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The stellar populations of local dwarfs

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Abstract. Recent progress in our knowledge of stellar populations in local dwarf spheroidal galaxies is briefly discussed. A few results are summarized including wide field observations of stellar populations and their spatial variations, studies of AGB and variable stars, extension to near-infrared wavelengths, and the interpretation effort based on synthetic color-magnitude diagrams and chemical evolution models.

Keywords. galaxies: dwarf, Local Group, galaxies: stellar content, galaxies: evolution

1. Introduction

The study of stellar populations of nearby dwarf galaxies provides a powerful means of learning, albeit indirectly, about the evolution of low mass galaxies at large look-back times. Galaxies in the Local Group are close enough that they can be resolved in the constituent stars and studied using the classical tools of stellar population work, the HR diagram in the first place. Diagnostics derived from the color-magnitude diagram of local dwarf galaxies are used to pinpoint and, to some extent, quantify the presence of young, intermediate-age (1–9 Gyr), and old ($\gtrsim$ 10 Gyr) stellar populations and to reconstruct their histories of star formation. Recent advances with spectroscopy of individual stars and nebulae provide complementary information to understand their chemical enrichment histories. I will focus here on the resolved stellar populations of dwarf spheroidal (dSph) galaxies, with the exclusion of nearest Milky Way companions and the dwarf galaxies around M 31 and in nearby groups, which are the subject of other contributions to this conference. I refer the reader to existing reviews (Mateo 1998, Da Costa 1998, van den Bergh 2000, Grebel 2000, Tolstoy 2003, Gallagher & Grebel 2004) for earlier work and a comprehensive account of stellar populations in Local Group dwarfs as emerged from the last decade of HST and ground-based studies.

2. The stellar populations of dwarf spheroidal galaxies

2.1. *Stellar populations: recent results*

Direct age measurements of the main-sequence turnoff in nearby dSph, as well as indirect evidence from horizontal branch stars in more distant dwarfs, have shown that all dwarf spheroidals in the Local Group are characterized by a common early epoch of star formation approximately coeval to the Galactic globular clusters (10–13 Gyr ago) (e.g., Held *et al.* 2000; Grebel 2000). This initial star formation episode is predominant in some dSph, but the general evidence is for multiple episodes or a continuous star formation until very recent times.

Two examples of the color-magnitude diagrams (CMDs) of "young" and "old" dwarf spheroidal galaxies are shown in Fig. 1: in both cases, the stellar populations show a complexity typical of a range of age and metallicity. Fornax (see Fig. 1, left panel; also

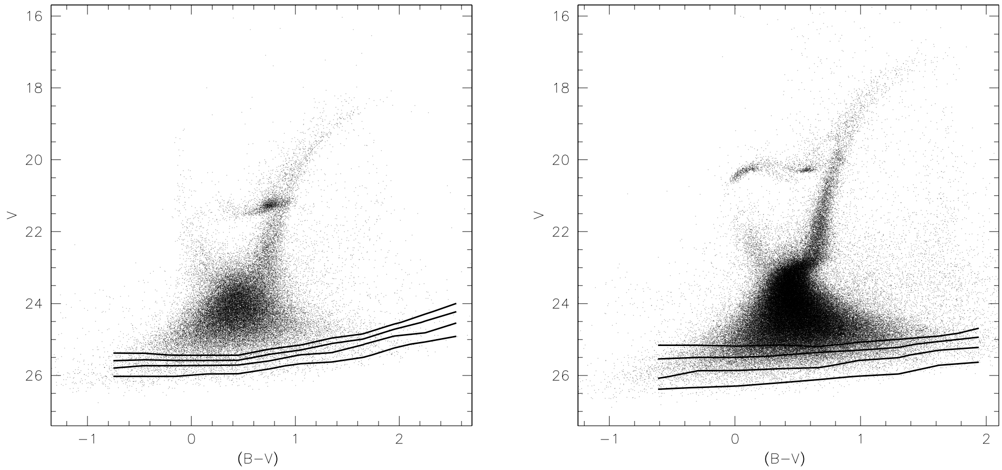

Figure 1. Wide-field color-magnitude diagrams of Fornax (*left*) and Sculptor (*right*) dwarf spheroidals based on ESO/WFI observations (Rizzi *et al.* 2005, in prep.).

Saviane et al. 2000) is an example of a "young" dwarf spheroidal: its CMD is characterized by a "blue plume" of main-sequence stars indicating an extended period of star formation, until a few hundred Myr ago. The very wide red giant branch clearly shows the presence of a mix of old and intermediate-age stars with different metal abundances. Pont *et al.* (2004) have recently studied the star formation and chemical enrichment in a central region of Fornax by combining VLT photometry and stellar spectroscopy. Their observations suggest an increase in star formation rate and metallicity in the last few Gyr: the metallicity distribution of Fornax is centered at [Fe/H]= −0.9 with a long tail of metal-poor stars extending to [Fe/H]= −2.0 and a number of stars as metal-rich as [Fe/H]= −0.4.

The Carina dwarf is another example of dSph galaxy with a prominent intermediate-age population. With two main bursts occurring 5 and 11 Gyr ago, and a small population of stars on a younger main sequence (up to 0.6 Gyr ago), Carina is the best example of an episodic star formation history (see Monelli *et al.* 2003; and refs. therein). This galaxy also provides the most dramatic example of an "age-metallicity degeneracy", i.e. the balance of competing and superposed effects of a younger age and an increasing metallicity on the CMD distribution of red giant stars. Yet its very narrow red giant branch, seemingly contrasting the multiple star formation episodes, does not imply a small range in [Fe/H]. A quantitative analysis of the CMD of Carina based on synthetic diagrams shows that the narrowness of the RGB is indeed consistent with the combined effects of the star formation and chemical enrichment history (Rizzi *et al.* 2003). The presence of a wide range in metallicity is confirmed by spectroscopy (Koch *et al.* 2004).

Figure 1 (right panel) shows the color-magnitude diagram of Sculptor. Sculptor is an "old" dwarf spheroidal galaxy lacking a significant star formation in the last 5 Gyr. It shows a particularly strong radial variation in the HB morphology index, which is accompanied by a spatial gradient in the RGB stars in the outer regions (Harbeck et al. 2001; Tolstoy *et al.* 2004; Babusiaux et al. 2005). The composite nature of the RGB (in particular the existence of a substantial metal-poor component) suggested by previous studies is not confirmed by recent photometry (Babusiaux *et al.* 2005). The presence of these gradients in both the HB morphology and the RGB implies that a significant

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metallicity gradient must be present (Rizzi *et al.* 2004). Using spectroscopic estimates of [Fe/H] for RGB stars, Tolstoy *et al.* (2004) indeed find two components among red giant stars, with the metal-rich component more centrally concentrated than the metal-poor stars.

Similar CMD morphology gradients are seen in Sextans dSph (Harbeck et al. 2001; Lee *et al.* 2003). Our own synthetic CMD analysis suggests that in this case the stellar population gradient is driven by both metallicity and age variations. A hint for the origin of the changes in the stellar populations within Sextans dSph may also come from a comparison with internal kinematics. Indeed, Kleyna et al. (2004) associate a cold, inner stellar component having velocity dispersion close to zero with the change in the stellar populations near the center.

Other recent studies of old, metal-poor dwarf spheroidals include Draco, Ursa Minor, and Cetus (Aparicio *et al.* 2001; Carrera et al. 2002; Wyse *et al.* 2002; Sarajedini et al. 2002). In Draco and Ursa Minor, the metallicity distribution is narrow yet with a measurable spread and slightly different shapes indicating different star formation histories (Bellazzini *et al.* 2002).

2.2. *An extended star formation in old dwarf spheroidals ?*

One interesting result of wide-field observations is that star formation may have continued at a low rate up to a recent (a few Gyr) epoch even in predominantly old dwarf spheroidals. In the CMD of Sextans, Ursa Minor, and Sculptor (see Fig. 1), a "plume" of stars is obviously present above the main-sequence turnoff. If those stars are main sequence stars, their presence implies a modest rate of star formation up to ~ 2 Gyr ago, after the bulk of stars was formed at old epochs. However, the possibility cannot be ruled out that these stars are "blue stragglers" like those found in globular clusters, which are likely to be the evolved products of mass transfer in old binary systems (see Lee et al. 2003). The recent studies of Ursa Minor and Sextans conclude that the "blue plume" is more likely to be made of old GC-like "blue stragglers" rather than intermediate-age normal main-sequence stars (Carrera et al. 2002; Lee *et al.* 2003). A similar interpretation is proposed for the "blue plume" stars in Sculptor (Rizzi *et al.* 2004), while a different conclusion is reached by Aparicio *et al.* (2001) for Draco, where an analysis of the red clump and subgiant branch stars supports the existence of an intermediate age population, up to 2–3 Gyr ago. These different interpretations obviously affect our picture of early star formation in old dwarf spheroidals and their relation to the reionization era (see Grebel & Gallagher 2004).

2.3. *Evolved stellar populations*

The intermediate-mass stars on the extended asymptotic giant branch (AGB), in particular the carbon-rich (C) stars, are important tracers of intermediate-age populations in dwarf galaxies (for a review of AGB stars in Local Group galaxies, see Groenewegen 2004). Because of their high luminosities and distinctive spectral features, C stars are relatively easy to identify on the basis of narrow-band and near-infrared colors. Carbon star surveys have been conducted by different groups (e.g., Kerschbaum *et al.* 2004; Battinelli & Demers 2005; Harbeck *et al.* 2004). The formation of C stars is both a function of the star formation history and metallicity. Because of this dependence on metallicity, not only is the ratio between carbon-rich and oxygen-rich cool giants, C/M, globally a function of galaxy metallicity (see, e.g., Battinelli & Demers 2005, and references therein) but also it can be used to map *local* abundance variations across galaxies. New models including revised effects of variable opacity in carbon-rich stars are now able to better reproduce the observed distribution of luminous AGB stars in near-infrared CMDs (Marigo 2002).

Since even a few luminous AGB stars can significantly contribute to the integrated light of galaxies, studying the behavior of AGB stars in nearby dwarfs represents an important step towards a successful intepretation of the spectra of distant dwarf galaxies. Evolutionary population synthesis models focusing on intermediate-age populations and their contribution to the integrated light have been presented by Mouhcine & Lançon (2003).

The cool AGB as well as the RGB stars are best observed in the near-infrared, where bolometric corrections to intrinsic luminosities and effective temperatures are smaller, making interpretation of the observations on the basis of stellar evolution models more reliable. The optical-near infrared colors of RGB stars are more sensitive to metallicity than optical (or infrared) colors alone, in particular for old, metal-poor systems. This alleviates the age-metallicity degeneracy and allows an improved estimate of both mean metallicities and metallicity distributions (Babusiaux *et al.* 2005; Gullieuszik *et al.*, this conference). If we exclude the Sagittarius dSph, which is close enough to be studied with the 2MASS database (e.g., Cole 2001), the sensitivity and small size of near-infrared instrumentation have limited the number of studies to very few dwarf spheroidals (Menzies *et al.* 2002; Pietrzyński *et al.* 2003; Babusiaux et al. 2005). Ongoing wide-area studies of dSph galaxies by our group as well as other teams aim at filling this gap, especially using the new wide-field instruments.

2.4. *Variable stars as stellar population tracers*

Pulsating variable stars have been studied in dSph galaxies for many years (Mateo 1998). Besides providing independent distance estimates to the galaxies, variable stars can trace the presence and properties of different stellar generations. In particular, RR Lyrae variables originate from the oldest stars ($\gtrsim$ 10 Gyr), so that an old stellar population can be detected even when the data are too shallow or confusion-limited to reach the main sequence turnoff of low-mass stars. Measurements of RR Lyrae metallicity based on their pulsational properties (period and amplitude of the light curve) help us to reconstruct the metal enrichment history of dwarf spheroidals. In addition, the radial distribution of variable stars in different classes can be used to map the gradients in their parent stellar populations (e.g., Gallart *et al.* 2004).

Several recent studies have addressed the properties of variable stars in dSph galaxies (e.g., Leo I: Held *et al.* 2001; Fornax: Bersier & Wood 2002, Poretti *et al.* 2005, in prep.; Carina: Dall'Ora *et al.* 2003; Draco: Bonanos *et al.* 2004; Phoenix: Gallart *et al.* 2004; and references therein). The RR Lyrae in most dSph galaxies appear to be intermediate between those in Oosterhoff type I and type II globular clusters (e.g., Dall'Ora *et al.* 2003), a characteristic shared by the globular clusters belonging to Fornax dSph (Mackey & Gilmore 2003).

Other classes of variable stars bear information on the stellar content of local dwarfs. An interesting class is Anomalous Cepheids, which are found numerous in dSph galaxies, where their number per unit luminosity seems to be correlated to the galaxy metallicity and luminosity (e.g., Pritzl *et al.* 2005). That Anomalous Cepheids are related to the short-period Classical Cepheids found in (dwarf) irregular galaxies is still a matter of debate (Dolphin 2002; Baldacci *et al.* 2004; Marconi et al. 2004; Gallart *et al.* 2004; Pritzl et al. 2005). As such, the Anomalous Cepheid would trace the intermediate-age populations rather than the old component.

2.5. *Modeling the star formation histories*

Presently, the main challenge is to interpret observational facts in terms of galaxy evolution and understand the chemical enrichment and star formation histories of dSph galaxies (see, e.g., Gallagher & Grebel 2004). Disentangling the age and metallicity

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variations of the stellar populations is a complex task that models based on evolutionary tracks and synthetic color-magnitude diagrams have recently undertaken (Hernandez *et al.* 2000; Ikuta & Arimoto 2002; Dolphin 2002; Rizzi *et al.* 2004; Pont et al. 2004). While in many cases the models assume a metal enrichment law, some chemical evolution models have started to shed some on the interplay of star formation and chemical evolution of dwarf spheroidal galaxies (e.g., Ikuta & Arimoto 2002; Carigi *et al.* 2002; Lanfranchi & Matteucci 2004). For example, in the Lanfranchi & Matteucci (2004) models, the metallicity distributions of stars in dSph galaxies are predicted using the star formation histories derived from the CMDs together with physical constraints such as the mass and gas content, and the observed abundance patterns from high-resolution spectroscopy (e.g., Tolstoy et al. 2003; Shetrone 2004). The overall properties of dwarf spheroidals imply very low star formation rates and a high efficiency of galactic winds in order to reproduce the observed gas fraction and abundance ratios, a conclusion on which the different models mostly agree.

Environmental factors, such as interaction with the Galaxy and M 31, may also influence the evolution of dSph galaxies. In the case of the Milky Way satellites, our understanding of the relationship between history of star formation and *orbital motions* can benefit from recent analyses of proper motions. For Fornax, the work of Dinescu *et al.* (2004) suggests that the termination of star formation about 200 Myr ago indicated by color-magnitude diagrams coincides with the time when Fornax crossed the Magellanic Plane. However, in the case of Carina, the history of star formation is not explained by passages through perigalacticon and the Galactic disk – the interval between multiple passages being too short to explain the main star formation episode about 6-7 Gyr ago (Piatek et al. 2003). Thus, while interaction with the Milky Way is suggested to be able to trigger or stop star formation (by gas removal), it is certainly not the only driving factor of their star formation histories.

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