Faint (and bright) variable stars in the satellites of the Milky Way

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Abstract. I describe two ongoing projects related with variable stars in the satellites of the Milky Way. In the first project, we are searching for dwarf Cepheid stars (a.k.a δ Scuti and/or SX Phe) in some of the classical dwarf spheroidal galaxies. Our goal is to characterize the population of these variable stars under different environments (age, metallicity) in order to study their use as standard candles in systems for which the metallicity is not necessarily known. In the second project we search for RR Lyrae stars in the new ultra-faint satellite galaxies that have been discovered around the Milky Way in recent years.

1 Introduction

The last two years have revealed a completely new picture in our understanding of the Galactic neighborhood with the discovery of $\sim$ 20 dwarf systems surrounding the Milky Way (MW), doubling the number of satellites known in 2014 ([1–9]), and narrowing the discrepancy between the predicted number of satellites in the standard Lambda Cold Dark Matter (LCDM) cosmological framework and observations, a problem known for many years as the missing satellites problem. Many of these new satellites are extremely low-luminosity systems and are opening research in a new low mass regime for galaxies. The role of these small ultra-faint satellites in the formation of galaxies like our own remains to be understood. Key to such characterization is accurate distance measurements toward the new galaxies.

Variable stars have a long tradition of being an excellent tool for studying the content and structure of stellar systems. RR Lyrae stars are not only excellent standard candles, but they also trace the old population of these systems. Anomalous Cepheids (which are brighter than RR Lyrae stars) are usually interpreted as belonging to an intermediate-age population (e.g., [10]). Below the horizontal branch, dwarf Cepheids may have been produced by different stellar populations and are potentially another good standard candle.

Here I discuss two ongoing projects to study and characterize variable stars in satellites of the Milky Way.

2 Faint variable stars: dwarf Cepheid stars in the Sextans dSph galaxy

δ Scuti and SX Phe stars (which I will collectively call dwarf Cepheid stars here) co-exist in the same region of the color-magnitude diagram (CMD) of dwarf spheroidal (dSph) galaxies. The region of

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the instability strip below the horizontal branch may contain not only main sequence pulsating stars (δ Scuti) from young and intermediate-age stellar populations, but also pulsating blue stragglers (SX Phe) belonging to the old stellar population. If a galaxy contains both types of populations, it is usually not possible to separate them and that is the reason why a collective name for both types of stars is useful.

The search for dwarf Cepheid stars in extragalactic systems has been difficult because of observational limitations. First, dwarf Cepheid stars are faint ($\sim 1.5 - 2.5$ magnitudes below the horizontal branch, which for distant systems are beyond the limit of most of the existing variability surveys, except for OGLE/MACHO in the Magellanic Clouds (see [11]). Second, dwarf Cepheids have very short periods (< 0.1 d) which in practice means that short exposure times ($\sim$ a few minutes) need to be used in order to correctly sample the light curves. This imposition on the exposure times requires the use of medium/large aperture telescopes in order to reach the magnitude of dwarf Cepheid stars in distant systems. Finally, several of the dSph galaxies around the MW extend over large areas of the sky and a complete census is observationally expensive unless a large field of view (FOV) imager is availiable at the telescope. It is important to note that all these difficulties will be naturally overcome by the LSST project ([12]).

The importance of finding and characterizing dwarf Cepheid stars resides in their potential use as standard candles. They are known to follow a clear period-luminosity (PL) relationship ([13]). It has been suggested that such PL relationship does not depend on color and/or metallicity ([14]). However, more systems with dwarf Cepheid stars coming from different environments (age, metallicity, star formation histories) are needed in order of establishing better constraints on their use as standard candles in systems for which the metallicity is not necessarily known. The dSph galaxies contain stars that inhabit a different age/metallicity range than those found anywhere else in the Galaxy and so offer the chance to study these variables from unique and otherwise hard to study populations.

Dwarf Cepheid stars have been searched so far only in three extra-Galactic systems: the LMC ([11]), Fornax ([15]) and Carina ([16–18]). Our study in Carina ([17]) has raised several interesting points: (i) Carina is very rich in dwarf Cepheid stars; (ii) There seems to be a fundamental difference between the dwarf Cepheid population in dSph galaxies and the Galactic field. While high amplitude dwarf Cepheid stars are extremely rare in the field ([19]), they are at least 100× more frequent in Carina. (iii) There are important differences observed among the properties of the dwarf Cepheid population of Carina, Fornax and the LMC which may be a reflection of a metallicity spread, depth along the line of sight, and/or different evolutionary paths of the dwarf Cepheid.

In collaboration with Javier Alonso-García (Universidad de Antofagasta, Chile), Mario Mateo (University of Michigan), Alistair Walker and David Nidever (NOAO), we have started a project to look for dwarf Cepheid stars in several satellite galaxies using the large FOV of the Dark Energy Camera (DECam, [20]) on the 4m Blanco telescope at Cerro Tololo Inter-American Observatory, Chile. One of our targets is the Sextans dSph system. Sextans is a low luminosity system located at 86 kpc. It does not have a strong intermediate age population but there is evidence of continuous star formation in the last $\sim$ 8 Gyrs ([21]) and a significant spread in metallicity ([22]). Figure 1 shows the spatial distribution of the variable stars (30 RR Lyrae stars, 2 Sextans dwarf Cepheid stars and 1 foreground dwarf Cepheid) we were able to identify in one of our DECam fields (out of 3 we observed), and the resulting CMD from that field, showing as well the variable stars. All the RR Lyrae stars found were previously known.

The field shown in Figure 1 is not centered at the galaxy but along the semi-major axis and contains stars between 13 and 134 arcmin from the center. We will present a complete coverage of the galaxy in a forthcoming paper. With these preliminary results it is clear that the population of dwarf Cepheid stars in Sextans is not as numerous as in Carina, which is probably a consequence of the small presence of intermediate-age stars in this galaxy. The periods of the two dwarf Cepheid stars in Sextans are

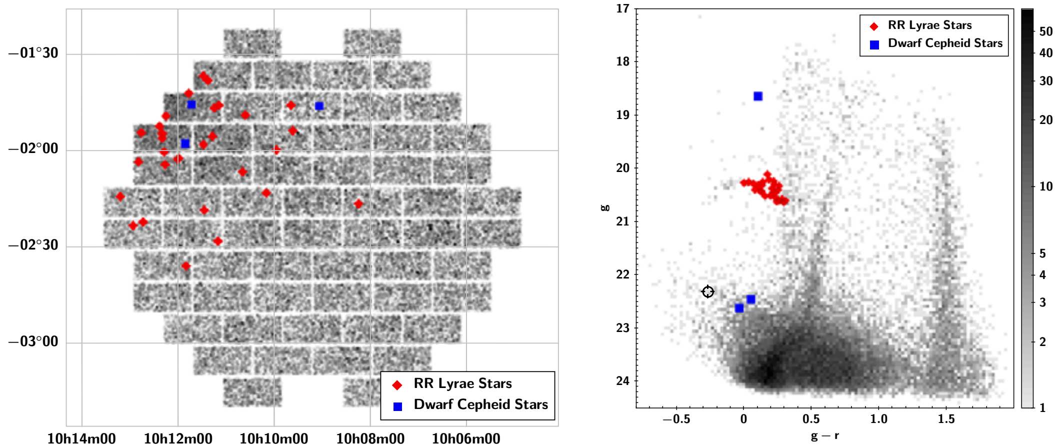

Figure 1. (Left) Spatial distribution of the variable stars in the DECam field. Colored symbols indicate the variable stars found in this field. For reference the center of Sextans is at RA = 10:13:03, DEC = –01:36:53. (Right) Hess diagram of stars closer than 60 arcmin of the center of Sextans. The bright dwarf Cepheid in the diagram is likely a foreground field star in the line of sight of the galaxy. That star is also the more distant from the center of Sextans.

0.0521 and 0.0576 days, which are shorter than the mean period of the dwarf Cepheid stars in Carina (which are shorter than the ones in Fornax and the LMC), following a trend with metallicity already suggested in [17]. This trend needs to be confirmed once the full galaxy has been explored.

3 Bright variable stars: RR Lyrae stars in the ultra-faint satellites of the Milky Way

RR Lyrae stars are excellent standard candles and thus provide an alternative method for determining the distance to galaxies. This is particularly important in distant and low luminosity systems lacking young populations (i.e., systems that cannot host Cepheids that could be used as distance indicators). In addition, estimation of accurate distances by isochrone fitting may be hard because usually there are very few stars in the upper part of the CMD, the contamination by field stars may be important due to the low density of stars in the system, and the main sequence turn-off may not be available in some cases due to their large distances. Improving the distance to the satellites allows a better determination of other parameters such as the physical size (half-light radius) and absolute magnitude of the systems.

As part of the Survey of the Magellanic Stellar History (SMASH, [23]), we obtained time series in *gri* with DECam of the recently discovered Hydra II ultra-faint dwarf ([4]). One RR Lyrae star was found in the system and allowed us to get a distance to Hydra II of 151 ± 8 kpc. With this value, the physical size and absolute magnitude of the galaxy were re-derived to $r_h = 76^{+12}_{-10}$ pc and $M_V = -5.1 \pm 0.3$. Details on this work can be found in [24].

Until now, all dwarf galaxies that have been adequately searched for variable stars have yielded RR Lyrae stars, which confirms that these systems predominantly contain old, metal-poor stellar populations. Figure 2, updated from [24], is a period-amplitude diagram of the RR Lyrae stars known in the Milky Way's ultra-faint satellites. It is clear that while the halo stars (black + symbols) concentrate toward the Oo I locus, most of the RR Lyrae stars in the ultra-faint dwarfs (including the only

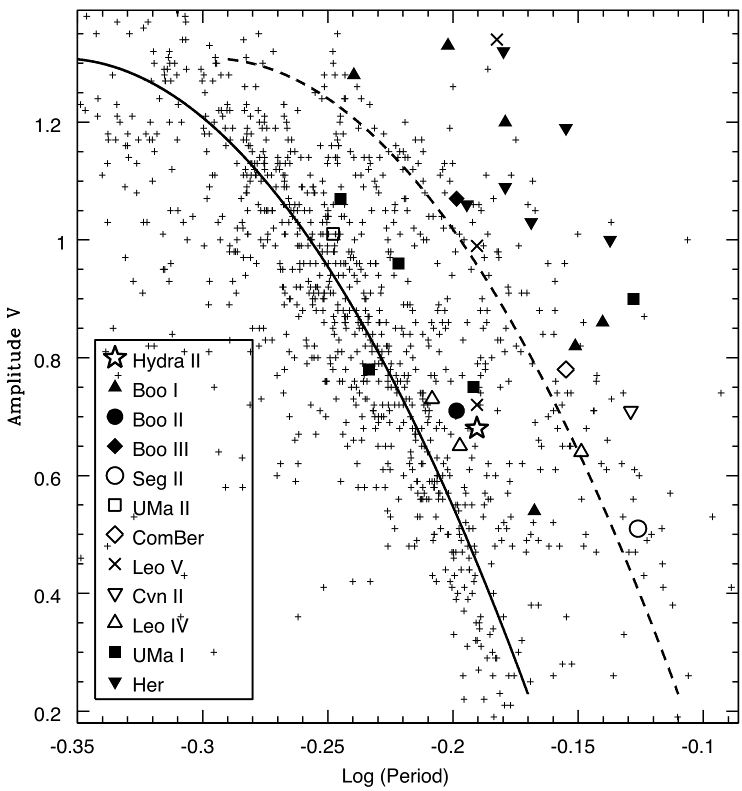

Figure 2. Period-amplitude diagram for fundamental mode RR Lyrae stars in the halo (small + symbols, [25]) and in the Milky Way's ultra-faint satellites. Reference for the later can be found in [24]. Leo V data are from [26]. The amplitudes for the stars in this galaxy are not *V* but *g*, but they should not differ by more than 0.2 mags. The locus of the Oosterhoff I and II groups are shown as a solid and dashed line respectively.

star in Hydra II) are mainly located in the region of the Oo-intermediate and Oo II loci. If the Milky Way was formed by the accretion of small sub-structures as expected by the LCDM cosmology, the ultra-faint galaxies may contribute to the Oo II tail of the population of halo RR Lyrae, but they do not seem to be the source of the main population. It seems that mergers with large galaxies such as Sagittarius and Fornax (which have a similar distribution as the halo in a period-amplitude diagram) are needed in order to reproduce the observed RR Lyrae population in the halo of the Milky Way.

4 Conclusions

Variable stars provide important information about the satellites of the Milky Way that goes from the possibility to obtain accurate distances (which allows to determine other physical parameters), to the study of the stellar populations that are present in those systems. They can also provide clues about the formation scenarios of the Milky Way.

Dwarf Cepheid stars are important to study since they are potentially good standard candles that could be used in the Local Group in the LSST era.

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