Project: Binary Populations in Ultra Faint Dwarf Galaxies

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Abstract: The orbital motion of close binary systems in ultra-faint dwarf galaxies (UFDs) may potentially inflate the velocity dispersions of the systems which are so far the only way to constrain the dynamical masses and therefore the dark matter content in these UFDs. We propose a long-term program to monitor the line-of-sight velocities of the brightest members in 6 UFDs in the course of next three years. In 2019B, we request 3 grey nights on Magellan/M2FS to obtain the first few epochs for this program. This long term program will not only identify individual binaries in these 6 UFDs, but also model the entire data set probabilistically to recover unbiased estimate of the velocity dispersions and the dynamical masses of the systems. In addition, understanding the binary populations in these UFDs will help us to assess the impact of binarity on other fainter and more distant UFDs in which such test is more expensive and difficult to accomplish.

Scientific Justification.

Ultra-Faint Dwarf galaxies (UFDs) are the faintest ($M_V \gtrsim -7.7$), oldest (Age$>$ 10 Gyr), most metal-poor ([Fe/H] < -2), and most dark matter dominated ($M_\odot/L_\odot > 100$) galaxies known (Simon 2019). As a result of their high dark matter content, UFD's are excellent laboratories for understanding the nature of dark matter. The number of UFDs and their density profile depends sensitively on the particle nature of dark matter, e.g. whether dark matter is warm (Lovell et al. 2014) or self-interacting (Rocha et al. 2013). UFDs are excellent targets to search for the dark matter annihilation or decay signal because of their low astrophysical backgrounds (Ackermann et al. 2015). The study of UFDs has been recently revived because dozens of new candidate dwarf galaxies were discovered by the Dark Energy Survey and other imaging surveys (e.g., Koposov et al. 2015a; Bechtol et al. 2015).

The dynamical mass and inferred dark matter content in UFDs, however, is solely derived from the line-of-sight velocities of the stars in the field of UFDs. In particular, the high dark matter content is inferred from the velocity dispersion of the member stars, with dispersions typically < 6 km/s (Simon 2019). Due to the intrinsic low dispersions of UFDs, concerns on these measurements have been raised by the community for three main reasons: (1) Due to their low luminosity, only a limited number of stars are bright enough to be observed by existing telescopes and instruments, with a large fraction having large velocity uncertainties due to the low S/N of the spectra. (2) The velocity dispersion depends on the systematic uncertainties of the velocity measurement, e.g. 1.5 - 2.2 km/s for Keck/DEIMOS (Simon & Geha 2007) and 1.0 km/s for Magellan/IMACS (Simon et al. 2017; Li et al. 2017). These systematic uncertainties are only several times less than the velocity dispersions of the smallest UFDs (Table 1) and make the velocity dispersion measurements less accurate. (3) Most importantly, for systems with small dispersions and small sample size, the orbital motion of close binary systems may affect the radial velocity measurement of one or more member stars at a given epoch, inflating the dispersion by a non-negligible amount (McConnachie & Côté 2010).

Binary stars have been detected in several UFDs (Koposov et al. 2011; Koch et al. 2014), and undetected binaries have previously inflated the velocity dispersions of several UFDs. For example, Kirby et al. (2015) initially identified Triangulum II as the most dark-matter-dominated galaxy known; however, subsequent multi-epoch observations found a binary star that had previously inflated its velocity dispersion (Kirby et al. 2017). With the new measurements, the dispersion of Triangulum II is unresolved, making it ambiguous for even classifying between star cluster and dwarf galaxy. The velocity dispersion of Boötes II (Koch et al. 2009) has been shown to be inflated by a binary star (Ji et al. 2016). Similarly, two binary stars in Carina II would have inflated the velocity dispersion by $>2\times$ without multi-epoch spectroscopy (Li et al. 2018). Recent studies on Milky Way field stars with APOGEE also show that the fraction of close binaries

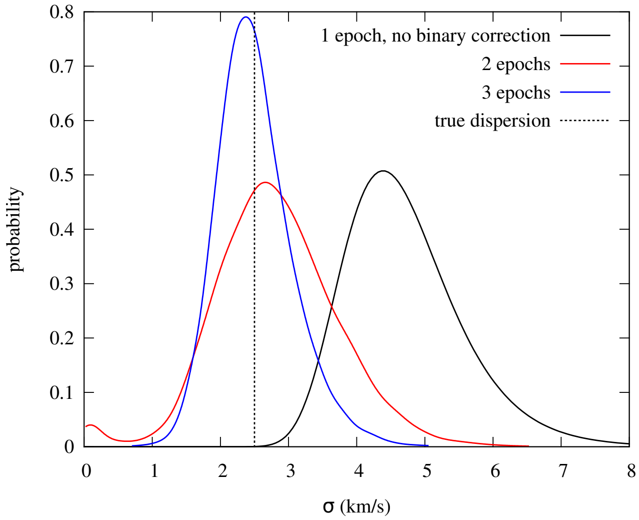

Figure 1: Velocity dispersion of a simulated UFD with 20 members, where the dashed vertical line shows the true velocity dispersion of these 20 members at 2.5 km/s. The black solid line shows the measured velocity dispersion constraint if only 1 epoch observation is taken. The dispersion is inflated due to the binary populations. Such inflation can be properly corrected after multi-epoch observations are taken.

Table 1: UFD targets for Project 1

Name	RA	Dec	Mv	$D_\odot$ (kpc)	r_h (')	σ_v (km/s)	$N_{\rm obs}{}^{(a)}$	$N_{\rm total}{}^{(b)}$	$N_{\rm M2FS}{}^{(c)}$
Hydrus I $^{(d)}$	37.389	−79.309	−4.71	27.5	7.42	2.7	30(30)	148	119
Reticulum II $^{(d)}$	53.920	−54.051	−3.88	31.6	5.52	3.3	25(24)	49	43
Carina II $^{(d)}$	114.107	−57.999	−4.50	36.3	8.69	3.4	18(18)	67	50
Coma Berenices I	186.745	23.907	−4.28	41.7	5.64	4.6	59(13)	46	40
Boötes I	210.020	14.514	−6.02	66.1	9.97	4.6	40(16)	138	96
Sagittarius II $^{(d)}$	298.169	−22.068	−5.20	69.2	2.00	2.7	22(9)	62	61

(a)$N_{\rm obs}$ is the number of members that have been identified and published in the literature, with the number in the apprentices the number of members brighter than $G \sim 20.6$. (b) $N_{\rm total}$ is the number of member stars in UFDs estimated based on the measured luminosity and distance of the UFDs, a old, metal-poor stellar population with a Chabrier IMF and a limiting magnitude of $G \sim 20.6$; (c) $N_{\rm M2FS}$ is the estimated number of members in one M2FS pointing assuming the member density of UFDs follows a Plummer profile; fiber collision is ignored in this estimation. (d) These UFDs are accessible in 2019B in one or both M2FS runs.

is likely higher in low metallicity systems (Badenes et al. 2018). Binaries thus likely inflate the velocity dispersions of many UFDs.

With two velocity epochs, binary stars with certain orbital periods can be identified and removed in subsequent velocity dispersion analysis. Another different and maybe better approach is to correct the velocity dispersion statistically by modeling the properties of the binary population (e.g., binary fraction, period distribution, etc.) using multi-epoch data (see, e.g., Martinez et al. 2011; Minor et al. 2018). We illustrate this in Fig 1, which shows one simulation on how the dispersion could be corrected in a UFD with 20 members observed. Assuming a binary fraction of 0.5 and a population with mean orbit period of 30 yr, the measured dispersion could be inflated to > 4 km/s if only one epoch of measurement is obtained. With 2nd and 3rd epochs each taken one year apart, the velocity dispersion can be properly corrected. Binary fraction studies have been performed in classical dwarf galaxies, finding significant variation in the binary fractions in different dwarf galaxies (0.3-0.7) (Minor 2013; Spencer et al. 2017, 2018), so it is hard to apply the binary populations from classical dwarfs to UFDs.

This proposal: We propose a long-term program to observe 6 Milky Way UFDs with M2FS to attack the above 3 concerns, with an emphasis on the third one. These concerns would be tackled by this program in the following ways.

(1): Sample Size. Table 1 shows 6 UFDs that have the highest number of bright members among all UFDs accessible from LCO. These UFDs are relatively luminous and/or close by, and we expect to obtain $40-120$ members (see $N_{\rm M2FS}$ column in Table 1) in each UFD with $G < 20.6$ (similar to $r < 20.6$). This will be the largest sample to precisely determine the velocity dispersion in UFDs. Such samples were not practical

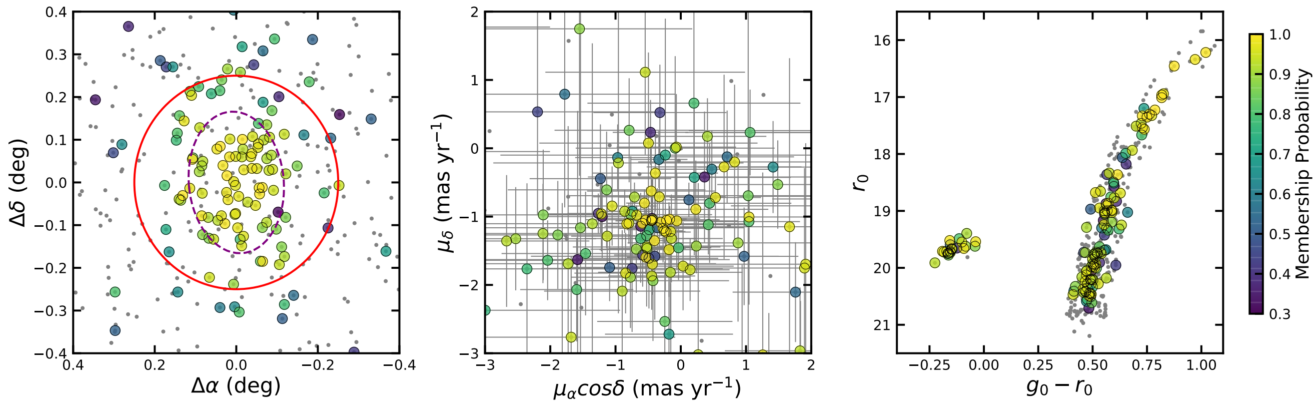

Figure 2: The membership probability of targets in Boötes I, in RA/Dec (left), proper motion space (middle), and color-magnitude diagram (CMD, right). Grey dots indicate low-probability members or non-members (membership probability $P_i < 0.3$). Targets were pre-selected with an metal-poor isochrone in CMD using DECam photometry. The membership probability is computed using methods detailed in (Pace & Li 2018). The dashed magenta ellipse shows the half-light radius of Boötes I, and the red circle shows the FOV of M2FS. Most high probable members can be observed with one M2FS pointing. These target stars all have proper motion in Gaia and therefore are relatively bright ($r_0 \lesssim 20.6$). Most of the targets are RGB members, with a small portion of blue-horizontal branch stars.

prior to *Gaia*, because the efficiency of finding RGB member stars was $\lesssim$20% in a spectroscopic sample due to high background contamination. Thus, although all these 6 UFDs have had published observations, only about half of the brightest members were previously identified (see the number in the apprentices of $N_{\rm obs}$ column in Table 1). Fortunately, the target density is significantly reduced by the parallax and proper motion information provided by the second data release (DR2) of *Gaia*. The membership probability (P_i) of every target belonging to a UFD has been calculated based on its proper motion, sky location, and CMD position (see details in Pace & Li 2018). Figure 2 shows Boötes I as an example, where targets with $P_i > 0.3$ are shown. With one pointing of M2FS, we expect to get a total of ~ 85 members from ~ 105 targets. This greatly increases the target selection efficiency and ensures that one M2FS observation will allow us identify most of the brightest members in our target UFDs.

(2): Velocity precision. M2FS is the most ideal instrument for such a study thanks to its large FOV (~ 30 arcmin in diameter), high spectral resolution ($R \sim 20000$), high multiplexing (up to 256 fibers), and stability in velocity measurements as a fiber-fed spectrograph. Previous velocity measurements using the Mg b triplet achieve a systematic uncertainty of 0.3 km/s (Walker et al. 2016), matching other fiber-fed spectrographs at similar spectral resolution (e.g., Koposov et al. 2015b) and multiple times better than lower-resolution slit spectrographs like DEIMOS and IMACS. As part of the program, we will obtain spectra of nearby globular clusters during twilight to properly assess and improve the systematic uncertainties.

(3): Binarity. We plan to obtain 5-7 epochs of observations over the course of 3 years on these UFDs, with rough intervals of 10 days, 3 months, 6 months, 1 year, 2 years and 3 years (with possible fluctuations in the intervals depending on the availability of the UFDs and the scheduling of M2FS runs). The cadences proposed here will not only allow us to identify individual binary stars in each UFD with different orbital periods, but also provide a large sample to determine the binary period distribution as well as the binary fractions in these UFDs. The dataset will allow us to determine unbiased estimates of the velocity dispersion of these 6 UFDs. In addition, we will be able to use this dataset to assess how binarity would affect the velocity dispersion of UFDs in general. We will also measure the variations in the binary fraction in these UFDs, and assess whether similar binary corrections could be applied to other fainter or more distant UFDs (where a sample of over 40 members is hard to obtain).

We request 3 grey nights on Magellan/M2FS to obtain the first 1-3 epochs on 4 UFDs in 2019B. The 3 epochs will be split between the 2 M2FS runs, which are usually 2-3 months apart. For one of the M2FS runs, we plan to observe at the start and end of the run, which will have a cadence of roughly 7–10 days, allowing us to identify binary stars with very short orbital periods and large amplitudes. Similar observations will be taken in 2020A for the remainder of the UFDs.

This program requires long term accessibility on a large aperture telescope with a relatively large field-of-view multi-object spectrograph, making it difficult to be conducted so far. As a Carnegie-Princeton Fellow for the next 5 yr (with Hubble for the first 3 yr), this program is well aligned with PI's research plans at Carnegie. Furthermore, this program will have close collaboration with the M2FS team, who has extensive experience on UFD kinematics with M2FS (Walker et al. 2015, 2016) and on binary fraction studies in classical dwarf spheroidal galaxies (Olszewski et al. 1996; Spencer et al. 2017, 2018).

Auxiliary science: for the brighter RGB stars, the stacked spectra over several epochs will have sufficient S/N to determine metallicities from the calcium triplet, which would provide a very large sample for studying metallicity distribution functions in UFDs.

Technical Description.

Instrument Setup: We plan to use the high-resolution mode of M2FS with Echelle grating and a $\sim$ 40-nm-wide filter, providing a wavelength coverage of 8374–8787 Å and a spectral resolution $R \sim 20000$. This setting takes 2 orders and therefore can feed up to 128 targets in one exposure. This matches well with the number of targets we have for each UFD. Since most of the targets of this program are RGB stars, observing in the NIR maximizes the S/N. Furthermore, this wavelength range covers all three Calcium triplet lines, allowing for velocity and metallicity determination. In addition, sky emission lines in this range can be used to calibrate possible wavelength shifts between the arc and science frames, improving the systematic uncertainties in velocity determination.

The required filter is not currently available and we plan to purchase it with a P^2 seed grant proposal via Carnegie (up to $5000) with excess covered by the M2FS team.

Exposure Time: Based on previous observations from the M2FS team, we estimate to get $S/N \sim 5$ per pixel at $r \sim 20.5$ with an exposure time of 2 hr at reasonable seeing and weather condition. Adding 20% overhead time, we expect to observe 3 UFDs in one night. Therefore, a total of 3 nights in 2019B will allow us to get 3 epochs (with 2 hr each) in 3 UFDs, or a total of 9 observations.

Scheduling: A subset of these 6 UFDs are available on the sky at any given time. Therefore, the M2FS run could be scheduled at any given time of the 2019B, provided that two runs are about 2-3 months apart. In detail, Sagittarius II, Hydrus I, and Reticulum II will be available in Sep and Oct 2019; Hydrus I, Reticulum II and Carina II will be available in Nov, Dec 2019 and Jan 2020. We therefore will take a total of 9 observations over 2 M2FS runs, with one run including two observation epochs on a given UFD. We therefore request 1 night in one M2FS run and 2 nights in the other, with preference of the 2-night run first. Although the target stars are the brightest RGB members in UFDs, their apparent faintness requires the observations to be taken in grey time.

Data reduction and Analysis: A M2FS pipeline has been developed by Co-I Ji for another program proposed in previous semesters. The pipeline can be easily adapted for this program with modifications on the wavelength coverage and the number of targets. The team has extensive expertise on reduction and analysis to obtain precise velocity measurements using the data collected from this proposal.

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