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Stellar archaeology in the Milky Way halo

Variable stars and stellar populations in the new Milky Way ultra-faint dwarfs

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Abstract. We summarize results from the photometric survey of a number of ultra-faint dwarf satellites of the Milky Way. We are studying these systems in a systematic way to characterize their stellar populations and structural parameters, as well as their variable star content, with the aim of deriving hints on the formation process of the Galactic halo.

Key words. Galaxies: Local Group–Galaxies: dwarf–Stars: variables: RR Lyr–Stars: C-M

1. Introduction

Dwarf spheroidal (dSph) galaxies (Mateo et al. 1998) play an important role in providing constraints on the Λ-Cold Dark Matter (Λ-CDM) theories of galaxy formation. These models predict that the halo of the Milky Way (MW), and of large galaxies in general, was built-up through accretion of "protogalactic-fragments" (the so called "building-blocks"), extracted from dSph galaxies tidally interacting with our Galaxy (Searle & Zinn 1978). To confirm this scenario, we should see remnants of these accretion processes, and find that the stellar properties observed in the MW halo are homogeneous to those of the MW dSph satellites. On the contrary, the stellar populations of the ten dSphs surrounding the MW known until 2005 (classical dSphs), show differences both in chemistry and in the properties of the variable stars, with respect to the MW halo stars. Moreover, their number is too small, compared to the several hundred satellites predicted by theory ("missing satellites problem", Moore et al. 1999; Klypin et al. 1999). In this scenario, the discovery of a new class of faint dwarf satellites around the MW (see e.g., Belokurov et al. 2006, 2010, and references therein) and the Andromeda galaxies (M31; see e.g., Richardson et al. 2011, and references therein) has opened a new window for the study of the formation history of large spirals. The new systems show a number of remarkable differences with respect to the "classical" dSphs:

i) they have much lower surface brightnesses ($\mu_V \gtrsim 28$ mag), for which they were named "ultra-faint" dwarfs (UFDs)
ii) they are very metal poor, with large metallicity dispersions and [Fe/H] values as low as −4 dex (see Tolstoy et al. 2009, and references therein). Such extreme abundances are not observed among the classical dSphs where only a few stars with [Fe/H]< −3.0 dex have been detected (Frebel at al. 2010) compared to the large number found in the MW halo
iii) they generally contain RR Lyrae stars that conform to the subdivision into Oosterhoff types I (Oo I) and II (OoII; Oosterhoff 1939)[1] observed for field and cluster MW variables. So far, the only exceptions among the UFDs are Canes Venatici I (CVn I, Kuehn et al. 2008), Leo T (Clementini et al. 2012) the brightest of the MW UFDs, and Ursa Major I (UMaI, Garofalo et al. 2013, submitted) that, like the classical MW dSphs have instead Oosterhoff-intermediate (Oo-Int) properties (Catelan 2009; Clementini 2010, and references therein); and, finally:
iv) the UFDs discovered so far outnumber by almost a factor of two the classical dSphs, thus partially reducing the "missing satellites problem" affecting the Λ-cold-dark-matter (ΛCDM) scenario of galaxy formation.

With their properties the UFDs are potentially much better analogues of the "building blocks" that contributed to the formation of the two large spirals in the Local Group than the classical dSphs. They have absolute luminosities similar to the globular clusters (GCs; $M_V \sim -7$ mag, on average) but they are more spatially extended than GCs (see, e.g., Fig. 1 of Clementini et al. 2012). Indeed, with typical half-light radii of $r_h \geq 100$ pc, they equal in size the "classical" dSphs.

All UFDs host an ancient population around 10 Gyr old. They have GC-like color-magnitude diagrams (CMDs) resembling the CMDs of metal-poor Galactic GCs (GGCs) such as M92 (NGC 6341), M15 (NGC 7078) and M68 (NGC 4590). Some of the MW UFDs have a distorted shape due to the tidal interaction with the MW.

[1] The Galactic globular clusters can be divided into two different groups according to the mean period of their ab-type RR Lyrae stars: Oosterhoff type I (Oo I) clusters have $\langle P \rangle = 0.55$ d, whereas type II (Oo II) clusters have $\langle P \rangle = 0.65$ d

2. Our project

We have obtained B, V and I time-series photometry of both MW and M31 UFDs (see also Coppola et al., and Garofalo et al. contributes in this volume) using a large number of different telescopes (1.5m Loiano, 1.8m Lowell, 2.2@ESO, WIRO, INT, TNG, SOAR, WHT, GTC, LBT Faulkes, LT, SUBARU, HST) to study the structural parameters, the stellar population properties, as well as the variable stars of these systems.

We have published results for the following UFDs: Bootes I (Boo I, Dall'Ora et al. 2006), CVn I (Kuehn et al. 2008), Canes Venatici II (CVnII, Greco et al. 2008), Coma (Musella et al. 2009), Leo IV (Moretti et al. 2009), Ursa Major II (UMaII, Dall'Ora et al. 2012), Hercules (Musella et al. 2012), Leo T (Clementini et al. 2012) and UMa I (Garofalo et al. 2013, submitted).

3. Strategy and results

Our investigation tools are

i) the comparison of the CMDs with both theoretical predictions and observed ridge-lines of Galactic GCs
ii) the analysis of the spatial distribution of the stellar populations, and
iii) the study of the properties of the variable stars (the RR Lyrae stars, in particular), detected in these systems.

The photometry is performed using ALLFRAME (Stetson 2000), to obtain homogeneous results from data often taken at a variety of different telescopes.

We compare the CMD with the ridge-lines of metal-poor Galactic GCs such as M15 or M68, using as a reference the GC that better describes the Red Giant and Horizontal branches of the system under study. The cluster ridge-lines are properly shifted in magnitude and color to best fit the to galaxy CMD, obtaining in turn an estimate of the reddening, metallicity and relative distance modulus. As the CMDs of the UFDs are often highly contaminated by the MW field stars, to distinguish the UFD stars we select sources close in color to the cluster ridge-line, the actual color interval depending on the photometric accuracy. For the UFDs that have been studied in spectroscopy our procedure for identifying member stars is validated by the comparison with the spectroscopically confirmed members. As an example of our procedures we show in Fig. 1 the comparison of the CMD of the Hercules UFD (Musella et al. 2012) with the ridge-lines of M68.

The variable stars identified in the UFDs can be used as tracers of the stellar population and of the episodes of star formation occurred in the host galaxy. In the UFDs we have studied so far we have mainly detected population II variables like the RR Lyrae and the SX Phoenicis stars, that both trace the very old stellar component, but we have also identified Anomalous Cepheids (ACs). Although the ACs have a still debated origin (see e.g. Marconi et al. 2004, and references therein), they likely are intermediate age stars (of ∼ 2 - 3 Gyrs).

The RR Lyrae stars are used to estimate the system distance through the M_V − [Fe/H] and Wesenheit relations. Furthermore, the properties and, specifically, the Oosterhoff type of the RR Lyrae stars can provide clues to understand the formation history of the MW halo. In fact, as well known, in the GGCs can be sharply divided in OoI and OoII clusters on the basis of the mean period of their type ab RR Lyrae (RRab). On the contrary, GCs in galaxies outside the MW and the Classical dSphs are preferentially classified as Oo intermediate. The Oosterhoff classification of the UFDs we have studied so far is summarized in Table 1, whereas Fig. 2 shows the position of the UFD's

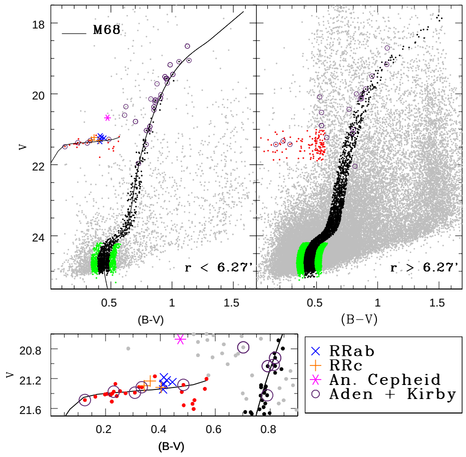

Fig. 1. *Top left:* $V, B - V$ CMD of the Hercules UFD, drawn from all the stellar-like objects (grey dots) within the galaxy half-light radius ($r_h \simeq 6.27'$, Sand et al. 2009). The black line is the ridgeline of the Galactic GC M 68. Black and green dots are stars respectively within ±0.05 mag in $B - V$ and from ±0.05 to ±0.1 mag from the ridgelines of M 68. Red dots are non-variable stars in the HB region. The fundamental-mode (RRab) and the first-overtone (RRc) RR Lyrae stars are marked by blue crosses and orange plus signs, respectively, the Anomalous Cepheid by a magenta asterisk. Open violet circles mark member stars of the Hercules UFD identified spectroscopically by Kirby et al. (2008) and spectrophotometrically by Adén et al. (2009). *Top Right:* $V, B - V$ CMD of all the stellar-like objects outside the half light radius. (Symbols and color-coding are as in the top left panel). *Bottom:* An enlargement of the HB region of the CMD in the top left panel.

RR Lyrae stars in the V-band period-amplitude (Bailey) diagram and the loci of Oo I and OoII Galactic GCs (solid lines). The vast majority of the MW UFDs appears to have OoII properties. Hence, from the pulsation point of view, many of these galaxies could resemble plausible "building blocks" of the Galactic halo.

The spatial distribution of the variables as well as of the stars selected as galaxy members can give very interesting information on the structure of the galaxy under study. The UFDs generally show very irregular and extended shapes (high ellipticity) and in some cases it

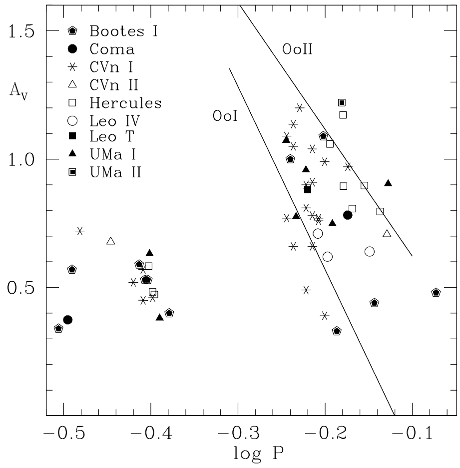

Fig. 2. *V*-band period-amplitude diagram of the RR Lyrae stars in the UFDs studied so far for variability. Solid lines are the positions of the Oo I and II Galactic GCs, from Clement & Rowe (2000).

Table 1. Number and properties of the variable stars in the UFDs we have studied so far

Galaxy	Number and type of variables (a)	Oo type
Bootes I	11 RR + 1 LPV	Oo II
Canes Venatici I	23 RR + 3 ACs	Oo Int
Canes Venatici II	2 RR	Oo II
Coma	2 RR + 1 SX Phe	Oo II
Leo IV	2 RR	Oo II
Uma II	1 RR	Oo II
Hercules	9 RR + 1 ACs	Oo II
Leo T	1 RR + 10 ACs	Oo Int
UMa I	7 RR	Oo Int

(a) Long Period Variable (LPV), RR Lyrae star (RR), Anomalous Cepheid (AC), SX Phoenicis star (SX Phe)

is very difficult to identify the galaxy central region due to the lack of a clear distinction between the properties of stars inside and outside the galaxy half light radius. Furthermore, in all the UFDs we have analyzed a number of the spectroscopically confirmed members and some of the variable stars are distributed well beyond the half light radius of the galaxy (Musella et al. 2012, and references therein). These results support the hypothesis that these dwarf galaxies are undergoing tidal interaction with the MW.

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