Stellar Populations in Dwarf Galaxies: A Review of the Contribution of HST to our Understanding of the Nearby Universe

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This review aims to give an overview of the contribution of the Hubble Space Telescope to our understanding of the detailed properties of Local Group dwarf galaxies and their older stellar populations. The exquisite stable high spatial resolution combined with photometric accuracy of images from the Hubble Space Telescope have allowed us to probe further back into the history of star formation of a large variety of different galaxy types with widely differing star formation properties. It has allowed us to extend our studies out to the edges of the Local Group and beyond with greater accuracy than ever before. We have learnt several important things about dwarf galaxy evolution from these studies. Firstly we have found that no two galaxies have identical star formation histories; some galaxies may superficially look the same today, but they have invariably followed different paths to this point. Now that we have managed to probe deep into the star formation history of dwarf irregular galaxies in the Local Group it is obvious that there are a number of similarities with the global properties of dwarf elliptical/spheroidal type galaxies, which were previously thought to be quite distinct. The elliptical/spheroidals tend to have one or more discrete episodes of star formation throughout their history and dwarf irregulars are characterized by quasi-continuous star-formation. The previous strong dichotomy between these two classes has been weakened by these new results and may stem from the differences in the environment in which these similar mass galaxies were born into or have inhabited for most of their lives. The more detailed is our understanding of star formation processes and their effect on galaxy evolution in the nearby Universe the better we will understand the results from studies of the integrated light of galaxies in the high-redshift Universe.

1. Introduction

This review is a survey of the Hubble Space Telescope (HST) studies of resolved stellar populations of nearby galaxies that have determined accurate global star formation histories going back several Gyr. The determination of such a detailed the star formation history depends upon the ability to accurately photometer many Gyr old stars. This was possible from ground based imaging for our nearest companions, the dwarf spheroidals, and the Magellanic Clouds. HST, with its outstanding combination of lower sky brightness, high resolution, and a stable and constant point spread function, has allowed us to probe further out into the Local Group and even beyond this to look at a much more diverse sample of galaxies than previously possible, and it has also allowed us renewed insights into our nearest neighbours.

I am leaving out any discussion of the considerable body of literature on the HST observations of the stellar populations of the Magellanic Clouds (e.g., Holtzman et al. 1999; Panagia et al. 2000) which technically do not count as dwarf galaxies (e.g., Tammann 1994; Binggeli 1994) but are often assumed to be so. Because these galaxies are so large on the sky it is difficult for HST by itself to gain a perspective of the global star-formation properties, although attempts are being made (e.g., Snecker-Hane et al. 1999). There

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are also numerous HST studies of stellar populations at the small scale of individual star clusters and H II regions in the Clouds (e.g., Da Costa 1999; Massey 1999; Hunter 1999). Studies of the stellar populations of the Magellanic Clouds could easily take up an entire review, not to say a conference, in their own right. I have also neglected considerable work on resolved stellar populations of dwarfs in the UV (e.g., Brown et al. 2000; Cole et al. 1998), because the detailed connection to quantifying a star formation history is unclear. This is also true of studies of star clusters around nearby dwarf galaxies (e.g., Da Costa 1999; Hodge et al. 1999; Mighell, Sarajedini & French 1998).

1.1. Dwarf Galaxy Types:

Classification is a difficult and often emotive business, and I do not attempt to seriously address this issue, except to make it easier for me to refer to the sample of galaxies in the Local Group in broad terms, and with my particular interest in their star-forming properties. So, bearing this caveat in mind let me introduce the four different classes of dwarf galaxies that should cover anything out there:

**Dwarf Irregular (dI) galaxies** are arguably the most common type of galaxy in the Universe (cf. Ellis 1997), they are not clustered around larger galaxies, but appear to have a fairly random distribution throughout the Local Group, and indeed in the Universe. They are usually loosely structured late-type gas rich systems with varying levels of star formation occurring in a haphazard manner across the galaxy. The velocity field of the HI gas in these systems can be dominated by random motions rather than rotation (e.g., Lo, Sargent & Young 1993, but see Skillman 1996), for the fainter dIs (e.g., Leo A; \(v_{\text{rot}} \sim 5\) km/s), but for the more massive dIs (e.g., NGC 6822, Sextans A) solid body rotation is clearly seen, with amplitudes of 30 – 40 km/s.

**Blue Compact Dwarf (BCD) galaxies** are gas rich systems dominated by a region of extremely active star formation, and resembling the massive HII regions which can be found in larger galaxies. They are thought to be forming stars at a rate which they can only maintain for a short period (e.g., Searle, Sargent & Bagnuolo 1973). This type of galaxy may be a dI undergoing a period of particularly active star formation (e.g., Tolstoy 1998a). Within the Local Group, IC 10 is a fairly good approximation of what we expect a BCD to look like (see van den Bergh 2000; Hunter et al. in prep.), and perhaps also IC 5152. The more distant BCDs could easily be embedded in larger low surface brightness galaxies, which are easier to see within the Local Group. There are several, classical, examples of BCDs just beyond the Local Group (e.g. NGC 1569 & VII Zw403).

**Dwarf Elliptical (dE) galaxies** are basically low luminosity Elliptical galaxies, with smooth surface brightness distributions (e.g., Ferguson & Binggeli 1994). They are typically dominated by an old stellar population, but as Baade already noticed in 1951, they are subject to the same extreme variations of stellar population as other dwarf galaxy types. Baade (1951) found that the archetypal dEs NGC 185 and NGC 205 contain B stars along with gas and dust. Recent detailed analysis suggests that several epochs of star formation over long time scales are needed to explain the characteristics of dE stellar populations (e.g., Ferguson & Binggeli 1994; Han et al. 1997). Most of the bright dEs (\(M_B < -16\)) appear to have nuclei, and there is some evidence that these are dynamically separate super-massive star clusters (e.g., M 54 in Sagittarius, Ibata et al. 1994; and NGC 205, Carter & Sadler 1990). dEs are strongly clustered with the largest galaxies, and four of the five dEs in the Local Group are found in proximity to M 31.

**Dwarf Spheroidal (dSph) galaxies** are basically low-surface brightness, non-nucleated dEs. Many argue that the dSph are merely the low luminosity tail of the dE galaxy class (e.g., Ferguson & Binggeli 1994), and the fact that they are often clustered around...
### Table 1. The Local Group

| name            | type  | $M_V$ | $\Sigma_0$ | $M_{tot}$/$H_0$ | $M_{tot}$/$H_0$ | $M_{tot}/H_0$ | [Fe/H] | [Fe/H] | [Fe/H] |
|-----------------|-------|-------|-------------|-----------------|-----------------|----------------|--------|--------|--------|
|                 |       |       |             | $10^9 M_\odot$ |                  |                |        |        |        |
|                 |       |       |             |                 |                  |                |        |        |        |
| **Spiral galaxies:** |   |   |   |   |   |   |   |   |   |
| M 31            | Sb    | -21.2 | 10.8        | $2 \times 10^6$ | 0.002           | +0.2           |        |        |        |
| Milky Way       | Sc    | -20.9 | 10.7        | $10^6$          | 0.004           | 0              |        |        |        |
| M 33            | Sc    | -18.9 | 10.7        | $10^5$          | 0.02            | -0.2           |        |        |        |
| **Irregular galaxies:** |   |   |   |   |   |   |   |   |   |
| NGC 3109        | Irr   | -15.7 | 23.6±0.2    | 6550            | 0.11            | -1.2 ± 0.2a   |        |        |        |
| LMC             | Irr   | -18.1 | 20.7        | 6000            | 0.5             | -0.7          |        |        |        |
| SMC             | Irr   | -16.2 | 22.1        | 2000            | 0.25            | -1.0          |        |        |        |
| **Dwarf Ellipticals:** |   |   |   |   |   |   |   |   |   |
| M 32            | dE2   | -16.7 | <11.5:      | 2120            | <0.001          | -1.1 ± 0.2    |        |        |        |
| NGC 205         | dE5   | -16.6 | 20.4±0.4    | 740             | 0.001           | -0.8 ± 0.1    |        |        |        |
| NGC 185         | dE3   | -15.5 | 20.1±0.4    | 130             | 0.001           | -1.2 ± 0.15   |        |        |        |
| NGC 147         | dE4   | -15.5 | 21.6±0.2    | 110             | <0.001          | -1.1 ± 0.2    |        |        |        |
| Sagittarius     | dE7   | -13.4 | 25.4±0.3    | 500             | <0.0001         | -1.0 ± 0.2    |        |        |        |
| **Dwarf Irregulars:** |   |   |   |   |   |   |   |   |   |
| NGC 6822        | dIrr  | -15.2 | 21.4±0.2    | 1640            | 0.08            | -0.7 ± 0.2a   |        |        |        |
| IC 10           | Irr   | -15.7 | 22.1±0.4    | 1580            | 0.10            | -0.7 ± 0.15a  |        |        |        |
| IC 1613         | dIrr  | -14.7 | 22.8±0.3    | 795             | 0.07            | -1.1 ± 0.2a   |        |        |        |
| IC 5152         | dIrr  | -14.8 | 400         | 0.15            | -0.6 ± 0.2a     |        |        |        |
| Sextans B       | dIrr  | -14.2 | 885         | 0.05            | -1.1 ± 0.3a     |        |        |        |
| Sextans A       | dIrr  | -14.6 | 23.5±0.3    | 395             | 0.20            | -1.4 ± 0.2a   |        |        |        |
| WLM             | dIrr  | -14.5 | 20.4±0.05   | 150             | 0.40            | -1.1 ± 0.2a   |        |        |        |
| Phoenix         | dIrr/dE | -10.1 | 33         | 0.006           | -1.9 ± 0.1      |        |        |        |
| Pegasus         | dIrr  | -12.9 | 58          | 0.09            | -1.0 ± 0.14a    |        |        |        |
| LGS 3           | dIrr/dE | -10.5 | 24.7±0.2    | 13              | 0.03            | -1.8 ± 0.3    |        |        |        |
| Leo A           | dIrr  | -11.4 | 11          | 0.72            | -1.6 ± 0.15a    |        |        |        |
| SagDIG          | dIrr  | -12.3 | 24.4±0.3    | 9.6             | 0.92            | -1.5 ± 0.3a   |        |        |        |
| DDO 210         | dIrr  | -10.0 | 23.0±0.3    | 5.4             | 0.35            | -1.9 ± 0.12   |        |        |        |
| EGB 0427+63     | dIrr  | -12.6 | 23.9±0.1    | -1.4 ± 0.1a     |        |        |        |        |        |
| **Dwarf Spheroidals:** |   |   |   |   |   |   |   |   |   |
| Fornax          | dE3   | -13.2 | 23.4±0.3    | 68              | <0.001          | -1.3 ± 0.2    |        |        |        |
| Ursa Minor      | dE5   | -8.9  | 25.5±0.5    | 23              | <0.002          | -2.2 ± 0.1    |        |        |        |
| Draco           | dE3   | -8.8  | 25.3±0.5    | 22              | <0.001          | -2.1 ± 0.15   |        |        |        |
| Leo I           | dE3   | -11.9 | 22.4±0.3    | 22              | <0.001          | -1.5 ± 0.4    |        |        |        |
| Sextans         | dE4   | -9.5  | 26.2±0.5    | 19              | <0.001          | -1.7 ± 0.2    |        |        |        |
| Carina          | dE4   | -9.3  | 23.9±0.4    | 13              | <0.001          | -2.0 ± 0.2    |        |        |        |
| Sculptor        | dE    | -11.1 | 23.7±0.4    | 6               | <0.004          | -1.8 ± 0.1    |        |        |        |
| Antlia          | dE3   | -10.8 | 24.3±0.2    | 12              | 0.08            | -1.8 ± 0.25   |        |        |        |
| Tucana          | dE5   | -9.6  | 25.1±0.06   | -1.7 ± 0.15     |        |        |        |        |        |
| Cetus           | dE4   | -10.1 | 25.1±0.1    | -1.9 ± 0.2      |        |        |        |        |        |
| Leo II          | dE0   | -9.6  | 24.0±0.3    | 10              | <0.001          | -1.9 ± 0.1    |        |        |        |
| And I           | dE0   | -11.9 | 24.9±0.01   | -1.5 ± 0.2      |        |        |        |        |        |
| And II          | dE3   | -11.1 | 24.8±0.05   | -1.5 ± 0.3      |        |        |        |        |        |
| And III         | dE6   | -10.3 | 25.3±0.05   | -2.0 ± 0.2      |        |        |        |        |        |
| And V           | dE3   | -9.1  | 24.8±0.2    | -1.6 ± 0.2      |        |        |        |        |        |
| And VI (Peg dSph) | dE3 | -11.3 | 24.3±0.05 | -1.6 ± 0.2 | | | | | |
| And VII (Cass dSph) | dE3 | -12.0 | 23.5±0.05 | -1.4 ± 0.3 | | | | | |

*a* these values were converted from [O/H] measurements, assuming constant [Fe/O] = 0.
bigger galaxies such as our Galaxy, M 31, and perhaps also NGC 3109 tends to support this. However it is also possible that at least a fraction of this class fit into a common evolutionary scenario with dIIs and BCDs, their past star-formation having been dominated by bursts (e.g. Carina). There are a number of so called transition objects, such as Phoenix, Antlia and LGS 3 which are hard to fit unambiguously into either the dE or dI class. They have very little or no present-day star formation, and yet they have associated HI gas, so it seems a fair assumption that they will form stars again before too long, and will then clearly belong to the dI class.

1.2. The Properties of Local Group Galaxies

Our local neighbourhood, the Local Group, is arguably as representative a piece of the Universe as any (e.g., van den Bergh 2000). What we learn about the properties of star formation and galaxy evolution here can justifiably be extrapolated to explain what we see in the distant, early Universe. That which is on our doorstep provides us with the chance to properly understand the dominant physical processes in great detail.

As with galaxy classification, there are different selection criteria which vary the number of dwarf and irregular galaxies included in a census of Local Group members. I have chosen to follow dynamical arguments (e.g., Irwin 1998), which tends to allow a slightly more distant limit to the distance from the centre than van den Bergh (2000). There is no straight forward boundary between the Local Group and the Sculptor, and many of the galaxies in this region could “belong to either”, by dynamical arguments. Listed in Table 1 are some basic properties of the galaxies I have assumed to be members of the Local Group. For each galaxy there is listed the absolute V magnitude ($M_V$), the central surface brightness in V ($\Sigma_0$), the total mass ($M_{tot}$), and the fraction of this total in HI gas, when I could find them. Also listed is an estimate of the mean metallicity of each galaxy, given as [Fe/H], for the sake of uniformity. Where the metallicity was “converted” from [O/H], this is noted. The rest of the values are predominantly based upon the colour of the red giant branch, and thus ought to be treated as lower limits. A lot of detail is glossed over in presenting a uniform “metallicity” for a range of galaxy type, as here (cf, Skillman 1998 for much more detail on this complex topic).

Most of the data in Table 1 came from Mateo (1998), which contains a very complete collection of what is known about Local Group dwarf galaxies. Mateo also provides explanations of the error bars, and where these data originally come from. The purpose of Table 1 is largely illustrative and I would recommend anyone who would like to use the values in this table to look them up in Mateo, and even better still in the original references provided there. I also recommend the detailed descriptions of the individual galaxies in van den Bergh (2000). The data for the more massive galaxies in the Local Group: the Milky Way, M31, M33 and the LMC/SMC are extracted from various standard sources, and not meant to be definitive, merely to illustrate the scale sizes between dwarf galaxies and their large neighbours in the Local Group.

The mass of the Local Group is dominated by three large spiral galaxies, namely our Galaxy, M 31 and M 33. However, the largest population by number are the dwarf type galaxies (see Table 1). The Local Group contains several examples of each class of dwarf galaxy, as defined above. All dwarf galaxy types could plausibly come from the same type of progenitor but for reasons of differences in initial dark matter content, or environment or chance encounters with other galaxies follow different evolutionary paths which result in the different present-day properties (e.g., Ferrara & Tolstoy 2000; Binggeli 1994; Davies & Phillips 1988).

The total mass of a galaxy has a critical impact on the ability of that galaxy to form stars. It determines how effectively gas can be compressed to increase the efficiency of
star formation and also how hard it is for supernova explosions to disrupt or even rid the system of gas delaying or preventing future star formation (e.g., Mac Low & Ferrara 1999; De Young & Heckman 1994; Dekel & Silk 1986). The lowest mass dwarf galaxies are often at the hairy edge of being able to retain their gas whilst forming stars, and many clearly have lost the battle. For the lowest mass galaxies any small perturbation
can have a dramatic impact on the evolution of these systems, and it is this sensitivity to initial conditions and random events which may explain some of the dispersion of the values in Table 1 (see Ferrara & Tolstoy 2000).

One of the few obvious correlations between dwarf galaxy properties is that between absolute magnitude \( (M_V) \) and global metallicity (\( e.g. \), Skillman, Kennicutt & Hodge 1989). If a reasonably uniform mass to light (M/L) ratio can be assumed, then this can be interpreted as a mass-metallicity relation. Those galaxies which fall significantly off the relation (\( e.g. \), extreme BCDs) can be assumed, with very good reasons, to have a significantly different M/L. Indeed some scatter in the M/L of average galaxies might well account for the scatter seen in the mass-metallicity relation (\( e.g. \), Ferrara & Tolstoy 2000).

A large uncertainty in proving or disproving this is the lack of reliable measurements of total (or dynamical) masses of dwarf galaxies.

Basically, the global star-formation properties of a galaxy appear to be dominated by the total mass. This may perhaps vary when galaxies interact and merge, but it is difficult to disentangle the effects of merging two small galaxies to form a bigger one and the temporary boost to the star formation rate from the merger. These two effects might balance each other - because taken at face value the luminosity/mass-metallicity relation seems to say that a galaxy knows how big it is from the earliest times. If a lot of dwarfs were added together they would retain the global metallicity of the original pieces, whilst increasing in luminosity. This simple arithmetic could also argue against merging having a significant impact upon Local Group galaxies, at least in recent times.

2. Why Study Dwarf Galaxies?

As demonstrated in Table 1 Local Group dwarf galaxies have a wide range of different properties. They span a large mean metallicity range, down the lowest seen anywhere. They also exhibit a range of gas fractions, and density, from no gas all the way to gas dominated. They are also to be seen in a range of proximities to other systems of varying mass. Thus a study of the dwarf galaxy members of the Local Group allows us to study star formation over a large range of initial conditions. When the star formation properties of the Local group galaxies are looked at together (\( e.g. \), Mateo 1998; Da Costa 1998; Grebel 1998), the only global statement that can be made with no fear of contradiction is that no two are exactly alike.

The smaller dwarf galaxies effectively have a single-cell mode of global star formation, which in principle ought to be more straightforward to comprehend than larger galaxies where different star formation regions can apparently be unaware of each other or interfere strongly with each other, or anything between these extremes. This, including spiral density waves, bars, jets and other dynamical effects can create severe complications to the straightforward interpretation of the relationship between gas and stars and star formation. Although, as can be seen by the results presented in this review, even these small galaxies are capable of a high degree of complexity, so “straight forward” is a very relative statement.

Dwarf galaxies have the added benefit for HST observations, that they are small enough, at the modest distances typical for Local Group members that a significant fraction of the surface area of a dwarf can typically fit into the WFPC2 field of view (see Figure 1).

The Local Group contains galaxies whose star formation histories should be typical of galaxy group members, and thus of star formation throughout the Universe. It must therefore include remnants of the epoch \(~ 5−8\) Gyr before the present when actively star forming galaxies produced the faint blue galaxy population seen at intermediate redshifts.
We can directly measure star formation histories of nearby galaxies back to the era of faint blue galaxies with sufficiently deep and accurate imaging and using established quantitative techniques for analysing colour-magnitude diagrams (e.g., Tosi et al. 1991; Tolstoy 1996; Aparicio et al. 1996).

Consistent with the properties of faint blue galaxies in redshift surveys, dwarf galaxies appear to have erratic star formation rates, and they can host bright, short lived bursts of star formation which could make these currently dim and inconspicuous galaxies dominate the luminosity of the Local Group for short periods of time. Because dwarfs are so numerous, it only requires each galaxy to burst once or twice in its life time before the dwarfs in the Local group are effectively always visible in redshift surveys. This means that these small galaxies could be dominating redshift surveys in the intermediate redshift range (e.g., Lilly et al. 1996). The ubiquitous faint blue galaxies seen in deep imaging and spectroscopic surveys at intermediate redshifts could be a population of dwarf galaxies.

3. Colour-Magnitude Diagram Analysis: How to Study Dwarf Galaxies

The study of resolved stellar populations provides a powerful tool to follow galaxy evolution consistently and directly in terms of physical parameters such as age (star formation history), chemical composition and enrichment history, initial mass function (IMF), environment, and dynamical history of the system. Photometry of individual stars in at least two filters and the interpretation of Colour-Magnitude Diagram (CMD)
morphology gives the least ambiguous and most accurate information about variations in star formation within a galaxy back to the oldest stars (see Figure 2). Some of the physical parameters that affect a CMD are strongly correlated, such as metallicity and age, since successive generations of star formation may be progressively enriched in the heavier elements. Careful, detailed CMD analysis is a proven, uniquely powerful approach (e.g., Tosi et al. 1991; Tolstoy & Saha 1996; Aparicio et al. 1996; Mighell 1997; Dohm-Palmer et al. 1997, 1998; Gallagher et al. 1998; Tolstoy et al. 1998; Tolstoy 1998a) that benefits enormously from the high spatial resolution of HST.

3.1. Useful Features in a Colour-Magnitude Diagram

Stellar evolution theory provides a number of clear predictions, based on relatively well understood physics, of features expected in CMDs for different age and metallicity stellar populations. There are a number of clear indicators of varying star formation rates at different times which can be combined to obtain a very accurate picture of the entire star formation history of a galaxy (see Figures 2 and 3). Here I provide a brief description of each of the separate indicators, in order of preference. The indicators are thus presented in an order which broadly represents the ease with which age and metallicity information can be extracted.

3.1.1. Main Sequence Turnoffs (MSTOs)

The Main Sequence is a well understood mass-luminosity-lifetime relation, which allows us to extract (relatively) unambiguous information about the star formation rate with time over the lifetime of a galaxy. With exposures (going down to $M_V \sim +4$) of the resolved stellar populations in nearby galaxies we can obtain the unambiguous age information that comes from the luminosity of MSTOs back to the oldest ages. The MSTOs do not overlap each other and hence provide the most direct, accurate information about the star formation history of a galaxy (see Gallart et al. 1999). MSTOs can clearly distinguish between bursting star formation and quiescent star formation. The age resolution that is possible does vary, becoming coarser going back in time, and can also be affected by metallicity evolution. Our ability to disentangle the variations in star formation rate depends upon the the intensity of the past variations and how long ago they occurred and which filters are used for observation.

3.1.2. The Core-Helium Burning Blue Loop Stars (BLs)

Stars of low metallicity and intermediate mass go on extensive “Blue Loop” (BL) excursions after they ignite He in their core. Stars in the BL phase are several magnitudes brighter than when on the main sequence ($M_V \lesssim -1$). The shape of these “loops” are a strong function of metallicity and age. They thus provide a more luminous opportunity to accurately determine the age and metallicity of the young stellar population (in the range, $\sim 1$ Gyr old) in nearby low metallicity galaxies The luminosity of a BL star is fixed for a given age, and thus subsequent generations of BL stars do not over-lie each other, and can be used to trace spatial variations in recent star formation over a galaxy (e.g., Dohm-Palmer et al. 1997b). The lower the metallicity of the galaxy, the older will be the oldest BLs and the further back in time an accurate spatially resolved star formation history can easily be determined.

3.1.3. The Red Giant Branch (RGB)

The RGB is a bright evolved phase of stellar evolution, where the star is burning H in a shell around its He core. It is characterized by a fairly constant maximum (or tip) luminosity (at $M_I = -4$), and stars are distributed all the way down to $M_I \sim +2$.
Metallicity is the most important effect in determining the width of the RGB in colour, especially for ages > 2 Gyr. However, correlations between age and metallicity can mask a metallicity spread, as ~ 4 Gyr of age difference can produce the same effect as 0.1 dex of metallicity difference, in (V−I). For a given metallicity the RGB blue and red limits are given by the age spread of the stars populating it (ages ≥1 Gyr), because as a stellar population ages the RGB moves to the red. However increasing the metallicity of a stellar population will also make the RGB redder, and thus produce the same effect as aging. This is the (in)famous age-metallicity degeneracy problem. The result is that if there is metallicity evolution within a galaxy, it is impossible to uniquely disentangle effects due to age and metallicity on the basis of the optical colours of the RGB alone.

3.1.4. The Red Clump/Horizontal Branch (RC/HB)

Red Clump (RC) stars (M_V ~ +0.5), low-mass analogues of the BL stars, and their lower mass cousins the Horizontal Branch (HB) stars (M_V ~ 0.) are core He-burning stars, and they don’t obey a simple mass-luminosity law, as their core mass is mostly independent of their total mass. Their luminosity and colour varies depending upon age, metallicity and mass loss (Caputo, Castellani & degl’Innocenti 1995). The extent in luminosity of the RC can be used to estimate the age of the population that produced it (see Tolstoy 1998b). This age measure is independent of absolute magnitude and hence distance.

The classical RC and RGB appear in a population at about the same time (after ~ 0.9–1.5 Gyr, depending on model details), where the RGB are the progenitors of the RC stars. The lifetime of a star on the RGB, t_{RGB}, is a strongly decreasing function of M_{star}, but the lifetime in the RC, t_{RC} is roughly constant. Hence the ratio, t_{RC} / t_{RGB}, is a decreasing function of the age of the dominant stellar population in a galaxy, and the ratio of the numbers of stars in the RC, and the HB to the number of RGB is sensitive to the star formation history of the galaxy (e.g. Cole 1999; Gallagher et al. 1998; Tolstoy et al. 1998; Han et al. 1997). Thus, the higher the ratio, N(RC)/N(RGB), the younger the dominant stellar population in a galaxy.

The presence of a large HB population on the other hand (high N(HB)/N(RGB) or even N(HB)/N(MS)), is caused by a predominantly much older (>10 Gyr) stellar population in a galaxy. The HB is the brightest unambiguous indicator of very lowest mass (hence oldest) stellar populations in a galaxy, it is however impossible to use it to infer star formation rates at these ancient epochs, because of the “second parameter effect” (e.g., Fusi Pecci & Bellazzini 1997), which decouples the HB lifetimes from initial conditions, is well known, but not yet understood, from globular cluster studies.

3.1.5. The Extended Asymptotic Giant Branch (EAGB)

Extended Asymptotic Giant Branch (EAGB) stars are very bright, red evolved stars (M_V > −4, and typically V − I > 1.5). The temperature and colour of the EAGB stars in a galaxy are determined by the age and metallicity of the population they represent. However there remain a number of uncertainties in the comparison between the models and the data (e.g., Gallagher et al. 1998; Lynds et al. 1998). It is necessary that more work is done to enable a better calibration of these very bright indicators of past star formation events. The future of this field probably lies in infra-red observations of these stars.

3.2. Monte-Carlo Simulations of CMDs

One of the most impressive advances in interpreting observed CMDs in terms of a detailed star formation history has come from the technique of re-creating an observed CMD from
model stellar evolution tracks by means of Monte-Carlo simulations. This technique has the advantage that it can account for the many uncertainties which plague our understanding of a CMD in what is arguably the most physically realistic manner. This approach was pioneered by Tosi and co-workers in Bologna (e.g., Tosi et al. 1991), and has since been used and adapted as the standard method of CMD analysis (e.g., Tolstoy & Saha 1996; Aparicio et al. 1996; Dolphin 1997; Hernandez et al. 1999).

The main uncertainties in the interpretation of CMDs of nearby galaxies come from: estimates of the distance of the galaxy; the foreground and internal extinction, both the absolute values, and the patchiness can be uncertain; metallicity, and how this might vary in time within the galaxy; the initial mass function, what it is and if it might vary; the fraction of binary stars in the CMD; photometric errors, or the accuracy with which measurements can be made; incompleteness, which is a measure of how the number of stars detected per resolution element affects both the determination of photometric errors and the number of stars of different luminosities that will be hidden behind and in the wings of brighter neighbours; and last but not least and perhaps most difficult of all the uncertainties in the theoretical models of stellar evolution. One problem for the modelers is to find useful data sets to compare with models. Globular clusters are excellent test data for checking low metallicity and very old models, and open clusters are mostly quite metal rich. Dwarf galaxies tend to be dominated by intermediate and even young metal-poor stellar populations, and so it is hard to find fiducials. The result is that we are forced to try and understand what is happening with an uncertain star formation history and uncertain model effects all at the same time. Any one of the uncertainties
Table 2. HST CMDs of Local Group Dwarf Galaxies

**Dwarf Ellipticals:**
- M 32: Grillmair et al. 1996
- NGC 205: Jones et al. 1996
- NGC 185: Geisler et al. in prep
- NGC 147: Han et al. 1997
- Sagittarius: Mighell et al. 1997

**Dwarf Irregulars:**
- NGC 6822: Wyder et al. 2000
- IC 1613: Cole et al. 1999; Dolphin et al. 2000
- IC 5152: snap-shot in archive
- IC 10: Hunter et al. in prep
- Sextans B: no data
- Sextans A: Dohm-Palmer et al. 1997a,b
- WLM: Dolphin 2000; Rejkuba et al. 2000
- Phoenix: Holtzman et al. 2000
- Pegasus: Gallagher et al. 1998
- LGS 3: Miller et al. in prep
- Leo A: Tolstoy et al. 1998
- SagDIG: no data
- DDO 210: no data
- EGB 0427+63: no data

**Dwarf Spheroidals:**
- Fornax: Buonanno et al. 1999
- Ursa Minor: Mighell & Burke 1999; Feltzing et al. 1999; Hernandez et al. 2000
- Draco: Grillmair et al. 1998
- Leo I: Gallart et al. 1999; Hernandez et al. 2000
- Sextans: no data
- Carina: Mighell 1997; Hernandez et al. 2000
- Sculptor: Monkiewicz et al. 1999
- Antlia: no data
- Tucana: Seitzer et al. in prep
- Cetus: no data
- Leo II: Mighell & Rich 1996; Hernandez et al. 2000
- And I: Da Costa et al. 1996
- And II: Da Costa et al. 2000
- And III: Da Costa et al. in prep
- And V: Armandroff et al. in prep
- And VI: Armandroff et al. in prep
- And VII: snap-shot in archive

listed here could (and have) produced (long) papers in their own right. They can have profound effects on the star formation history determined from a CMD.

So, clearly a great deal of care has to be taken not to over-interpret CMDs, because having so many factors which affect the modeling means that there is a lot of parameter space to explore, and the effect of all the uncertainties is to smear out features which can result in a very shallow minimum to any $\chi^2$ estimate or Likelihood function to find the best model. Each change of initial assumptions requires generation of a complete new set of models and goodness of fit assessment. This can be computationally intensive and, in the end, it can be difficult to find a unique solution. Best solutions are only ever one
Figure 4. A Leo A (I, V−I) CMD from two orbits of WFPC2 observations (one in filter F555w and one in F814W), from Tolstoy et al. (1998). Also shown is a possible star formation history from detailed modeling of the CMD, and consistent with the known details of the stellar population, such as the luminosity spread of the RC; the width of the RGB; and the presence of BLs. The error bars shown are not in any specific sense statistical, they merely give an indication of how flexible the star formation rate at any time can be before significantly affecting the good match of this model to the data (see Tolstoy et al. for details).

out many that are possible. It is thus important to tie in star formation rate variations to distinct and well determined features in a CMD, and to justify all variations that are seen. This is especially true in older populations where very small and subtle changes can have dramatic impacts on assumed age and metallicity variations (c.f. Tolstoy & Saha 1996; Tolstoy et al. 1998), and see Figure 3.

In Figure 3, I have created a series of model CMDs (see Tolstoy 1996), which, for a constant metallicity, show the variations that age can give to a CMD distribution. In the younger populations this is obvious, but as older populations dominate it takes very accurate photometry to distinguish between dramatically different ages of stellar populations. If metallicity is involved this becomes even more tricky because age and metallicity can produce very similar effects on an RGB (see §3.1.3). The CMDs in Figure 3 are made assuming a galaxy at 700 kpc, and only one orbit of integration time in each filter. This means there is no MSTOs older than about 800 Myr, which explains why there is such similarity between CMDs which have differing proportions of population older than about 800 Myr.

Despite this dramatic list of problems, surprisingly detailed and robust results have come out from the analysis of CMDs. In the next section I will illustrate some of the most impressive CMDs and their analyses which have come from HST data for all the different classes of dwarf galaxy, as defined in §1.1.

4. HST Observations of Local Group Dwarf Galaxies

There have been a number of spectacular results from HST imaging of the resolved stellar populations in Local Group dwarf galaxies (see Table 2). In the next sections I provide examples of some of the most beautiful HST CMDs for a selection of dwarf galaxies in the Local Group, and just beyond:
Figure 5. On the right-hand side is the new (V, V−I) CMD of Sextans A from Dohm-Palmer et al. 2000, in prep. It consists of 8 orbits in F555W and 16 in F814W, and shows the presence of the RC and goes further down the Main Sequence than the previous 2-orbit CMD of Dohm-Palmer et al. (1997). On the left-hand side is the recent star formation history of Sextans A determined from the BL stars by Dohm-Palmer et al. (1997).

4.1. Leo A

Leo A (DDO 69) is a gas-rich dI galaxy, with an extremely low HII region abundance (≈3% solar, van Zee, Skillman & Haynes 1999). The interpretation of a CMD from two orbits of WFPC2 data (Tolstoy et al. 1998; see Figure 4) is based upon extremely low metallicity (Z=0.0004; or [Fe/H]=−1.7) theoretical stellar evolution models (Fagotto et al. 1994; see also Figure 3), which suggest that this galaxy is predominantly young, i.e., < 2 Gyr old. A major episode of star formation 900−1500 Gyr ago can explain the RC luminosity and also fits in with the interpretation of the number of anomalous Cepheid variable stars seen in this galaxy. The presence of an older, underlying globular cluster age stellar population could not be ruled out with these data, however, using the currently available stellar evolution models, it would appear that such an older population is limited to no more than 10% of the total star formation to have occurred in the centre of this galaxy. Theoretical models of the chemical evolution of dwarf galaxies by Ferrara & Tolstoy (2000) imply that, even though this galaxy is extremely metal-poor, an underlying older stellar population is required to build up the current metallicity. Perhaps this older population resides in an outer halo. Of course, neither the chemical evolution models nor the existing CMDs can distinguish between an old population which formed in a large burst, or more sedate and roughly constant rate through-out a longer time.

4.2. Sextans A

Sextans A (DDO 75) is a gas-rich dI galaxy with a low metal abundance ([Fe/H]≈ −1.4), and active star formation, which is located on the periphery of the Local Group (1.4 Mpc away). The initial WFPC2 CMD of Sextans A, based on two orbits of telescope time, shows several clearly separated populations that align well with stellar evolution model predictions for a low metallicity system (see Dohm-Palmer et al. 1997a,b). This was the first time a BL sequence had been so definitively identified in a CMD (see the CMD in Figure 5). The star formation history from the main sequence and BL stars (in Figure 5) was determined by Dohm-Palmer et al. for the last 600 Myr using theoretical stellar
Figure 6. Here we see a gallery of movie still frames created by Robbie Dohm-Palmer (c.f. Dohm-Palmer et al. 1997), which show how the intensity of star formation varies spatially with time across Sextans A. These are preliminary results, which combine the two WFPC2 pointings on Sextans A so that the spatial coverage of nearly the whole luminous centre of the galaxy is achieved. The time separation between each frame is not uniform, and was chosen to highlight interesting features. See Dohm-Palmer et al. 1997; 2000 for more details. The newer data is on top, and despite the presence of young blue stars and H-α, this does not seem to be representative of a global increased star formation rate in this part of the galaxy, unlike the lower area which has vigorous star formation over the last several hundred million years.
Figure 7. The IC 1613 (I, V−I) CMD from 8 orbits of WFPC2 observations (four in filter F555w and four in F814W) of a field right in the centre of IC1613, away from any bright HII regions, from Cole et al. (1999). This was a fairly crowded field and fairly brutal cuts in S/N were made for this CMD. Also shown is a possible age-metallicity relation for IC 1613, also from Cole et al. Each region of the figure is labelled with the CMD feature that constrains the metallicity to lie within the shaded region. Abbreviations are given in the text; and in addition WR denotes the Wolf-Rayet star; HII denotes the H II regions; RSG and BSG are red and blue super giants. The dotted line shows the mean age-metallicity relation for the SMC.

The spatial distribution of the BL stars was then used to determine the spatial variation of the star formation across Sextans A with time (see Figure 6). Figure 6 is a preliminary result including new WFPC2 data which covers the whole galaxy (Dohm-Palmer et al. 2000, in prep). The modeling concludes that in the past 50 Myr, Sextans A has had an average star formation rate that is \(\sim 10\) times that of the average over the history of the galaxy. This current activity is highly concentrated in a young region in the South-East roughly 25 pc across. This coincides with the brightest HII regions and the highest column density of HI. Between the ages of 100 and 600 Myr ago, the star formation has been roughly constant at slightly above the average value. There are regions (200–300pc across) with a factor of \(\sim 5\) enhancement in star formation rate with a duration of 100–200 Myr.

4.3. IC 1613

IC 1613 is a Magellanic type dI galaxy, with young stars of SMC-like metallicity (\(\sim 10\)% solar), which was first resolved into stars by Baade (1928), it was later used by Baade (1963) to illustrate the archetypal “Baade’s sheet” of underlying RGB (population II) stars, which have now been found to exist in most, if not all Local Group dwarfs (e.g., Sandage 1971; Hodge 1986; Saha 1995). IC 1613 is to date the only Local Group dI (excluding the Magellanic Clouds), in which RR Lyrae variables have been detected (Saha et al. 1992; Dolphin et al. 2000).

This spatially extended galaxy has had two pointings with WFPC2, one in the central region (Cole et al. 1999, see Figure 7) and one in the outskirts (Dolphin et al. 2000, Figure 8). The two CMDs, despite being in quite different environments within the galaxy, look remarkably similar.

The main-sequence luminosity function provides evidence for a roughly constant star
formation rate of ($\sim 3.5 \times 10^{-4} M_\odot yr^{-1}$) across the central WFPC2 field of view ($0.22 kpc^2$) during the past $\sim 250-350$ Myr, and going back to $\sim 1$ Gyr in the outer field (Tolstoy et al. in prep.). Structure in the BL function implies that the star formation rate was $\sim 50\%$ higher 400-900 Myr ago than today. The blue HB was also detected in both IC 1613 pointings, again showing that the ancient stars in this galaxy are uniformly distributed in the inner and outer regions of IC 1613. It was already known that IC 1613 contains a population of RR Lyrae variable stars (Saha et al. 1992) in its outer halo, and hence an ancient stellar population, but this is the first time that a deep enough CMD was made to detect the HB. From the different populations identified and modeled, an approximate age-metallicity relation for IC 1613 was determined (see Figure 7), which appears, like the present day metallicity, to be similar to that of the SMC.

The natural HST orbital cadence of 90 minutes is ideal for the detection of short period variable stars, such as RR Lyrae. As the second WFPC2 pointing in the outskirts of IC 1613 consisted of 8 orbits in F555W and 16 orbits in F814W this data set contains just enough distinct observations to be able to identify and classify short period variables in the WFPC2 field of view (Dolphin et al. 2000). These are plotted on top of the deeper CMD of the outer region in Figure 8. There are 13 RR Lyraes, which unambiguously mark out the presence of the modestly populated HB, and also 11 short-period Cepheids, which are indicators of an intermediate-age population in IC 1613.

### 4.4. WLM

WLM (Wolf-Lundmark-Melote; DDO 221) is another large Local Group Magellanic dI galaxy, with approximately SMC-like present-day metallicity. It is the only dI galaxy in the Local Group with a bona-fide globular cluster (see Hodge et al. 1999).

The HST pointing on WLM in September 1998 must rate as an extremely efficient one.
Figure 9. The WFPC2 (V, V−I) CMD of WLM, the combined results from photometry on the 3 WF chips. The data were taken over 4 orbits, 2 in both F814W and F555W, from Dolphin (2000). Also shown are the star formation history and the chemical evolution history that Dolphin derives from these data.

Figure 10. Here are the STIS/CCD imaging results for WLM from Rejkuba et al. (2000). On the left is the CMD in the raw STIS photometric system (LP, CL−LP) and on the right is the CMD after conversion to a standard photometric system (I, V−I). These data were taken in parallel to the WFPC2 data shown in Figure 9.

The WFPC2 PC chip contained the globular cluster, and was used for a study of this unique object (Hodge et al. 1999). The remaining 3 WF chips contained stars from the field population of WLM, and were used by Dolphin (2000) to study the star formation history of the field population of this galaxy. The RC is clearly detected (see Figure 9), it is less clear if there is an HB present. The star formation history and the corresponding metal enrichment history which Dolphin determined from the WFPC2 CMD are also shown in Figure 9. The models are most reliable for the young and intermediate-age populations. Finally, as part of a targeted STIS parallel survey program, STIS images were also taken in parallel to the WFPC2 primary observations in both broad band filters available (Clear [CL] and Long Pass [LP], see Gardner et al. 1998), at a position about 4′ away from the WFPC2 position. The STIS CCD in combination with these extremely
broad filters means the images go fainter than the WFPC2, however the field of view is also a lot smaller ($\sim 25'' \times 50''$). It had been shown theoretically that these (very broad) STIS filters can be usefully transformed to an effective V and I (Gregg & Minniti 1997), and this has been confirmed by the results of Rejkuba et al. 2000 (see Figure 10) using these parallel data from WLM. They clearly detect a RC (as Dolphin 2000, in the inner WFPC2 field of view does), but unlike Dolphin they clearly detect a HB. This is due to the increased sensitivity of the STIS CCD; the Dolphin WFPC2 CMD barely reaches the HB magnitude, whereas the STIS CMD clearly goes beyond.

4.5. Leo I

Leo I is a nearby (250 kpc) relatively isolated dSph. It has been poorly studied from the ground because of the proximity of the 1st magnitude star, Regulus. However WFPC2 has produced one of its most detailed CMDs from Leo I (Gallart et al. 1999; see Figure 11). The CMD goes down to an absolute magnitude, $M_V = +4.5$ on the Main Sequence. This depth of CMD allows a very accurate star formation history to be determined from MSTOs (Gallart et al. 1999, see Figure 11). They found that most (70−80%) of star formation activity in Leo I occurred between 1 and 7 Gyr ago. A fairly uniform star formation rate dropped dramatically about a Gyr ago, and around 300Myr it seems to have stopped altogether. It is not clear from these results whether or not Leo I contains an ancient (>10 Gyr old) stellar population. It does not have an obvious HB, and it is one of the few dSph not to have a detected RR Lyrae population but a very large population of anomalous Cepheids (Lee et al. 1993). This is consistent with the Gallart et al. models which find that this galaxy is dominated by an intermediate-age, metal poor, stellar population.

4.6. Andromeda II

Andromeda II (And II) is a dSph companion to M 31. The WFPC2 CMD (Da Costa et al. 2000; see Figure 12) shows a predominantly red HB (like in most other dSphs). In And II there is no evidence for a radial gradient, unlike, And I (Da Costa et al. 1996), or NGC 147 (Han et al. 1997). In And II Da Costa et al. also detect probable RR Lyrae variable stars, although the number of images taken of And II are not sufficient to accurately classify the variables found, but those identified with the colours of the HB can safely be assumed to be RR Lyrae variables. To interpret the And II CMD in terms of a star formation history Da Costa et al. have used a combination of standard Galactic globular cluster CMDs scaled to reproduce the And II mean abundance and abundance dispersion, to interpret the observed HB morphology (see Figure 12). They find that at least 50% of the total stellar population must be younger than the age of the globular clusters. This inference is strengthened by the small number of upper-AGB carbon stars, and the relatively faint luminosities ($M_{bol} \sim -4.1$) of these stars. These upper-AGB carbon stars have assumed ages of around 6−9 Gyr, whilst the existence of blue HB and RR Lyrae variable stars argues for the presence of an old (>10 Gyr) population. Thus, And II must have had an extended epoch of star formation like many of the Galactic dSphs. The RGB colors yield a mean abundance of $<[\text{Fe/H}]>= -1.49\pm0.11$ and a surprisingly large internal abundance spread, of about 0.36 dex. It is not possible to model the abundance distribution in And II with single component simple chemical enrichment model. However, a simple model with a dominant “metal-poor” ($[\text{Fe/H}]= -1.6$) and a “metal-rich” ($[\text{Fe/H}]= -0.95$) component appears to produce the best match (see Figure 12).
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4.7. NGC 147

NGC 147 is a dE galaxy associated with M 31. There are WFPC2 CMDs at two positions in this galaxy, at inner and outer positions (Han et al. 1997, see Figure 13). There are significant differences between the inner and outer field stellar populations (as can be seen at a glance of Figure 13), and these cannot be explained by differences in crowding properties of these fields, even though the inner field is extremely crowded. The RGB suggests a metallicity of [Fe/H]=−0.9 in the inner, central field and [Fe/H]= −1.0 in the outer one, and the outer field shows a weak tendency of increasing metallicity with galactocentric radius. The RGB also shows evidence of a metallicity dispersion in NGC 147, with a larger dispersion closer to the centre of the galaxy. The age of most of the stars in the RGB is assumed to be >5 Gyr. The small population of EAGB stars does show the presence of an intermediate-age population (a few Gyr old), which seems to be larger towards the centre of the galaxy, contrary to the bulk of the older stars. The HB stars are more populous towards the outer part of the galaxy. Again, consistent with an age (and metallicity) gradient within NGC 147. The absence of any main sequence stars shows that any star formation completely ceased at least a Gyr ago.
Figure 12. Here are presented, on the left-hand side, the WFPC2 CMDs for 11 orbits of exposure time on Andromeda II transformed to the standard (V, B−V) magnitude system, from Da Costa et al. (2000). The candidate variables have been excluded from these plots. The lower left-hand CMD is identical to the upper, but shown superposed with the giant branches of the standard globular clusters M68 ([Fe/H] = −2.09), M55 ([Fe/H] = −1.82), NGC 6752 ([Fe/H] = −1.54), NGC 362 ([Fe/H] = −1.28), and 47 Tuc ([Fe/H] = −0.71). The filled symbols give the mean And II RGB colours in ±0.1 V magnitude bins. On the right-hand side, the upper panel is a composite CMD made up from observed CMDs of the Galactic globular clusters M 55 ([Fe/H] = −1.82), NGC 1851 ([Fe/H] = −1.29), and 47 Tuc ([Fe/H] = −0.71), with the relative star numbers (44/45/11), scaled to reflect the And II abundance distribution. This CMD clearly has relatively more blue HB stars than And II has. In the lower right-hand panel all the NGC 1851 blue HB and 40% of the M 55 blue HB stars have been replaced with red HB stars from NGC 362 (80%) and 47 Tuc (20%), and the HB morphology of the “model” CMD is now a better match to that which is observed. See Da Costa et al. for many more details.

4.8. VII Zw403

VII Zw403 (UGC 6456) is definitely not in the Local Group, but at a distance of ∼4.5Mpc, it is most likely an isolated member at the far side of the M 81 group. The WFPC2 CMD (see Figure 14, from Lynds et al. 1998) is the best example of a resolved BCD. Also shown in Figure 14, is a possible star formation history determined from a quantitative analysis of the CMD from Lynds et al. Another study of the same HST observations of VII Zw 403 is presented by Schulte-Ladbeck et al. (1999a), and they get similar
results. The HST CMD of this relatively distant galaxy is directly comparable to to ground based observations of closer dwarf galaxies. The similarity between Figure 14 and the ground-based CMD of NGC 6822 of Gallart et al. (1994) is quite startling, especially in the properties of the EAGB. Clearly this is a similarity which needs further study. NGC 6822 is close enough to calibrate the EAGB versus star formation history determined from the detection of older MSTOs.

VII Zw403 is also one of the first galaxies to have a NICMOS, IR CMD (Schulte-Ladbeck et al. 1999b), which detects a large number of red super-giant and AGB stars, and reaches the tip of the RGB in J and H. In principle extending the colour baseline out from the optical to the IR offers advantages for separating out different stellar phases from one another (e.g. Bertelli et al. 1994). However, without high S/N IR data the photometric errors significantly limit the improvement.

5. New Results from a New Telescope

In the future, the large, ground based telescopes can play a vital complementary role to the HST. With their relatively wide fields of view and larger apertures, ground based telescopes will become the instruments of choice for imaging the extended and less crowded halo populations of the nearby galaxies. Large telescopes on the ground are also ideal for spectroscopic follow-up on individual stars in a CMD to determine abundances and the internal dynamics of nearby galaxies. To show that competition from new ground based facilities is coming along fast, in Figure 15 I show CMDs for three Local Group galaxies (and a calibration globular cluster) from the VLT, and the FORS1 imaging/spectrograph. These data were taken in excellent seeing conditions in August 1999, and have been published in preliminary form by Tolstoy et al. (2000). The galaxies Cetus, Aquarius (DDO 210), and Phoenix were selected because they are relatively

Figure 13. Here are shown the WFPC2 (I,V−I) CMDs for two fields in NGC 147, from Han et al. (1997), which come from 9 orbits of telescope time. On the left-hand side is the CMD for the inner most field of NGC 147, which does very close into the extremely crowded heart of this small galaxy. This CMD contains nearly 80 000 photometered stars. This means that the relative numbers of stars is also indicated by density contours overlying the points. Also over-plotted are the average error bars on the photometry at given magnitudes, and also Galactic globular cluster fiducials for M 15 and 47 Tuc. This is then done identically on the right-hand side for the outer field of NGC 147, which contains only about half the number of stars in the central field. It also contains a much more distinctive HB, which is not only a function of the reduced crowding in the outer field. See Han et al. for more details.
nearby, open-structured dI/dSph systems. Because of the excellent seeing conditions we were able to obtain very deep exposures covering the densest central regions of these galaxies, without our images becoming prohibitively crowded. From these images we have made very accurate CMDs of the resolved stellar population down below the magnitude of the HB region. In this way we have made the first detection of RC and/or HB populations in these galaxies, which reveal the presence of intermediate and old stellar populations. In the case of Phoenix we detect a distinct and populous blue HB, which indicates the presence of quite a number of stars >10 Gyr old. These results further strengthen evidence that most, if not all, galaxies no matter how small or metal poor contain some old stars. Another striking feature of our results is the marked difference between the Colour-Magnitude diagrams of each galaxy, despite the apparent similarity of their global morphologies, luminosities and metallicities. For the purposes of accurately interpreting our results we have also made observations in the same filters of a Galactic globular cluster, Ruprecht 106, which has a metallicity similar to the mean of the observed dwarf galaxies.

6. Conclusions

A survey of the resolved stellar populations of all the galaxies in our Local Group provides a uniform picture of the global star formation properties of galaxies with a wide variety of mass, metallicity, gas content etc., and makes a sample that ought to reflect the star formation history of the Universe and give results which can be compared to high redshift survey results (e.g., Steidel et al. 1999). Initial comparisons suggest these different approaches do not yield the same results (Tolstoy 1998b; Fukugita et al. 1998), but the errors are large due to the lack of detailed star formation histories of nearby galaxies. The CMDs presented here whilst beautiful and dramatic represent the tip of the iceberg for the Local Group. Most of the observations reported here consisted of 1 or 2 orbits of integration time per filter. To really complete a detailed census of the nearby resolved stellar populations we need to go as deep as the sensitivity limit given in Figure 2 for all Local Group galaxies, to detect the oldest MSTOs. This includes the
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Figure 15. Here are four VLT/UT1 (R, B–R) CMDs for three Local Group galaxies (DDO 210, Cetus and Phoenix) and one youngish (12–13 Gyr old) globular cluster (Ruprecht 106), from Tolstoy et al. (2000). DDO 210 and Cetus had exposure times of 3000sec in R and 3600sec in B; roughly equivalent to a total of 3 orbits of HST. Phoenix received only 1600sec in R and 1800sec in B, and Ruprecht 106 30sec in R and 80sec in B. Representative error bars are plotted for each data set, and the fiducial RGB and HB from Ruprecht 106 data are over-plotted on each of the galaxy CMDs.

large Local Group galaxies, such as M 31, which along with our Galaxy represent the dominant mode of star formation in the Local Group. With data like this we will know the star formation history of the Local Group, going back to the earliest times. We have also shown that data from ground based telescopes in excellent seeing with active optics can compete with HST images, and indeed make an excellent complement, by being more blue sensitive, and having a larger field of view. It is only with the deepest exposures of the most crowded regions that HST is still the undisputed winner, because it is hard to gain enough exposure time in excellent stable seeing conditions on the ground, as nowhere under the Earth’s atmosphere can ideal conditions be guaranteed. It looks promising that Adaptive Optics on large ground based telescopes will one day rival HST
supremacy, but this is an endeavour that will be restricted to infra-red wavelengths for the foreseeable future. HST must lead the way to extend detailed star formation studies past the Galaxy and its immediate satellites.

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