Star Formation Histories of Nearby Dwarf Galaxies

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Abstract. Properties of nearby dwarf galaxies are briefly discussed. Dwarf galaxies vary widely in their star formation histories, the ages of their subpopulations, and in their enrichment history. Furthermore, many dwarf galaxies show evidence for spatial variations in their star formation history; often in the form of very extended old populations and radial gradients in age and metallicity. Determining factors in dwarf galaxy evolution appear to be both galaxy mass and environment. We may be observing continuous evolution from low-mass dwarf irregulars via transition types to dwarf spheroidals, whereas other evolutionary transitions seem less likely.

Keywords: Dwarf galaxies, Local Group, galaxy evolution, star formation

1. Introduction

Dwarf galaxies are the most frequent type of galaxies in nearby galaxy groups and clusters, and probably in the Universe. They are the primary building blocks of more massive galaxies in hierarchical clustering scenarios and are believed to have been even more numerous at earlier times. The best studied dwarf galaxies are nearby dwarfs where individual stars can be resolved and evolutionary histories can be derived in great detail. Hence the most detailed information is available for our immediate neighbors, the dwarf satellites of the Milky Way. A growing body of data is becoming available also for more distant dwarf galaxies in the Local Group and beyond owing largely to observations with the Hubble Space Telescope (HST). Apart from deep observations of selected galaxies our ongoing HST snapshot survey of nearby galaxies is rapidly increasing the number of dwarf galaxies within 5 Mpc for which resolved upper-red-giant-branch photometry is available. Furthermore, observations with large 8m – 10m ground-based telescopes such as Keck, Gemini, Subaru, and the Very Large Telescope (VLT) are playing an increasingly important role.

For the purpose of this review we will consider all galaxies with absolute \( V \) magnitudes \( M_V > -18 \) mag and with diameters of a few kpc or less as dwarf galaxies. Dwarf galaxies are important not only as future constituents of larger galaxies, but also in their own right. They span a wide range of masses, luminosities, mean metallicities, gas content, kinematic properties, and mean ages. Dwarf galaxies are found in different environments ranging from voids to loose groups
and dense galaxy clusters, and from relative isolation within groups to close proximity of massive galaxies. Dwarf galaxies allow us therefore to study the impact of external environmental effects and of internal properties such as gas content and galaxy mass on galaxy evolution. Knowledge of their internal kinematics may help to understand the nature of dark matter, and their global kinematics make them valuable dynamical probes of the dark halos of massive galaxies and clusters.

The existing, detailed studies have revealed a surprising diversity in the star formation histories of dwarf galaxies. Each galaxy shows evidence for a complex evolution that is clearly distinct from the single-age, single-metallicity history characterizing a typical globular cluster. Moreover, even within the same morphological subclass no two dwarf galaxies are alike and differ considerably in their enrichment histories and/or time and length of their star formation episodes. However, common global properties are beginning to emerge, and this review will concentrate on identifying them rather than on describing the differences. For recent reviews that describe the properties of Local Group dwarf galaxies in great detail we refer to van den Bergh (1999; 2000).

2. Types of dwarf galaxies

A variety of terms are in use for different morphological types of dwarf galaxies, and different authors use different definitions.

**Dwarf spirals** comprise S0, Sa, Sb, Sc, and Sd galaxies with $M_V > -18$, central surface brightnesses of $\mu_V > 23$ mag arcsec$^{-2}$, $\text{H}i$ masses of $M_{\text{HI}} < 10^9 M_\odot$, large mass-to-light ratios. Early-type dwarf spirals are discussed in Schombert et al. (1995), while Matthews & Gallagher (1997) describe properties of late-type dwarf spirals. Dwarf spirals tend to be chemically inhomogeneous and contain a range of ages just as massive spirals. Later-type dwarf spirals have lower metallicity and less gas (McGaugh 1994) than the earlier types. Dwarf spirals may exhibit well-defined spiral structure or may appear to be in transition from spirals to irregulars such as Magellanic irregulars (Sm, Sdm). 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.

NGC 3109, a galaxy at a distance of 1.33 Mpc in the nearby Sextans-Antlia group may be considered the closest dwarf spiral since it shows extended spiral structure (Demers et al. 1985) apart from features of an irregular galaxy.
Blue compact dwarf galaxies (BCDs) comprise H II galaxies, blue amorphous galaxies, and certain types of Wolf-Rayet galaxies. Gas, stars, and starburst regions tend to be centrally concentrated in BCDs. Due to their pronounced compact starbursts BCDs have high surface brightnesses ($\mu_V < 19$ mag arcsec$^{-2}$). The H I masses of BCDs are $\lesssim 10^9 M_\odot$ and can exceed the inferred stellar mass. While BCDs tend to be rotationally supported, exhibit solid-body rotation and evidence for dark matter, chaotic motions are detected as well, and part of the extended gas may be kinematically decoupled from the galaxies (van Zee et al. 1998). BCDs may be fitted by $r^{1/4}$ laws in some cases, exponential profiles in others, or composite profiles (Doublier et al. 1999).

The BCD closest to the Local Group is NGC 6789 at a distance of only 2.1 Mpc (Drozdovsky & Tikhonov 2000), while the Local Group does not contain galaxies of this type.

Dwarf irregular galaxies (dIrrs) are gas-rich galaxies with an irregular optical appearance usually dominated by scattered H II regions. They typically have $\mu_V < 23$ mag arcsec$^{-2}$, $M_{HI} < 10^9 M_\odot$, and $M_{tot} < 10^{10} M_\odot$. The H I distribution is usually clumpy and much more extended than even the oldest stellar populations. In low-mass dIrrs gas and stars may exhibit distinct spatial distributions and different kinematic properties. Metallicities tend to increase with decreasing age in the more massive dIrrs, indicative of enrichment. Solid body rotation is common, though not all dIrrs rotate, especially not very low-mass dIrrs. dIrrs are found both in clusters and groups as well as in the field.

The dIrr closest to the Milky Way is the Small Magellanic Cloud (SMC) at a distance of ~ 60 kpc.

Dwarf elliptical galaxies (dEs) are spherical or elliptical in appearance, tend to be found near massive galaxies, usually have little or no detectable gas, and tend not to be rotationally supported. DEs are compact galaxies with high central stellar densities and are typically fainter than $M_V = -17$ mag, have $\mu_V < 21$ mag arcsec$^{-2}$, $M_{HI} < 10^8 M_\odot$, and $M_{tot} < 10^9 M_\odot$. DEs may contain conspicuous nuclei (nucleated dEs, dE(N)) that may contribute up to 20% of the galaxy’s light. The fraction of dE,N is higher among the more luminous dEs. S´ersic’s (1968) generalization of a de Vaucouleurs $r^{1/4}$ law and exponential profiles describes the surface density profiles of nucleated and non-nucleated dEs and dSphs best (Jerjen et al. 2000a).

The closest dE is NGC 185, a companion of M31, at a distance of 620 kpc from the Milky Way. The closest dE,N is M32, another M31 companion, which has a distance of ~ 770 kpc from the Galaxy.

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1 Note that while M32 is a dwarf elliptical according to the definition of a dwarf galaxy adopted in this paper, but is more akin in its properties to classical, giant
Dwarf spheroidal galaxies (dSphs) are diffuse, gas-deficient, low-surface-brightness dwarfs with very little central concentration. They are not always distinguished from dEs in the literature. DSphs are characterized by $M_V \gtrsim -14$ mag, $\mu_V \gtrsim 22$ mag arcsec$^{-2}$, $M_{HI} \lesssim 10^5 M_\odot$, and $M_{tot} \sim 10^7 M_\odot$. They include the optically faintest galaxies known. DSphs are usually found in close proximity of massive galaxies and are generally not supported by rotation. Their velocity dispersions indicate the presence of a significant dark component when virial equilibrium is assumed.

The closest dSph galaxy is Sagittarius, which is currently merging with the Milky Way.

Tidal dwarf galaxies form in mergers and interactions from debris torn out of more massive parent 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). Potential candidates for nearby tidal dwarf galaxies are discussed by Hunter et al. (2000). For more information on properties and formation I refer to the contributions by Mirabel and by Brinks in these proceedings.

3. Star formation characteristics

Photometric imaging is the method of choice to derive star formation histories of galaxies that can be resolved into individual stars. Through comparison with synthetic color-magnitude diagrams based on evolutionary models very detailed star formation histories can be determined. For more distant objects we have to rely upon integrated colors and spectral energy distributions. More information about models and techniques can be found in the contributions by Matteucci, by Tosi, and by Bruzual in these proceedings. Metallicities (such as stellar [Fe/H] or nebular oxygen abundances) are derived photometrically and through spectroscopy (see contributions by Peimbert and by Hill in this volume). The gas content is usually measured through 21cm observations and narrow-band imaging.

Individual dwarf galaxies can show a wide range of evolutionary histories even within the same subclass. Dwarf galaxies vary widely in the amount of enrichment that they experienced, in their star formation rates and the length of star formation episodes, in their gas content, in their number of globular clusters (if any), etc.
3.1. Old Populations

A common property of all dwarf galaxies studied in sufficient detail so far appears to be the presence of an old population, which in many cases turns out to be the dominant population. Furthermore, old populations tend to be spatially more extended than younger ones. Whether this is an effect of the increased dispersal of older stars as a function of time, of expansion due to mass loss, or other effects is unclear.

The term “old population” usually refers to stars with ages of 10 Gyr and more. These populations can be unambiguously traced through the detection of horizontal branch stars or more accurately through the corresponding main-sequence turnoffs. Main-sequence turnoffs at the distance of M31 (770 kpc) occur at $V \sim 28$ mag, which illustrates why accurate age dating of the oldest populations is impossible in all but the closest dwarfs. Horizontal branches are 3 – 3.5 mag brighter than the oldest main-sequence turnoffs, but their detection can be difficult in regions of significant crowding or in galaxies with significant intermediate-age populations, which can obscure horizontal branches in a color-magnitude diagram.

Deep main-sequence photometry (largely based on HST imaging) has established that a number of Local Group galaxies share a common epoch of ancient star formation. Main-sequence photometry reveals that the oldest globular clusters in the Milky Way halo and bulge, in the LMC (an irregular galaxy but not a dwarf according to the definition adopted here), in the Sagittarius dSph, and in Fornax are coeval. Similarly, the oldest field populations in the dSphs Sagittarius, Draco, Ursa Minor, Fornax, Sculptor, Carina, and Leo II have the same relative age as the oldest Galactic globular clusters.

The existence of blue horizontal branches in globular clusters in M31, in the dIrr WLM, and the dE NGC 147 are interpreted as indicative of ages similar to those of the old Galactic globular clusters. The blue horizontal branch in the field populations of the dSphs Sextans, Leo I, Cetus, And I, And II, and Tucana, in the dIrr/dSph Phoenix, in the dIrr IC 1613, and in the dEs NGC 185 and NGC 147 appear to imply comparatively old ages. Second-parameter effects other than age, however, may also play an important role here.

Possible evidence for delayed formation of the first significant (i.e., clearly observable) old population may exist in other dwarf galaxies: The absence of a blue horizontal branch in the field populations of the dIrrs SMC, WLM, Leo A, and DDO 210 (as well as in the large spiral M33) may indicate that the bulk of the old population in these galaxies formed a few Gyr later than the oldest Milky Way globular clusters. These galaxies span a range of distances from more massive galaxies,
and there is no obvious reason for the apparent difference in the oldest significant star formation episodes.

For a list of references for the studies of the individual galaxies quoted here see Grebel (2000).

In dwarf galaxies well beyond the Local Group (at distances of 2 Mpc and more) the available studies tend not to go deeper than a few magnitudes below the tip of the red giant branch. Both integrated colors and the detection of red giant branches in dwarf spirals and BCDs indicate the presence of past star formation episodes in these objects (e.g., Papaderos et al. 1996; Lynds et al. 1998; Schulte-Ladbeck in this volume). Without photometry at least down to the horizontal branch the age of these bona fide “old” populations is difficult to constrain, but there is clearly evidence for populations older than 2 Gyr.

3.2. Star formation and spatial variations

Star formation in the disks of dwarf spirals appears to be largely driven by spiral density waves. Dwarf spirals appear to have experienced continuous, low-level star formation over a Hubble time and will likely continue in the same manner for a long time. Rotation, shear, metallicity, and H\textsc{i} surface density tend to decrease toward later types (e.g., McGaugh 1994; de Blok et al. 1995).

BCDs have one or several centrally concentrated starburst regions, which may contain super star clusters. With H\textsc{i} densities of up to $\sim 10^{21}$ atoms cm$^{-2}$ in active regions BCDs exceed the Toomre instability criterion for star formation, which facilitates their high star formation rate (e.g., Taylor et al. 1994, van Zee et al. 1998). Many BCDs are observed in isolation without recognizable companions, hence interactions do not seem to be the agent for the vigorous star formation.

The interstellar medium (ISM) in dIrrs is highly inhomogeneous and porous, full of small and large shells and holes. Star formation may be driven by homogeneous turbulence, which creates local densities above the star formation threshold (e.g., Stanimirovic et al. 1999). Lower gravitational pull and the lack of shear in absence of differential rotation imply that H\textsc{i} shells may become larger and are long-lived (Hunter 1997). Diameters, ages, and expansion velocities of the H\textsc{i} shells increase with later Hubble type (Walter & Brinks 1999) and scale approximately with the square root of the galaxy luminosity (Elmegreen et al. 1996). Shell-like structures, H\textsc{i} holes, or off-centered gas may be driven by supernovae and winds from massive stars following recent star formation episodes or tidal interactions. Indeed, evidence for outward propagating star formation within a central H\textsc{i} shell was found in the dIrr Sextans A in the Sextans-Antlia group (van Dyk et
Numerous shells with propagating star formation along their rims were uncovered in the dIrr IC 2574 in the M81 group (Walter & Brinks 1999), while tidal interactions may be responsible for the off-centered H i distribution, asymmetric H i disks, or counterrotation seen in the dIrr NGC 55 in the Sculptor group (Puche et al. 1991) and in the fairly isolated dIrr NGC 4449 in the CVn I cloud (e.g., Hunter et al. 1999). On a global, long-term scale, however, star formation has essentially occurred continuously at a constant rate with amplitude variations of 2–3 (Tosi et al. 1991, Greggio et al. 1993) and is largely governed by internal, “local” processes (Hunter 1997).

The best-studied dEs are the four dE companions of M31. They have dominant old and intermediate populations, but can also show recent, centrally concentrated star formation as in the case of NGC 185 (Martínez-Delgado et al. 1999). The H i in these dEs ranges from almost non-existent to counterrotating to being consistent with expectations from stellar mass loss (e.g., Sage et al. 1998).

DSSphs, in contrast, have been found to be devoid of gas within their optical radii down to column densities of \(2 \text{ to } 6 \cdot 10^{17} \text{ cm}^{-2}\) (e.g., Young 2000). However, H i with matching radial velocities was detected in their surroundings (Carignan 1999; Blitz & Robishaw 2000), which may have been removed through ram pressure effects. While DSSphs have predominantly old and intermediate-age populations, the intermediate-age fraction increases roughly with Galactocentric distance, which may be caused by the decreased impact of ram pressure and tidal stripping (e.g., van den Bergh 1994). Intermediate-age and younger populations, where present, tend to be centrally concentrated. This may indicate that star formation could be sustained longer in the centers, where gas was retained for a more extended period. Even in DSSphs that are largely old there is some evidence for spatial variations in star formation history: red horizontal branch stars are often found more centrally concentrated than blue horizontal branch stars (e.g., in Sculptor; Hurley-Keller et al. 1999). However, this trend is not observed in all DSSphs — And II is a counterexample (Da Costa et al. 2000). The metallicity spread found in “single-age” DSSphs such as the faint Milky Way companions Draco und Ursa Minor indicates that their early star formation episode must have been sufficiently extended to allow for this enrichment. While their luminosity functions are indistinguishable from those of old Galactic globular clusters (Grillmair et al. 1998; Feltzing et al. 1999), the abundance ratios of the DSSphs suggest that their nucleosynthetic histories differed from those of average Galactic halo stars in terms of having lower \([\alpha/\text{Fe}]\) ratios (Shetrone et al. 2000).

In summary, the following modes of star formation are observed among nearby dwarf galaxies: (1) Continuous star formation with a
constant or varying star formation rate over a Hubble time and gradual enrichment; this mode appears to hold for dSphs, massive dIrrs, and possibly BCDs. (2) Continuous star formation with decreasing star formation rate that ceases eventually. Examples include low-mass dIrrs, dEs, and most dSphs. (3) Distinct star formation episodes separated by Gyr-long periods of quiescence. So far only one example of this mode is known, the Carina dSph (e.g., Hurley-Keller et al. 1998). It is unclear what caused the gaps and the subsequent onset of star formation, and why this dSph does not show chemical enrichment.

Dwarf galaxy evolution as a whole appears to be determined both by environmental effects and by galaxy mass. Indeed all morphological types of LG dwarf galaxies tend to follow global relations between absolute magnitude, mean metallicity, and central surface brightness. The more luminous a galaxy the higher its metallicity. These relations hold also for most dwarfs outside of the Local Group. For a more detailed discussion see Skillman (these proceedings).

4. Potential evolutionary transitions?

Can dwarf galaxies of one morphological type evolve into another?

As was argued by van Zee et al. (1998), the rotation of BCDs make it unlikely that these dwarfs could evolve into dEs as they would need to get rid of their angular momentum. Also, BCDs are often found in the field, whereas dEs are predominantly found in dense cluster environments. Similarly, the compact, concentrated structure of BCDs suggests they do not evolve into dIrrs. Nor is there an obvious mechanism to achieve the required expansion as dIrrs have a by a factor 2 larger envelope scale length. Under favorable conditions, evolution from BCDs to nucleated dwarf ellipticals may be possible (Marlowe et al. 1999).

An interesting case combining both properties of a dE and a spiral was recently uncovered by Jerjen et al. (2000b): They show that the dE,N IC 3328 shows weak underlying spiral structure and is likely a nearly face-on dS0 galaxy. Knezek et al. (1999) studied three mixed-morphology, gas-rich transition-type candidates and found that neither of them is likely to evolve into a dE over the next Hubble time.

The presence of intermediate-age or even young populations in some of the more distant dSphs, the possible detection of associated gas in the surroundings of several dSphs, indications of substantial mass loss, 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 may eventually evolve into dSphs, which may be fostered by external effects such as ram pressure and tidal stripping. The dSph Fornax with its significant young (100–200 Myr) population despite the absence of gas may represent an advanced stage of such a transition (Grebel & Stetson 1999).

The [O/Fe] abundances in dSphs were found to be systematically higher than in other galaxies, particularly dIrrs (Richer et al. 1998). The ratio of [O/Fe] serves as a measure of the star formation time scale, since Fe is produced by SNe Ia and II with a significantly longer enrichment time scale than O. As dSphs lack H II regions, direct measurements of their O abundances are based on planetary nebulae. Planetary nebulae were detected in only two dSphs so far, namely Fornax and Sagittarius, which are also the two most massive dSphs. [O/Fe] ratios in dIrrs, on the other hand, are derived from H II region abundances. As discussed in Richer et al. (1998), these measurements represent the maximum of the stellar O abundances, whereas planetary nebulae are a measure of the mean stellar O abundance. A correction for this increases the difference in [O/Fe] ratios in these two types of galaxies further. However, I am not aware of similar, published [O/Fe] ratio measurements in dIrrs of comparable mass as dSphs, i.e., with masses of a few times \(10^7\) M\(_\odot\). Such low-mass dIrrs include LGS 3, Phoenix, and GR 8, and are also called “transition-type” galaxies to indicate that they may be evolving from dIrrs to dSphs. It is important to compare dSphs to this specific type of low-mass dIrr since only here galactic wind properties and galactic potential (which determine chemical enrichment) may have been comparable to those in dSphs if we assume that dSphs are not the result of a catastrophic event such as a merger, nor underwent extreme mass loss. Similarity is furthermore supported by the fact that the measured stellar velocity dispersion of LGS 3 is comparable to that of dSphs (Cook et al. 1998). Mateo (1998) argues that the three transition-type galaxies lie on the same branch as dSphs when plotting [O/H] or [Fe/H] versus absolute magnitude. Thus the chemical properties of dSphs do not seem to contradict the proposed evolution from low-mass dIrrs to dSphs outlined above, though additional data would certainly be useful. The distinction between dSphs and dIrrs may be more a matter of semantics than of physics.

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