 0.2	<0.096	4.2
And III	dSph	00 35 34	+36 29 52	760 ± 70	$0.07_{\rm M31}$	−10.2	25.3 ± 0.1	−1.7 ± 0.2	0.09?	1.0
NGC 147	dE5	00 33 12	+48 30 29	755 ± 35	$0.10_{\rm M31}$	−15.1	21.6 ± 0.2	−1.1 ± 0.4	<.005	131.0
And V	dSph	01 10 17	+47 37 41	810 ± 45	$0.12_{\rm M31}$	−9.1	24.8 ± 0.2	−1.9 ± 0.1	Undet.	0.4
And II	dSph	01 16 30	+33 25 09	680 ± 25	$0.16_{\rm M31}$	−11.8	24.8 ± 0.1	−1.5 ± 0.3	Undet.	2.4
NGC 185	dE3p	00 38 58	+48 20 12	620 ± 25	$0.17_{\rm M31}$	−15.6	20.1 ± 0.4	−0.8 ± 0.4	0.13	125.0
Cas dSph	dSph	23 26 31	+50 41 31	760 ± 70	$0.22_{\rm M31}$	−12.0	23.5 ± 0.1	−1.5 ± 0.2	Undet.	5.0
IC 10	dIrr IV/BCD	00 20 17	+59 18 14	660 ± 65	$0.25_{\rm M31}$	−16.0	20.4 ± 0.4	−1.3 ± 0.4	98.0	160.0
And VI	dSph	23 51 46	+24 34 57	775 ± 35	$0.27_{\rm M31}$	−11.3	24.3 ± 0.1	−1.7 ± 0.2	Undet.	2.6
LGS 3	dIrr/dSph	01 03 53	+21 53 05	620 ± 20	$0.28_{\rm M31}$	−9.8	24.7 ± 0.2	−1.7 ± 0.3	0.2	1.3
Peg DIG	dIrr/dSph	23 28 36	+14 44 35	760 ± 100	$0.41_{\rm M31}$	−12.9	. . .	−2.0 ± 0.3	3.4	12.0
IC 1613	dIrrV	01 04 47	+02 07 02	715 ± 35	$0.50_{\rm M31}$	−15.3	22.8 ± 0.3	−1.4 ± 0.3	58.0	63.6
Cet	dSph	00 26 11	−11 02 40	775 ± 50	$0.68_{\rm M31}$	−10.1	25.1 ± 0.1	−1.7 ± 0.2	Undet.	0.9
Leo A	dIrrV	09 59 26	−02 46 37	800 ± 40	$0.98_{\rm bary}$	−11.7	. . .	−2.1 ± 0.4	7.6	4.1
WLM	dIrrIV–V	00 01 58	−15 27 39	945 ± 40	$0.84_{\rm M31}$	−14.4	20.4 ± 0.1	−1.4 ± 0.4	63.0	50.2
Tuc	dSph	22 41 49	−64 25 12	870 ± 60	$1.11_{\rm bary}$	−9.6	25.1 ± 0.1	−1.7 ± 0.2	<0.015	0.6
DDO 210	dIrr/dSph	20 46 52	−12 50 53	950 ± 50	$0.96_{\rm bary}$	−10.9	23.0 ± 0.3	−1.9 ± 0.3	2.7	0.8
Sag DIG	dIrrV	19 29 59	−17 40 41	1060 ± 100	$1.18_{\rm bary}$	−12.0	23.9 ± 0.2	−2.3 ± 0.4	8.6	6.9
NGC 3109	dIrrIV–V	10 03 07	−26 09 32	1360 ± 100	$1.75_{\rm bary}$	−15.7	23.6 ± 0.2	−1.7 ± 0.4	820.0	160.0
Ant	dIrr/dSph	10 04 04	−27 19 55	1330 ± 100	$\sim 0.04_{\rm N3109}$	−11.2	. . .	−1.9 ± 0.2	0.72	2.4
Sex A	dIrrV	10 11 01	−04 41 34	1440 ± 70	$0.53_{\rm N3109}$	−14.6	23.5 ± 0.3	−1.9 ± 0.4	54.0	55.7
Sex B	dIrrIV–V	10 00 00	+05 19 56	1320 ± 140	$0.73_{\rm N3109}$	−14.2	. . .	−2.1 ± 0.4	44.0	40.7
IC 5152	dIrrIV–V	22 02 42	−51 17 44	1700 ± 150	$1.83_{\rm bary}$	−14.8	. . .	−1.4 ± 0.5	67.0	70.3
KKR 25	dIrr/dSph	16 13 48	+54 22 16	1860 ± 120	$1.79_{\rm bary}$	−10.5	24.0 ± 0.2	−2.1 ± 0.3	1.0	1.2
GR8	dIrrV	12 58 40	+14 13 03	2200 ± 300	$2.50_{\rm bary}$	−11.6	22.3 ± 0.2	−2.0 ± 0.4	9.6	3.4

NOTE.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds (J2000.0).

REFERENCES.—The galaxy type nomenclature of van den Bergh 1994 was adopted, adding " N " (nucleated) for Sgr, NGC 205, and M32. References for heliocentric distances: Grebel 2000 except for LGS 3 (Miller et al. 2001), Leo A (Dolphin et al. 2002; Schulte-Ladbeck et al. 2002), Sag DIG (Karachentsev, Aparicio, & Makarova 1999), the Sextans-Antlia group (van den Bergh 1999b), IC 5152 (Zijlstra & Minniti 1999), KKR 25 (Karachentsev et al. 2001), and GR 8 (Dohm-Palmer et al. 1998). References for absolute *V* magnitudes: van den Bergh 2000 except for Sgr (Majewski et al. 1999), Draco (Odenkirchen et al. 2001), IC 10 (Richer et al. 2001), LGS 3 (Miller et al. 2001), Sextans-Antlia group (van den Bergh 1999b), IC 5152 (Zijlstra & Minniti 1999), KKR 25 (Karachentsev et al. 2001), and GR 8 (Mateo 1998). Central surface brightnesses: Mateo 1998 except for Draco (Aparicio et al. 2001), And V, VI, and Cas dSph (Caldwell 1999), IC 10 (Richer et al. 2001), Cetus (Whiting, Hau, & Irwin 1999), DDO 210 (Lee et al. 1999), KKR 25 (Karachentsev et al. 2001). Red giant branch metallicities: Grebel 2000 except for Sgr (Cole 2001), Leo I and II (Smecker-Hane et al. 2003), Leo A (Schulte-Ladbeck et al. 2002), UMi, Dra, Sex (Shetrone et al. 2001), Scl, For (Tolstoy et al. 2003), KKR 25 (Karachentsev et al. 2001), and our ongoing redetermination of red giant branch metallicities using archival WFPC2 images (Harbeck et al. 2001). H I masses were recalculated from the integrated flux density or from upper limits assuming a uniform H I column density within the tidal radius (§ 2.2), using the updated heliocentric distances given above. Other references: Sgr: Koribalski, Johnston, & Otrupcek (1994, assuming an angular size of 10° × 4°); LMC: Kim et al. 1998; SMC: Stanimirović et al. 1999; UMi, Dra, Sex, Leo I: Young 2000; For, Leo II: Young 1999; Car: Mould et al. 1990; Scl, And II, And III, And V, And VI, Cas dSph, DDO 210, LGS 3, Peg DIG: Blitz & Robishaw 2000; And I: Thuan & Martin 1979; Cet: Huchtmeier et al. 2001; Phe: St-Germain et al. 1999; Tuc: Oosterloo et al. 1996; Ant: Barnes & de Blok 2001; KKR 25: Karachentsev et al. 2001; and Mateo 1998 for the remainder.

2.1. *Self-consistent Metallicities*

In order to ensure that we compare the chemical abundances of equivalent stellar populations in dIrr's, transition-types, and dSph's, we concentrate here on the estimated mean stellar [Fe/H]-values of old populations. Old stellar populations have been detected in each dIrr, transition type, and dSph studied to sufficiently faint magnitudes. We neglect nebular α-element abundances measured in H II regions or planetary nebulae (PNs). The former refer to the *present-day* gas abundances of young populations. The latter form from progenitor stars with masses $< 8\ M_\odot$ and ages $> 10^8$ yr but cannot be readily associated with any specific age stellar population. Since young metal-rich populations will produce more PNs than older metal-poor populations, luminous PNs help to probe the interstellar medium oxygen abundances at the epoch when star formation last occurred, once certain corrections are applied (Richer, McCall, & Arimoto 1997). However, PNs have been detected so far in only two dSph's. Another problem arises from variations in the iron-peak to α-element abundances, which depend on prior star formation histories modulated by the details of gas-loss mechanisms (e.g., Burkert & Ruiz-Lapuente 1997; Recchi, Matteucci, & D'Ercole 2001). Hence, we consider here only the mean metallicities of old stellar populations, which can be approximately measured in a consistent manner in both types of galaxies.

For old stellar populations in dSph's and dIrr's a large metallicity data set has become available in recent years, based on spectroscopic and photometric abundance determinations for red giants. Spectroscopic measurements have been carried out for individual red giants in a number of nearby dwarfs (e.g., Suntzeff et al. 1993; Côté, Oke, & Cohen 1999; Bonifacio et al. 2000; Guhathakurta, Reitzel, & Grebel 2000; Shetrone, Côté, & Sargent 2001; Tolstoy et al. 2001; Shetrone et al. 2003; Smecker-Hane, Bosler, & Stetson 2003; Smecker-Hane & McWilliam 2003). Photometric metallicity estimates can be applied over much larger distances and are largely based on the empirical calibration by Da Costa & Armandroff (1990) and more recent refinements (e.g., Lee, Freedman, & Madore 1993; Caldwell et al. 1998).

The photometric methods use either the slope of the red giant branch in comparison with globular cluster fiducials or the mean $(V{-}I)_0$ color at a certain absolute I-band magnitude for old stellar populations. The absolute I-band magnitude is chosen such that contamination by asymptotic giant branch stars is reduced, while measuring at a luminosity where the mean color is still sensitive to metallicity. This results in metallicities on the Zinn & West (1984) [Fe/H] scale, in good agreement with spectroscopic results. The absolute accuracy of the photometric estimates is approximately ± 0.2 dex in galaxies where old stars dominate the red giant branch, while the relative accuracy is largely determined by photometric uncertainties and can be higher.

An important caveat of the photometric methods is the problem of the age-metallicity degeneracy in mixed populations: evolved stars belonging to intermediate-age populations overlap with the blue part of the red giant branch and may make the red giant branch appear more metal-poor than it really is. Synthetic color-magnitude–diagram modelling helps to reduce this degeneracy if all the various age tracers in a color-magnitude diagram are properly taken into account (e.g., Holtzman, Smith, & Grillmair 2000). Also, measurements based on red giant branches in the outer regions of dIrr's, where old populations dominate (e.g., Minniti & Zijlstra 1996; Harbeck et al. 2001), reduce contamination effects. Still, spectroscopy is the only way to unambiguously resolve the age-metallicity degeneracy for individual stars.

In Table 1 we list [Fe/H] abundance estimates based on the resolved red giant branches of nearby dwarf galaxies through intrinsically consistent methods (spectroscopy where available and otherwise photometric estimates). The σ-values quoted for [Fe/H] refer to the estimated abundance spread across the red giant branch in these galaxies, not to the uncertainty in the [Fe/H] determination.

2.2. *Baryon Content: Stellar Luminosities and* H I *Masses*

We used optical V-band luminosities (L_V) for the galaxies in our sample (Table 1). In gas-free dSph's all of the identified baryonic mass is in stars, whereas some of the baryonic matter in other dwarf galaxies is still in the form of gas. To put all dwarfs on a comparable baryon content scale, we calculated the "baryonic luminosity" $L_{V,\mathrm{bary}}$, as defined by Matthews, van Driel, & Gallagher (1998):

$$L_{V,\mathrm{bary}} = L_V + 1.33\ M_{\mathrm{H\,I}} \langle M_V/L_V \rangle^{-1}\ ,$$

where $M_{\mathrm{H\,I}}$ denotes the H I mass, the factor 1.33 accounts for the presence of helium, and $\langle M_V/L_V \rangle$ is the mean mass-to-luminosity ratio for the galaxy's stellar population in the V band. We assumed a constant stellar population mass-to-light ratio of 2 to derive the equivalent luminosity of the gas. This is a conservative estimate for a fading stellar population (e.g., Charlot, Worthey, & Bressan 1996; Schulz et al. 2002). Thus $L_{V,\mathrm{bary}}$ predicts the approximate luminosity that a dIrr galaxy would have at the point where it would have converted all of its gas into stars and had begun to fade.

For dwarf galaxies with significant amounts of interstellar matter we used the H I fluxes listed in Mateo (1998) or more recent publications (see table comments) together with the distances listed in Table 1 to calculate the H I masses via the standard relation

$$M_{\mathrm{H\,I}} = 2.36 \times 10^5 D^2 \sum S_v dv\ M_\odot$$

(e.g., Knapp, Kerr, & Williams 1978). Here D is the galaxy distance in megaparsecs and $\sum S_v dv$ is the total 21 cm line flux in jansky kilometers per second. We revisit the dwarf galaxy H I content issue in § 4.2.

Sensitive searches for H I within the tidal radii of dSph's resulted in upper column density limits of only a few 10^{17} cm^{-2} (Young 1999, 2000). The only exception is the Sculptor dSph, where H I with peak column densities of 2.2×10^{19} cm^{-2} was detected within the tidal radius (Carignan et al. 1998). While the location and radial velocity of the H I support its association with Sculptor, this gas may be part of a larger, unassociated complex merely seen in projection (Carignan 1999).

For gas-deficient dwarf galaxies upper limits are listed. Where available, these upper limit masses are derived from H I line flux limits in the recent literature (see table comments for references) and recalculated assuming that the H I fills the optical extent of these dwarf galaxies within their tidal radius at uniform gas column density. This assumption was made because the gas in dwarf galaxies usually is at least as extended as their optically visible bodies. In dIrr's the H I may be several times more extended than the optical galaxy (see Grebel 2002 for a review and references).

Nondetections of H I usually occur in low-mass dwarfs that are within 300 kpc of more massive galaxies. Their H I content, if present at all, may be truncated in its spatial extent as a result of ram-pressure effects, caused by the massive galaxy's gaseous corona, or by tidal effects (see § 5). Hence, the use of the tidal radius appears to be a reasonable compromise in these gas-deficient objects. We did not take into account detections of possibly associated H I *well beyond* the optical radius of some dSph's (§ 5.2.1). The comment " undet." refers to dSph's that were not detected in the northern Leiden-Dwingeloo Survey (Blitz & Robishaw 2000) or in the southern HIPASS survey (Huchtmeier, Karachentsev, & Karachentseva 2001) and for which no specific H I flux limits were published.

3. THE LUMINOSITY-METALLICITY RELATIONSHIP

Dwarf galaxies follow a well-known luminosity-metallicity relation: the more luminous a dwarf, the higher its mean metallicity (e.g., Grebel & Guhathakurta 1999). Higher luminosities usually imply higher masses and deeper gravitational potential wells, and/or higher luminous matter densities, and/or high recent star formation rates. In return, the more luminous galaxies may undergo stronger enrichment and, because of their deeper potential wells, also have an improved ability to retain the metals (e.g., Dekel & Silk 1986).

3.1. *Separate Branches for dIrr's and dSph's*

If dSph's and dIrr's are distinguished only by evolution induced by their environments after formation, then we might expect their older stellar populations to be similar. The older stars in both systems presumably formed under similar conditions before the dSph and dIrr evolutionary paths diverge. Differentiation by ram-pressure stripping alone is a simple example of this class of model. The dSph systems would evolve like their dIrr cousins until gas is removed, but before gas loss the two classes of galaxies would be similar. Comparisons of chemical abundances in older stellar populations, therefore, can provide powerful evolutionary tracers.

A plot of *V*-band luminosity L_V versus ⟨[Fe/H]⟩ (Fig. 1, *left*) shows a clear trend of increasing luminosity with increasing mean red giant branch metallicity for the dSph's (*filled circles*), which appears to extend to the more luminous dE's (*open circles*). The dIrr's (*open diamonds*) show a similar trend but are offset from the locus of the dSph's in that they are more luminous at the same metallicity (see also Mateo 1998 and references therein).

In other words, the dIrr's have too low a metallicity for their luminosity as compared with dSph's. Thus dSph's, most of which have been quiescent over at least the past few gigayears, must have experienced chemical enrichment faster and more efficiently than dIrr's, which continue to form stars until the present day. *This is a fundamental difference between dSph's and dIrr's.* Plausible progenitors of present-day dSph's would need to have undergone similarly rapid early evolution.

When plotting the baryonic luminosity against metallicity (Fig. 1, *right*), the locus of the dSph's remains unchanged, while the dIrr's move to higher luminosities as compared with the dSph's. Thus, if star formation in present-day dIrr's were terminated when all of their gas was converted into stars, then these fading dIrr's would be even further from the dSph luminosity-metallicity relationship, unless substantial chemical enrichment occurs in a long-lived stellar population that would produce a strong red giant branch.

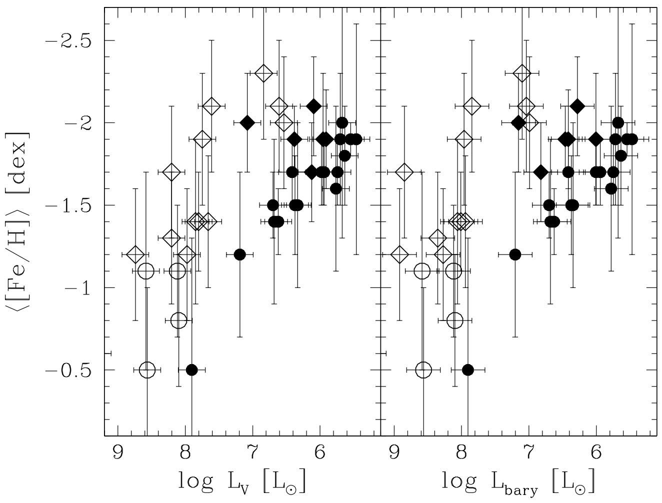

FIG. 1.—*V*-band luminosity (*left*) and baryonic luminosity (*right*, corrected for baryon contribution of gas not yet turned into stars; see § 2.2 for detail) vs. mean metallicity of red giants. Filled circles stand for dSph's, open circles for dE's, filled diamonds for dIrr/dSph transition-type galaxies, and open diamonds for dIrr's. DIrr's are more luminous at equal metallicity than dSph's. However, several dIrr/dSph transition-type galaxies coincide with the dSph locus. These objects are indistinguishable from dSph's in all their properties except for gas content.

Figure 1 shows that present-day dSph's are at least by a factor of 10 fainter in luminosity than present-day dIrr's at the same stellar metallicity (i.e., for the old stellar population). Models presented by Charlot et al. (1996) show that, for a galaxy to homologously fade by this amount—roughly 2 mag in M_V, an interval of $\gtrsim 15$ Gyr after the cessation of star formation is required. In other words, present-day dIrr's would need another Hubble time to turn into dSph's if for some reason all star formation were to cease now. For cases where cessation of star formation also is associated with loss of stars, e.g., in cases of tidal stripping, an even larger decline in surface brightness should occur (e.g., Mayer et al. 2001a). On the other hand, if star formation were to continue at a low level, as is expected to occur well into the future in most dIrr's because of their modest star formation rates and large gas reservoirs (Hunter 1997), the fading timescale would increase.

At the same absolute magnitude dIrr's tend to have lower surface brightnesses than dSph's (Fig. 2). If they were to stop forming stars, fading by 1 mag in absolute brightness would also imply a decrease in surface brightness by roughly this amount (Hunter & Gallagher 1985), as indicated by the arrow in Figure 2. For the majority of nearby dIrr's fading would thus result in galaxies with too low a surface brightness as compared with present-day dSph's. A few dIrr's (notably GR 8 and Sag DIG), as well as the three transition-type dwarfs for which surface brightnesses have been measured (LGS 3, DDO 210, and KKR 25), would, however, continue to coincide with the dSph locus in Figure 2.

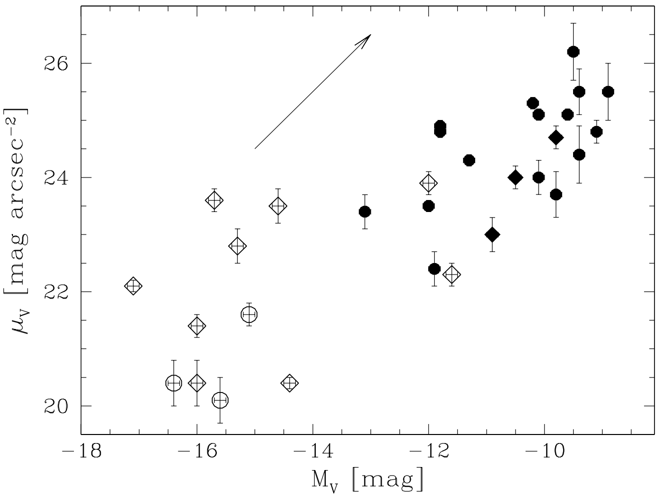

FIG. 2.—Absolute V-band magnitude M_V of dwarf galaxies vs. their central V-band surface brightness μ_V. The symbols for different galaxy types are the same as in Fig. 1. Luminous dIrr's tend to have lower central surface brightnesses than dSph's at the same absolute brightness. The arrow indicates the amount by which both M_V and μ_V would be reduced by fading following Hunter & Gallagher (1985). Only low-luminosity dIrr's and transition-type galaxies would arrive at (or retain) positions consistent with the dSph locus in this diagram, while for more luminous dIrr's fading would result in galaxies with too low a surface brightness as compared to present-day dSph's.

In addition to the issues of fading and rapid early enrichment, many dIrr's, and especially the more massive systems, would also need to find a mechanism to lose their angular momentum and their gas, if they are to become dSph's. We cannot consider most normal present-day dIrr's, which are not close satellites of giant galaxies, as likely precursors of dSph's over any reasonable timescale (see also Binggeli 1986, 1994).

3.2. *A Continuum of Transition-Type Dwarfs?*

Dwarf galaxies classified as possible dIrr/dSph transition-types in the literature are marked by filled diamonds in Figure 1. Five of these, namely, Phoenix, DDO 210, LGS 3, Antlia, and KKR 25, lie in the area of our diagram occupied by the dSph's. In the $L_{\rm bary}$-$\langle$[Fe/H]$\rangle$ diagram they outline the luminous edge of the dSph locus. Their H I masses are typically a few times 10^6 $M_\odot$, while dIrr's have H I masses $\geq 10^7$ $M_\odot$.

The sixth potential transition-type galaxy, Peg DIG, is found in the region of Figure 1 occupied by the dIrr's. Two metal-poor, faint dIrr's lie close to the dSph locus in the L_V-$\langle$[Fe/H]$\rangle$ diagram: GR 8 and Leo A. They move closer to the dIrr locus when $L_{\rm bary}$ is plotted instead, although, since Leo A has a dominant moderately young stellar population (Tolstoy et al. 1998), its stellar [Fe/H] may be underestimated (see Schulte-Ladbeck et al. 2002). We also tentatively exclude the Peg DIG from the transition group, based on the nature and level of its star-forming activity and substantial interstellar medium (see § 4.3.1).

The locations of Phoenix, DDO 210, LGS 3, and Antlia on the luminosity-metallicity plane indicate that these galaxies would closely resemble the classic dSph galaxies if they were to lose their gas. Indeed, in the $L_{\rm V}$-$\langle$[Fe/H]$\rangle$ diagram they would be essentially indistinguishable from dSph's. In this sense we may consider these four transition galaxies as present-day progenitors of dSph galaxies, whose properties (other than gas content and associated recent star formation) are fully consistent with the properties of dSph's. However, given the reasonable H I contents and low star formation rates of these galaxies, they are not rapidly evolving.

The nearby transition-type galaxies appear to close the gap between the late-type and early-type dwarf galaxies at the low-luminosity end, possibly even indicating the existence of a continuum of faint, low-mass dwarf galaxies between the dIrr and dSph morphological classes.

4. PROPERTIES OF TRANSITION-TYPE DWARFS

Are the overall properties of transition-type galaxies consistent with their being progenitors of dSph galaxies?

4.1. *Absence of Rotation*

If the ratio of rotational velocity $v_{\rm rot}$ versus velocity dispersion σ is $\lesssim 1$, random motions rather than rotation dominate (e.g., Lo, Sargent, & Young 1993). This appears to be the case for all dSph's whose stellar kinematics have been studied to date.

In contrast to more massive dIrr's, most of the low-mass dIrr and dIrr/dSph galaxies show little evidence for rotational support; e.g., GR 8, Leo A, LGS 3, Sag DIG, and DDO 210 do not display systematic rotation in their H I gas (Lo et al. 1993; Young & Lo 1997). The H I cloud apparently associated with Phoenix has a small velocity gradient that may either be due to rotation ($v_{\rm rot}\,\sigma^{-1} = 1.7$) or due to ejection from the galaxy (St-Germain et al. 1999). Peg DIG also has $v_{\rm rot}\,\sigma^{-1} = 1.7$ (Lo et al. 1993). No such data are available yet for Antlia and KKR 25. These H I velocity field measurements are consistent with either no ordered circular motion or very low levels of rotation ($v_{\rm rot} \leq 5$ km s^{-1}), supporting close kinship between dSph's and dIrr/dSph's, although obviously observations of *stellar* kinematics are essential to confirm this point. The need for further measurements of stellar velocities to constrain rotation also applies to many of the Local Group dSph's (e.g., the M31 dSph companions).

4.2. *Distances and* H I *Masses*

Plotting the H I masses in Table 1 versus distance from the closest massive galaxy (col. [5] in Table 1), we see a tendency for H I masses to increase with galactocentric distance (Fig. 3). This trend was also noticed by Blitz & Robishaw (2000), who confirmed the finding by Knapp, Kerr, & Bowers (1978), that for dSph's H I mass upper limits fall well below 10^5 $M_\odot$. Only fairly large galaxies, such as the Magellanic Clouds, IC 10, and M33, with H I masses $\gg 10^7$ $M_\odot$, seem to be able to retain their gas reservoirs when closer than ~250 kpc to giants. We note that weak lensing measurements and dynamical modelling indicate typical dark matter halo scales of 260 h^{-1} (e.g., McKay et al. 2002), of similar order as the distance range discussed here. These H I–rich satellite galaxies are at least two orders of magnitude more massive than the dSph's. The one transition-type galaxy within this distance range of a larger neighbor is Antlia, which is believed to be tidally interacting with NGC 3109 (§ 5.2.2).

Beyond distances of ~250 kpc from the two Local Group giant galaxies, a number of dIrr's and transition-type

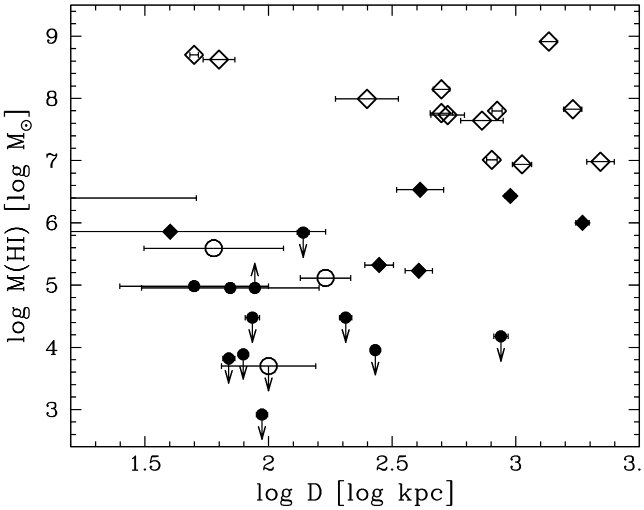

FIG. 3.—Dwarf galaxy H I mass versus distance to the nearest massive galaxy. The symbols are the same as in Fig. 1. Lower or upper H I mass limits are indicated by arrows. There is a general trend for the H I masses to increase with increasing distance from massive galaxies. DSph's lie typically below 10^5 $M_\odot$ in H I mass limits, while potential transition-type galaxies have H I masses of $\sim10^5$ to 10^7 $M_\odot$. DIrr galaxies usually exceed 10^7 $M_\odot$.

galaxies with substantial H I mass fractions are found. While the absence of such galaxies at smaller distances seems consistent with expectations from a distance-dependent ram-pressure/tidal-stripping scenario (see also § 5.2), we note that dIrr's and dSph's are seen throughout the Local Group, although very few dSph's at distances $\gtrsim$250 kpc are known. Environment cannot be the only factor responsible for the origin of dSph galaxies (see also Tamura & Hirashita 1999).

Detections of possibly associated H I clouds at distances of $\sim$10 kpc from the optical centers of five dSph's were reported by Blitz & Robishaw (2000; see Oosterloo, Da Costa, & Staveley-Smith 1996). Could these be former dIrr/dSph's, which were stripped recently?

For And V the claim of physically associated gas can be excluded because of a difference between the optical and H I radial velocity (Guhathakurta et al. 2000). Recent Arecibo observations did not confirm the earlier proposed H I detection near Leo I (Robishaw & Simon 2003, private communication). Matching the H I cloud seen projected in the vicinity of Tucana to this galaxy requires a measurement of an optical velocity, which is still missing. Oosterloo et al. (1996) consider it more likely that this cloud is either a high-velocity cloud or part of the Magellanic stream. The remaining two H I detections have velocities similar to the optical radial velocities of the adjacent dSph's, And III (Guhathakurta et al. 2000) and Sextans, which may indicate a connection with these dSph's, although the caveat of possible confusion with intergalactic gas clouds should be kept in mind.

None of the three dSph's with possibly associated H I (And III, Sextans, Tucana) contains either prominent intermediate-age (<10 Gyr) populations or young stars. The distances of these three dSph's from the closest spiral galaxy are $\sim$70 kpc (And III), $\sim$86 kpc (Sextans), and $\sim$870 kpc (Tucana); distance is not the common factor. Blitz & Robishaw (2000) suggest that ram-pressure stripping is the most probable cause for the removal of the gas, if the nearby H I clouds were indeed once part of the dSph's. However, at Tucana's location near the edge of the Local Group there is no obvious agent for ram-pressure stripping other than a hypothetical, highly inhomogeneous intergalactic medium (§ 5.2.3).

4.3. *Gas and Star Formation Histories*

The available data suggest that dSph's and transition dwarfs share similar star formation histories. Both contain substantial old stellar populations, with ages greater than 10 Gyr. A number of dSph's and all transition-type galaxies also contain intermediate-age populations (<10 Gyr). The present-day star formation activity in transition-type dwarfs, when present, occurs at low levels. Typical values are a few times 10^{-3} $M_\odot$ yr^{-1} (Mateo 1998), which are sufficient to produce the observed stellar populations, if continued over a cosmic time span. However, some transition dwarfs could exhaust the observed gas supplies in only a few gigayears, suggesting that, unlike the dIrr's, the transition-type galaxies may be approaching the end of their lives as actively star-forming galaxies.

In all cases the mean metallicities are low ($\langle$[Fe/H]$\rangle < -1$ dex). Metallicity spreads are observed among the red giant branch stars, indicating efficient enrichment processes within the old population and presumably similar modes of star formation. *The only significant difference between integrated properties of the classic dSph's and transition-type dwarfs appears to be the absence or presence of gas and the associated recent star formation rate.* We therefore may ask whether it is the presence or absence of gas that would be the norm in a small galaxy. Theoretical models support the former option; most dwarf galaxy models do not evolve to gas-free states (e.g., Mac Low & Ferrara 1999; Andersen & Burkert 2000; Carraro et al. 2001). In the remainder of this section we consider the observational case regarding this issue.

4.3.1. *Galaxies in Different Stages of Transition?*

A comparison of four well-studied low-mass dwarf galaxies provides a way to more closely examine relationships between dSph and transition-type galaxies.

The location of neutral gas in Peg DIG is well correlated with the optical structure of the galaxy, and H I concentrates near areas of recent star formation (Lo et al. 1993). Star formation in this dwarf galaxy at a distance of $\sim$410 kpc from M31 has continued at a roughly constant rate until today (Gallagher et al. 1998), and its H I mass is an order of magnitude higher than that in Phoenix and LGS 3. Despite its dIrr/dSph morphology this galaxy does not appear to be a likely progenitor of a dSph, since its properties are consistent with those of low-mass dIrr's.

The transition-type galaxy LGS 3 is at a distance of $\sim$280 kpc from both M31 and M33. It is unclear whether it is a companion of one of these spirals, but the larger mass of M31 implies that LGS 3 may belong to M31 (Miller et al. 2001). In optical images LGS 3 resembles Peg DIG. However, while the H I in LGS 3 is roughly symmetrically distributed around its optical center, its H I mass is only 1/10 of the stellar mass (Young & Lo 1997). LGS 3 formed the bulk of its stars very early on, and subsequent star formation proceeded at a continuous but decreasing rate (Miller et al. 2001).

Phoenix is a transition-type galaxy at a distance of ~400 kpc from the Milky Way. It experienced fairly continuous star formation until approximately 100–200 Myr ago (Holtzman, Smith, & Grillmair 2000), but, like LGS 3, appears to have formed most of its stars long ago. It is associated with an off-center, $\sim 10^5\ M_\odot$ H I cloud (St-Germain et al. 1999; Gallart et al. 2001). While the regular structure of this H I cloud argues against expulsion due to supernova explosions, Gallart et al. (2001) suggest that ongoing ram-pressure stripping may be removing the gas from Phoenix. More recent work (Irwin & Tolstoy 2002), however, shows that the velocity of the cloud and the optical velocity of the galaxy are in close agreement, making this scenario seem less likely.

The Fornax dSph (distance from the Milky Way ~ 140 kpc) contains a sizeable old stellar population, as evidenced through the detection of numerous RR Lyrae variables (Stetson, Hesser, & Smecker-Hane 1998; Bersier & Wood 2002). It is one of only two dSph's in the Local Group with ancient globular clusters (e.g., Buonanno et al. 1998), but the majority of its stars appear to be of intermediate age. Fornax experienced a decreasing level of star formation until stellar births ceased 100–200 Myr ago, making it the dSph with the most recent star formation (Stetson et al. 1998; Grebel & Stetson 1999). The nearby Fornax system is the largest, most massive, and most luminous galaxy of the four dwarfs discussed in this subsection, and it experienced the strongest chemical enrichment. That it contains a young population is unusual for a dSph and indicates that the removal of its star-forming interstellar medium must have occurred recently. The recent proper-motion estimate by Piatek et al. (2002) indicates that Fornax is currently close to perigalacticon and may be bound to the Local Group rather than to the Milky Way (see § 5.2.1).

Fornax, Phoenix, and LGS 3 closely resemble each other in several ways: all experienced star formation until 100–200 Myr ago; all have prominent intermediate-age populations, as evidenced by, e.g., their red clumps and subgiant branches; and they all have substantial old populations traced by well-populated horizontal branches. None of the three dwarfs shows evidence for rotation, and the H I mass in Phoenix and LGS 3 amounts only to a few $10^5\ M_\odot$. Phoenix and LGS 3 could easily pass as dSph's, if they did not contain measurable amounts of gas, and Phoenix may soon reach a dSph-like gas deficiency if its gas is indeed in the process of being removed. Do these three dwarfs, then, represent galaxies in different phases of transition into purely gas-free dSph systems?

4.3.2. *The Transition-Type Dwarf Candidates at Larger Distances*

Less detailed information is available for the other transition-type galaxies discussed in § 3, since observations of the depth needed to constrain star formation histories have yet to be made.

DDO 210 experienced star formation until ~100 Myr ago (Lee et al. 1999). While it does contain neutral gas, its H I is asymmetrically distributed with respect to the optical center of the galaxy; the H I is clumpy and shows a larger angular extent to the north (Lo et al. 1993). The H I comprises one-half or one-third of the estimated total mass of DDO 210.

KKR 25 is a very isolated transition-type galaxy at a distance of ~1.9 Mpc in the direction of the Hercules-Aquila void (Karachentsev et al. 2001). It resembles the other transition-type galaxies in stellar content. Its small H I mass is roughly half of its dynamical mass (leaving remarkably little room for a dense dark matter halo). Its star formation history is poorly known, owing to its distance. KKR 25, however, is an important object that has transition-type characteristics, but is very far from giant galaxies; its transition status presumably is intrinsic to the galaxy.

4.3.3. *Isolated dSph's*

While the trends in morphological properties, gas content, and in star formation history with distance appear to support a scenario in which transitions between low-mass galaxies are aided by environmental effects (see also van den Bergh 1994; Grebel 1997), this scenario cannot explain the existence of the gas-deficient dSph's Tucana and Cetus at large distances from the Local Group spirals. Both these dwarfs are dominated by old stellar populations and do not contain prominent intermediate-age or young populations. The star formation histories of these two dSph's indicate that their early evolution was governed by extended episodes of star formation that led to considerable metallicity spreads. These two dSph's even show radial population gradients in their old stellar populations, while Tucana may have a bimodal metallicity distribution that could be indicative of multiple starbursts (Harbeck et al. 2001; Sarajedini et al. 2002).

In the luminosity-metallicity diagram Tucana and Cetus are indistinguishable from other dSph's. Their existence demonstrates that present-day environment cannot be the only factor responsible for the existence of dSph galaxies.

5. GAS REMOVAL MECHANISMS

Observations and theory appear to agree in predicting that most dwarf galaxies should be able to retain a reasonable fraction of their primordial gas supplies. If evolution from transition-type dwarfs to dSph's is to occur, then effective mechanisms must exist to remove interstellar gas. In the following we briefly review several possible gas removal mechanisms.

5.1. *Internal Mechanisms*

5.1.1. *Gas Expulsion through Star Formation*

While star formation may certainly lead to galactic winds and significant metal losses from dwarf galaxies, numerical models indicate that star formation is unlikely to be a generally valid agent for the *complete* removal of gas. Stellar-powered blow-away of the entire interstellar medium is predicted to occur only in galaxies with total masses below $5 \times 10^6\ M_\odot$ (Burkert & Ruiz-Lapuente 1997; Hirashita 1999; Mac Low & Ferrara 1999; Andersen & Burkert 2000; Ferrara & Tolstoy 2000). However, no galaxies with such low total masses are known. The inferred total masses of dSph's comfortably exceed this limit, assuming that they contain dark matter (Mateo 1998). The assumption of internal virialization leads to essentially the same estimated dynamical mass for all Galactic dSph's ($10^7\ M_\odot$; Gallagher & Wyse 1994).

Furthermore, neither the transition-type dwarfs nor the dSph's show compelling evidence for the major starbursts needed to produce large-scale gas blowouts in their star formation histories (to the extent that such events would be resolvable). In particular, there is no evidence of dSph's whose star formation terminated after a major starburst. With the exception of the clearly episodic star formation history of the Carina dSph (Smecker-Hane 1997; Hurley-Keller, Mateo, & Nemec 1998) the star formation histories of dSph's are consistent with fairly continuous star formation whose rate subsided at recent times (see Grebel 1999, 2000 for reviews).

This is consistent with the existence of dwarf galaxies with apparently similar masses to those of the dSph's, but with substantial H I gas reservoirs (e.g., LGS 3, DDO 210, and KKR 25; Table 1). Moreover, the large metallicity spreads observed in a number of dSph's that are dominated by ancient star formation episodes (Shetrone et al. 2001, 2003; Ikuta & Arimoto 2002; Carigi, Hernandez, & Gilmore 2002), as well as radial gradients in old populations (Harbeck et al. 2001), indicate that dSph's were not only able to hold on to a significant amount of the metals that they produced, but also experienced extended ancient star formation episodes. Recent detailed analyses of the age-metallicity evolution favor leaky-box models (e.g., Smecker-Hane & McWilliam 2003) or even closed-box models (e.g., Tolstoy et al. 2003).

5.1.2. *Gas Exhaustion by Star Formation*

Davies & Phillips (1988) suggest that the gas in dSph's was consumed completely by star formation. However, star formation efficiencies are usually fairly low, typically in the range from 1% to 9% per event in Galactic giant molecular clouds (Carpenter 2000). Even though upper limits for the efficiency of low-mass star formation may reach 30% to 50% when the effects of massive stars are neglected (Matzner & McKee 2000), one expects to find that much of the gas remains after stars form. Thus, we observe the common pattern, where the mass of interstellar gas exceeds that of recently formed stars.

Furthermore, in order for star formation to occur, the gas density probably must exceed some critical value to produce gravitationally bound gas clouds where stars can condense. Galaxies with low gas pressure are dominated by warm neutral interstellar matter (ISM; with temperatures $\lesssim 10^4$ K). The gas can cool down and form molecular clouds only in regions with localized high pressure. In absence of shear and density waves, turbulence may locally lead to long-lived clumps with higher density (Elmegreen & Hunter 2000). In this model the condensation of stars occurs in local density peaks and ceases once the gas density becomes lower than some critical threshold for gravitational collapse (van Zee et al. 1997). This results in low global efficiency, scattered star formation that cannot consume all of the available star-forming gas.

A dwarf galaxy left on its own therefore should evolve into an object with little or no active star formation, even though significant amounts residual gas would remain (e.g., see models of Carraro et al. 2001).

5.1.3. *Gas Replenishment*

The absence of detectable amounts of interstellar gas in dSph's is surprising since the slow replenishment of the ISM naturally will occur due to mass ejected from stars in the course of their evolution. Stellar population models with normal initial mass functions and low metallicities show that stellar mass-loss rates decline as the population ages, scaling approximately as t^{-1} at late times (e.g., Jungwiert, Combes, & Paulouš 2001). The Schulz et al. (2002) simple stellar population models give a total mass return of ≈5% of the present day stellar mass in a system that is passively aging from 4–12 Gyr after its formation. Limits on the H I masses in dSph's typically lie in the range of 0.1% to 1% of the current stellar mass (see Table 1). Detectable amounts of H I then should build up in dSph's in at most a few gigayears if stellar mass loss is retained and becomes neutral (Young 2000). Yet this is not observed.

Hence, we face two substantial questions: How and why did dSph progenitors lose their initial supplies of gas? What prevented their refilling with gas lost by stars to the point where they could be detected in the recent, sensitive 21 cm H I line surveys (see also §§ 5.2 and 5.3)?

5.2. *External Mechanisms*

5.2.1. *Gas Removal through Ram-Pressure Stripping?*

Ram-pressure stripping long has been suspected of playing a major role in producing gas-deficient dSph galaxies (e.g., Eskridge 1988; van den Bergh 1994). In order for ram-pressure stripping to occur, the following condition has to be met (e.g., Gunn & Gott 1972):

$$P_{\rm ram} \sim \rho_{\rm IGM} v^2 > \frac{\sigma^2 \rho_{\rm gas}}{3} \ .$$

Here $P_{\rm ram}$ denotes the ram pressure, $\rho_{\rm IGM}$ the gas density in the intragalactic medium (IGM), v the velocity of the galaxy through the IGM, σ the galaxy's velocity dispersion, and $\rho_{\rm gas}$ its gas density. Use of this simple estimate for ram-pressure stripping is supported by numerical models (e.g., Mori & Burkert 2001; Quilis & Moore 2001).

Murali (2000) estimates a mean gaseous halo density of $n_{\rm H} < 10^{-5}$ cm^{-3} at 50 kpc from the Milky Way, which implies that at larger distances the Local Group IGM density should be even lower. Dwarf galaxy radial velocities set a lower limit for their space velocities, which likely do not exceed a few hundred kilometers per second in order for them to remain bound to the Milky Way or M31. Ram-pressure stripping is favored by proximity to giant galaxies, where halo gas densities may already exceed 10^{-4} cm^{-3} at distances of several tens of kiloparsecs (Stanimirović et al. 2002) and where relative orbital velocities will be highest.

Is the dSph Fornax (§ 4.3.1), then, a galaxy that could have experienced ram-pressure stripping recently? Piatek et al. (2002) suggest that Fornax is close to perigalacticon, that it has a large tangential velocity (310 ± 80 km s^{-1}), and that it may not be bound to the Milky Way. While the uncertainties of the proper motion measurement are still large, we use the resulting space velocity of Fornax, its stellar velocity dispersion of ~10 km s^{-1} (Mateo 1998), and $\rho_{\rm IGM} < 10^{-5}$ cm^{-3} to estimate the internal average gas density below which ram pressure stripping could have occurred: We find $\rho_{\rm gas} \lesssim 10^{-2}$ cm^{-3}, corresponding to an average column density of $\lesssim 10^{19}$ cm^{-2}. We note that the IGM gas density is a conservative upper limit, considering that Fornax is at ~3 times the distance of the Magellanic Stream. Moreover, Fornax's negative Galactocentric radial velocity indicates that is still approaching perigalacticon and has not yet passed through denser parts of the Galactic halo. Hence, it appears questionable whether ram-pressure stripping through a homogeneous gaseous medium could have removed Fornax's gas so efficiently.

Internal gas densities differ from dwarf galaxy to dwarf galaxy. In Phoenix, the *peak* H I column density is a few times $\sim 10^{19}$ cm^{-2} or $\rho_{\rm gas} \sim 3 \times 10^{-3}$ cm^{-3}. In low-mass dIrr's and dSph's the internal velocity dispersions are $\sigma \lesssim 10$ km s^{-1}. We assume furthermore that the IGM is homogeneous. Our order-of-magnitude estimate using the above formula shows that, for interstellar gas surface densities of $\sim 10^{19}$ cm^{-2}, the ram pressure is roughly balanced within a typical dwarf galaxy located in a galactic halo with $n_{\rm H} \sim 10^{-5}$ cm^{-3}. For galaxies with lower interstellar gas densities ram-pressure stripping in galactic halos becomes increasingly effective. Since dwarf galaxies usually have heterogeneous interstellar media with varying densities, ram pressure may strip gas from their least dense regions when they encounter a relatively dense gas in a halo or the IGM (see Bureau & Carignan 2002).

The present-day mean density of the IGM beyond galaxy halos in the Local Group is thought to be $n_{\rm H} \leq 10^{-5}$ cm^{-3}, which is too low to remove H I even from dIrr/dSph dwarfs (see Quilis & Moore 2001) unless peculiar velocities are very high. This problem is more severe for dIrr galaxies. For example, in Leo A, with its peak H I column densities of greater than 10^{20} cm^{-2}, ram pressure due to any uniform Local Group IGM will have little effect on the gas. So the question of how transition dwarfs (let alone dSph's) became as gas-poor as is observed today remains unanswered.

A partial solution to this problem possibly lies in the evolution of the Local Group IGM. In the past the IGM may have been denser and perhaps also clumpier. During the formation starbursts of giant galaxies, galactic winds would have been strong, giant galaxies probably had larger "spheres of influence" within which the IGM would be highly perturbed, and dwarf galaxies could be stripped (Hirashita, Kamaya, & Mineshige 1997; Scannapieco, Ferrara, & Broadhurst 2000).

An obvious shortcoming of models that rely on proximity to giant galaxies for gas removal from dwarf systems is the existence of the Cetus and Tucana dSph's far from the Milky Way and M31. One possibility is that both of these dwarfs once were near one of the Local Group giants, where they were stripped of their gas, but subsequently escaped toward their present locations. However, the time for them to reach their present-day locations from the inner Local Group would be 6 to 10 Gyr for a space velocity of 100 km s^{-1}, and so gas refill from stellar mass loss is an issue (§ 5.1.3).

This difficulty might be overcome if, following stripping of an unbound dwarf galaxy in a close passage near a giant, the Local Group IGM could remove stellar mass loss as it is injected. A rough estimate can be made by assuming that stellar mass loss fills an initially gas-free dwarf in a sound crossing time of 100 to 300 Myr. In this case the gas density within a dwarf like Cetus or Tucana is $\lesssim 10^{-5}$ cm^{-3}, with an ISM mass corresponding to about 1000 $M_\odot$. Even a very low density IGM with $\rho_{\rm IGM} \sim 10^{-7}$ should be able to produce ram-pressure stripping under these conditions in the few hundred megayear timescale.

5.2.2. *Tidal Stripping in Progress?*

Apart from ram-pressure stripping, tidal stripping may be a valid mechanism to rid low-mass galaxies of their gas, *if* their orbits bring them near enough to massive galaxies. The dIrr/dSph galaxy Antlia is a close ($\geq$40 kpc) companion of the more massive, gas-rich dIrr NGC 3109 (van den Bergh 1999b). Antlia appears to have had a close encounter with NGC 3109 about 1 Gyr ago, which caused a warp in the disk of NGC 3109 (Barnes & de Blok 2001). It now has a low H I mass of $\sim 7 \times 10^5$ $M_\odot$. How much gas was lost from Antlia during the encounter is unknown, but Antlia may be a good candidate for tidal gas stripping.

However, tidal stripping does not seem to be a universally valid agent for the removal of gas, unless the more distant dSph and transition-type systems are on extremely eccentric orbits. And even in this case replenishment of their interstellar medium by mass lost from evolving stars will likely present a problem because of the long time interval between any hypothetical perigalacticon passages. An example of a gas-devoid dSph that shows no signature of tidal stripping is the strongly dark-matter–dominated, nearby Milky Way satellite Draco (Odenkirchen et al. 2001), one of the closest Galactic dSph's.

5.2.3. *Stripping by the Local Group IGM?*

An alternative possibility for explaining the free-flying Local Group dSph's could be an inhomogeneous IGM. If the IGM is heterogeneous and contains regions where $n_{\rm H} > 10^{-5}$ cm^{-3}, then encounters with such clumps could remove H I gas in proto-dSph's that are far from giant galaxies. The details will depend on the geometry of the encounter. Robishaw, Simon, & Blitz (2002) propose that the high-velocity cloud seen near LGS 3, which is kinematically distinct from this galaxy, may have tidally interacted with LGS 3 during a passage $\sim 10^8$ yr ago. It has been suggested that the supergiant H I shell structure observed in the dIrr NGC 6822 may have been caused by interaction with a massive H I cloud (de Blok & Walter 2000). This idea was also suggested as a model for the off-center H I in the Phoenix dSph/dIrr by Gallart et al. (2001), and it remains a viable option even after the Irwin & Tolstoy (2002) revision of the galaxy's radial velocity. The necessary structure in the Local Group IGM could result, for example, from disturbances associated with the passage of galaxies through the IGM (see Silk, Wyse, & Shields 1987). Another possibility is that initial rapid stripping of gas from some dwarfs occurred at relatively early times, when the IGM may have been denser and more highly clumped.

Is there evidence for a heterogeneous IGM in the Local Group? High-velocity clouds appear to be mostly local objects in close proximity (i.e., within several kiloparsecs) to massive galaxies such as the Milky Way (Wakker 2001), which makes them unlikely agents for stripping of the more distant dSph galaxies. Compact high-velocity clouds may be at larger distances (e.g., Braun & Burton 2001), but recent HIPASS results (Putman et al. 2002) imply that they are largely part of local features, such as the Magellanic Stream. As such they may be capable of affecting nearby dSph's. Previously reported H I clouds without optical counterparts in galaxy clusters could not be confirmed (van Driel et al. 2002 and references therein). Searches of nearby groups of galaxies for H I clouds down to masses of 3×10^6 $M_\odot$ yielded nondetections (de Blok et al. 2002), indicating that the present-day IGM is not usually clumpy on these mass and density scales. The lowest column density limits reached so far are $\sim 10^{18}$ cm^{-2} (Zwaan 2001, corresponding to upper bound density limits of a few times 10^{-4} cm^{-3} if sizes of 1 kpc are assumed), which appears to render a highly clumpy IGM at the present epoch less likely. Less massive clumps or more widespread IGM inhomogeneities at earlier epochs, however, are not ruled out.

At low densities the IGM will be photoionized by the UV background radiation in combination with any local sources. Gas in this regime will not show up in H I surveys. However, UV and X-ray line studies can find such material through its line absorption if it contains metals. Recent UV and X-ray absorption-line studies suggest that intermediate-temperature ionized gas is present in galaxy groups, with local densities perhaps as high as 10^{-4} cm^{-3} (Fang et al. 2002; Nicastro et al. 2002; Sembach et al. 2003). The origin of such features is not fully established, but they are most likely due to a combination of cosmic-structure growth and disturbances associated with galaxies (e.g., Oort 1970; Davé et al. 2001).

5.3. *Ionized Gas*

The absence of neutral gas does not exclude the presence of ionized gas in dSph's, and so surveys also have been made for diffuse ionized gas in a few dSph. An ultraviolet absorption-line search for an ionized corona with $\geq 10^5$ K around the dSph Leo I, which experienced star formation until $\sim$2 Gyr ago, was unsuccessful (Bowen et al. 1997; column density limit less than 2×10^{17} cm^{-2}). Similarly, a search for a 10^6 K component in the dSph Fornax, where star formation ceased 100–200 Myr ago, yielded no detection (Gizis, Mould, & Djorgovski 1993).

However, gas may be present at lower ionization levels (associated with gas at $T \leq 10^4$ K) and hence have escaped detection. Such gas would likely have a kinetic temperature comparable to the velocity dispersion of the dSph's and stay bound to the dSph's. Sources of ionization would include the distance-dependent Galactic UV radiation field, which would work for dSph's within a few hundred kiloparsec distance from massive spiral galaxies, or recent star formation events (Lin & Murray 1998; Mashchenko, Carignan, & Bouchard 2002). Internal sources of ionization that could operate in isolated dSph's, such as Tucana and Cetus, include SNe Ia heating (Burkert & Ruiz-Lapuente 1997), hot white dwarfs (Dupree & Raymond 1983), or UV-bright postasymptotic giant branch stars (de Boer 1985).

Ionized gas at $\sim 10^4$ K would not have been seen in previous surveys, and even the most sensitive emission-line observations can detect only relatively large amounts of diffusely distributed ionized gas in Galactic dSph's. Such a gas component, if it exists and if it accounts for a significant fraction of the missing ISM in dSph's, would avoid the problem of finding gas *removal* mechanisms.

One would then still be faced with the question of explaining why certain dwarfs, the dIrr's and some dE's, contain neutral gas, while the ISM remains fully ionized in others with fewer OB stars or other obvious internal ionization sources. However, if the ISM *were* to become ionized in dSph's, then it would expand, have lower densities, and therefore would be more vulnerable to ram-pressure stripping. Such a process may have occurred during the reionization of the universe, potentially cutting off the supplies of gas for star formation in dwarf galaxies (see Thoul & Weinberg 1996; Barkana & Loeb 1999; Bullock et al. 2000). However, if this effect were too widespread, then it would not be consistent with the wide range of stellar population ages and gas content found in many Local Group dwarfs. We plan to return to a discussion of this issue in a later paper.

5.4. *Gas Removal Summary*

Evidently, small galaxies might lose their gas early on because of the effects of reionization, or they could be stripped of gas when they venture too close to a giant galaxy, particularly if it is in a starburst phase, as may have been common when galaxies were young. Near the present-day Local Group giants the combination of tides and ram-pressure stripping, likely with the aid of leaking ionizing radiation (Mashchenko et al. 2002), can clean gas from small galaxies. We further expect that galaxies with relatively low masses and less ISM will be more readily relieved of their gas when in proximity to giant systems. Thus, in the giant galaxy–stripping model dwarf galaxies that evolved into nearly gas-free states as they came near a giant galaxy were most readily converted into dSph's. This model predicts that *no* gas-free dSph's should be found outside of galaxy groups, and none are known at the present time. The intermediate cases presented by Tucana and Cetus, dSph's far from any large galaxies, then, are critical. They either may be runaways from the inner Local Group, or, if the IGM is clumpy, stripped by dense areas of the Local Group's IGM.

6. SUMMARY AND CONCLUSIONS

When dSph's formed most of their stars, they must have contained substantial amounts of interstellar gas and would presumably have resembled present-day dIrr's or related classes of galaxies. Yet somehow star formation ceased and gas was lost, and these objects evolved into dSph's. That this process took place at different times is clear from the range in mean stellar population ages in the nearby dSph galaxies. Continuity, then, suggests that the birth of dSph's should be an ongoing process and that " pre-dSph " galaxies may exist in or near the Local Group. This leads to the question of whether plausible dSph progenitors can be identified among well-studied dwarf galaxies with resolved stellar populations in our immediate cosmic neighborhood, and whether evidence exists for a continuing transformation from gas-rich to gas-poor dwarfs. An alternative scenario would be that dSph's form a separate class of their own, with properties predefined at birth, as suggested by Binggeli (1994) and supported by Skillman & Bender (1995).

Our analysis of the luminosity-metallicity relation based on chemical abundances of red giants shows the well-known separation between dIrr's and dSph's in the sense that dIrr's are too metal-poor for their luminosity as compared with dSph's. Mere fading would not turn typical dIrr's into typical dSph's, since they would also fade in surface brightness, resulting in surface brightnesses below those of dSph's at the same luminosity. Conversely, the rapid initial enrichment that old populations in dSph's experienced is not observed in dIrr's, where star formation and enrichment proceed slowly over a Hubble time. The dIrr's also would need to lose their angular momentum and interstellar medium, since neither rotation nor gas are detected in typical dSph's. Hence, transformation from dIrr's to dSph's through gas loss alone appears to be unlikely, and in this regard our conclusions parallel those of a number of earlier studies (e.g., Binggeli 1986; Thuan 1986).

The dIrr/dSph transition-type galaxies exhibit stellar and optical structural properties consistent with those of dSph's, while containing H I gas. The dIrr/dSph systems also fall near the dSph locus in the luminosity-metallicity relation. Like dSph's, they show very little or, more commonly, no rotation in their H I and have stellar populations whose properties closely resemble those in a number of dSph's. Their present-day star formation rates are very low, and a complete cessation of stellar births would not significantly alter their position in the luminosity-metallicity diagram. The transition-type dwarfs appear to be gas-rich examples of dSph systems. As none is in danger of complete gas exhaustion due to ongoing star formation, a gas-cleaning process seems necessary to convert them into dSph's. Evidently early astration was comparatively rapid in both transition-type and dSph galaxies, so their internal conditions near the time of their formation were probably factors in defining their subsequent evolution. We therefore find the transition-type dwarfs to constitute plausible progenitors of dSph's.

We briefly considered various mechanisms whereby dwarfs could lose their interstellar matter and discussed possible examples of ongoing gas removal. Intrinsic processes currently seem to play a negligible role, and tidal effects alone appear to be incapable of having completely removed the gas from dSph's (unless the dSph orbits, which are still unknown, are highly eccentric and we have missed the rare gas-stripping episodes; see Mayer et al. 2001a, 2001b). The most plausible generic gas removal mechanism appears to be ram-pressure stripping, and at present this will be effective in removing primordial gas reserves only when dwarfs pass near giant galaxies. This, in combination with tidal effects, may explain the clustering of dSph's around the Local Group spirals. We discuss the case of the dSph Fornax, which lost its gas during the past 100 Myr and which is approaching its perigalacticon, but find ram-pressure stripping through a homogeneous IGM to be little likely to be responsible for the removal of Fornax's ISM.

Beyond the halos of spirals a smooth Local Group IGM, with its low estimated upper limit gas density of $n_{\rm H} < 10^{-5}$ cm^{-3}, will have little impact on the typical H I disks of even small dwarfs (see § 5.2.1 and Mayer et al. 2001a). Yet we find a mixture of gas-deficient dSph's (Cetus and Tucana) along with gassy dIrr galaxies in the outer regions of the Local Group. Due to gas return from dying stars, some process must act to have kept neutral gas from collecting in the outer Local Group dSph's, even if they were stripped of gas during a close passage to a spiral or some other past anomalous event. We find that a low-density IGM can keep stellar mass loss from collecting. We also speculate that inhomogeneities in the Local Group IGM, such that some regions have densities of $n_{\rm H} > 10^{-5}$ cm^{-3}, could strip dwarfs with low intrinsic gas densities. This option receives support from recent indications for inhomogeneities in the Local Group IGM derived from ultraviolet and X-ray absorption-line measurements. The Local Group gas-stripping scenario implies that gas-free dwarf galaxies will not be found in locations without an IGM; isolated dSph galaxies outside of groups or clusters of galaxies should not exist.

Alternatively, some of the missing gas in dSph's may simply be ionized and at temperatures near 10^4 K, which would explain why it was not detected in H I 21 cm line surveys or in UV absorption-line studies. A combination of background and internal stellar ionization sources will be sufficient to sustain a relatively massive ionized interstellar medium, even in isolated, H I–deficient dSph's, such as Tucana. Sensitive Fabry-Pérot techniques may make the detection of ionized interstellar matter in dSph's possible, if such gas exists (Gallagher et al. 2003). Since ionization will reduce gas densities (and gravitational binding energies), it would also make it easier to strip interstellar matter from dwarfs. A combination of ionization and low-level ram-pressure stripping should prevent the accumulation of gas lost from evolving stars in Local Group dSph's.

Environmental effects clearly have played a role in shaping the morphology-distance relation and the gas content of dwarf galaxies, but they are certainly not the sole determining factor. For instance, while the gas content of low-mass dwarfs increases with increasing distance from a massive galaxy, transition-type dwarf galaxies, with their low H I masses, exist both in the wider surroundings of massive galaxies as well as in the field. Furthermore, the current environment may have little connection with the formation of isolated dSph's like Tucana or Cetus. In this picture the Local Group dSph galaxies arose from a combination of factors. One parameter is closeness to one of the giant galaxies, but we argue that "genetics" is also important. The metallicities in older stars in dSph's suggest relatively rapid initial and mid-life star formation depleted gas supplies, making them vulnerable to stripping. Transition dwarf dIrr/dSph's, then, are examples of this class of galaxy that have retained their cool gas, while the more leisurely evolving dIrr's are distinguished by having more gas and angular momentum, while being less chemically evolved.

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