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Invited Review Paper

Dwarf Spheroidal Galaxies: Keystones of Galaxy Evolution

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ABSTRACT. Dwarf spheroidal galaxies are the most insignificant extragalactic stellar systems in terms of their visibility, but potentially very significant in terms of their role in the formation and evolution of much more luminous galaxies. We discuss the present observational data and their implications for theories of the formation and evolution of both dwarf and giant galaxies. The putative dark-matter content of these low-surface-brightness systems is of particular interest, as is their chemical evolution. Surveys for new dwarf spheroidals hidden behind the stars of our Galaxy and those which are not bound to giant galaxies may give new clues as to the origins of this unique class of galaxy.

1. INTRODUCTION

The astrophysical significance of small extragalactic systems, the dwarf and related classes of galaxies, remains unclear (Hodge 1971). Did these galaxies once lie along the main path of galaxy formation, or are they merely collections of leftover matter produced by secondary processes? Are they strongly bound, or are they dissolving in the Galactic tidal field? (Hodge 1964; Hodge and Michie 1969). Cold dark matter (CDM) models for galaxy formation have served to focus these issues. In CDM, low-mass galaxies would be the first objects to become bound and drop out of the expanding Universe (Blumenthal et al. 1984).

In general, these small systems should not have survived to the present day, but should be subsumed into larger systems (White and Rees 1978; Moore et al. 1993), or, more correctly, their dissipationless dark halos should have merged, with the fate of the visible galaxy being very uncertain (Lacey and Cole 1993; Kaufmann and White 1993). The baryonic material will keep its separate identity only if it has dissipated enough energy to be more tightly bound than the next level of the hierarchy (White 1983; Cen and Ostriker 1993); this may indeed be the case (Navarro et al. 1994). The ideas of the CDM model lead naturally to the question of whether dark-matter-dominated, low-mass galaxies exist in nature, and to the build-up of luminous galaxies like the Milky Way by merging of substructure (e.g., reviewed by Silk and Wyse 1993). Extracting the merging history—and future—of the Milky Way Galaxy may be possible by study of satellite galaxies.

As a result there have been renewed efforts to measure the spatial distributions, dynamics, structures, and other properties of low-mass galaxies in a variety of environments (Faber and Lin 1983; Lin and Faber 1983; Thuan et al. 1987; Eder et al. 1989; Puche and Carignan 1991; Vader and Sandage 1991; Ferguson and Sandage 1990), including low-surface-brightness galaxies (Disney and Phillipps 1987; Impey et al. 1988; Schombert et al. 1992; Sandage et al. 1985; Karachentseva et al. 1984). The advent of automated plate-measuring machines and large-format CCDs coupled to multi-object spectrographs has resulted in data for large numbers of individual stars in several of the Galactic dwarf spheroidal (dSph) systems, together with rigorous searches for more companions to our Galaxy.

Satellite galaxies at high Galactic latitude may often be found by simply plotting stellar surface density contours projected on the sky. For example, the dwarf galaxy discovered in the Sextans constellation, latitude $b=42.3$, by Irwin et al. (1990) is clearly seen in their Fig. 1(b), which plots all stellar objects down to the plate limit ($B_J \sim 22.5$); note the paucity of objects classified as stars—the contours plotted start at 1.5 images/arcmin^2 and increase in steps of 0.5 images/arcmin^2. The dwarf has an angular extent of a degree or so. Dwarf galaxies could be hiding at lower latitudes, where there is sufficient foreground disk that the over-density of the satellite is too small a perturbation to be detected by a simple sum of all stellar images. An example of this is the Sagittarius

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dwarf, recently discovered (Ibata et al. 1994) as part of a survey of the kinematics of the bulge (Gilmore and Ibata 1994). The dwarf initially manifested itself as a moving group, with very distinct kinematics from the bulge, and rather localized in angular position. The color–magnitude diagram of the field where the moving group is seen kinematically contains a fairly obvious core-helium-burning red "clump," indicative of an intermediate-age population, and giant branch, which are not detected in those fields where the stars have normal bulge kinematics. Isolating stellar images which have the color and apparent magnitude of the clump, and plotting isodensity contours of the difference between the "moving group" field and an offset field, revealed the spatially extended dwarf galaxy (Ibata et al. 1994). The isophotes are very aspherical, suggestive of tidal stresses. The distance to the dwarf may be estimated from the clump/HB magnitude, resulting in a position ~12 kpc from the Galactic center on the other side of the Galaxy, ~5 kpc below the disk plane. The dwarf is inferred to be rather massive, similar to the Fornax dwarf galaxy, from application of the observed luminosity–metallicity relation of the extant satellite galaxies (Caldwell et al. 1992), and from the red clump/giant population. At least three globular clusters have kinematics and distances that are suggestive of their being physically associated with the dwarf galaxy. Follow-up deep photometry has confirmed the dSph nature of the Sagittarius dwarf and the intermediate age, ~10 Gyr (Mateo et al. 1994).

Multiobject spectroscopy on large telescopes has provided radial velocities and chemical abundances for large enough samples of stars in the Galactic dSph to begin to make quantitative analyses of the internal dynamics and enrichment histories, while deep, large-area color–magnitude diagrams allow the dSph stellar populations to be disentangled from the foreground Galaxy. Proper motions of the Galactic-companion dSph are beginning to become available, and will constrain the orbits of these objects. Searches for low-surface-brightness dwarfs beyond the Local Group using large-format CCDs should reveal counterparts to the local dSph; large-area photometric surveys such as the Sloan Digital Sky Survey will provide ideal datasets for identification of dSph. This review aims to put these new and anticipated results in context.

The least-massive known galaxies are the dSph systems. The dSph galaxies exist at a key position in the hierarchy of spheroidal stellar systems—although as we discuss further below, whether or not they are bound is open to question. In some properties they appear to be the logical extension of the diffuse dE galaxy structural family to low luminosities (Wirth and Gallagher 1984; Kormendy 1985), and yet in some respects also resemble low-luminosity disk galaxies (Kormendy 1987). Additionally, they overlap in luminosity with the more massive globular star clusters such as 47 Tuc or Omega Centauri (Webbink 1985).

However, despite their similarities in total stellar luminosities, dSph galaxies and globular cluster have dramatically different structures (de Carvalho and Djorgovski 1992). Globulars are centrally concentrated and have central stellar densities, even in the relatively unconcentrated Palomar globulars, that are >100 times the central stellar densities of the much more diffuse dSph galaxies (Webbink 1985; Djorgovski 1993). A wide-field image of the Ursa Minor dSph is shown in Fig. 1. Indeed, our current understanding of star formation suggests that the stars in dSph could not have formed at the currently observed low stellar densities. Evidently something happened between the epoch of star formation and now, a "something" that is most probably related to the inferred low escape velocities of these diffuse systems (Dekel and Silk 1986). The presence of globular star clusters in the Fornax dSph demonstrates that at least this dSph is a true galaxy, and extends the trend for all known globular star clusters to be bound to galaxies (although the search for truly intergalactic globular clusters continues; Arp and Madore 1979). The significance of the fact that the Fornax dwarf has many more globular clusters per unit galaxy luminosity than expected from normal galaxies is not clear, although perhaps the lower tidal field and lack of other internal destruction mechanisms could be a factor (Rodgers and Roberts 1994).

Equilibrium dynamical models which require large dark-matter densities have now been constructed for several dSph galaxies, being most extreme (in terms of mass-to-light ratio), for the Draco and Ursa Minor galaxies (Lake 1990a; Pryor and Kormendy 1990). In an insightful pair of papers Faber and Lin (1983) and Lin and Faber (1983) suggested that the presence of a dominant dark-matter component is the key feature which distinguishes galaxies from star clusters (luminous mass cannot be the crucial factor) and that all small galaxies have similar and large dark-matter components. Since the publication of these papers evidence has been mounting for dark matter in the dwarf *irregular* galaxies, with the trend that lower-luminosity disk systems (Sc and later) have relatively more dark matter (Puche and Carignan 1991; Ashman et al. 1993). It is tempting to identify the dSph galaxies as the gas-poor counterparts of irregulars, but many questions remain, some of which we address in this review.

A summary of the currently known galaxies in the Local Group is given in Table 1 (based on van den Bergh 1992). The membership of the Local Group also becomes uncertain at larger distances, e.g., for galaxies like Leo A (see van den Bergh 1994; Hoessel et al. 1994).

We define a dSph to be a galaxy with a total luminosity of $M_B > -14$, low optical surface brightness (fainter than 22 V mag per square arcsec) and no nucleus. Note that this definition excludes NGC 205, NGC 147, NGC 185 and many of the elliptical dwarfs found in the Virgo cluster, even those of low surface brightness (Binggeli and Cameron 1991). In particular, *bona fide* dSph galaxies, and certainly all dSph systems for which we will have good dynamical models in the near future, are located near the Milky Way and M31, two massive spirals. The close association between the dSph dwarfs and massive galaxies has a number of significant consequences which have been individually discussed in the literature during the past decade. In this paper we will (1) revisit the implications of the satellite status of Galactic dSph systems, especially in terms of the assumption of dynamical equilibrium; (2) consider why such connections might occur between dwarf and giant galaxies; and (3) emphasize the importance of resolving these questions.

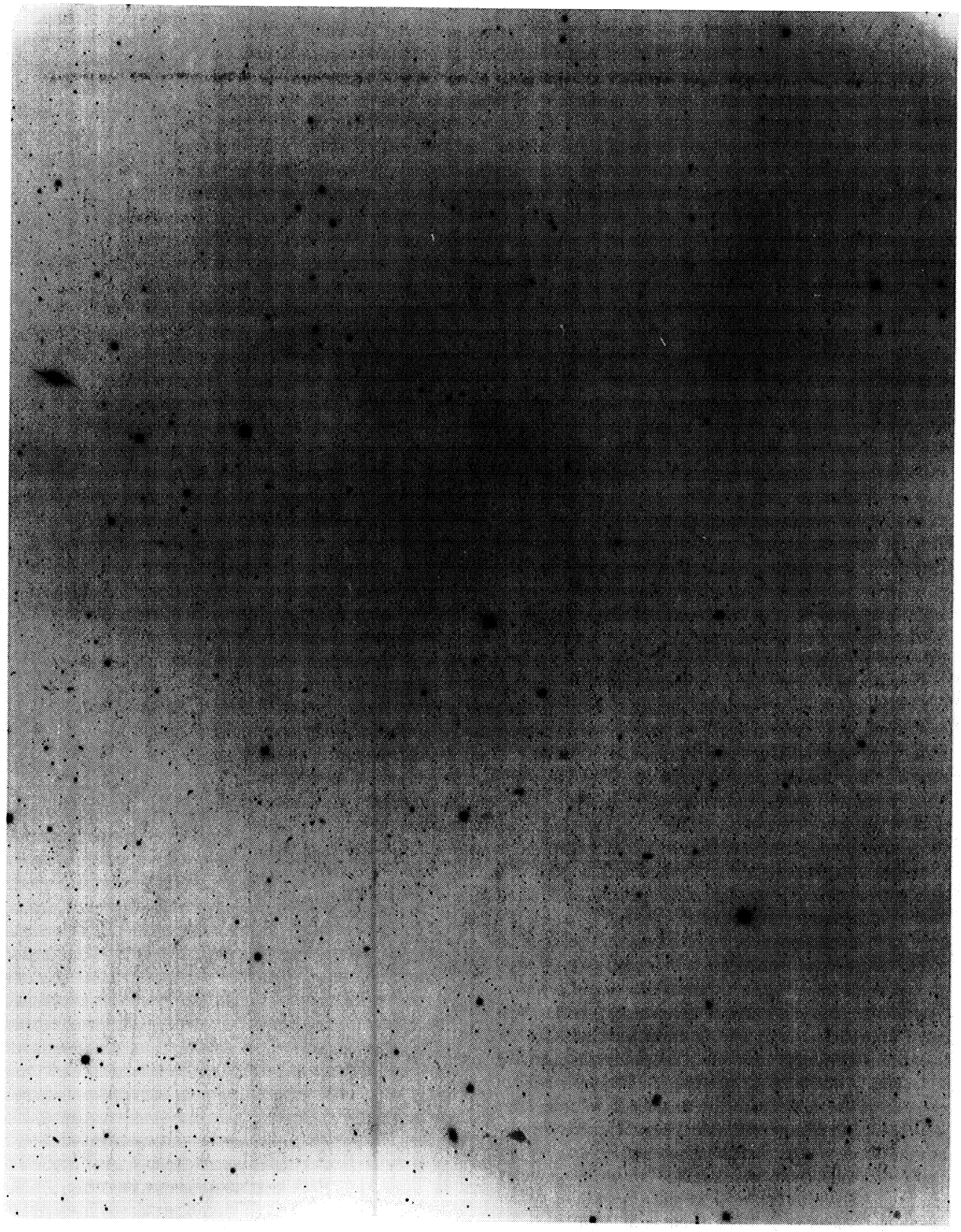

FIG. 1—This print is from a IIIa-J plate taken with the Kitt Peak 4-m Mayall telescope as part of an ongoing astrometric program. It shows the diffuse cloud of stars which mark the main body of the Ursa Minor dSph. The orientation is north up and east to the left; a more detailed finding image can be found in Cudworth et al. (1986). The dSph galaxies are difficult to detect when individual stars are unresolved due to their very low optical surface brightnesses, and yet the optical may be the best waveband for finding this type of purely stellar galaxy. (Courtesy of K. Cudworth, Yerkes Observatory.)

TABLE 1
The Local Group

	ID	Type	M_V
Giants:			
	M31=NGC 224	Sb I-II	−21.1
	Milky Way	SABb/c	−20.6
	M33=NGC 598	Sc II-III	−18.9
	LMC	Im III-IV	−18.1
Gas-rich dwarfs:			
	NGC 6822	Im IV-V	−16.4
	SMC	Im IV-V	−16.2
	IC1613	Im V	−14.9
	WLM	Im IV-V	−14.1
	DDO 210	Im V	−11.5
	LGS 3	dIm/dSph	−10.2
	Phoenix	dIm/dSph	−9.5
Gas-poor dwarfs:			
	M32=NGC221	E2	−16.4
	NGC 205	dE	−16.3
	NGC 185	dE	−15.3
	NGC 147	dE	−15.1
	Fornax	dSph	−13.7
	Sagittarius	dSph	−13::
	And I	dSph	−11.8
	And II	dSph	−11.8
	Leo I	dSph	−11.7
	Sculptor	dSph	−10.7
	And III	dSph	−10.3
	Sextans	dSph	−10.0
	Leo II	dSph	−9.9
	Tucana	dSph	−9.5
	Carina	dSph	−9.2
	Ursa Minor	dSph	−8.9
	Draco	dSph	−8.5

2. BASIC PROPERTIES OF dSph GALAXIES

Recent papers by, among others, Da Costa (1992), Caldwell et al. (1992), Mateo et al. (1993), Zinn (1993), and Kormendy and Bender (1994) provide good overviews of dSph galaxies. Properties of the Galactic dSph systems can be divided into three main areas consisting of structural parameters (mass, size, internal kinematics), stellar populations (ages, chemical elemental abundances, binary star fractions, gas content), and environment factors (orbits, correlations between internal properties and Galactocentric radius). A summary of basic dSph characteristics drawn from the current literature (Hodge 1982; Zaritsky et al. 1989; Demers and Irwin 1993; Lehnert et al. 1992) is given in Table 2.

2.1 Structure

The dSph are apparently ellipsoidal galaxies of low central surface brightness. Their stellar density profiles, like those of other dE systems, are fit either with low central-concentration King models or with exponential disks having scale lengths of 100–400 pc (see Fig. 2). The outer radii of these systems are difficult to determine due to their large angular sizes and faintnesses. Visual central surface brightnesses are in the range of 22–26 mag/arcsec^2 and are not strongly correlated with the absolute visual magnitudes, which extend down to $M_V = -9$ for the Ursa Minor system (Lake 1990a; Mateo et al. 1993; Nieto et al. 1990).

The dSph, like other dEs, are in one way more "disky" than even spirals. Where van der Kruit and Searle (1982) have found the exponential stellar disks of spirals often end rather abruptly after about five scale lengths, the Andromeda dSph remain exponential in form out to nearly seven scale lengths, where they are lost into the sky background (Arman-

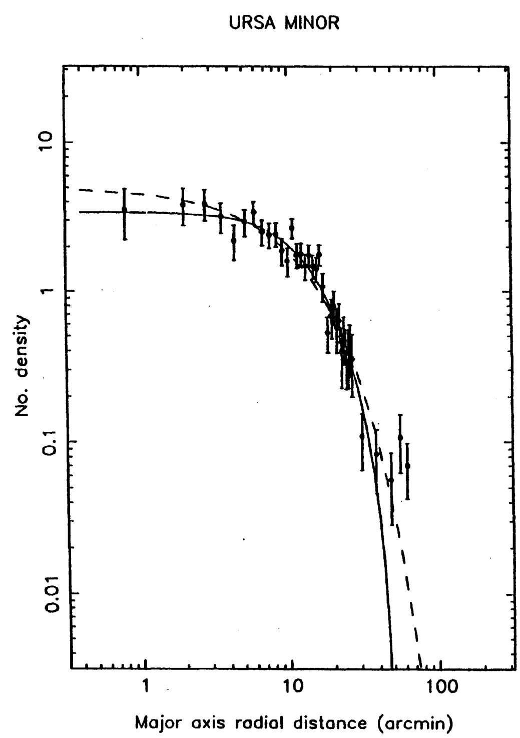

FIG. 2—Shown above is the mean radial-stellar-density profile for the Ursa Minor dSph as presented by Hargreaves et al. (1994a), copyright 1994, Royal Astronomical Society; reproduced with permission on the basis of measurements by M. Irwin and D. Hatzidimitriou (in preparation) with the Cambridge APM. The solid line is a King model fit which shows a core and outer tidal cutoff with a possible excess of stars. The dotted line is an exponential profile fit.

TABLE 2
dSph Properties

Galaxy	D_G	M_V	μ_0	V_r	σ_v	[Me/H]	Age
Carina	93	−9.2	...	14	6	−1.5	Int–Old
Draco	75	−8.5	...	−95	9	−1.6 - −2.4	Old
Fornax	140	−13.7	23.2	−34	10	−1.0 - −1.8	Int–Old
Leo I	270	−11.7	22.3	177	...	−1.3	Int–Old
Leo II	215	−9.9	23.8:	16	...	−1.9	Old:
Sagittarius	12::	−13::	25.4	176	...	−1.2	Int
Sculptor	79	−10.7	24.1	74	7	−1.5 - −2.0	Old
Sextans	85	−10.0	25.5	78	6	−1.7 - −2.5	...
Ursa Minor	65	−8.9	25.1	−88	11	−2.2	Old

Notes: D_G is the Galactocentric distance in kpc, μ_0 is central surface brightness in V mag/square arcsec, V_r is the Galactocentric radial velocity in km/s and σ_v is the observed stellar velocity dispersion in km/s. Distances and radial velocities are from Zaritsky et al. (1989), except for Leo II (Lee et al. 1993), Sagittarius (Ibata, Gilmore and Irwin 1994), and Sextans (Irwin et al. 1990; da Costa et al. 1991). The M_V are from van den Bergh (1992), with the exceptions of the Sagittarius dwarf (Ibata, Gilmore and Irwin 1994) and Leo II (Demers and Irwin 1993); small differences are found in tabluations of M_V but given the uncertainties of typically 0.3 mag for measurements of these low-surface-brightness systems (e.g., see Hodge 1982; da Costa et al. 1991), these dominate over most of the stated distance uncertainties. The surface brightness of the Sagittarius dwarf is taken from Mateo *et al.* (1994). Abundances are from the literature and include results from spectroscopy of individual stars (e.g., Lehnert et al. 1992) and derivations based on giant branch properties (e.g., Lee et al. 1993). Stellar population ages are our assessments based on the current literature where stellar populations with ages of $\leq$ 10 Gyr are classified as intermediate age.

droff et al. 1993). The presence of such smooth edges in dSph and dE galaxies are not understood, but could be a symptom of the effects of tidal heating (Aguilar and White 1986). However, it should be remembered that perhaps as many as ten orbits are required before a tidal radius is well defined, with no sustained memory of the initial radius (Seitzer 1985), and the dSph are sufficiently distant that this is a substantial fraction of a Hubble time. The (projected) axial ratios of the dSph are in the range of $0 \lesssim (1-b/a) \lesssim 0.6$ (Hodge 1971; Caldwell et al. 1992), and are not very different from the range seen in dwarf irregular galaxies (Lin and Faber 1983; note that the axial ratios of the dSph may be due in part to tidal stretching, as discussed below).

Internal kinematics are now available for most of the known Galactic dSph galaxies from high precision observations of radial velocities of individual stars, with more data being analyzed. Several points stand out from the current kinematic data (Kormendy 1985; Pryor and Kormendy 1990; Ashman 1992; Freeman 1993; Suntzeff et al. 1993; Hargreaves et al. 1994a,b):

(1) The central velocity data can be fit by a simple Gaussian projected-velocity distribution function, but it is not yet established that this distribution is independent of location within the galaxy, though this is the model generally used. The spatial variation of the internal stellar kinematics is of great importance in constraining dynamical models, but the data analyzed to date have not allowed any strong conclusions; data which several research groups have in hand should be capable of distinguishing dark-matter models.

(2) All of the dSph central velocity dispersions are in the 5–12 km s^{-1} range. This is near the magic velocity dispersion of young stars and H I gas in the thin disks of spirals (van der Kruit and Shostak 1984), generally believed to have something to do with hydrogen cooling at $T<10{,}000$ K, and to the stellar velocity dispersions in globular star clusters (Illingworth 1976), but is larger than the velocity dispersions of typical OB associations. The velocity dispersions also do not correlate with optical luminosities. If interpreted using the virial theorem, the conclusion is that the dSph all have approximately the same mass, while their luminosities span a wide range.

(3) There is no evidence for rotational support to very low levels in some of the dSph for which suitable spatially resolved kinematic data are available, such that $v/\sigma<0.3$ in the Fornax (Freeman 1993) and Sculptor dSph systems. In this regard the dSph, although appearing moderately flattened, are like other dE galaxies in being supported by anisotropic velocities (Bender and Nieto 1990; Mateo et al. 1991). A shear-velocity field has been detected in the Ursa Minor dSph (Hargreaves et al. 1994b), consistent with rotation about the apparent major axis, with v/σ of order unity in the outer regions. These data are interpreted as the result of tidal stretching along the initial minor axis combined with the generation of a net azimuthal steaming by preferential tidal stripping of stars on prograde orbits (Hargreaves et al. 1994b). Spatially resolved kinematics will allow better equilibrium dynamical models to be constructed for dSph galaxies, as has been done for globular clusters (Lupton et al. 1989; Gunn and Griffin 1979).

The density structures of dSph galaxies have been widely discussed in the literature, especially in connection with the "dark-matter problem." The simplest approach for finding core M/L ratios is to fit core velocity dispersion data, together with the star-count brightness profiles, to equilibrium dynamical models with isotropic velocity dispersions (Lake 1990a; Pryor and Kormendy 1990; Hargreaves et al. 1994a). This process yields M/L values in the range from 5–15 for the Fornax and Sculptor dSph systems and up to 100 for the Ursa Minor, Sextans, and Draco systems. These models applied to Ursa Minor, Carina, and Draco also give high central densities, of about $0.1 M_\odot/pc^3$, most of which must be in the form of dark matter (Lin and Faber 1983). This contrasts with inferred central dark-matter densities of $\lesssim 0.01 M_\odot/pc^3$ for gas-rich dwarf irregulars (Puche and Carignan 1990) and typical spiral galaxies (Kent 1987). The lack of rotational support to some of these dSph however implies *anisotropic* velocity dispersions; as shown by Pryor and Kormendy (1990), use of anisotropic models would result in a somewhat reduced core-mass density. The uncertainties and subtleties associated with the determination of M/L are discussed, for example, by Hargreaves et al. (1994a,b), and in Binney and Tremain (1987).

Lack of knowledge about orbits also complicates discussions of the internal dynamics of the dSph. If we assume that the Galactic dSph are on only moderately elliptical orbits, then the orbital periods are several times longer than the internal crossing times. Alternatively, if these dSph are now making their apo-Galacticon passages on highly eccentric orbits, then since the time spent in the dense inner Galaxy is a small fraction of the orbital period, the time scale for varia-

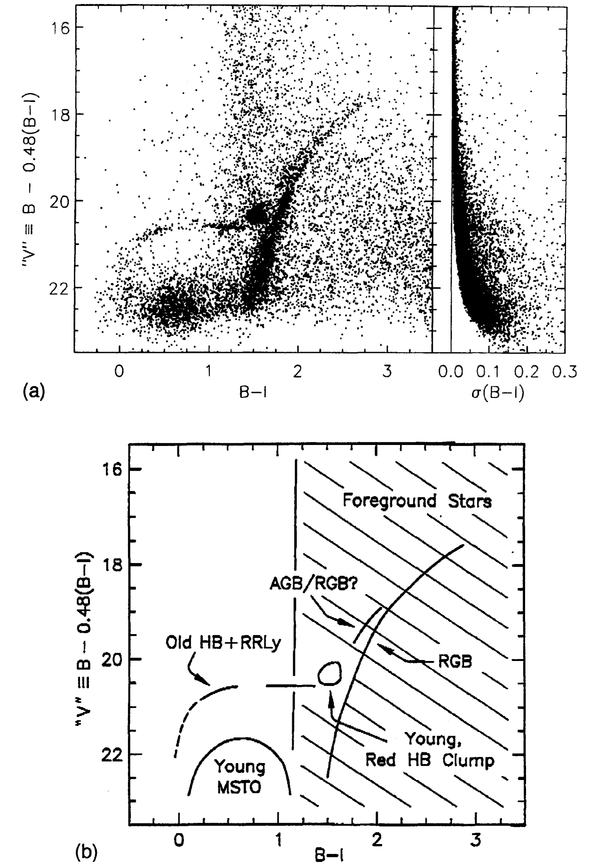

FIG. 3—The color–magnitude diagram in the top panel for the Carina dSph from Smecker-Hane et al. (1994), copyright 1994, American Astronomical Society; reproduced with permission. This plot clearly shows a well-defined giant branch (RGB), an asymptotic giant branch (AGB), horizontal branch (HB) including the RR Lyrae variables, red clump, and main-sequence turnoff. This type of CMD results from a mixture of old and intermediate-age stellar populations as outlined by the descriptive guide in the lower panel of the figure.

tions in the tidal field produced by the Milky Way may be close to the internal crossing time. Thus the question of the degree to which dSph galaxies are in dynamical equilibrium remains open. The ongoing efforts to measure proper motions of the nearest dSph galaxies (Scholz and Irwin 1993; Majewski and Cudworth 1993; Cudworth et al. 1994), which will allow three-dimensional orbits to be determined, will be a good test of models.

2.2 Stellar Populations

The dSph galaxies occupy an intermediate position in terms of stellar populations. Their metal abundances as inferred from the spectra and colors of red giants fall in the regime defined by Galactic globular clusters, with most Galactic dSph galaxies having mean metallicities similar to the peak of the halo globular clusters, or −1.5 dex. An example of a color–magnitude diagram for the Carina dSph is shown in Fig. 3, taken from Smecker-Hane et al. (1994).

However, dSph galaxies are unlike most globulars in that a range of abundances is present in several of the Galactic dSphs (see Table 2). Further, the globular clusters of the Fornax dwarf do not all have the same chemical abundance, but range from −1.35 to −1.93 dex (Dubath et al. 1992). In addition, the Fornax, Carina, Draco, and Leo I dSphs have intermediate-age stellar populations, identified from AGB stars and a tentative turnoff population, with an inferred last epoch of major star formation of near 5 Gyr (Aaronson 1986; Mighell 1990; Mighell and Butcher 1992; Lee et al. 1993; Smecker-Hane et al. 1994; reviewed by Freedman 1994). These four dSph systems therefore are fundamentally different from globular star clusters, and it is likely that age spreads also exist in other dSphs, but these are not trivially detected in faint old stellar populations where the main-sequence turnoff is difficult to identify (Freedman 1994). Indeed, the stellar population of Leo I is predominantly of intermediate age, with no obvious signature of very old stars (Demers et al. 1994). There may be a trend of the percentage of intermediate-age stars with distance from the MIlky Way, such that the more distant the dSph, the larger the fraction of younger stars (Silk et al. 1987; van den Bergh 1994), although the newest Galactic dSph, the Sagittarius dwarf, does not fit this trend.

The evolution of gas in small galaxies is probably largely controlled by the flow of matter into and out of the systems. Due to the low escape velocities of dSph galaxies, the ability of these systems to retain SNe ejecta is limited (Larson 1974; Vader 1986; Dekel and Silk 1986) and thus metallicities will depend on mass loss perhaps even more than on the star-formation history (Sandage 1965; Vader 1986; De Young and Gallagher 1990). Furthermore, the internal dynamical evolution of the system may be greatly affected by galactic winds. Meurer et al. (1992) have found compelling evidence for star-formation-driven gas loss from a dwarf galaxy; ongoing surveys (Marlowe 1995) will allow an estimate of the importance of galactic winds in general. In addition small galaxies may be able to capture cooling gas from the circumgalactic environment, allowing rejuvenation of the stellar population (Silk et al. 1987)—thus competition for gas could provide an explanation for trend of intermediate-age population with distance from the Milky Way. This process will further modify metallicity distributions, with possible signatures in chemical element ratios—those elements primarily synthesized in Type II supernovae, such as oxygen, may be affected more than those elements primarily synthesized in the deaths of long-lived progenitor stars, such as iron (Wheeler et al. 1989; Gilmore and Wyse 1991).

The galactic-wind model for Galactic dSph also seems to be consistent with the lack of any detectable interstellar matter in these systems. Searches for cool gas via the H I 21 cm line have yielded only upper limits (Knapp et al. 1978; Mould et al. 1990) with $M_{\rm H\,I}/L_V \lesssim 0.01$, although the confusing effects of the Magellanic Stream and high-velocity H I complicate searches for cool gas in nearby galaxies. This should be compared with the $M_{\rm H\,I}/L_V$ ratios of 0.01–0.1 observed for some dE and transition dSph/dIrr galaxies, such as the Phoenix dwarf (Carignan et al. 1991). As a group the Galactic dSph galaxies are among the most H I-poor galaxies known.

An examination of Table 2 suggests the complexities expected from galactic-wind models are present in chemical abundances of the Galactic dSph retinue. The most massive systems have higher metallicities as predicted by wind-induced mass-loss models, but the presence of an intermediate-age stellar population in Carina indicates that other effects have also been important. In a wind mass-loss model we would expect that the presence of intermediate-age stellar populations, the metallicity levels and the galactic mass correlate, and yet this does not appear to be strictly true. However, the low mean metallicity of the stars in dSph galaxies is indeed the expected signature for galaxies where chemical evolution has been strongly influenced by gas loss via winds rather than by astration, assuming an invariant stellar Initial Mass Function (IMF; Hartwick 1976). In addition, the distribution of stellar metallicities in a few dSph appear to be skewed as expected if sudden loss of gas truncated the chemical evolution (Suntzeff 1993).

2.3 Orbits and Environment

The orbits of the dSph galaxies will not be fully known until proper motion measurements begin to become available within the next few years. These measurements are extremely difficult because the proper motions are expected to be small. For example, a transverse velocity of 100 km s^{-1} at a distance of 50 kpc yields a proper motion of about μ=0.5 milliarsec yr^{-1}. This is currently just feasible by using extragalactic objects to define the stationary reference background on deep plates taken with large reflectors over multidecade time baselines (see Majewski and Cudworth 1993; Kroupa et al. 1994).

Even in the absence of detailed orbits, the available radial velocities, however, already present an interesting picture (Zaritsky et al. 1989). If the dSph were on circular orbits then their Galactocentric radial velocities should be a small fraction of the circular velocity at their locations. For example, if we adopt a maximal-mass model for the Galaxy with V_c=220 km s^{-1} at 100 kpc, we would expect $V_r \lesssim 25$ km s^{-1} for near circular orbits: thus we immediately see that most of the Galactic dSph cannot have circular orbits. Little and Tremaine (1987) and Fich and Tremaine (1991) analyzed the dynamics of dSph systems in the context of determining the Galactic mass distribution. They conclude that most of the nearby dSph are likely to be bound to the Milky Way and have phase-mixed over their orbits, which have a range in eccentricities. Thus it is proper to assume that most dSph galaxies have completed several orbits around the Milky Way since their formation, and with the possible exception of Leo I (Byrd et al. 1994), are not newly acquired members of the Galactic family.

Three additional interesting points emerge from these discussions: (1) With the exception of the disturbed Saggitarius dSph, the innermost Galactic dSph are currently located near the estimated outer radius of the Galactic dark halo, $R \gtrsim 50$ kpc. (2) The orbits of some dSph may be sufficiently extended that the influence of M31 needs to be taken into account. (3) In the absence of proper motion measurements, we cannot prove that the dSph are bound to the Milky Way.

3. THE PRICE OF PROXIMITY: EFFECTS OF THE MILKY WAY

The array of Galactic dSph galaxies presents us with a highly ordered distribution across the sky. As noted several years ago (Kunkel and Demers 1976; Lynden-Bell 1982a,b) most of the dSph systems fall near either the great circle defined by the Magellanic Stream or a second, nearby great circle which perhaps associated with the Fornax system. The Galactic dSph retinue does not have the appearance expected if these systems were being captured from a postulated reservoir of faint dwarf systems (Tremaine 1987; Majewski 1994). If we want to make dSph galaxies as independent entities, then a plausible physical mechanism must be found to order these systems into the present, near polar-ring structure about the Milky Way.

One might appeal to dynamical friction to accomplish the task of selecting which Galactic satellites could survive. However, even for a dark-matter dominated system with $(M/L)_V=100$, the dynamical friction time scales can be estimated from standard relationships (e.g., Binney and Tremaine 1987) to give

$$t_{\rm df} \sim (M_{\rm gal}/M_{\rm satellite}) t_{\rm crossing} > 10^{12} \text{ yr},$$

for circular orbits at the present radii of the inner Galactic dSph. The masses of existing dSph galaxies are too low by a factor of 100 for dynamical friction to be important at their present locations. And even if the orbits were eccentric, an equivalent circular radius of <10 kpc is needed for these systems to experience orbital decay in less than 10^{10} yr. The orbits of the well-studied dSph galaxies around the Milky Way have yet to be profoundly influenced by dynamical friction (Quinn and Goodman 1986). As a corollary, there appears to be no obvious way for dynamical forces associated with a spheroidal Galactic dark halo to have aligned an initially random distribution of dSph galaxies into the current near-polar-orbit array.

A second destruction mechanism for satellites of galaxies is tidal heating and disruption. In its simplest form this process can be viewed as the shrinking of a zero-velocity surface about a mass distribution. A rough guide to the tidal radius r_j is then given by the Jacobi limit (Binney and Tremaine 1987), essentially that disruption occurs when the mean density of the satellite and parent galaxy are equal. This can be written in a useful form for the dSph systems as

$$r_j = 1.5[(L_V(\text{dSph})/10^7 L_\odot)(10^{12} M_\odot / M_{MW}) \times (M/L_V)_{\rm dSph}]^{1/3} (D/100 \text{ kpc})\text{kpc}.$$

Thus for the Draco dwarf with $L_V = 2\times10^5 L_\odot$, $D=75$ kpc, the tidal radius is $r_j = 300(M/L_V)^{1/3}$ pc, or $r_j < 600$ pc for a normal stellar composition. While the radii of dSph galaxies are extremely difficult to determine observationally, Lake (1990a) suggests that the photometric radii based on the Hodge star counts for the Draco and Ursa Minor dSphs are $r_* > 25$ arcmin, or >0.5 kpc. Thus the sizes of the dSph are at least close to the expectations of a simple tidal model, although their internal velocity dispersions suggest that they are actually too tightly bound for tidal shredding to be effective.

The real situation is certainly even more complex than indicated by this rough calculation. For example, Kuhn and Miller (1989) suggest that resonant coupling may enhance tidal heating and also lead to the disruption of dSph galaxies. More extensive discussions of the complex dynamical issues associated with tidal interactions can also be found in the literature describing the destruction of globular star clusters (e.g., Aguilar 1993, and references therein). We also note that the qualitatively expected effects of tidal heating are clearly present observationally in outer regions of some elliptical galaxies (Kormendy 1977).

Another tidal limit may be set if dSph get sufficiently close to the Milky Way to interact with the disk. This could produce disk shocking which will influence the internal structures of dSph when their densities are comparable to that of the local disk (Aguilar 1993; Capaciolli et al. 1993). Additionally, passages through the outer, gas-rich Galactic disk would lead to an external ram pressure on gas within dSph, especially if the disk extends in ionized gas beyond the neutral H I edge (Maloney 1992). This mechanism would then further reduce the ability of these systems to retain gas. Such an effect may be operative on the Magellanic Clouds, producing the Magellanic Stream (Mathewson et al. 1987; Wayte 1991), although a straightforward tidal origin for the Stream remains viable (Gardiner et al. 1994). Note that both bound and unbound orbits of the LMC are consistent with the present proper motion measurements (Kroupa et al. 1994).

With the recognition of tidal heating as a destructive mechanism for dSph galaxies, we can divide models of the internal dynamics of dSph systems into two major classes. The equilibrium models deal with each galaxy individually and assume that external processes have had a negligible effect on the internal structures. This class of model yields high dark-matter densities for some dSph galaxies, including the Carina system which is currently too far from the Milky Way to experience significant tidal effects (Pryor and Kormendy 1990). In this picture a universal structure for the dSph would be that of dense galaxies which are gravitationally equivalent to rocks and are not influenced by the Galactic tides. The spatial distribution of dSph galaxies then is in roughly a steady state and will evolve only slowly in response to dynamical perturbations (e.g., passages of the Magellanic Clouds).

An alternative view is that the dSph are as fragile as they appear from their low stellar-surface densities. These systems then are being tidally heated and thus eventually will be destroyed (Kuhn and Miller 1989; Kuhn 1993). In this model the Galactic population of dSph galaxies is evolving, and some systems could have been disrupted in the past. Indeed we would expect that the innermost mean radius where dSph systems are found might move outward with time as closer-in objects are disrupted. The present-day dSph galaxies then would be remnants of what may once have been a more extensive satellite population.

4. CONSEQUENCES OF "THE DARK-MATTER PROBLEM"

The central issue in interpretation of the velocity dispersion observations is whether or not the dSph galaxies are in dynamical equilibrium states. If they are equilibrium systems, then a dominant dark-matter component is required in several dSph systems. Furthermore, this dark component is inferred to have central densities that are ten times larger than those derived for more luminous galaxies. The nature of the dark matter is also an open issue at present, with baryonic dark matter perhaps favored by the high densities, which are suggestive of dissipative material. However, should the dSph be in the process of disruption, then obviously the virial theorem should not be applied, and the presence of an excess density of dark matter is not secure.

We now consider the implications of the dark-matter problem by considering three possible cases:

4.1 Nonbaryonic Dark Matter

Faber and Lin (1983) used equilibrium dynamical models to conclude that the dSph probably have very high mass-to-light ratios, and therefore contain large amounts of dark matter. This was later put in the cosmological context of the hierarchical clustering Cold Dark-Matter scenario, where the first scales to turn-around, and presumably form stars, are of the mass scale of dwarf galaxies (Blumenthal et al. 1989). The properties of these systems and their possible identification with present-day dwarf galaxies is discussed in Dekel and Silk (1986). The persistence of dwarfs in groups of galaxies is unclear—the CDM halos of typical, i.e., "1σ," perturbations on this scale most certainly merge, but the fate of the luminous components is unknown (Lacey and Cole 1993; Kauffman and White 1993).

However, the large inferred central dark-matter densities of the dSph suggest that in this picture, the dSph evolved from higher amplitude density fluctuations, greater than 3σ, which collapsed and virialized at high redshift, $1+z \sim 20$ (cf. Evrard 1989). The dSph would then be the most ancient galaxies. They are also relatively close to the Galaxy, and highly clustered, which may be consistent with the statistics of density peaks (Kaiser 1984; Bardeen et al. 1986). The very dense individual dark halos of the dSph would retain their identity even *within* the outer dark matter halo of the Milky Way. Thus this model (3σ dwarfs in CDM) is dynamically self-consistent. The low stellar densities would result from galactic winds. In this model stars are born at normal densities and then expand in response to mass loss driven by winds and supernovae from massive stars, although the details remain to be calculated. In particular it is very hard to understand why the dissipationless stellar population should have expanded in response to gas loss while the dark matter remained dense.

4.2 Baryonic Dark Matter

Alternatively, the high densities inferred for the dSph dark matter could be an indication of dissipation, consistent with the dark matter being baryonic (Lake 1990b). The recent identification of "gold-plated" candidate microlensing events in lines of sight towards the Magellanic Clouds, interpreted as lensing of background stars in the Clouds by foreground dark objects in our Galaxy (Alcock et al. 1993; Aubourg et al. 1993), consistent with lensing by objects with subsolar mass, has revitalized interest in brown dwarfs as halo dark matter. However, this would require that the stellar IMF at the time of dark halo formation were very different from the present-day IMF, and indeed different from the IMF of the stellar halo which appears to show a downturn below a few tenths of a solar mass, much like the disk (Dahn 1994). It may be that the lensing events observed are more like those seen towards the Galactic bulge (Udalski et al. 1993), which are believed due to normal low-mass stars, and that both lens and source are in the Clouds. Further, deep K-band imaging of high-latitude fields has failed to find evidence for faint red stellar objects (Hu et al. 1994), as have observations with the *Hubble Space Telescope* (Bahcall et al. 1994). Baryonic dark matter playing a dominant role in dSph would have the further requirement that the IMF be variable from dSph to dSph.

Larson (1987) has suggested that an IMF biased towards massive stars could self-consistently provide dark remnants and also provide self-enrichment to give a correlation between M/L and [Fe/H], which has an uncertain observational status in the Galactic dSph. However, as above, quite how the dark matter remains dense while the stars become diffuse is unclear. This problem is exacerbated by the need to prevent too much enrichment from the massive stars, which requires very significant gas loss, many times that of the mass left behind. This must occur on a time scale which is rapid compared to the star formation rate, but slow compared to the internal crossing time, to avoid unbinding the system. Thus dSph with no evidence for extended star formation are particularly difficult in this scenario.

A skew in the IMF (rather than truncation, which would further exacerbate potential problems with unbinding the system) should be detectable from the value of the ratios of alpha-capture elements to iron peak elements from Type II supernovae (Wyse and Gilmore 1992). This effect reflects the variation of oxygen and other nucleosynthetic yields with supernova progenitor masses. For example, a slope with power-law index flatter by unity from the IMF in the solar neighborhood produces enhancements in oxygen relative to iron that is perhaps a factor of three higher than that seen (already a factor of three above solar) in the halo stars in the solar neighborhood (Wyse and Gilmore 1992).

Note that in the lowest-mass gas-rich galaxies for which good rotation curve data exist, there is an apparent relationship between the gravitational field and the H I gas. This manifests itself in the sense that the observed rotation curve is a scaled version of the rotation curve one would derive from the H I alone (Puche and Carignan 1991). A similar effect is also seen in the outer parts of massive galaxies (Bosma 1982). One is tempted to conclude that, like the H I, the halo dark matter is indeed baryonic (Gallagher 1990), consistent with indications from Big Bang Nucleosynthesis that a large fraction of baryons are dark (Walker et al. 1991), and indeed just the amount of dark matter inferred on the sale of galactic halos. However, it should be noted that the recent detection of unexpectedly large amounts of deuterium in a quasar absorption line system by Songaila et al. (1994) and by Carswell et al. (1994) would, if confirmed by observations of other systems, make ubiquitous baryonic dark-matter haloes impossible.

4.3 No Dark Matter (NDM)

The possibility that dSph do *not* contain the dark matter inferred from the analyses of the velocity data could arise in two ways. Firstly, the internal orbital motions of the expected population of binary stars—found to be ubiquitous, at the 30% level, in all normal stellar systems—will cause a zero-point offset in the observed velocity dispersion. The long-period binaries could provide a contribution of a few km / s^{-1} to the dispersion, which is very difficult to remove compared to the more obvious higher orbital motion outliers. However, this is uncomfortably close to the amplitude required to remove the need for dark matter, once subtracted off from the observed velocity distribution to obtain the center-of-mass motions of the binaries in the potential well of the dSph. Indeed, Suntzeff et al. (1993) find that a binary fraction of 25% in giant stars, with periods between 1 and 1000 yr, is sufficient to increase the velocity dispersion to observed values even given a true M/L of only 3, as seen in normal old stellar populations. This effect needs careful modeling (Mathieu 1985; Suntzeff et al. 1993; Hargreaves et al. 1994a).

Secondly, it is not firmly established that the dSph with very high inferred M/L ratios are in virial equilibrium. In this case there may be no dark matter (NDM), and the dissolution time scale is the critical parameter—it cannot be too short! For example, in this interpretation present observations would suggest that 3/9 of the dSph companions to the Milky Way would be in the process of coming apart, presumably due to tidal stresses, and so without a steady source of dSph, we require that the dissolution time be greater than 25% of the age of the stellar populations of the dSph—or $\gtrsim 5$ Gyr. Furthermore, the association of apparently high M/L values with the *cores* of dSph galaxies exacerbates this difficulty. While these problems are somewhat ameliorated if some dSph are not bound to the Galaxy, the problem of supply of dSph remains. Also unanswered in this model is the origins of marginally bound galaxies with ultra-low stellar densities.

The NDM model is in principle feasible because most models predict that the dissolution of marginally bound dSph will not be sudden. Lynden-Bell (1982b) noted that the major axes of the stellar bodies of many dSph galaxies may align with their orbits, as predicted for galaxies that are being tidally distorted. This effect has been nicely illustrated by McGlynn (1990) in his Fig. 2(c). Since particles which become unbound have low positive energies, they thus only slowly drift away from their distressed parent galaxy. As discussed in a slightly different context by Tremaine (1993), a tidally disrupted object will spread out into a tidal stream of length s determined by the spread in orbital frequency over the size of the object. After time t, the size of the remnant relative to the radius of the satellite at which tidal stripping began is $s/R_{\text{satellite}} \sim \Omega t$, where Ω is the angular frequency of a circular orbit at the galactocentric radius where the satellite was disrupted. For disruption at 50 kpc, after 1

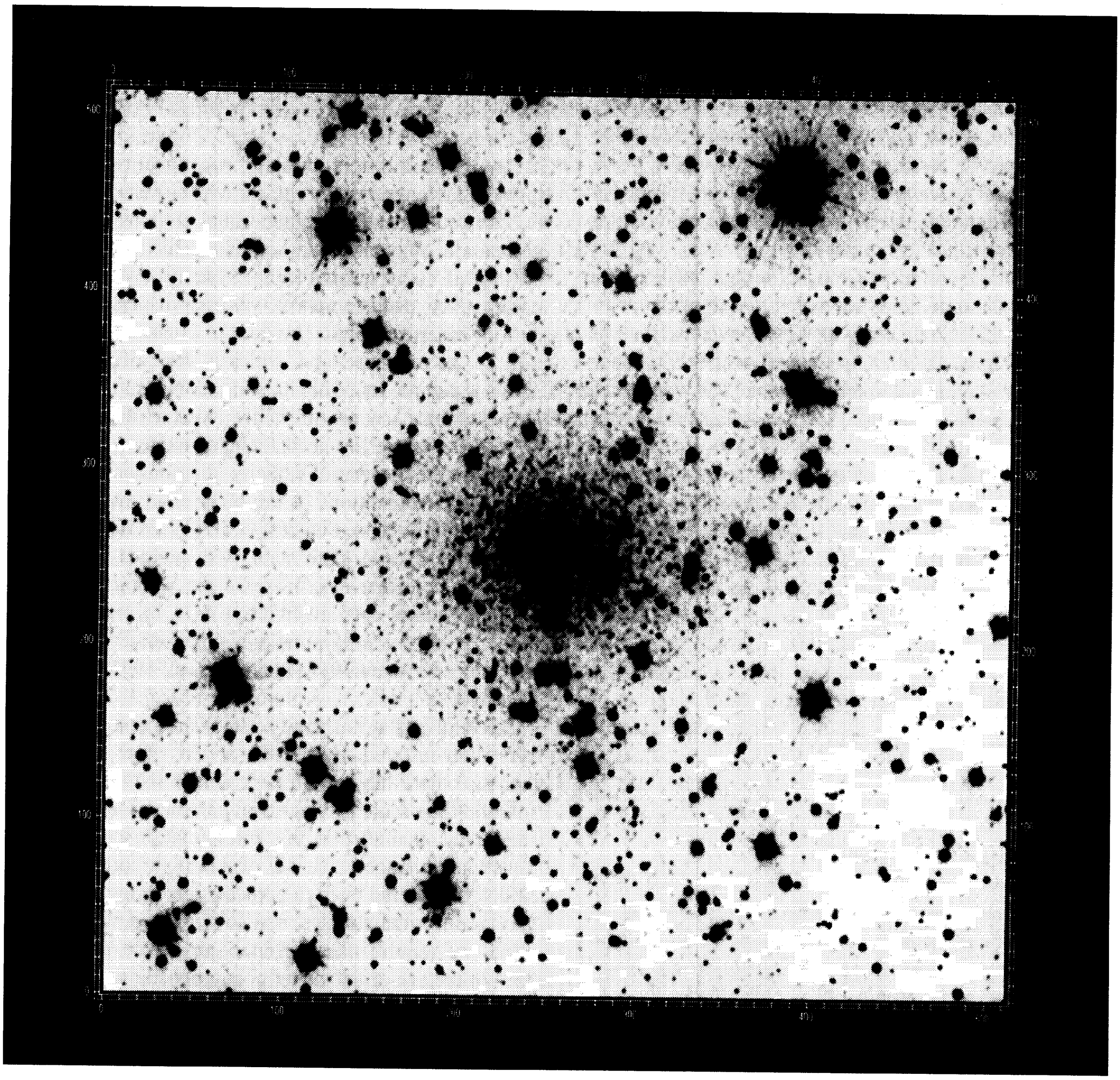

FIG. 4—This CCD image shows the And I dSph. Structurally And I resembles both the Galactic dSph systems and fainter, non-nucleated dE galaxies found in the Virgo CLuster of galaxies. Taken from Caldwell et al. (1992), copyright 1992, American Astronomical Society; reproduced with permission.

Gyr the satellite is spread out to only four times its original size. As mentioned above, CDM models lead to the expectation of significant phase-space structure in the Milky Way, remnants of disrupted subsystems, which may have been observed as "halo moving groups" [e.g., Arnold and Gilmore (1992)]. The disruption model for the Galactic dSph system, promoted by Kuhn (1993), cannot be dismissed out of hand, but also does not address the questions of how these galaxies initially formed, the origins of high *core M/L* values, and why they now have such low central-stellar densities. However, it is clear that at least the Sagittarius dwarf and Ursa Minor show evidence for ongoing tidal stretching/disruption, as discussed above.

An objection to this model that is often raised concerns the supply of dSph, since unless there is both creation and destruction, we are observing the dSph at a privileged epoch. However, there may indeed be a source of dSph in the interaction between the Milky Way and companions. As noted earlier, the dSph and the Magellanic Clouds are not uniformly located on the sky, but occupy two great circles (Kunkel and Demers 1976; Lynden-Bell 1982a,b). This suggests a tidal-debris origin—the break-up of "the Greater Magellanic Galaxy" and some other now-defunct companion galaxy—for the dSph. This model has several attractive features: (i) It directly addresses the nonrandom spatial distribution of the known Galactic dSph. (ii) Objects that are plausibly self-gravitating dwarf galaxies have been found in the process of formation in both observed and numerical model tidal-tails (Barnes and Hernquist 1992; Mirabel et al. 1992). (iii) This model naturally gives velocity dispersions for dSph that are close to the 10 km s H I velocity dispersion of typical galactic disks. (iv) This will yield low-density galaxies (Gerola et al. 1983).

One has still to explain possible problem areas such as why there are no dSph of the metallicity of the LMC, the internal kinematics which seem to require dark matter in the more distant dSph companions of the Milky Way, and the large range of star-formation ages.

5. DWARF SPHEROIDAL GALAXIES BEYOND THE MILKY WAY

5.1 The Andromeda dSph Galaxies

The Galactic family of dSph galaxies is not unique. van den Bergh (1972a,b) discovered four candidate dSph galaxies near the M31 galaxy, one of which (And IV) turned out to be a star cluster in the M31 disk (Jones 1993). The remaining three galaxies, And I, And II, and And III, have been shown by Caldwell et al. (1992) to be structurally similar to Galactic dSph in terms of optical scale lengths, luminosities, and surface brightnesses (see Fig. 4).

The parallel between properties of Galactic and M31 dSph also extends to stellar-population characteristics. These galaxies are like those associated with the Milky Way in showing no very recent star formation but a range in stellar ages. And I is dominated by an old stellar population (Mould and Kristian 1990), while And II (Aaronson et al. 1985) and And III (Armandroff et al. 1993) contain AGB stars that are indicators of small intermediate-age (several Gyr) stellar populations. The improved photometry for And I and And III of Caldwell et al. provide estimates of the total luminosity that place the Andromeda dSph on the luminosity–metallicity relationship defined by the Galactic dSph, as does And II (König et al. 1993). König et al. (1993) also show that there exists significant spread in the metallicity of the giant branch in And II, as may be expected from the inferred age spread.

By their very existence the Andromeda dSph immediately show that the dSph cannot be produced by a very rare process. Even though surveys for dSph are still not fully complete around M31, it evidently is poorer in dSph than the Milky Way, despite its larger bulge, close diffuse dwarf E companions NGC 205 and NGC 185, and ongoing interaction with M32. That the M31 dSph follow a similar luminosity–metallicity relationship as the Milky Way systems—albeit for only two objects and with considerable scatter—also suggests that the evolution of the stellar populations is likely to be largely controlled by internal processes. For example, if dSph were produced by galactic wind sweeping of small companion galaxies or by the break-up of a larger system, then the metallicity–luminosity relationship could well differ between host galaxies. What is not known is whether the M31 dSph show any evidence for dense dark matter, and whether, like their Milky Way cousins, a range in M/L exists.

5.2 Independent dSph Galaxies

As we move further away from the Milky Way, there is naturally less information about any class of galaxy. This is an especially severe problem for the dSph systems due to their small sizes and extremely low surface brightnesses. These objects are challenging to find and study even as companions to M31, and indeed even in the extended Milky Way

TABLE 3
Important Observational Programs

Objective	Surveys	Deep Ptm	Multi-Wavelength	Spectra Hi-Res	Lo-Res	Proper Motion
1. More dSphs	C		I			
2. Radial Profiles		C			I	
3. Kinematics				C	I	C
4. Gas Content		C	C			
5. Metallicity		I	I	C	I	
6. Stellar Ages		C	I	I	C	I
7. Orbits	I	I		I	I	C

Explanation and notes:

Table entries refer to important (I) or critical (C) observations. Deep Ptm includes imaging to faint levels such as is planned with the HST, Surveys are wide angle studies, Multi- Wavlength includes radio, radio, infrared, VUV, and other types of measurements, Spectra are high and low spectral resolution for stars, and Prop Motion are absolute proper motion determinations.

The objectives are (1) Find more examples of dSph galaxies around the Milky Way and in the nearby universe; (2) Measure radial stellar surface density profiles and shapes; (3) Determine internal radial velocity distribution functions versus radius; (4) Undertake surveys for ionized, neutral and molecular gas, including circumstellar ejecta; (5) Stellar metallicity determiniations, including abundance ratios for key elements which are sensitive to the nucleosynthesis history; (6) Ages of stars; and (7) Orbits for individual Galactic dSph systems.

system. However, the Tucana Dwarf has been suggested to be a distant, isolated dSph by Lavery and Mighell (1992), who interpreted their color–magnitude diagram as being that of a dSph galaxy at a distance of about 1 Mpc. These results are confirmed by deep images taken by Seitzer et al. (1994) with the Wide Field Planetary Camera 2 on the *Hubble Space Telescope*, and thus the Tucana Dwarf demonstrates that dSph galaxies can exist as independent entities, not physically associated with any large galaxy. In addition, there exist fascinating low-luminosity galaxies which have mixed dIrr/dSph traits. Thus we currently are not completely certain if true, very low-luminosity dSph exist which are not associated with giant galaxies.

Within the Local Group of Galaxies the dwarf system LGS3 presents an interesting example of a possible transition object. LGS3 is not near any giant systems, shows no evidence for H II regions which would indicate the presence of ongoing large scale star formation (Hunter et al. 1993), and yet contains a little H I, $M(\text{H I}) \leq 10^6 M_\odot$ (Lo et al. 1993). Thus LGS3 seems to be a near-dSph, possibly approaching the stellar fossil phase of its life. Perhaps closer to the dSph systems is the Phoenix dwarf, which is a low-surface-brightness galaxy with even less H I (Carignan et al. 1991) and a dSph-like stellar population with a few younger stars included (van de Rydt et al. 1991). The distance estimate of van de Rydt et al. for Phoenix places this galaxy at a distance comparable to M31, such that it is not bound to a major galaxy. However, this estimate is based on correctly identifying the evolutionary state, and hence luminosity, of resolved red stars, and may very well be an underestimate. So perhaps we are seeing some evidence that the final step in becoming a "pure" dSph galaxy takes longer in isolated systems than in dwarfs which are companions to giants, a point which can be explored as the statistics on faint galaxies in the Local Group improve in coming years (van den Bergh 1994a,b).

The extensive studies of diffuse dwarf E galaxies in the Virgo cluster also have begun to give partial answers to these issues (e.g., Binggeli and Cameron 1991). Photometry of these galaxies suggest that the diffuse dwarf E and dSph galaxies may lie on the same surface brightness–luminosity relationship (see Bender et al. 1993), although for such low-brightness galaxies selection effects are a major concern (Phillipps et al. 1988). In addition both classes of galaxies can be fit with exponential radial brightness profiles, often have low rotation velocities for their observed degree of flattening (Bender and Nieto 1990), and likely have similar luminosity–metallicity correlations. Kormendy and Bender (1994) use new observations of Virgo Cluster ellipticals to strengthen this connection. They suggest that dwarf diffuse Es and dSphs are not only a single structural class, but that this class should be called the dwarf spheroidals. Sandage and Hoffman (1991) present a related argument for parallelism between dE and dSph systems in discussing the existence of Phoenix dwarf-like transition morphology galaxies which sit between the dwarf irregular and dwarf diffuse E/S0 classes. Physically the dE/dSph galaxy family can be attributed to similar evolutionary processes in which mass loss has been a key ingredient (Binggeli 1994).

6. CONCLUDING THOUGHTS

Dwarf spheroidal galaxies present a nearby, albeit dim, challenge to current ideas about the formation and evolution of galaxies. The significance of these objects will become clearer within the next few years as new observations yield better information on their most fundamental properties. An outline of some possibilities is given in Table 3. We can therefore look forward to expanding our knowledge of the dSph in several key areas.

(1) The "dark-matter issue" is critical to understanding the true nature of the dSph galaxies. This issue contains several unresolved questions. First, we have not yet rigorously shown that the nearer dSph galaxies are in dynamical equilibrium. Until we can establish the dynamical states of the dSph, we will not know if or how much dark matter is required. If some dSph systems are indeed now dissolving, then we should also search for ultralow surface-brightness clouds or moving groups of stars which could mark the presence of previously disrupted Galactic dSph galaxies (Freeman 1990; Arnold and Gilmore 1992; Zinn 1993; Majewski 1993). Indeed, the best indications that the Galaxy has been caught in the act of eating a companion galaxy have come from radial-velocity surveys (Ibata et al. 1994).

At the other extreme, conventional equilibrium dynamical models of the Draco and Ursa Minor galaxies require very high densities of dark matter. If the dark matter in these objects is nonbaryonic, then the high densities imply very early formation times (see Peebles 1989 for this argument), and the dSph could well be the oldest class of galaxy. Yet high densities could also be due to dissipative processes and therefore a sign that this dark matter is baryonic. It is too early to draw broad conclusions about the nature of nonbaryonic dark matter on the basis of properties of Galactic dSph galaxies alone.

(2) The nonrandom distribution of the Galactic retinue of dSph satellites may be a prime clue of the origins of these systems. As emphasized by Lynden-Bell (1982a,b) and more recently by Majewski (1994), this pattern is suggestive of the production of dSph galaxies via the tidal disruption of larger systems. In this model it is hard to see how the remnants would retain very high densities of nonbaryonic dark matter. We therefore place a high priority on determining if the two great circles of Galactic dSph systems represents a physical association, e.g., through searches for dSph galaxies located elsewhere around the Milky Way and via proper motion measurements to determine orbital directions for, especially, the nearer dSph systems. As always with the dSphs, nothing is simple, and the radial-velocity data already defy any straightforward model for the orbital distributions.

(3) Some of the basic properties of the dSphs, such as metallicity and presence of an intermediate-age population may correlate with Galactocentric distance D_G (Silk et al. 1987). This is puzzling in view of the radial-velocity data which suggest that the dSph are not on high angular momentum orbits that cover small ranges in D_G. The crossing times for these orbits are short and so we might expect that even if radial gradients were introduced during the formation of dSph galaxies, they would have been rapidly reduced by orbital mixing. Better data are needed to define the significance of radial trends in the properties of Galactic dSph systems, and this should include comparisons between the properties of Galactic and external dSph galaxies (Armandroff et al. 1993).

(4) Many Galactic dSph satellites have had complicated evolutionary histories. Although these dSph galaxies have low densities and tiny escape velocities (even if dark matter is present), they have a range in either stellar metallicities or ages. Both features require the host galaxy to have been influenced by multiple generations of stars, in contrast to the single stellar generations found in most Galactic globular star clusters. The kinds of processes responsible for these evolutionary complexities can be revealed as new measurements define the properties of the main-sequence luminosity functions in the nearest dSph companions to the Milky Way. Similarly, abundance determinations of iron peak elements, which have an important source in long-lived Type Ia supernovae, versus elements such as O, Mg, or Si which are predominantly formed in Type II supernovae will enhance our understanding of the way in which the dSph became polluted to modest levels with metals.

(5) We are in one way indeed observing the dSph at a special epoch. Although several dSph supported star formation as recently as perhaps 3 Gyr in the past, none of the dSph are thought to currently be capable of producing new stars. It is therefore important to understand why these galaxies have dropped out of the league of star-forming galaxies on a time scale that is only a fraction of the cosmic time. In this regard, the possible existence or not of a reservoir of "proto-dSph" is a critical issue. It may be that this "special epoch" is related to the collapse of bound groups of galaxies (cf. Silk et al. 1987), in which case the existence or not of isolated dSph is crucial.

(6) Study of the satellite galaxies of the Milky Way will

elucidate the formation and evolution of the Milky Way itself, and hence that of typical spiral galaxies. Hierarchical-clustering scenarios of galaxy formation lead naturally to a synthesis of the ideas presented by Eggen et al. (1962), whereby the stellar halo formed during a rapid, monolithic collapse phase, and by Searle and Zinn (1978), whereby an extended more chaotic accretion phase formed the stellar halo.

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