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Stellar archaeology in the Milky Way Halo

Variable stars and stellar populations in the new Milky Way satellites discovered by the SDSS

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Abstract. We summarize results from the photometric survey of the recently discovered faint Milky Way satellites: Bootes I, Coma, Ursa Major II, Canes Venatici I, Canes Venatici II and Leo IV. Our team is studying these systems 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 1998) play an important role in providing constraints on 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, show differences both in chemistry and

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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"). Solving the "missing satellites problem" would require the discovery of many new stellar systems around the MW (Walsh et al. 2009).

Over the past few years, the analysis of the Sloan Digital Sky Survey (SDSS; York et al. 2000) data has led to the discovery of several faint companions of the MW. The impact of these new discoveries has been dramatic: the new systems include seventeen new satellites (2 faint Globular Clusters [GCs], ten confirmed faint dSph galaxies, and five not well classified objects) doubling the number of MW companions known prior to the SDSS discoveries, and their number is expected to increase further. The dSph galaxies surrounding the MW can be divided into two groups: "bright" dSphs, mainly discovered before 2005, and "faint" dSphs, discovered in the past 2-3 years, primarily from analysis of imaging obtained by the SDSS.

"Bright" and "faint" dSphs lie in two separate regions in the absolute magnitude versus half-light radius plane (see Figure 8 of Belokurov et al. 2007, hereafter B07). The confirmed faint dSphs are Bootes I, Bootes III, Ursa Major, Ursa Major II, Canes Venatici I, Canes Venatici II, Coma, Leo IV, Leo T and Hercules (Willman et al. 2005a,b; Zucker et al. 2006a; Grillmair 2006; Zucker et al. 2006b; Belokurov et al. 2006, 2007; Irwin et al. 2007; Walsh et al. 2007; Belokurov et al. 2008; Grillmair 2009). They have similar sizes and lower luminosities than the already known systems ($r_h \geq 100$ pc, $M_V \sim -7$ mag, $\mu_V > 28$ mag/arcsec^{-2}). The five debated objects are: Bootes II, Leo V, Willman 1, Segue 1 and Segue 2 (Belokurov et al. 2007; Willman et al. 2005a; Walsh et al. 2007; Belokurov et al. 2009). They are fainter than the other confirmed SDSS dSphs, and have size intermediate between GCs and dSphs. They could either be objects at the luminosity and mass limit of galaxy formation, or tidally disrupted remnants. The new objects: i) are the darkest known stellar systems, with mass to luminosity ratios ranging from 35 to 1000; ii) are as metal poor as stars in the MW halo; iii) show an irregular shape due to the tidal interaction with the MW halo; iv) host an ancient population (t∼13 Gyr), and therefore can contain RR Lyrae stars and v) with their (increasing) number could contribute to solve the "missing satellite problem".

The study of the Oosterhoff (1939) dichotomy is a very useful tool to derive information on the formation history of the Galactic halo. In fact, the Galactic GCs show a sharp division between the so-called Oosterhoff type I (OoI), characterized by an average period of the ab-type RR Lyrae stars of $\langle P_{ab} \rangle \sim 0.55$ d, and Oosterhoff type II (OoII) having instead $\langle P_{ab} \rangle \sim 0.65$ d, and with very few clusters with $\langle P_{ab} \rangle \sim$ ranging between 0.58 and 0.62 d (the so-called "Oosterhoff gap"). The "bright" dSph satellites of the MW, and their GCs, are generally intermediate between the two Oosterhoff classes (Catelan 2009) and therefore cannot represent "building blocks" of the Galactic halo.

In this context, our group is carrying out an extensive observational campaign of the new SDSS galaxies, to obtain *B*, *V* and *I* photometric time-series, using a large number of different telescopes (1.5m Loiano, 1.8m Lowell, 2.2@ESO, WIRO, INT, TNG, SOAR, WHT) to study the structural parameters, the stellar population properties, as well as the RR Lyrae stars of these systems. Our tools are: i) the comparison of the color-magnitude diagrams (CMDs) with both theoretical predictions and observed ridgelines 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. Photometry is performed by using ALLFRAME (Stetson 1994), to obtain homogeneous results, notwithstanding the use of different telescopes and detectors.

2. Results

Our analysis has been completed and published for Bootes I (Dall'Ora et al. 2006), Canes Venatici I (Kuehn et al. 2008),

Table 1. Results on the new faint SDSS dSphs

Galaxy	$E(B-V)$ (mag)	μ_0 (mag)	D (kpc)	RR Lyrae	$< P_{ab} >$ (d)	Oo type
Bootes I	0.02	19.11 ± 0.08	66 ± 3	11	0.69	OoI
Canes Venatici I	0.03 ± 0.02	21.62 ± 0.06	210^{+7}_{-8}	23	0.60	Oo-int
Canes Venatici II	0.015 ± 0.010	21.02 ± 0.06	160^{+4}_{-8}	3	0.743	OoII
Coma	0.045 ± 0.015	18.13 ± 0.08	42^{+2}_{-1}	2	0.66971	OoII
Leo IV	0.04 ± 0.01	20.94 ± 0.07	154 ± 5	3	0.655	OoII
Ursa Major II	...	...	...	1	0.66	OoI

Canes Venatici II (Greco et al. 2008), Coma (Musella et al. 2009), and Leo IV (Moretti et al. 2009), while work is in progress for Ursa Major II, Hercules, and Bootes II. Observations of Bootes III, Leo V and Leo T are planned for next year. All the new faint dSphs we have studied so far turned out to have CMDs resembling those of metal-poor Galactic GCs. For this reason, we determined their reddening and the metallicity by comparison with the mean ridgelines of the metal poor Galactic GC that better fit the horizontal branch (HB) and the red giant branch (RGB) of each galaxy (typically, M15 or M68, which have $[Fe/H] = -2.15$ dex (Durrell & Harris 1993), and −2.1 dex (Walker 1994), respectively). The vast majority of these galaxies appear to be distorted and elongated. Their CMDs often are heavily contaminated by field stars and background galaxies at every magnitude level. For this reason, to identify stars most likely belonging to the systems, we select only sources lying near the reference GC mean ridgeline (the adopted distance from the mean ridgeline depending on the accuracy of the photometry, with typical ranges between 0.05 mag and 0.1 mag). The identification of stars belonging to the analysed dSphs, obtained with this method, is confirmed in an excellent way, by the comparison with the spectroscopic studies of Simon & Geha (2007); Martin et al. (2007); Kirby et al. (2008), where membership is established by means of radial velocity measurements.

Bootes I (Dall'Ora et al. 2006): we found 5 RRab, 5 RRc, 1 RRd, and 1 Long Period Variable in the galaxy, whose CMD is well described by the mean ridgeline of M15. By the comparison with M15 and using the RR Lyrae stars we obtain a new determination of metallicity, reddening and distance. From the analysis of the RRab stars we derive $< P_{ab} >= 0.69$ d and classify this galaxy as an OoII system (see Table 1 and Fig.1).

Canes Venatici I (Kuehn et al. 2008): this galaxy is more similar in luminosity and other properties to the "bright" dSphs. This evidence was confirmed by our analysis: i) the CMD is much more complex than that of the other SDSS galaxies we have analyzed so far; ii) we have identified about 80 candidate variables in the galaxy, but accurate light curves have been obtained only for 18 RRab, 5 RRc and 3 Anomalous Cepheids. The mean period of the RRab variables is 0.6 d and classifies this galaxy as an Oosterhoff intermediate.

Canes Venatici II (Greco et al. 2008): in this faint dSph we found only 1 RRab and 1RRc with OoII properties, and many candidate Blue straggler stars. The CMD is well described by the mean ridgeline of M15 and the stars likely belonging to the galaxy (according to the above described method) show a roughly spherical distribution. These two occurrences could suggest that Canes Venatici II is a metal poor GC, however the half-light radius is 5-6 times larger than observed for NGC 2419, the largest of the Galactic GCs.

Coma (Musella et al. 2009): this galaxy is among the faintest and nearest of the SDSS new discoveries. Its CMD is well described by the M68 mean ridgeline. The distribution of the stars we select as members, is elongated with an irregular and extended shape, likely caused by the tidal interaction with the MW halo. We found 1 RRab, 1 RRc and 1 short period variable in the galaxy and classified it

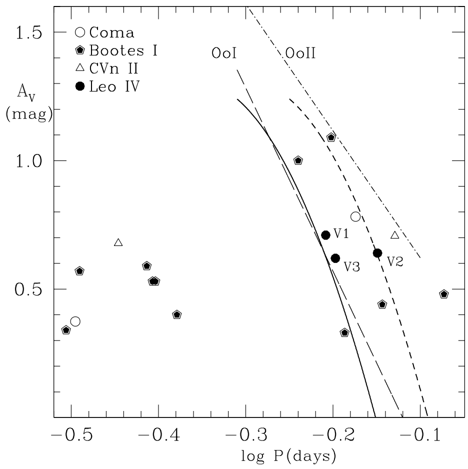

Fig. 1. V-band period-amplitude diagram of RR Lyrae stars in the Coma, Bootes I, CVn II, and Leo IV dSphs. Long-dashed and dot-dashed lines show the position of the Oo I and Oo II Galactic GCs. Period-amplitude distributions of the bona fide regular (solid curve) and well evolved (dashed curve) RRab stars in M3, from Cacciari et al. (2005), are also shown for comparison.

as an OoII system.

Leo IV (Moretti et al. 2009): the galaxy CMD appears to be heavely contaminated at every magnitude level by field objects belonging to the MW. To select member stars and to determine the galaxy metallicity and reddening, we used the mean ridgeline of M15, that well describes the RGB and the HB of this dSph. The star distribution shows a galaxy almost dissolved in the MW field, with a very elongated and irregular shape. We identified 3 RRab pulsators and 1 SX Phe variable, and classified the galaxy as an OoII system.
Ursa Major II: data analysis for this galaxy is in progress. First results show the presence of multiple populations in the CMD, confirmed by the spectroscopic membership analysis (Simon & Geha 2007; Martin et al. 2007; Kirby et al. 2008). We found only 1 RRab with a period of 0.66 d and tentatively classified the galaxy as an OoII.

3. Conclusions

generally so small, that assigning an Oosterhoff type can be difficult, still all the new faint dSphs, except Canes Venatici I, seem to have Oosterhoff II properties. Our results are summarized in Table 1, where for each galaxy we list galaxy name (column 1), reddenig (column 2), distance modulus (column 3), distance (column 4), number of RR Lyrae star (column 5), mean period of the RRab stars (column 6), and Oosterhoff type classification (column 7). These results seems to suggest that from the pulsational point of view the faint dSphs could resemble plausible "building blocks" of the Galactic Halo.

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