Dwarf Galaxies in the Local Group and in the Local Volume

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Abstract

After summarizing the characteristics of different types of dwarf galaxies I briefly review our current state of knowledge of dwarf galaxy evolution in the Local Group, for which we now have a fairly detailed although by no means comprehensive picture. All Local Group dwarfs studied to date contain an old population, though its fraction varies considerably. The majority of the dwarf companions of the Milky Way shows evidence for a common epoch of ancient star formation. Spatial variations in star formation are frequently observed in many dwarf galaxies in the Local Group and beyond. These spatial variations range from a seemingly stochastic distribution of star-forming regions in gas-rich, high-mass dwarfs to radial gradients in low-mass dwarfs. The global mode of star formation may be either continuous with amplitude variations or episodic. High-mass dwarf galaxies tend to form stars over a Hubble time, whereas low-mass dwarfs eventually cease to form stars, possibly aided by environmental effects. Much less is known about the content and properties of dwarf galaxies in the Local Volume, which we are trying to remedy through a large observational effort. Dwarf galaxies in the Local Volume follow a similar trend with absolute magnitude, mean metallicity, and central surface brightness as the Local Group dwarfs do, and appear to be subject to morphological segregation.

1 Introduction

Galaxies cover a vast range of types and properties. The by far most frequent type of galaxy are dwarf galaxies, i.e., galaxies with low mass, low luminosity, low metallicity, and small in size. The terminological distinction between dwarf galaxies and "normal" or giant galaxies is poorly defined and is used in different ways by different authors. For the purpose of this paper we shall use the absolute V-band magnitude as a simple distinguishing criterion and consider all galaxies fainter than $M_V = -18$ mag as dwarf galaxies. A potentially more meaningful criterion would be mass rather than luminosity since dwarf galaxies have a range of different mass-to-light ratios. Such a definition would, for instance, consider all galaxies with masses of 1/10 or 1/100 of M^* as dwarf galaxies. However, since *masses* are unknown for most dwarf galaxies while luminosities are a directly measurable observable, we will use the luminosity criterion here.

In hierarchical structure formation scenarios dwarf galaxies (or more generally: small dark matter halos) are important building blocks of more massive galaxies and should have been even more numerous in the early Universe. Accordingly, the dwarfs we observe today are considered survivors of an initially much richer population. Interestingly, at the low-mass end we observe fewer dwarf galaxies today than the number of predicted surviving dark matter halos (e.g., Klypin et al. 1999). This may imply that we are either missing a large fraction of low-mass galaxies, that these halos do not have optically detectable counterparts, or that the scenarios are wrong.

Today's dwarf galaxies are the closest currently known counterparts of the early galaxy-forming fragments. Their star formation histories may hold the clue to understanding the conditions and

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evolution of the early Universe. Especially low-mass dwarf galaxies tend to have experienced little enrichment and few star formation episodes, i.e., they are "simple systems" as compared to more massive galaxies. These properties make the study of their evolutionary histories particularly interesting. They are also interesting objects from the point of view of stellar evolution since here we can study star formation histories in low-metallicity environments, investigate mass functions in low-mass, low-density environments, study the impact of neighboring massive galaxies on star formation, find out about preconditions for star cluster formation, etc.

These studies give the most accurate and reliable results where stellar populations can actually be resolved into individual stars. This makes nearby dwarf galaxies in the Local Group and Local Volume excellent targets.

The Local Group is the small group of galaxies around the Milky Way and M31. Within a zero-velocity surface of 1.2 Mpc (Courteau & van den Bergh 1999), the Local Group contains 36 known or suspected member galaxies. Since the orbits of these galaxies are still unknown, it is uncertain whether all of them are members, although one usually assumes that dwarf galaxies within ~ 200 kpc of a more massive galaxy are bound satellites of that galaxy. On the other hand, we may be missing quite a few low-luminosity members that have yet to be discovered. For example, recent searches three to four years ago uncovered four new, faint Local Group dwarfs (Armandroff, Davies, & Jacoby 1998; Karachentsev & Karachentseva 1999; Armandroff, Jacoby, & Davies 1999; Whiting, Hau, & Irwin 1999).

The Local Volume (and Local Void) comprises the volume with a radius of about 5 Mpc. It includes galaxies with velocities ≤ 500 km s^{-1} that are either part of small galaxy groups or field galaxies. The exact number of galaxies and their faint-end census in the Local Volume remain unknown. A recently completed all-sky search led to the detection of ~ 600 dwarf and low-surface-brightness galaxies, whose angular extent indicates that they may belong to the Local Volume (Karachentsev et al. 2000a). More than half of these objects were new discoveries.

2 Morphological types of dwarf galaxies

Dwarf spiral galaxies are found among S0, Sa, Sb, Sc, and Sd galaxies. They have central surface brightnesses of $\mu_V \gtrsim 23$ mag arcsec^{-2}, H I masses of $M_{\rm HI} \lesssim 10^9$ M$_\odot$, and usually large mass-to-light rations inferred from rotation curves (e.g., Schombert et al. 1995; Matthews & Gallagher 1997). Dwarf spirals are at the high-mass end of the dwarf galaxy distribution. Early-type dwarf spirals show rotation curves typical for rotationally supported exponential disks, while late-type dwarf spirals are slow rotators or exhibit solid-body rotation. Dwarf spirals show slow continuous star formation. Later types tend to be more metal-poor and gas-poor than earlier types (McGaugh 1994). Very late-type spirals may be in transition to irregulars. Dwarf spirals are found in clusters and in the field.

Blue compact dwarf galaxies (BCDs) are actively star-forming objects with centrally concentrated starbursts. Both gas and stars show pronounced central concentration, contributing to the compact appearance, fueling the starburst, and leading to high central surface brightnesses (typically $\mu_V \lesssim 19$ mag arcsec^{-2}). Various subtypes of dwarf galaxies exhibit BCD characteristics including H II galaxies, blue amorphous galaxies, and certain types of low-mass Wolf-Rayet galaxies. The H I masses of BCDs are $\leq 10^9$ M$_\odot$ and may exceed the stellar mass. Part of the very extended gas may be kinematically decoupled from the galaxies (van Zee, Skillman, & Salzer 1998). In their inner parts BCDs show solid-body rotation. BCDs are often observed in relative isolation away from the dense centers of clusters or groups.

Dwarf irregular galaxies (dIrrs) are irregular in appearance and appear dominated by scattered bright H II regions in the optical. In H I these gas-rich galaxies show a complicated fractal pattern full of shells and clumps. In the more massive dIrrs the H I distribution is usually much more extended than even the oldest stellar populations. In some cases evidence for gas accretion has been observed (e.g., Wilcots & Miller 1998). In less massive dIrrs the H I may be displaced with respect to the stellar light distribution, either off-centered or showing a ring-like structure with a central depression (e.g., Young & Lo 1997a). DIrrs are characterized by $\mu_V \lesssim 23$ mag arcsec^{-2}, $M_{\rm HI} \lesssim 10^9 M_\odot$, and $M_{\rm tot} \lesssim 10^{10} M_\odot$. The more massive dIrrs show increasing chemical enrichment with decreasing age. In low-mass dIrrs gas and stars may show distinct spatial distributions and kinematics. Solid-body rotation is common among the more massive dIrrs, while low-mass dIrrs occasionally do not show measurable rotation. DIrrs are found in clusters, groups, and in the field. They exhibit little concentration toward massive galaxies. Massive dIrrs may continue to form stars over a Hubble time (Hunter 1997). Very low-mass, gas-poor dIrrs, on the other hand, may be evolving towards dwarf spheroidals.

Dwarf elliptical galaxies (dEs) are spherical or elliptical in appearance, compact, have high central stellar densities and are typically fainter than $M_V = -17$ mag. Other characteristics include $\mu_V \lesssim 21$ mag arcsec^{-2}, $M_{\rm HI} \lesssim 10^8 M_\odot$, and $M_{tot} \lesssim 10^9 M_\odot$. They tend to be found close to massive galaxies, usually have little or no detectable gas, and are often not rotationally supported. If gas is detected it may show an asymmetric distribution, be less extended than the underlying stellar light, and may be kinematically distinct (Young & Lo 1997b; Sage, Welch, & Mitchell 1998; Welch, Sage, & Mitchell 1998). DEs may show pronounced nuclei that can contribute up to 20% of the galaxy's light. The fraction of these nucleated dEs (dE(N)) increases among more luminous dEs. The surface density profiles of dEs and dE(N)s are best described by Sérsic's (1968) generalization of a de Vaucouleurs $r^{1/4}$ law and exponential profiles (Jerjen et al. 2000).

Dwarf spheroidal galaxies (dSphs) are diffuse, gas-deficient, low-surface-brightness dwarfs with very little central concentration. They are characterized by $M_V \gtrsim -14$ mag, $\mu_V \gtrsim 22$ mag arcsec^{-2}, $M_{\rm HI} \lesssim 10^5 M_\odot$, and $M_{tot} \sim 10^7 M_\odot$. DSphs are the faintest, least massive galaxies known. The upper limits for their H I are usually even below the amounts expected from normal stellar mass loss. DSphs are usually found in close proximity of massive galaxies and do not appear to be supported by rotation. Their velocity dispersions indicate the presence of a significant dark component when virial equilibrium is assumed.

The difference in the spatial distribution of dEs and dSphs on the one hand and dIrrs on the other hand is also known as *morphological segregation* or as the morphology–density relation for dwarf galaxies and may be a signature of environmental effects on galaxy evolution.

Tidal dwarf galaxies form from the debris torn out of more massive galaxies during interactions and mergers. In contrast to other dwarf galaxies they do not contain dark matter and may have high metallicities for their luminosity depending on the evolutionary stage of the parent galaxy (Duc & Mirabel 1998). Masses, sizes, gas content, etc. of tidal dwarfs depend critically on the conditions during the interaction and on the parent galaxy. It is possible that certain dIrrs and dSphs are tidal dwarfs that formed relatively early. For instance, various authors suggested that the Milky Way dwarf companions may be part of two or more major debris streams in polar orbits (e.g., Majewski 1994; Lynden-Bell & Lynden-Bell 1995). Potential candidates for nearby tidal dwarf galaxies based on their intrinsic properties are discussed by Hunter et al. (2000).

3 Dwarf Galaxies in the Local Group

The dwarf galaxies studied most extensively to date are dwarf galaxies within the Local Group. Of the above mentioned types, the Local Group contains dIrrs, dEs, and dSphs as well as galaxies that may be in transition from dIrrs to dSphs.

The results from the detailed studies of Local Group dwarfs can be (incompletely) summarized as follows.

Local Group dwarfs were found to vary widely in their star formation histories, mean metallicity and enrichment histories, times of their major star formation episodes, fractional distribution of ages and subpopulations. Indeed no two dwarf galaxies are alike, not even if they are of the same morphological type or have similar luminosities (Grebel 1997). In part their properties appear to be correlated with galaxy mass and with environment (proximity to massive galaxies).

In many Local Group dwarfs spatial variations in star formation history were detected. In general, there is a tendency for the younger populations to be more centrally concentrated (and possibly more enriched), whereas older populations are more extended. This may in part be an effect of dynamical evolution, but may also indicate that star formation was able to continue over an extended period of time in the central regions since these may have been able to retain gas longer (or may have been rejuvenated by gas inflow in accretion events). For a summary of population gradients in a number of Local Group dSphs, see Harbeck et al. (these proceedings). Harbeck et al. conclude that presence or absence of these gradients does not show a clear correlation with environment.

A common property to all dwarf galaxies studied in sufficient detail so far is the presence of an old population. All claims of discoveries of purely young galaxies have subsequently been refuted once deeper images or data with better coverage of the outskirts of these galaxies became available. Deep ground-based imaging of the "halos" of dIrrs led to the detection of old red giant branches (e.g., Minniti & Zijlstra 1996) All dSphs and dEs for which deep photometry was obtained revealed horizontal branches, a clear indicator of old populations. The nearest candidate for a dwarf spiral, NGC 3109, shows a presumably old red giant branch in its outer regions (Minniti, Zijlstra, & Alonso 1999). Deep imaging of BCDs has revealed the presence of intermediate-age and possibly old populations (e.g., Lynds et al. 1998), as already inferred from integrated colors.

The oldest populations in the majority of nearby dIrrs and dSphs are indistinguishable in age from the oldest globular clusters in the Galactic halo and bulge (for a full list and references, see Grebel 2000). This indicates a common epoch of the oldest measurable star formation episode. Relative ages were derived from deep photometry extending below the main-sequence turn-off. In at least one dIrr (the Small Magellanic Cloud), however, significant star formation appears to have started with a delay of 2–3 Gyr. Data of sufficient depth and quality to carry out differential age-dating of the oldest populations are so far only available for Milky Way companions, i.e., dwarf galaxies within ~ 300 kpc.

Nearby dwarf galaxies typically show one of two modes of star formation: Continuous or episodic. High-mass dwarf galaxies tend to form stars fairly continuously with amplitude variations of up to a factor of three. They can continue to form stars over another Hubble time without exhausting their gas supply. They exhibit gradual enrichment, since many of the metals produced in star formation episodes are recycled later on. This mode of star formation is observed in high-mass dIrrs and dwarf spirals. Lower-mass dIrrs, dEs, and dSphs show continuous star formation with decreasing star formation rates. In dEs and dSphs, only little gas or no gas at all is observed, and star formation has ceased at the present time. One dSph in the Local Group, Carina, shows episodic or repetitive star formation: This galaxy underwent star formation episodes separated by 2 Gyr long episodes of quiescence. Yet no significant enrichment appears to have occurred if one interprets the narrowness of the red giant branch as an indication of a narrow metallicity range. This may suggest that the later episodes took place with accreted gas. Alternatively, age and metallicity may conspire to form one narrow red giant branch. The resolution of this question requires spectroscopy. It is not yet understood what caused the periods of quiescence and the renewed onset of star formation lateron.

DSphs around the Milky Way tend to have increasing fractions of intermediate-age populations with increasing distance from the Milky Way, suggestive of the impact of environmental effects: Tidal and ram pressure stripping may have removed most of the gas from nearby dSphs very early on, whereas more distant dSphs were able to retain their star-forming material for longer periods of time (e.g., van den Bergh 1994). The two dSph galaxies with the shortest Galactocentric distances (Ursa Minor and Draco) are essentially entirely old. These two are also the two least massive dwarfs. The second most massive dSph in the Local Group, Fornax, ceased to form stars only about 200 Myr ago (Grebel & Stetson 1999). (Here the term "mass" assumes that luminosity traces mass.) Hence the star formation history depends on parent galaxy mass. There are a number of uncertainties with this simplified picture though. Firstly, we do not know the orbits of the Milky Way companions and cannot tell whether their present-day positions are typical for their past distances from the Milky Way. We also do not know how close they came to the Milky Way in the past, and what role interactions played. Secondly, no fully satisfactory mechanism for the gas loss has been found so far. Simulations indicate that internal effects such as supernovae winds are insufficient to rid a dwarf galaxy of its gas (Mac Low & Ferrara 1999). Mayer et al. (2001) suggest that tidal shocks during perigalactic passages close to a massive galaxy may convert dIrrs into dSphs. They show that their simulations can reproduce the observed global properties of the Milky Way dSph companions as well as the morphology-density relation. Taking this model one step further, we would not expect to find isolated dSphs. Thus thirdly, if environmental effects determine the evolution of low-mass dwarfs, the existence of the dSph Tucana in the distant outskirts of the Local Group is hard to explain. This isolated dSph does not show evidence for gas or young or intermediate-age populations.

The M31 dSph companions, which span a similar range of distances around M31 as the Milky Way dSphs around the Galaxy provide a valuable source for testing the ram pressure/tidal stripping scenario. Interestingly, these galaxies do not show evidence for the presence of young or intermediate-age populations as traced by extended blue main sequences or pronounced concentrations of red clump stars. Our preliminary analysis shows little indication for evolutionary trends and present-day distance to M31.

We may be observing ongoing evolution from low-mass dIrrs to dSphs. Low-mass dIrrs show little or no rotation and have low current star formation rates. Their H I is not necessarily concentrated on the optical center of the dwarf. The so-called transition-type galaxies may be in an advanced phase of evolution from dIrrs to dSphs. The measured stellar velocity dispersion of the dIrr/dSph galaxy LGS 3 is comparable to that of dSphs (Cook et al. 1998). Mateo (1998) argues that the three transition-type galaxies LGS 3, Phoenix, and GR 8 lie on the same branch as dSphs when plotting [O/H] or [Fe/H] versus absolute magnitude. The recent stellar radial velocity determination for Phoenix by Gallart et al. (2001) argues in favor of the H I detected in the vicinity of Phoenix being associated with this dIrr/dSph galaxy, which experienced star formation as recently as 100 Myr ago (Holtzman et al. 2000). The dSph Fornax, which still formed stars some 200 Myr ago (Grebel & Stetson 1999) while being devoid of gas at present (Young 1999), may be a former dIrr that only recently finished its transition to a dSph.

4 Dwarf galaxies in the Local Volume

Nearby dwarf galaxies outside of the Local Group have been studied in much less detail. We are currently carrying out an HST WFPC2 snapshot survey to obtain upper red giant branch photometry of 200 nearby dwarf galaxies, and supporting ground-based observations to obtain surface photometry, spectroscopic abundances, and velocities (Grebel et al. 2000). At the same time, we are working on extending the census of dwarf and low-surface-brightness galaxies to fainter magnitudes using the Sloan Digital Sky Survey.

Our HST snapshot program yields information about the recent star formation history and qualitative information about intermediate-age populations. It allows us to determine distances based on the tip of the red giant branch. The slope of the red giant branch can be used for

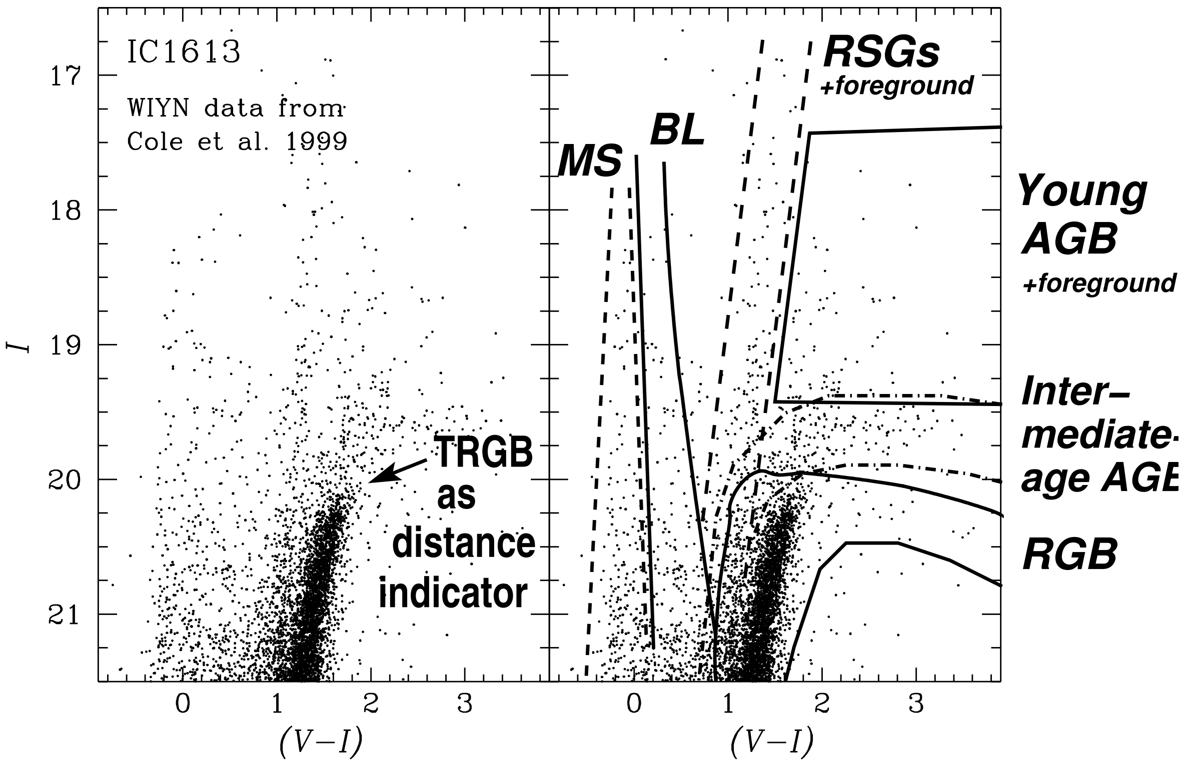

Figure 1: Color-magnitude diagram (CMD) of the upper portion of the red giant branch of the Local Group dIrr IC 1613 (courtesy of Andrew Cole, see Cole et al. 1999) to illustrate the information content of shallow CMDs of dwarf galaxies beyond the Local Group. The young main sequence (MS) and He-burning blue loop stars (BL) trace star formation events during the past $\sim$ 10 to $\sim$ 300 Myr, while He-burning red supergiants and giants mark events ranging from $\sim$ 10 Myr to $\sim$ 1 Gyr. Young asymptotic giant branch (AGB) stars tend to have ages older than 25 Myr, while the intermediate AGB represents star formation older than $\sim$ 1 Gyr. The tip of the red giant branch (TRGB) can be used as a distance indicator for old populations more metal-poor than [Fe/H] = -0.7 dex. The RGB slope and width yields estimates of the mean metallicity of the old population and of its metallicity spread. Depending on the mix of populations, age-metallicity degeneracy effects may constrain the interpretation.

photometric metallicity estimates (see Figure 1 for a schematic color-magnitude diagram). This allows us to derive both projected distances to the target galaxies and deprojected distances between galaxies within galaxy groups. We can thus study the morphology–density relation in galaxy groups in three dimensions rather than only in projection. Studies using projected distributions of dwarf galaxies in nearby groups suggest that dSphs and dEs tend to lie near massive galaxies, whereas dIrrs appear to be more widely distributed (e.g., Jerjen, Binggeli, & Freeman 2000). In Figure 2a we show the the *deprojected* distances of dwarf galaxies around the Milky Way, M31, and M81. The majority of these dwarfs are dSphs and dEs. In all three cases, we see the qualitatively similar tendency for the dSphs and dEs to concentrate around the closest massive galaxy.

Considering our knowledge of the recent star formation history (based on the observed presence or absence of young and intermediate-age populations) and of galaxy metallicity (through photometry or spectroscopy) we can furthermore study the influence of environment on galaxy evolution. Moreover, we can test the validity of global relationships such as the metallicity–surface brightness–luminosity relation (first illustrated for oxygen abundances and luminosities by Skillman, Kennicutt, & Hodge 1989). In Figure 2b this relation is shown for dwarf galaxies in the Local Group and for dSphs in the M81 group. The mean metallicities for the M81 dSphs are at present purely based on photometry. In spite of the significant scatter, dwarf galaxies in both groups show the expected positive correlation between luminosity, surface brightness, and metallicity.

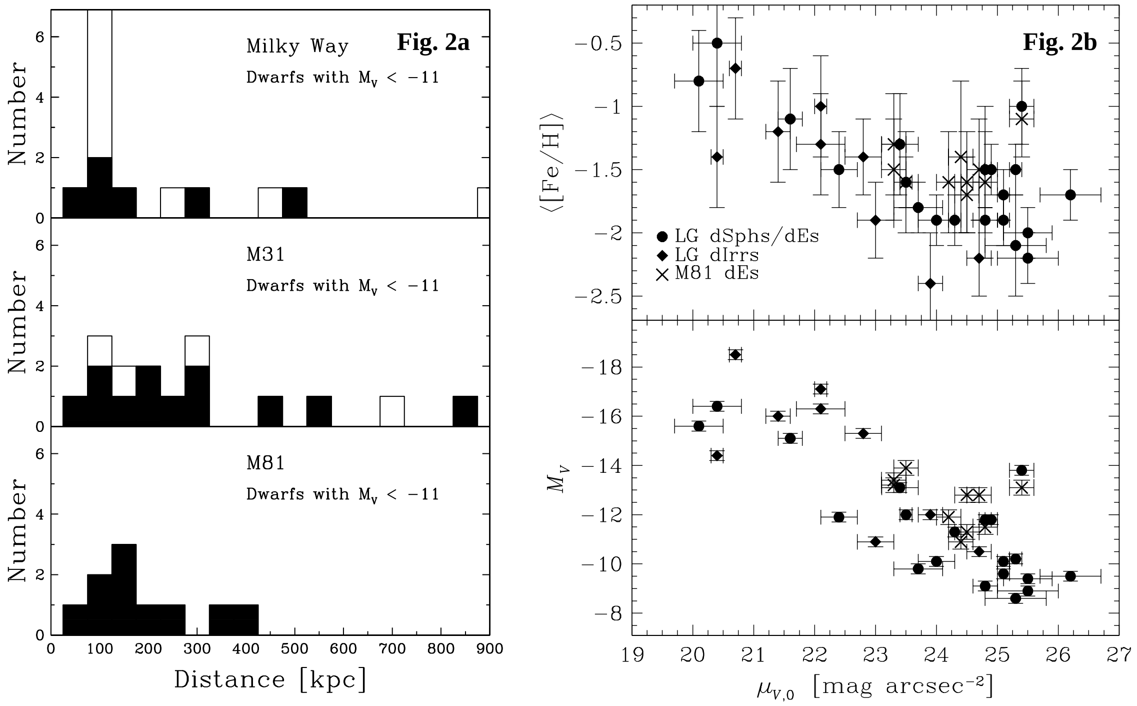

Figure 2: *Left panel:* The number of dwarf galaxies as a function of distance from the Milky Way (upper left panel), from M31 (central left panel), and from M81 (lower left panel). Filled histogram bars stand for dwarf galaxies with $M_V < -11$ mag in order to facilitate the comparison with the M81 surroundings, since for M81 we only have data for galaxies more luminous than this absolute V magnitude. The unfilled histograms denote dwarf galaxies fainter than this absolute magnitude. The majority of the dwarf galaxies in the left panel are dSphs and dEs. In the case of M81, only dSphs are plotted. These galaxies show a clear concentration toward massive primaries. *Right panel:* Dwarf galaxies in the Local Group and in the M81 Group all tend to show a positive correlation between mean metallicity, absolute magnitude, and central surface brightness although the scatter exceeds the formal uncertainties of the individual measurements. The data for the Local Group dwarfs were taken from Grebel (2000; note that the metallicity error bars here are intended to represent metallicity spread rather than uncertainty). The data for dwarf galaxies in the M81 Group are from Caldwell et al. (1998) and Karachentsev et al. (2000b; 2001).

That dwarf galaxies show common trends for their integrated properties in spite of their individual differences and irrespective of environment may indicate that galaxy mass is a determining factor in dwarf galaxy evolution. On the other hand, the morphology–density relation illustrates that environment is an important factor. Clearly, many important questions require further research, including the mechanisms governing dwarf galaxy evolution, the origin of the morphology–density relation, delayed evolution versus an ancient common epoch of early star formation, gas loss mechanisms, metal loss versus metal retention, enrichment as a function of time, presence and nature of dark matter, and satellite orbits, the uniqueness or generality of the Local Group, and differences between groups of galaxies. We are only at the beginning of the exploration of the properties and evolution of the most frequent type of galaxy, the dwarf galaxies. The new era of large telescopes and a multi-wavelength approach promises to help us solve many of these fundamental questions.

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