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Stellar Populations of the Outer Milky-Way Halo

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Abstract. The stellar spheroidal components of the Milky-Way contain the oldest and most metal poor of its stars. Inevitably the processes governing the early stages of Galaxy evolution are imprinted upon them. According to the currently favoured hierarchical bottom-up scenario of galaxy formation, these components, specially the Galactic halo, are the repository of most of the mass built up from accretion events in those early stages. These events are still going on today, as attested by the long stellar streams associated to the Sagittarius dwarf galaxy and several other observed tidal substructure, whose geometry, extent, and kinematics are important constraints to reconstruct the MW gravitational potential and infer its total (visible + dark) mass. In addition, the remaining system of MW satellites is expected to be a fossil record of the much larger population of Galactic building blocks that once existed and got accreted. For all these reasons, it is crucial to unravel as much of this remaining population as possible, as well as the current stellar streams that orbit within the halo. The best bet to achieve this task is to carry out wide, deep, and multi-band photometric surveys that provide homogeneous stellar samples. In this contribution, we summarize the results of several years of work towards detecting and characterizing distant MW stellar systems, star clusters and dwarf spheroidals alike, with an emphasis on the analysis of data from the Dark Energy Survey (DES). We argue that most of the volume in distance, size and luminosity space, both in the Galaxy and in the Clouds, is still unprobed. We then discuss the perspectives of exploring this outer MW volume using the current surveys, as well as other current and future surveys, such as the Large Synoptic Survey Telescope (LSST).

Keywords. Galaxy: halo, Galaxy: stellar content, Galaxy: structure

1. Introduction

We may loosely define the *outer halo* of the Milky-Way as those regions at Galactocentric distances $\gtrsim 20$ kpc. It is approximately at this radius, although with a large spread from one author to the other, that a steepening in the stellar density profile has been identified (Bland-Hawthorn & Gerhard 2016, and references therein). This is also roughly the transition boundary between the two halo components previously identified by Carollo *et al.* (2007). With this definition in mind, and considering that the virial radius of our Galaxy is of $\simeq 250-300$ kpc (e.g. Gómez *et al.* 2015), it is clear that the outer Milky-Way halo covers the vast majority of the Galactic volume. Contrary to the inner halo, inhabited by most globular clusters and halo stars, the very sparsely populated outer halo remains relatively unexplored. Another reason for studying the outer halo is that it is expected to be dominated by the dark matter component of the Galaxy. The dark matter dominated MW potential can then be reconstructed by modelling the orbits of the baryonic component. The outer MW halo harbors considerable stellar substructure which can be used as dynamical probes. On small scales, one finds many globular clusters (GCs) and faint halo clusters (FHCs), and most of the system of MW dwarf satellite galaxies. On large scales, there is evidence for a vast polar structure (VPOS), as

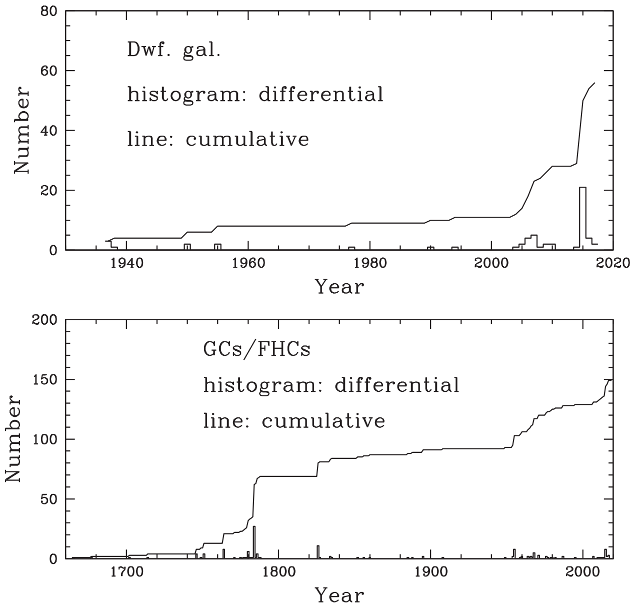

Figure 1. Upper panel: distribution of MW dwarf companions as a function of the year of their discovery. Besides the Magellanic Clouds, known for centuries, the first two dwarfs identified were Fornax and Sculptor, in 1938. The histogram shows the differential distribution, whereas the line shows the cumulative one. Lowe panel: differential and cumulative distribution of MW globular clusters and faint halo clusters as a function of year of discovery. Notice the much broader time span caused by the discovery of classical GCs over 200 years ago.

well as a system of stellar systems associated to the Magellanic Clouds (Pawlowski *et al.* 2015; Jethwa *et al.* 2016).

2. Recently discovered MW companions

Wide angle, deep and homogeneous photometric surveys have recently led to an extraordinary increase in the number of known distant MW dwarf galaxies and star clusters. Figure 1 shows the evolution of the discovery rate of MW dwarfs (upper panel) and GCs/FHCs (lower panel). While most of the rich, dense and high surface brightness GCs have been discovered more than 200 years ago, the last decades of the 20^{th} century have revealed many more extended and poorer clusters, such as those from the Palomar survey (POSS, Abell 1955, and references therein), and clusters from Near Infra-Red surveys, such as the Two-Micron All-Sky Survey (2MASS, Skrutskie *et al.* 2006). In the outer halo, an additional increase in the clusters census was recently brought by the Sloan Digital Sky Survey (SDSS, York *et al.* 2000), the Panoramic Survey Telescope and Rapid Response System 1 (PanSTARRS, Laevens *et al.* 2015) and the Dark Energy Survey (DES, The Dark Energy Survey Collaboration 2005), among others. Even more dramatic is the increase in the number of dwarf galaxies (upper panel), with two distinct recent episodes: the one prior to 2010 is dominated by SDSS, while the high peak in 2015 is largely due to first and second year DES data, although with contributions from other surveys.

DES has been providing an enourmous amount of photometric data on stars in the Galaxy, in the periphery of the Magellanic Clouds and other satellite galaxies. The first year DES data have revealed nine new MW companions (Bechtol *et al.* 2015; Koposov

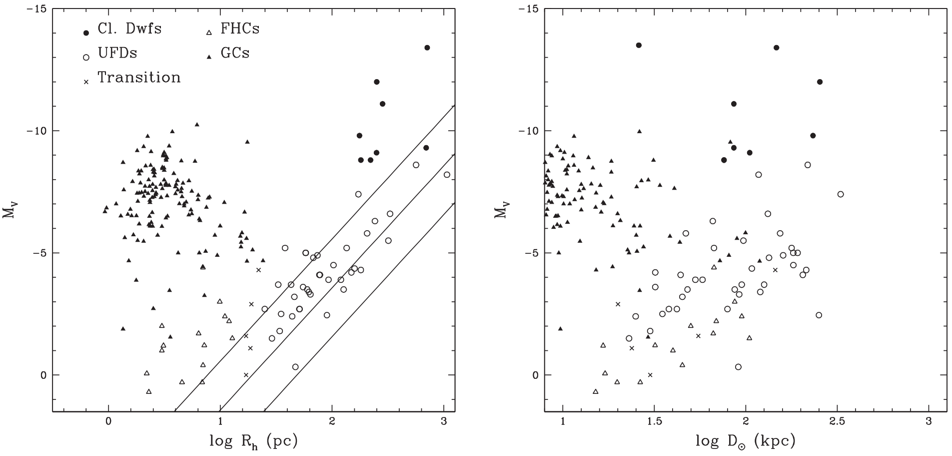

Figure 2. Left panel: distribution of MW star clusters, dwarf galaxies and transition objects in the V band absolute magnitude M_V vs. half-light radius R_h plane. The different types of systems are coded as indicated in the panel. The diagonal lines represent constant surface brightness values of 28,30,32 mag arcsec^{-2}. Right panel: distribution of MW star clusters, dwarf galaxies and transition objects in the V band absolute magnitude M_V vs. heliocentric distance $D_\odot$ plane. The symbols are identical as in the previous panel.

et al. 2015) consistent with being ultra-faint dwarf galaxies (UFDs). A subsequent analysis based on first and second year data have led to eight additional discoveries (Drlica-Wagner *et al.* 2015). Luque *et al.* (2016) have presented in detail one of the methods responsible for these initial discoveries, which we call SparSEx. SparSEx uses a matched-filter algorithm applied to CMD data. It is based on previous works by Rockosi *et al.* (2002) and Balbinot *et al.* (2011) to search for stellar substructure in photometric catalog data. The algorithm generates on-sky maps of the number of stars consistent with being drawn from simple stellar populations (SSPs) of different ages, metallicities and distances. SparSEx then uses SExtractor (Bertin & Arnouts 1996) to find peaks in these maps, which are then ranked according to the statistical significance of their detection relative to the background and to the frequency in which they appear in the matched-filter maps of different SSPs. The code has been succesfully validated in SDSS data and contributed to the initial DES discoveries. Besides, its application to DES has led to the identification of other stellar systems, including DES 1, the first genuine halo cluster identified by the DES collaboration (Luque *et al.* 2016), and two possible companions of the Sagittarius dwarf galaxy (Luque *et al.* 2017).

3. Future perspectives: extending the discovery space

Figure 2 shows the distribution of MW companions, dwarf galaxies and star clusters alike, in the luminosity vs. size and luminosity vs. distance planes. The list of dwarfs comes from McConnachie (2012) and is complemented by all published discoveries from the past 5 years that we are aware of, including the FHCs and UFDs. The classical GCs were taken from Harris (2010). There are two important features in these plots. First, the clear gap in size separating GCs from classical dwarf galaxies is no longer seen at low luminosities. The transition objects shown are those whose nature was considered dubious in the discovering papers themselves. Second, there are obvious selection biases against low surface brightness and/or distant stellar systems. Notice that, due to the logarithmic scale of the M_V vs. $D_\odot$ plot on the right of Figure 2, most of the MW volume is in fact uncharted for systems with M_V > -5.

The census of MW companions is therefore still quite incomplete. Future surveys, most specially the one from the *Large Synoptic Survey Telescope* (Ivezic *et al.* 2008, LSST), should greatly increase the coverage of the luminosity-size-distance discovery space. It is important to be able to make forecasts of how complete a sample of MW satellites will be as a function of position in this space for any given survey. With that in mind, we have developed a simple approach to estimate the efficiency of detection of stellar systems in discovery space. It does not require extensive numerical experiments with synthetic clusters and dwarfs being added to actual or simulated data, and searched for using some specific object finder. Our method uses isochrone models in a range of ages, metallicities and distances. We assume a given initial mass function (IMF), either from Chabrier (2003) or Kroupa (2001), to estimate the expected number of stars from an SSP of some stellar mass, down to some survey magnitude limit, and within an area on the sky corresponding to the apparent half-light radius of the system. We then model the expected number of field Galactic stars based on Trilegal (Girardi *et al.* 2012) to estimate the statistical significance of the excess of stars of a the object relative to the field. We have tested this simple approach against the simulations from Koposov *et al.* (2008) for SDSS and from Bechtol *et al.* (2015) for DES, and managed to recover their detection efficiencies in the 3D discovery space with minimal tuning.

Applying this approach to the expected limits of the final DES coadd catalog (after 5 years of data, Y5) and of LSST (after 5 years) indicates a significant improvement in detection efficiency over the next decade. DES Y5 data will allow efficient detection of MW satellites at least 1.5mag fainter than it was possible using first year data. The gain will be larger (by 2.5-3.0 mag) for the distance range from 80-150 kpc, since it is for this range that the incremental photometric depth will allow reaching the main-sequence turn-off of old and metal-poor populations, typical of MW companions. As for LSST, it is expected to add $\simeq$ 1.5mag in M_V relative to DES Y5, up to $\simeq$ 2.5 mag in M_V for distances beyond 200 kpc.

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