The Local Group

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Abstract. Local Group galaxies such as the Milky Way, the Magellanic Clouds and M31 are being used by a number of international collaborations to search for microlensing events. Type and number of detections place constraints on dark matter and the stellar populations within and along the line of sight to these galaxies. In this review I briefly discuss the stellar populations, evolutionary histories, and other properties of different types of Local Group galaxies as well as constraints on the dark matter content of these galaxies. Particular emphasis is placed on the dwarf companions of the spiral galaxies in the Local Group.

1. Introduction

The “Local Group” is the small group of galaxies around the Milky Way and M31. The size of the Local Group is not well known, and its galaxy census is incomplete for low-surface-brightness galaxies. Recent studies suggest that the radius of the zero-velocity surface of the Local Group is $\sim 1.2$ Mpc (Courteau & van den Bergh 1999) when a spherical potential is assumed. Within this radius 35 galaxies have been detected (see Grebel 2000a for a list). Since information about orbits is lacking it is unknown which ones of the more distant galaxies within and just outside of the adopted Local Group boundaries are actually bound to the Local Group. Many faint Local Group galaxies were only discovered in recent years, and searches are continuing. Hierarchical cold dark matter (CDM) models predict about 10 times more dark matter halos than the number of known Local Group satellites (e.g., Klypin et al. 1999). Compact high-velocity clouds (Braun & Burton 1999), which appear to be dark-matter-dominated with total estimated masses of a few $10^8 \, M_\odot$ may be good candidates for the “missing” satellites.

The Local Group comprises galaxies with a variety of different morphological types, a range of masses, ages, and metallicities, and differing degrees of isolation. Their proximity makes these galaxies ideal targets for detailed studies of their star formation histories from their resolved stellar populations and of galaxy evolution in general. Furthermore, Local Group galaxies provide a convenient set of targets for studies of the nature of dark matter. Several Local
Group reviews have appeared in the past few years, including Mateo (1998), Grebel (1997, 1999, 2000a), and the very detailed recent reviews by van den Bergh (1999, 2000). Reviews dealing with dark matter in Local Group dwarf spheroidals include Mateo (1997) and Olszewski (1998).

![Diagram of the Local Group (LG)](image)

**Figure 1.** A scaled 3-D representation of the Local Group (LG). The dashed ellipsoid marks a radius of 1 Mpc around the LG barycenter (assumed to be at 462 kpc toward $l = 121.7$ and $b = -21.3$ following Courteau & van den Bergh 1999). Distances of galaxies from the arbitrarily chosen plane through the Milky Way are indicated by solid lines (above the plane) and dotted lines (below). Morphological segregation is evident: The dEs and gas-deficient dSphs (light symbols) are closely concentrated around the large spirals (open symbols). dSph/dIrr transition types (e.g., Pegasus, LGS 3, Phoenix) tend to be somewhat more distant. Most dIrrs (dark symbols) are fairly isolated and located at larger distances. Also indicated are the locations of two nearby groups.

2. Local Group galaxy content and distribution

The most massive and most luminous Local Group galaxies are the two spirals Milky Way and M31 ($\approx 10^{12}M_\odot$, $M_V \approx -21$ mag). The third, less luminous and less massive Local Group spiral M33 does not have any known companions and belongs to the M31 subsystem. About two thirds of the Local Group galaxies are found within 300 kpc of the two spirals. The majority of these close
companions are dwarf spheroidal and dwarf elliptical galaxies. The ensemble of
dwarf irregular galaxies, on the other hand, shows little concentration toward
the two large spirals (although the two most massive Local Group irregulars,
the Large and the Small Magellanic Cloud (LMC and SMC), are close neighbors
of the Milky Way and interact with it as well as with each other). This cor-
relation between morphological type and distance from massive galaxies is also
known as morphological segregation and may be to some extent a consequence
of evolutionary effects.

Whether a galaxy should be considered a dwarf galaxy is somewhat arbi-
trary, and different authors use different criteria. For the purpose of this review
all galaxies with $M_V > -18$ mag will be considered dwarf galaxies, which results
in 31 dwarfs, excluding only the three spirals and the LMC. We distinguish the
following basic types of dwarf galaxies in the Local Group:

- Dwarf irregulars (dIrrs) with $M_V > -18$ mag, $\mu_V \lesssim 23$ mag arcsec$^{-2}$, $R \lesssim 5$ kpc, $M_{HI} \lesssim 10^9 M_\odot$, and $M_{tot} \lesssim 10^{10} M_\odot$. DIs are irregular in their
optical appearance, gas-rich, and show current or recent star formation.
Several of the dIrrs contain globular or open clusters.

- Dwarf ellipticals (dEs) with $M_V > -17$ mag, $\mu_V \lesssim 21$ mag arcsec$^{-2}$, $R \lesssim 4$ kpc, $M_{HI} \lesssim 10^8 M_\odot$, and $M_{tot} \lesssim 10^9 M_\odot$. DEs look globular-cluster-
lke in their visual appearance with a pronounced central concentration.
All dEs are companions of M31. Two of the four dEs (M32, NGC 205)
are nucleated. M32, a dE very close to M31, has a central black hole and
follows the same scaling relations as large elliptical galaxies, whereas the
other dEs resemble dSphs and are therefore called spheroidals by van den
Bergh (1999, 2000). All dEs except for M32 contain globular clusters.

- Dwarf spheroidals (dSphs) with $M_V > -14$ mag, $\mu_V \gtrsim 22$ mag arcsec$^{-2}$, $R \lesssim 3$ kpc, $M_{HI} \lesssim 10^5 M_\odot$, and $M_{tot} \sim 10^7 M_\odot$. These galaxies show very
little central concentration and are dominated by old and intermediate-age
stellar populations. Only three (Sgr, For, And I) contain globular clusters.
With the exception of two isolated dSphs (Tuc and Cet) all known dSphs
are close neighbors of M31 or the Milky Way. Dsphs are gas-poor systems.
Sensitive searches for HI in dSphs yielded only low upper limits, but recent
studies detected extended HI clouds in the surroundings of some dSphs
that may be associated with them judging from the similarity of their
radial velocities (Carignan et al. 1998, Blitz & Robishaw 2000).

A few dwarf galaxies (Phe, LGS 3) are classified as “transition-type” objects
and may be evolving from low-mass dIrrs to dSphs. These dIrr/dSph galaxies
are found at distances of $250$ kpc < $D_{Spiral} < 450$ kpc. The Local Group does
not contain blue compact dwarf galaxies, dwarf spirals, or massive ellipticals.

3. The Local Group spirals

The Local Group spirals have the most complex and varied star formation histo-
ries of all Local Group galaxies. Different subpopulations can be distinguished
by their ages, metallicities, and kinematics. The oldest populations are found in
the halos and thick disk components. Extremely metal-poor ([Fe/H] < −3 dex) halo stars are tracers of the earliest star formation events (Ryan et al. 1996), but it is difficult to derive ages for them.

The earliest significant star formation episodes in the Galactic thick disk appear to have occurred 13 Gyr ago, while the thin disk began to experience multiple bursts of star formation ∼ 9 Gyr ago (Rocha-Pinto et al. 2000). The metallicity in the thin disk depends more strongly on Galactocentric radius than on age and shows a large spread at any position and age (Edvardsson et al. 1993).

While halos may have largely formed through accretion of metal-poor Searle & Zinn (1978) fragments, bulges also host metal-rich old populations (mean metallicity of the Galactic bulge: −0.25 dex; Minniti et al. 1995), indicating that they experienced early and fast enrichment. M31 appears to have undergone rapid enrichment as a whole, whereas M33 shows a pronounced radial abundance gradient. The mean metallicity of M31’s halo is −1 to −1.2 dex, more metal-rich than the halo of the Milky Way (∼ −1.4 dex) and of M33 (∼ −1.6 dex). While M31’s bulge emits ∼ 30% of the visible light of this galaxy, M33 lacks a bulge.

M31’s total number of globular clusters may be as high as ∼ 600. The Milky Way contains ∼ 160 globulars, and in the smaller M33 54 globulars are currently known (see Grebel 2000b for a review of star clusters in the Local Group). Main-sequence photometry of Galactic globular clusters suggests a range of ages spanning more than 3 Gyr. We lack such detailed information for M31’s and M33’s globulars, but the blue horizontal branch (HB) morphology observed in some of them may suggest similar ages as for the Milky Way globulars. On the other hand, the red HBs of M33’s globulars may indicate that star formation was delayed by a few Gyr (Sarajedini et al. 1998).

The spiral arms in all three galaxies contain numerous OB associations and young star clusters. The UV line strengths of massive OB stars suggest that the young population of M31 is comparable to that of the Milky Way, whereas M33 resembles the Large Magellanic Clouds (Bianchi, Hutchings, & Massey 1996). Present-day star-forming regions in the Milky Way range from very extended associations to compact starburst clusters such as the central cluster of NGC 3603 and the clusters Quintuplet and Arches near the Galactic center. M31’s current star-forming activity is low. The increase in cluster formation in M33 over the past 10 – 100 Myr may be correlated with gas inflow into M33’s center (Chandar, Bianchi, & Ford 1999).

Warps in the stellar and H I disks of the Milky Way and M31 may have been caused by tidal interactions with the Magellanic Clouds and M32, respectively. The Milky Way disk may also have been significantly distorted by interacting with the currently merging Sagittarius dwarf galaxy (Ibata & Razoumov 1998). M33’s stellar and H I disks are tilted with respect to each other, but no nearby companion is known that might be responsible.

4. Star formation histories of Local Group dwarf galaxies

The star formation histories of dwarf galaxies in the Local Group vary widely. No two galaxies are alike; not even within the same morphological type. The reasons for this diversity are not understood. It seems that both galaxy mass and environment play important roles in the evolution of these low-mass objects.
4.1. Methods and limitations

Star formation histories of resolved dwarf galaxies are commonly derived through photometric techniques. The most widely used method consists of sophisticated modelling of the observed color-magnitude diagrams (CMDs) through synthetic CMDs taking into account photometric errors, seeing, and crowding effects. For a recent review of procedures and techniques see Aparicio (1999). The methods are limited by the quality of the observations and by how closely theoretical evolutionary models reproduce observational features. For instance, Olsen (1999) notes that old red giant branches of evolutionary models may fit the observations poorly, which can lead to an underestimation of the contribution of the old population. Free parameters in modelling include the adopted initial mass function slope and the binary fraction.

Additional constraints can be imposed by using special types of stars as tracers of certain evolutionary phases. For instance, the presence of HB stars and RR Lyrae variables is a reliable indicator of an old population even when sufficiently deep main-sequence photometry is lacking. It is important to keep in mind that the age resolution that can be obtained is not linear and decreases strongly for older populations. Whereas young populations with short-lived, luminous massive stars can be accurately age-dated to within a few million years, the accuracy for the oldest, long-lived evolutionary phases is of the order of a few billion years. Relative ages of resolved old populations with high-quality, deep main-sequence photometry, on the other hand, can be established with a resolution of a Gyr or less through direct comparison with CMDs of Galactic globular clusters. In the following, “young” refers to populations with ages < 1 Gyr, “intermediate-age” denotes the age range from 1 Gyr to 10 Gyr, and “old” stands for ages > 10 Gyr.

Owing to the availability of 10-m class telescopes, spectroscopic measurements of stellar abundances are now feasible for individual supergiants and the brightest red giants in galaxies as distant as the M31 subgroup. Together with emission-line spectroscopy of H\textsc{ii} regions, these data help to constrain the metallicity and metallicity spread in certain evolutionary phases. Still, accurate metallicity information as a function of time is lacking for almost all galaxies.

The increasing amount of data on internal kinematics and dwarf galaxy proper motions are beginning to constrain their dynamical history. Unfortunately accurate orbital data are not yet available for almost all of the Local Group galaxies, making it difficult to evaluate the suggested impact of environmental effects and interactions discussed later.

4.2. Old populations

A common property of all Local Group dwarfs studied in detail is the existence of an old population, whose presence can be inferred either from HB stars and/or from photometry reaching below the oldest main-sequence turnoff. Old populations may be difficult to detect in the central portions of galaxies with significant intermediate-age or young populations, as the location of these stars in a CMD may obscure an old HB. Also, coverage of only a small field of view may be insufficient to reliably detect a sparsely populated HB (compare the findings of Gallart et al. 1999 and Held et al. 2000 for Leo I). Age dating of the oldest populations is reliably possible only where high-quality photometry well below
the oldest main-sequence turnoff exists; a challenge for present-day telescopes already for galaxies at the distance of M31. Definite statements about the existence of an old population are possible only where the photometry reaches at least the HB; feasible in principle with present-day telescopes out to distances \( \approx 3 \) Mpc.

Deep main-sequence photometry based largely on *Hubble Space Telescope* data revealed that the ages of the oldest populations in the LMC (Holtzman et al. 1999), Sagittarius (Layden & Sarajedini 2000), Draco, Ursa Minor (Feltzing, Gilmore, & Wyse 1999), Sculptor (Monkiewicz et al. 1999), Carina (Mighell 1997), Fornax (Buonanno et al. 1998), and LeoII (Mighell & Rich 1996) are as old as the oldest Galactic globular clusters and bulge populations. Thus all of these galaxies share a common epoch of early star formation. Similarly old ages were inferred from the existence of blue HBs in Sextans (Harbeck et al. 2000), LeoI (Held et al. 2000), Phoenix (Smith, Holtzman, & Grillmair 2000), IC 1613 (Cole et al. 1999), Cetus (Tolstoy et al. 2000), AndI (Da Costa et al. 1996), AndII (Da Costa et al. 2000), NGC 185 (Geisler et al. 1999), NGC 147 (Han et al. 1997), Tucana (Lavery et al. 1996), M31 (Ajhar et al. 1996), potentially in M32 (Brown et al. 2000), and spectroscopically for one of NGC 6822’s globular clusters (Cohen & Blakeslee 1998). Assuming that age is the second parameter determining HB morphology the apparent lack of a blue HB in M33 globular clusters (Sarajedini et al. 1998) and in the field populations of WLM (Dolphin 2000), Leo A (Tolstoy et al. 1998), DDO 210 (Tolstoy et al. 2000) and the Small Magellanic Cloud (SMC) may be interpreted as evidence for delayed formation of the majority of the old population in these galaxies. Furthermore, the oldest globular cluster in the SMC, NGC 121, is a few Gyr younger than the oldest Galactic globulars (Shara et al. 1998) A complete lack of an old population has so far not been established in any Local Group galaxy.

4.3. Spatial variations of stellar populations

Not surprisingly properties such as gas and stellar content, age structure, metallicity distribution, density, and scale height vary as a function of position within a galaxy. Spatial variations in the distribution of stellar populations of different ages are found in all types of galaxies, underlining the importance of large-area coverage when trying to determine the star formation history of a galaxy.

The oldest populations turn out to be spatially most extended. Spiral galaxies in the Local Group show pronounced population differences between disk, halo, and more intricate spatially and kinematically distinct subdivisions. In massive irregulars such as the LMC spatial variations are traced by, e.g., multiple distinct regions of concurrent star formation. These regions can remain active for several 100 Myr, are found throughout the main body of these galaxies, and can migrate.

In low-mass dIrrs and several dSphs the most recent star formation events are usually centrally concentrated. A radial age gradient may be accompanied by a radial metallicity gradient, indicating that not only gas but also metals were retained over an extended period of time. Occasionally evidence for shell-like propagation of star formation from the central to adjacent regions is found. Dsphs that are predominantly old tend to exhibit radial gradients in their HB morphology such that the ratio of red to blue HB stars decreases towards the
outer parts of the dwarfs. If such second-parameter variations are caused by age then this would indicate star formation persisted over a longer period of time in the centers of these ancient galaxies.

4.4. Differences in gas content

The H\textsubscript{i} in dIrrs is generally more extended than the oldest stellar populations and shows a clumpy distribution. Gas and stars in a number of low-mass dIrrs exhibit distinct spatial distributions and different kinematic properties. Shell-like structures, central H\textsubscript{i} holes, or off-centered gas may be driven by recent star formation episodes (Young & Lo 1996; 1997a,b). H\textsubscript{i} shells, however, do not always expand, which may argue against their formation through propagating star formation (Points et al. 1999, de Blok & Walter 2000).

Ongoing gas accretion appears to be feeding the starburst in the dIrr IC 10 (Wilcots & Miller 1998). An infalling or interacting H\textsubscript{i} complex is observed in the dIrr NGC 6822 (de Blok & Walter 2000).

DEs in the Local Group contain low amounts of gas (a few 10\textsuperscript{5}M\textsubscript{\odot}; Sage, Welch, & Mitchell 1998) or none (NGC 147). The apparent lack of gas in dSphs (e.g., Young 2000) continues to be hard to understand, in particular when considering that some dSphs show evidence for recent (Fornax: \sim 200 Myr, Grebel & Stetson 1999) or pronounced intermediate-age star formation episodes (e.g., Carina: 3 Gyr; Hurley-Keller, Mateo, & Nemec 1998; Leo I: 2 Gyr; Gallart et al. 1999). Gas concentrated in two extended lobes along the direction of motion of the Sculptor was detected beyond the tidal radius of this galaxy (Carignan et al. 1998). This gas may be moving inwards or away from Sculptor. Its amount is consistent with the expected mass loss from red giants, though that does not explain its location along the probable orbital direction of Sculptor. Blitz & Robishaw (2000) suggested the existence of similar gas concentrations with matching radial velocities in the surroundings of several other dSphs. Simulations by Mac Low & Ferrara (1999) suggest that total gas loss through star formation events can only occur in galaxies with masses of less than a few 10\textsuperscript{5}M\textsubscript{\odot}. Blitz & Robishaw discuss tidal effects as the most likely agent for the displacement of the gas. However, the absence of gas in Cetus and Tucana, two isolated dSphs in the Local Group, requires a different mechanism.

4.5. Star formation histories

Local Group dwarf galaxies vary widely in their star formation histories, chemical enrichment, and age distribution; even within the same morphological type. Despite their individual differences, however, they tend to follow common global relations between, e.g., mean metallicity, absolute magnitude, and central surface brightness. Galaxy mass as well as external effects such as tides appear to play major roles in their evolution.

Sufficiently massive irregulars and dIrrs exhibit continuous star formation at a variable rate. They can continue to form stars over a Hubble time and undergo gradual enrichment. Galaxies such as the LMC (Holtzman et al. 1999, Olsen 1999), SMC, and WLM (Dolphin 2000) have formed stars continuously and experienced considerable chemical enrichment spanning more than 1 dex in [Fe/H]. Their star formation rate, on the other hand, varied and shows long
periods of low activity. Interestingly, in the LMC cluster and field star formation activity show little correlation.

Low-mass dIrrs and dSphs often show continuous star formation rates with decreasing star formation rates. They typically show dominant old (or intermediate-age) populations with little or no recent activity. A similar evolution appears to have occurred in dEs. DSph companions of the Milky Way tend to have increased fractions of intermediate-age populations with increasing Galactocentric distance, indicating that external effects such as tidal or ram pressure stripping may have affected their star formation history (e.g., van den Bergh 1994). The two closest dSphs to the Milky Way (other than the currently merging Sagittarius dSph) are Draco and Ursa Minor, which are dominated by ancient populations and are also the least massive dSphs known – possibly due to the early influence of Galactic tides, though present-day positions may not reflect early Galactocentric distances, and reliable orbital information is lacking.

The Local Group dwarf galaxy to show the most extreme case of episodic star formation with Gyr-long periods of quiescence and distinct, well-defined subgiant branches is Carina (Smecker-Hane et al. 1994, Hurley-Keller et al. 1998). It is unclear what caused the interruption and subsequent onset of star formation after the long gaps. Also, the apparent lack of chemical enrichment during these star formation episodes is surprising.

4.6. Potential evolutionary transitions

Fornax is the second most luminous dSph galaxy in the Local Group. The young age of its youngest measurable population (∼ 200 Myr, Grebel & Stetson 1999) is astonishing considering its lack of gas. Just a few hundred Myr ago Fornax would have been classified as a dIrr. What caused Fornax to lose all of its gas after some 13 Gyr of continuous, decreasing star formation is not clear.

The presence of intermediate-age populations in some of the more distant Galactic dSphs, the possible detection of associated gas in the surroundings of several of them, indications of substantial mass loss discussed elsewhere in this paper, morphological segregation, common trends in relations between their integrated properties, and the apparent correlation between star formation histories and Galactocentric distance all seem to support the idea that low-mass dIrrs will eventually evolve into dSphs if their environment fosters this evolution. DSphs may be the natural final phase of low-mass dIrrs, and the type distinction may be artificial. The six dSph companions of M31 span a similar range in distances as the Milky Way dSphs (Grebel & Guhathakurta 1999). A study of whether their detailed star formation histories (not yet available) show a comparable correlation with distance from M31 would provide a valuable test of the suggested impact of environment.

The mass (traced by the luminosity) of a dwarf galaxy plays a major role in its evolution as indicated by the good correlation between luminosity and mean metallicity (e.g., Caldwell 1999). The observed lack of rotation in dSphs requires that its hypothesized low-mass dIrr progenitor must have gotten rid of its angular momentum, which may occur through substantial mass loss. However, this scenario does not account for the existence of isolated dSphs such as Tucana. Alternatively, the progenitor may have had very little rotation to begin with. Either way, the subsequent fading must have been low since otherwise dIrrs
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and dSphs would not follow such a fairly well-defined common relation. Several authors (e.g., Mateo 1998) suggested that the luminosity-metallicity relation is instead bimodal with separate loci for dIrrs and dSphs in the sense that at a given luminosity a dIrr tends to be more metal-poor than a dSph, excluding evolutionary transitions. Hunter, Hunsberger, & Roye (2000) go a step further and suggest that a number of Local Group dIrrs might have formed as ancient tidal dwarfs that lack dark matter, are essentially non-rotating, and contribute to the increased scatter in the absolute magnitude–mean metallicity relationship for $M_B < -15$ mag.

5. Dark matter

Dark matter is a significant component of many Local Group galaxies. Spiral galaxies exhibit H I rotation curves that become approximately flat at large radii and that extend 2–3 times beyond the optically visible galaxy. Global mass-to-light ratios ($M/L$) inferred from rotation curves of spirals are typically $\leq 10$ M⊙/L⊙ for the visible regions ($\sim 1 – 3$ M⊙/L⊙ in disks, $\sim 10 – 20$ M⊙/L⊙ in bulges), while the dark matter in halos seems to significantly exceed these values (Longair 1998). This motivates efforts to determine the nature of the dark matter through microlensing in the Galactic halo and toward the Galactic bulge as detailed elsewhere in this volume, and through pixel microlensing of stars in the disk of M31 by dark massive objects in M31’s halo (Crotts 1992).

In gas-rich dwarfs the presence of dark matter is inferred as well from H I rotation curves. Some of the less massive dIrrs are rotationally supported only in their centers, while the majority of dSphs studied so far does not show evidence for rotation at all. Chaotic gas motions dominate in low-mass dIrrs, and the H I column density distribution is poorly correlated with the stellar distribution (Lo, Sargent, & Young 1993). In the dE NGC 205, which is tidally interacting with M31, integrated light measurements revealed that the stellar component is essentially non-rotating though the H I shows significant angular momentum (Welch, Sage, & Mitchell 1998). In gas-deficient dSphs kinematic information is based entirely on stars. Most dSphs show no rotation. Their velocity dispersions are typically $\geq 7$ km s$^{-1}$. Assuming virial equilibrium velocity dispersions and rotation curves can be translated into virial masses. The derived total $M/L$ ratios of Local Group dwarf galaxies present an inhomogeneous picture ranging from $\sim 1$ to $\sim 80$ (see compilation by Mateo 1998).

Compact high-velocity clouds (CHVCs) are a subset of high-velocity H I clouds with angular sizes of only about 1 degree on the sky. They show infall motion with respect to the barycenter of the Local Group. Preliminary estimates place them at distances of 0.5 to 1 Mpc in contrast to the extended nearby high-velocity-cloud complexes (Braun & Burton 1999). Their rotation curves imply high dark-to-H I ratios of 10–50 if distances of 0.7 Mpc are assumed, and masses of $10^7$ M⊙ (Braun & Burton 2000). CHVCs may be a significant source of dark matter and may represent pure H I/dark-matter halos prior to star formation. We are currently carrying out an optical wide-field survey to establish whether they also contain a low-luminosity, low-density stellar component, which would imply the discovery of a new, very dark type of galaxy, help to refine CHVC distances and allow detailed studies of their stellar populations.
5.1. Dwarf spheroidal galaxies and dark matter

Galactic dSphs are of particular interest in efforts to elucidate the nature of dark matter since they may be dark-matter-dominated and can be studied in great detail due to their proximity. From an analysis of the kinematic properties of Draco and Ursa Minor Gerhard & Spergel (1992a) exclude fermionic light particles (neutrinos) as dark matter suspects because phase-space limits would then require unreasonably large core radii and masses for these two galaxies.

The initial measurements of velocity dispersions in dSphs were criticized for including luminous AGB stars and Carbon stars, whose radial velocities may reflect atmospheric motions, and for neglecting the impact of binaries (see Olszewski 1998 for details). Subsequent studies concentrated on somewhat fainter stars along the upper RGB, carried out extensive simulations to assess the impact of binaries (Hargreaves, Gilmore, & Annan 1996; Olszewski, Pryor, & Armandroff 1996), obtained multi-epoch observations (e.g., Olszewski, Aaronson, & Hill 1995), and increased the number of red giants with measured radial velocities to more than 90 in some cases (Armandroff, Olszewski, & Pryor 1995). These studies established that the large velocity dispersions in dSphs are not due to the previously mentioned observational biases. Kleyna et al. (1999) show that the currently available measurements for the two best-studied dSphs, Draco and Ursa Minor, are not yet sufficient to distinguish between models where mass follows light (constant M/L throughout the dSph) or extended dark halo models when interpreting the velocity dispersions as high M/L ratios due to large dark matter content. Mateo (1998) and Mateo et al. (1998) argue that the relation between total M/L and $V$-band luminosity for dSphs can be approximated well when adopting a stellar M/L of 1.5 (similar to globular clusters) and an extended dark halo with a mass of $2 \times 10^7 M_\odot$, suggesting fairly uniform properties for the dark halos of dSphs.

Luminosity functions (LFs) of old stellar systems can provide further constraints on the nature of dark matter. The main-sequence LFs of old field populations in the Galactic bulge (Holtzman et al. 1998), LMC and SMC (Holtzman et al. 1999), Draco (Grillmair et al. 1998), and Ursa Minor (Feltzing et al. 1999) are in excellent agreement with the solar neighborhood IMF and LFs of globular clusters that did not suffer mass segregation. Since globular clusters are not known to contain dark matter, one would expect to find differences in the LF of dark-matter-rich populations if low-mass objects down to 0.45 M$_\odot$ were important contributors to the baryonic dark matter content. Furthermore, these studies demonstrate that the LF in objects with a wide range of M/L ratios does not differ much. The possible contribution of white dwarfs (or lack thereof) is discussed elsewhere in these proceedings.

5.2. Tidal effects rather than dark matter?

Instead of a smooth surface density profile that one might expect from a relaxed population, Ursa Minor shows statistically significant stellar density variations (Kleyna et al. 1998). Fornax’s four ancient globular clusters are located at distances larger than the galaxy’s core radius. Dynamical friction should have lead to orbital decay in only a few Gyr (much less time than the globular clusters’ lifetimes) and have turned Fornax into a nucleated dSph. Simulations by Oh, Lin, & Richer (2000) suggest that the best mechanism to have prevented this
evolution is significant mass loss through Galactic tidal perturbation and the resulting decrease in the satellite galaxy’s gravitational potential, which may have increased the clusters’ orbital semimajor axes and efficiently counteracted the spiralling-in through dynamical friction. The detection of a possible extended population of extratidal stars around the dSph Carina might imply that this galaxy has now been reduced to a mere 1% of its initial mass (Majewski et al. 2000). If such significant tidal disruption is indeed real and widespread then the present-day stellar content of nearby dSphs cannot easily be used to derive evolutionary histories over a Hubble time. Furthermore, extended extratidal stars are not expected if the galaxy is dark-matter dominated (Moore 1996).

Additional indications in favor of the impact of galactic tides come from the structural parameters of dSphs (Irwin & Hatzidimitriou 1995), which seem to imply tidal disruption in several cases. Furthermore, substantial tidal disruption by the Milky Way is evidenced by the Magellanic Clouds and Magellanic stream, by the Sagittarius dSph, and by Galactic globular clusters (Gnedin & Ostriker 1997; Grillmair et al. 1995; Leon, Meylan, & Combes 2000). Tracer features include gaseous and stellar tidal tails (Putman et al. 1998; Majewski et al. 1999; Odenkirchen et al. 2000). The conversion of velocity dispersions into M/L ratios and dark matter fractions assumes virial equilibrium, a condition that is violated in the case of severe tidal disruption.

Tidal heating due to resonant orbital coupling between the time-dependent Galactic gravitational field and the internal oscillation time scales of dSphs (Kuhn & Miller 1989; Kuhn 1993; Kuhn, Smith, & Hawley 1996) may inflate the dSphs’ velocity dispersions, but see Pryor (1996) for arguments against the efficiency of this mechanism.

As shown by Piatek & Pryor (1995) tides can, but need not inflate the global M/L/ratio to values. Indeed, in a galaxy suffering tidal disruption the velocity dispersion can be sustained at its virial equilibrium value, and the central density is maintained even after substantial mass loss (Oh, Lin, & Aarseth 1995). Pryor (1996) noted that a velocity gradient across a galaxy that is larger than the velocity dispersion is the clearest signature of tidal disruption, but such a gradient is not obvious in the Galactic dSphs.

Kroupa (1997) and Klessen & Kroupa (1998) proposed that stellar tidal tails may look like dSphs when seen along the line of sight, an orientation that follows naturally from their N-body simulations. The ordered motions in the tidal remnants would appear as increased velocity dispersion since they occur along the line of sight. These models can roughly reproduce the observed correlations between central surface brightness, absolute magnitude, and M/L. The predicted line-of-sight extension of the dSphs can be tested, in principle, through accurate measurements of the apparent width of their HBs. The predicted high orbital eccentricity, a consequence of the required radial orbits in the model, could be checked through accurate proper motion measurements with astrometric satellite missions such as SIM and GAIA. The tidal remnants may be leftovers from earlier mergers as suggested by the observation that the Galactic dSph galaxies appear to be located near at least two polar planes or great circles (the Magellanic Stream and the Fornax–Leo–Sculptor Stream; e.g., Kunkel & Demers 1996; Kunkel 1979; Lynden-Bell 1982; Majewski 1994). Such tidal remnants would not likely contain dark matter. The observed ages and abundances
of galaxies potentially associated with “streams” constrain the time at which
the break-up of a more massive parent could have occurred. This event must
have happened very early on when the parent had not yet experienced signif-
icant enrichment. Siegel & Majewski (2000) suggest that galaxies potentially
belonging to a stream may have originated from a common $-2.3$ dex progenitor
and subsequently followed their own evolution.

The impact of Galactic tides remains a valid alternative to large amounts
of dark matter in nearby dSphs. The determination of velocity dispersions of
distant or even isolated dSphs, which are unlikely to be subject to tidal effects,
is an important test of whether high M/L ratios in dSphs are largely caused
by environmental effects (see, e.g., the discussion in Bellazzini, Fusi Pecci, &
Ferraro 1996). Stellar velocity dispersions indicative of high M/L were found in
the most distant ($\sim 270$ kpc) potential Milky Way dSph companion Leo I (Mateo
et al. 1998) and in the outlying ($\sim 280$ kpc) M31 transition-type satellite LGS 3
(Cook et al. 1999), but measurements of truly isolated Local Group dSphs such
as Tucana and Cetus are still lacking.

5.3. Modified Newtonian dynamics

Modified Newtonian dynamics (MOND, Milgrom 1983a,b), which alters New-
ton’s second law at low accelerations by introducing a multiplicative acceleration
constant of $1.2 \cdot 10^{-8} \text{ cm s}^{-1}$, results in M/L ratios that do not require the pres-
ence of dark matter. While many attempts have been made to disprove MOND
(e.g., Gerhard & Spergel 1992b), none of the presently existing measurements
has been able to unambiguously refute MOND for either disk galaxies (van den
Bosch & Dalcanton 2000) or dwarfs (e.g, Milgrom 1994; 1995; Côté et al. 1999).
MOND remains a possible alternative to dark matter.

5.4. Implications for microlensing

Microlensing surveys are concentrating on the Galactic bulge, the Galactic halo
through monitoring of sight lines toward the Magellanic Clouds, and on M31
through pixel lensing. All of these surveys concentrate on fields with high-
density, luminous background populations. Results and constraints on dark
matter from these surveys are discussed elsewhere in this volume.

The remaining Local Group dwarf galaxies are less well suited for classical
microlensing studies. Advantages of using other dwarfs are that one can probe
additional lines of sight and can take advantage of the large optical depth to
microlensing since the sources are outside of the Milky Way halo. Also, in
nearby dSphs crowding won’t be much of a problem. However, the efficiency of
such studies would be drastically reduced as compared to the ongoing studies
since the targets are faint and stellar densities are low. This requires not only
longer exposure times or larger telescopes but also implies much longer time
scales before a significant number of events can be observed.

As discussed earlier the high velocity dispersions in low-mass dwarfs may
arise from large amounts of dark matter. This increases the possibility that
one may observe self-lensing when monitoring dwarfs rather than events in the
Galactic halo, an effect that is negligible when turning to distant Galactic globu-
lar clusters instead (Gyuk & Holder 1998). As always, variable stars may act as
contaminants. Future large survey telescopes such as the proposed Dark Matter
The Local Group Telescope (Tyson, Wittman, & Angel 2000) can provide routinely deep exposures of nearby Local Group dwarf galaxies once per night as a regular by-product of their search for cosmological weak lensing.

6. Summary

The Local Group, an ensemble of 35 galaxies most of which are dwarf companions of either M31 or the Milky Way, contains galaxies with a wide variety of masses, luminosities, star formation histories, and chemical and kinematic properties. No two galaxies in the Local Group experienced the same star formation history even within the same morphological type. Star formation episodes vary in length and times ranging from continuous star formation with variable star formation rates to gradually declining rates and episodic star formation, accompanied by either gradual chemical enrichment or almost no enrichment at all. Old populations are a common property of all Local Group galaxies studied in detail so far, though not all appear to share a common epoch of the earliest measurable star formation. Spatial variations in ages and abundances are observed in most Local Group galaxies ranging from widely scattered active regions in high-mass galaxies to centrally concentrated younger star formation episodes in low-mass dwarfs. Both galaxy mass and galaxy environment appear to have a major impact on galaxy evolution. Interactions such as ram pressure and tidal stripping seem to influence the evolution of less massive galaxies, contributing to the observed morphological segregation. Rotation curves and stellar velocity dispersions indicate the presence of dark matter in the majority of Local Group galaxies, although alternative explanations cannot be ruled out. The properties of the stellar populations in these galaxies as well as orbital and kinematic information can impose constraints on the nature and ubiquity of dark matter. Owing to faintness, low stellar density and hence low event probability as well as likeliness of self-lensing, Local Group dwarf galaxies other than the Magellanic Clouds are poorly suited for classical microlensing surveys but might become of interest for future large telescopes that routinely monitor a major fraction of the sky on a nightly basis.

Acknowledgments. This work was supported by NASA through grant HF-01108.01-98A from the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS5-26555. I gratefully acknowledge support from the organizers who covered my local expenses. Last but not least I like to thank the editors for their patience while this manuscript was finished.

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