Project: A Census of the Outer Halo Star Cluster Population

PI: Ting Li

Co-Is: Joshua Simon (OCIW), Alexander Ji (OCIW), Ian Thompson (OCIW), Andrew Pace (CMU), Alex Drlica-Wagner (Fermilab), Sid Mau (Chicago)

Abstract: Large photometric surveys have discovered a large number of faint stellar systems in the outer halo ($\gtrsim$30kpc), including the ultra-faint dwarf galaxies and low-luminosity star clusters. It has become increasingly difficult to distinguish between these two populations, but the distinction is crucial to robustly measure the faint end of the galaxy luminosity function. Large amounts of telescope time have been invested in the dwarf galaxies, but the faint star clusters have not been well-studied. These clusters are of some intrinsic interest as well, as they extend the globular cluster population down to very low luminosities. Here, we propose to undertake the first systematic survey of faint Milky Way star clusters to characterize their orbits and metallicities and create a sample of targets for future high-resolution followup. In 2020A we will observe six faint outer halo star clusters ($M_V > -4$) with Magellan/IMACS.

Scientific Justification.

Globular clusters and dwarf galaxies are both satellites of Milky Way, which are seen as groups of a few hundred to few hundred million stars in one location on the sky. Both types of satellites are relatively old ($\gtrsim$10 Gyr) and gas-free systems with no recent star formation. The fundamental difference between the two classes is that globular clusters are thought to be dark matter free and simple stellar populations, while dwarf galaxies are dark matter dominated and have extended star formation histories. Photometric data provides the size and luminosity of these systems, which is enough to classify the more luminous systems ($M_V < -6$) as a dwarf galaxy or globular cluster. Globular clusters are usually much more compact (half light radius $r_h < 10$ pc) while dwarf galaxies have a much larger size ($r_h > 100$ pc) at a similar luminosity (see left panel of Fig. 1).

This formerly clean classification has been upended over the past 10 years. Deep and wide-area photometric surveys (e.g., SDSS) have discovered a few dozen of the so-called ultra-faint dwarf galaxies ($M_V > -7.7$, $M_\star \lesssim 10^5$ M$_\odot$). These dwarf galaxies have been the subject of intense study, as they are the luminous counterparts to the least massive dark matter halos and thus are interesting for cosmology, galaxy formation, reionization, and nucleosynthesis (Brown et al. 2014; Ji et al. 2015; Simon 2019). These surveys have also discovered more than a dozen fainter star clusters in the Milky Way's outer halo (> 30 kpc). The faintest dwarf galaxies and the faintest star clusters are difficult to distinguish based only on their luminosity and radius.

However, galaxies and star clusters can be separated using resolved stellar spectroscopy. Galaxies exhibit clear evidence for dark matter (measured kinematically with a velocity dispersion) and extended star formation histories (measured chemically with a metallicity dispersion), while star clusters have neither (Willman & Strader 2012). Successful classifications have been made for the majority of known ultra-faint dwarf galaxies (e.g., Simon & Geha 2007; Martin et al. 2007). However, an increasingly common result is that only upper limits can be placed on the velocity dispersion and metallicity dispersion for the faintest dwarf galaxies candidates at $M_V \geq -4$ (see "suspected dwarfs" in Fig. 1). The failure to resolve the velocity and metallicity dispersions is mainly caused by two factors: (1) fewer stars are bright enough for spectroscopy at lower luminosity, so the velocity and metallicity dispersion usually have larger uncertainties; and (2) only a small dynamical mass is needed for a system to have mass-to-light ratio in excess of 100; e.g., $M_{\rm dyn} = 10^5$ M$_\odot$ for a dwarf galaxy at $M_V \sim -2$ ($M_\star \sim 10^3$ M$_\odot$). This dynamical mass usually corresponds to a velocity dispersion of only $\sim 1 - 2$ km/s, which is hard to resolve with a small sample and any existing instruments. The physical sizes of most of these objects also lie in the ambiguous classification region between 10-40 pc. Recently, we have started invoking chemical differences between UFDs and globular clusters as classification, as the confirmed dwarf galaxies have very different abundances of neutron-capture elements compared to globular clusters (e.g., Ji et al. 2019). However, this empirical criterion is based on an incomplete study of low-luminosity and/or metal-poor star clusters.

The lack of conclusive classifications for faint Milky Way satellites has very important consequences. Because so few galaxies have been confirmed in this luminosity range ($0 \lesssim M_V \lesssim -4$), each one has an outsized influence on the derived luminosity function (e.g., Bose et al. 2018) and the completeness-corrected number of Milky Way satellites (e.g., Kim et al. 2018). Most importantly, the new dwarf galaxies discovered by upcoming surveys (e.g. LSST, WFIRST) will be even fainter and more difficult to follow up. If their size continues being smaller, it will make the classification even harder.

Our current efforts have focused on trying to understand and resolve the velocity and metallicity dispersions of the faintest and most compact dwarf galaxies. However, it is equally crucial to understand the properties of the outer halo star clusters and see if they differ from dwarf galaxies in other ways. Until now, almost no spectroscopic followup has been conducted on the outer halo star clusters, simply because they have been viewed as less interesting. As a result, **we lack even the most basic information of their radial velocity and mean metallicity**. Obtaining these measurements could potentially find other ways to separate star clusters and dwarf galaxies. For example, if all the existing star clusters are relatively metal-rich ([Fe/H] > -2), similar to the brighter globular clusters, then we can use the mean metallicity to classify the two populations. We can also compare orbital parameters (e.g., eccentricity, pericenter) for clusters and dwarfs and see if this is useful for classification. Furthermore, identifying bright member stars in these clusters also enables subsequent followup with high-resolution spectroscopy, which will help us validate the empirical classification based on the abundance of neutron-capture elements.

Star cluster formation is also an interesting topic in itself. Although globular clusters have been studied for decades, very few outer halo clusters have been studied. Are these faint outer halo clusters an extension of the Galactic clusters, or did they accrete with other dwarf galaxies? Determining the metallicities and orbits will also help answer this question.

This proposal: We propose to use Magellan/IMACS to observe a sample of outer halo star clusters at $M_V \lesssim -4$, $D \gtrsim 30$ kpc and $r_h \lesssim 13$ pc, which is a parameter region with almost no spectroscopic information[1]. We then select a subset from the list to make sure that they are accessible from Magellan in 2020A. We further restrict to the clusters whose luminosity and distance suggests at least 3 member stars at $r < 20.5$ that we can use to determine the mean metallicity and systemic velocity. The resulting star clusters are listed in Table 2 (in Target List). None of these clusters has published spectroscopy so far. With proper motions from Gaia DR2, we can also derive the star cluster orbits. The metallicity and orbital information will be compared with both classical globular clusters and confirmed ultra-faint dwarf galaxies. If more than 10 members are identified in a cluster, we will also examine the velocity dispersion and metallicity dispersion, and confirm if they are consistent with zero which is what we expect in these presumably dark matter free systems.

Technical Description.

Instrument Setup: We will use the same instrument and setup as our dwarf galaxy program, i.e. 1200/9000 grating with 0.7" slit width, providing R $\sim$ 11,000 spectra covering 7500-8800 Å wavelength range. We rely on telluric absorption bands to correct velocity offsets resulting from slit centering errors. The velocities and metallicities will mainly determined by the the Ca triplet lines near 8500Å.

[1]Segue 3 and Laevens 3 are the only star clusters that have published spectroscopic study at this parameter space.

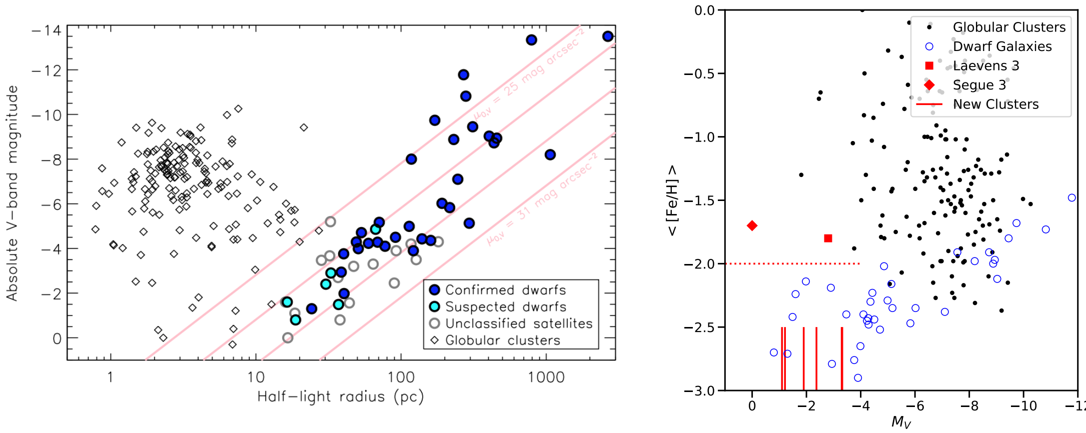

Figure 1: (left) Luminosity (M_V) and half-light radius (r_h) of the dwarf galaxies and globular clusters (figure from Simon 2019). At the faint end, the boundary between these two classes become vague. Star clusters at $M_V < -4$ and $r_h \lesssim 13$ pc are the targets of this proposal. (right) Metallicity vs luminosity; figure adapted from Simon et al. (2017). Open blue circles are confirmed dwarf galaxies which follows a well-defined luminosity-metallicity relation (Kirby et al. 2013). Black dots are globular clusters (Harris 2010). The metallicity of the faintest star clusters at $M_V < -4$ are largely unknown. Laevens 3 (red square) and Segue 3 (red diamond) are the only faint and metal-poor outer halo star clusters with a spectroscopic metallicity measurement (Longeard et al. 2019; Fadely et al. 2011). The M_V of our six targets are indicated as red vertical lines.

Our custom data reduction pipeline produces velocities precision to 1.0 km/s at S/N = 20 and 3.0 km/s at S/N = 5 (Simon et al. 2017; Li et al. 2017), and metallicity precision at 0.15 dex at high S/N (Simon et al. 2017).

Exposure Time and Scheduling: We aim to achieve S/N = 5 per pixel at r = 20.5 for each cluster. This requires a total of 4-5 hr exposure per cluster on bright nights. We therefore request 3 nights in 2020A to observe 6 clusters. Since our clusters are distributed over a range of RA, we prefer to have 3 nights over 2 runs, one night in Feb/Mar and two nights in Jun/Jul. Since the wavelength coverage is at NIR, we could use bright time (preferably excluding ±1 day from full moon).

Progress to date: This is a new program, but the PI has previously been awarded Magellan/IMACS time via UChicago, resulting in 3 published first author papers in the past 2 years (Li et al. 2017, 2018b,a)

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Target list:

Table 1: Outer halo star clusters for Project 2

Name	RA	Dec	M_V	Distance (kpc)	r_h (pc)	$N_{\mathrm{mem}}(r < 20.5)^{(a)}$	$N_{\mathrm{mem}}(r < 21.0)^{(a)}$
Eridanus III	35.700	-52.280	-2.37	87.1	4.93	3	4
DES 4	82.100	-61.720	-1.10	31.3	7.58	3	6
Gaia 3	95.060	-73.410	-3.30	48.4	7.45	15	19
PS1 1	289.170	-27.830	-1.90	29.6	4.69	8	15
Kim 2	317.200	-51.170	-3.32	100.0	12.06	5	9
Balbinot 1	332.680	14.950	-1.21	31.9	7.24	3	6

(a) N_{mem} are expected member of stars at $r < 20.5$ or $r < 21.0$, estimated based on the luminosity and distance of the clusters.