OBSERVING REQUEST
University of Arizona Observatories

Year: 2015 **Term:** Jan–Jul **Proposal type:** short-term

The Origin of Substructure within Galactic Satellites

P.I.: Edward Olszewski (SO; *edo@as.arizona.edu*; 621-1973)
CoI(s): Matthew Walker (Carnegie Mellon), Mario Mateo (Michigan)

Abstract of Scientific Justification

We have used multi-fiber echelle spectrographs at the MMT and Magellan for years, assembling the largest and best samples of member stars in several dwarf spheroidal galaxies. These samples, and work by others, have shown that each dwarf galaxies has somewhat unique chemo-dynamical proerties, that when better studied, will reveal more about how these galaxies formed and evolved, and more about the underlying dark matter halos. We concentrate here on Carina in the South using Magellan and M2FS (a new pair of fiber spectrographs designed and built by Mario Mateo and Carnegie staff), and Sextans in the North, using the MMT plus Hectochelle. Carina, while photometrically showing obvious signs of episodic star formation (multiple main sequence turnoffs), does not show this on the red giant branch. There must be a range in metallicites and in metallicity-related changes in the radial distribution of such stars, but the real picture has eluded complete understanding, despite previous efforts. M2FS is the best system in the world for this work, and in fact, was designed for such projects. Sextans shows a density enhancement in its innermost regions, significant kinematic differences in the center, and a rapid change of horizontal-branch mix with radius in the innermost regions. Aside from a medium-resolution first study based on a small number of stars, thse features have not been fully characterized or explained, and certainly are not understood in a general context. Hectochelle is perfect for this study. We are also now armed with a substantial better analysis package written by Matthew Walker, whichs takes full advantage of the photons we collect. For the Carina project, Mario Mateo will ask for an equal number of nights through Michigan. Since Olszewski is a "builder" of M2FS, he has signed off on the use of this PI instrument.

Summary of observing runs requested for this project

Run	Telescope	Cage	Instrument	PI	AO	Nights	Moon	Scheduling Optimal	Scheduling Acceptable	Sharing Poss.	Sharing Adv.
1	Mag2	f/9	M2FS	*		3	dark	Jan15-Mar30	Jan-Mar	yes	yes
2	MMT	f/5	Hectochelle			3	dark	Jan-Mar	Jan-Mar	yes	yes

Scheduling constraints and unusable dates *(up to 4 lines)*: both instruments are operated in a queue, so what we need are equivalent hours at the correct LSTs.

no text past this line

A ⋆ appended to the proposal type indicates a continuation proposal; a ⋆ appended to the name of a proposer indicates the proposer is a (graduate) student; a proposer whose name is underlined is certified on the proposed telescope/instrument combination; if a ∗ appears within the PI or AO box in the observations summary table, the instrument is a PI instrument and/or Adaptive Optics are requested – signatures are required on the next page.

Target list (attach list if longer than 26 objects)

#	Object	RA	Dec	mag / color / type / redshift / comment / etc.
1	Carina	06:42	-50:58	to V=21
2	Sextans	10:13	-01:00	to g=21

Approval for Instrument Use from PI: Olszewski

Graduate students *(provide the following information for* ***each*** *student named as PI or CoI on the cover page. Have the advisor's signature(s) appear on* ***all*** *submitted copies)*

Student's Name	Advisor's Name	Advisor's Signature	2nd-yr	Thesis

Scientific Justification

We propose here to use M2FS at Magellan, built expressly for our dwarf galaxy projects, and Hectochelle at the MMT, to attack two issues in studying the dark matter content and evolution of the Carina and Sextans dwarf spheroidal galaxies. Mateo (the PI of this PI instrument, M2FS) and Olszewski and Walker (and Michigan grad student Jeb Bailey and Carnegie staff Steve Shectman, Ian Thompson and Jeff Crane) are considered "builders" of M2FS in the SDSS sense, and run the queue and do all of the observing for our projects, and to date, other projects at Arizona, Michigan, MIT, Carnegie and others.

Highlights of our programs: We have been working on dwarf spheroidal galaxies, ultrafaint dwarfs, and tidal streams for many years. We highlight here some of our major accomplishments.

First, we have acquired the largest spectroscopic samples of stars with the smallest velocity errors per star, in Carina, Draco, Ursa Minor, Fornax, Sextans, Leo I and Leo II. We have used these data ourselves to estimate masses and mass distributions and central dark matter densities and total sizes of the dark matter halos (Walker et al. 2007, ApJ, 667, L53; Mateo et al. 2008, ApJ, 675, 201, Walker & Penarrubia 2011, ApJ,742, 20). In addition, we have made the data publicly available, and they've been downloaded and analyzed directly by nearly 100 different groups of investigators, ranging from dynamical modelers to astro-particle physicists. Two, we have placed robust half light masses on several dwarfs (Walker et al. 2009, AJ, 704, 1274). We have shown that at large distances, the velocity dispersion of Fornax is actually falling, allowing us to set limits on the size of the dark matter halo (Walker et al. 2009, AJ, 704, 1274). We have discovered two ultrafaint dwarfs, Segue 2 and Leo 5 (Belokurov et al. 2008, ApJ, 686L, 83; Belokurov et al. 2009, MNRAS, 397, 1748), and we confirmed Pisces 2 and Segue 3 from deep imaging (Belokurov et al., 2010, ApJ, 712L, 103). We have shown the Segue 2 seems to be embedded in a diffuse larger structure, suggesting that some of the 'ultrafaint' satellites were delivered originally as satellites of larger, less dense dwarfs that were subsequently destroyed by tides. Finally, we have found and confirmed the most distant globular cluster, Crater (Belokurov et al. 2014, MNRAS, 441, 2124; Mateo et al., in preparation).

In addition, we have created an "almost pipeline" data reduction and analysis package. Our Hectochelle Draco results (Walker et al., submitted to MNRAS) will soon become the first published use of this Bayesian analysis suite. At the end of the sci-just we give a summary of the reduction package.

The current proposal:Carina As we and others have shown, several of the dwarf spheroidals (e.g., Fornax, Sculptor, Sextans) have chemo-dynamically distinct stellar populations (Tolstoy et al. 2004, ApJ, 617L, 119, Walker & Penarrubia 2011): in each case a relatively compact, kinematically cold, metal-rich population is embedded within a more diffuse, hotter, metal-poorer population. We have previously used this phenomenology to estimate halflight masses of both populations and thereby to measure the slope of the dark matter density profile (Walker & Penarrubia 2011). Yet despite their utility in such investigations, the origins of these distinct populations remain unclear. Possibilities range from different 'in-situ' star-forming episodes within the same dark matter halo to dry mergers of populations formed in once-distinct subhalos. A first step toward addressing this mystery is to fully characterize the age, metallicity, luminosity and velocity dispersion of each sub-population in each dwarf, thereby allowing comparisons based on macroscopic properties of the dwarfs themselves.

Among the Milky Way's 'classical' dSphs, Carina has always been an oddball. First, while there are hints of a mild metallicity gradient, no obviously chemo-dynamically distinct populations have been detected (Koch et al. 2006, AJ, 131, 895, Walker & Penarrubia 2011). Second, while Carina's multiple main sequence turnoffs clearly indicate episodic star formation, the narrow red giant branch looks more like that of a globular cluster, implying a strong metallicity-age conspiracy (Hurley-Keller, Mateo & Nemec, 1998, AJ, 115, 1840). Yet the origin of this conspiracy remains mysterious, given that Fornax, like Carina, is dominated by intermediate-age stars but still has a red giant branch significantly thickened by its metallicity spread.

Koch et al (2006) used medium-resolution, Ca-triplet observations to derive calcium-triplet metallicities for 437 Carina stars, with ambiguous results. Likewise our older, MMFS (the previous generation fiber system before the new M2FS) data for 1463 stars showed little/no evidence for radial metallicity trends in Carina, but the data (S/N $\sim$3) were optimized for radial velocities instead of metallicities. Carina's clearly episodic star formation implies that it must have distinct stellar populations, and we aim to be the first to detect them spectroscopically.

We can achieve significant radial coverage and observe “all” the red giant candidates in Carina’s vicinity by targeting five 30-arcmin fields (the diameter of the corrected M2FS field). Each field would be observed in three setups to target most of the stars to V=21.5. Based on our previous experience with MMFS and Hectochelle, and our previous experience with Carina, we’ll expose 4x45min, or 3 hours. Overhead is roughly 45 min per field, counting calibrations and plate changes. Fifteen setups are therefore 56 hours, or ten nights (Carina is never up all night). We are only asking for 3 nights from UA and 3 nights from Michigan. We should be able to observe 2000 stars with good weather. We may have to ask for 2-4 more nights in 2015B.

Now armed with our new spectrographs and our new analasis package (see details below), we are in a position to use this large number of spectroscopically-determined [Fe/H] to break the age-metallicity degeneracy and uncover Carina’s evolutionary history.

The current proposal: Sextans At the center of Sextans, visible even in the shallow star counts of Irwin and Hatzidimitriou (1995, MNRAS, 277, 1354), there is a significant bump in stellar density. Furthermore, the horizontal branch morphology changes rapidly near this feature (Harbeck et al. 2000, AJ, 122, 3092). Kleyna et al (2004, MNRAS, 354, L66) show, with velocities measured for only 40 stars, that the central velocity dispersion is close to zero. They hypothesize that a cold star cluster sank to the center of Sextans and dissolved. We have devised a Bayesian mixture model that allows a given data set (for spectroscopically- as well as photometrically-derived quantities) to receive contributions from multiple sub-populations (including any contributed by a dissolved cluster and/or foreground), on the basis of velocity, chemical abundance, color and age. However, in order to be effective this analysis requires a sample of 1000 member stars, about double what we achieved with our original MMFS data (Walker et al. 2009, AJ, 137, 3100). Our MMT sample from last year helps, but was designed to cover a 3$\times$3 degree part of Sextans, not concentrating on the center, and not trying to observe all stars at the center.

In this proposal we want to observe a central pointing of Sextans using Hectochelle, specifically concentrating on the inner 10-armin radius. There are 1179 stars to g=21.5 in the SDSS Sextans catalog in the 1-degree Hecto field. We can observe about 220 stars at a time (we don’t gain much by restricting stars to the inner 10 arcmin radius because of fiber collisions). Five setups at 3.75 hours per setup (3 hours of exposure plus calibrations plus configuration change) is 19 hours. In Feb and March, that becomes 3 nights, and 4 nights in April, when Sextans is available. Since both M2FS (Carina) and Hectochelle (Sextans) are operated in a queue, we need “equivalent hours” and we need “hours without competition from other queue projects.”

Sextans is a notoriously difficult object to observe because of its low density, large field-star contamination, and large area on the sky. This makes it perfect for the large area and multiplexing ability of Hectochelle.

Analysis package: We have recently completed a new, Bayesian framework for analyzing faint stellar spectra. Our first paper, on our Draco Hectochelle observations and our analysis using this package, is currently under review at MNRAS.

Operating on extracted, wavelength-calibrated (but not rebinned) spectra along with associated variance spectra, our new analysis simultaneously estimates velocity as well as stellar-atmospheric parameters (Teff, logg, [Fe/H], [alpha/Fe]) by fitting an entire library of synthetic spectra (computed on the AMBRE grid developed for the Gaia-ESO survey). Our many repeat measurements and comparisons to published estimates indicate that, for a typical spectrum with s/n $\sim$ 5 per pixel, we recover accurate parameter estimates with median precision of 1 km s^{-1} in velocity, 150 K in Teff, 0.4 dex in log(g), and 0.2 dex in [Fe/H] and [alpha/Fe]. Furthermore, we have shown that we recover accurate solar values for twilight-sky spectra as well as for spectra from stars in common with normal high-resolution abundance determinations. Our estimation of gravity also gives new information to diagnose foreground contamination, and even allows us to derive crude distances to stars. Figures 1 and 2 show the power of this package, as seen in MMT Hectochelle spectra of Draco.

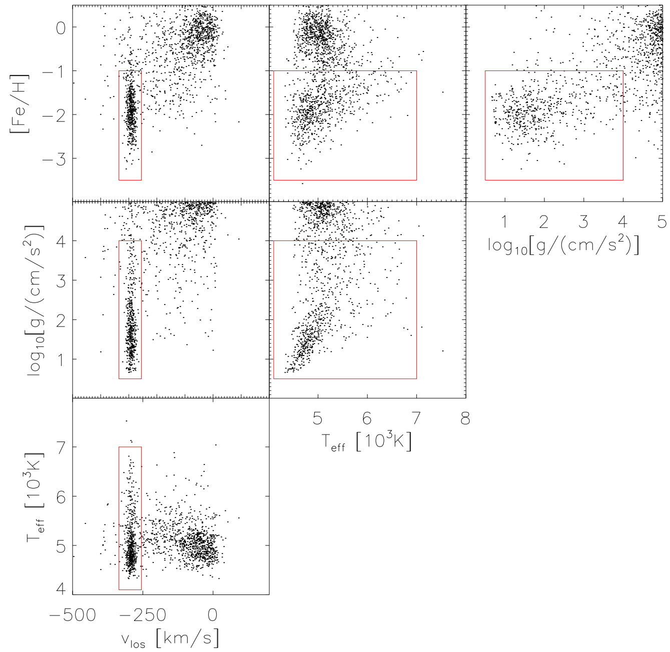

Figure 1: Relations among physical parameters for the 1478 unique stars (members and nonmembers) in our Hectochelle sample for Draco. Red boxes are drawn, by eye, to enclose likely Draco members with $V_{los} \sim -290$ km s^{-1}, and relatively low log(g) and [Fe/H]; 451 stars have parameter estimates that lie inside all the boxes.

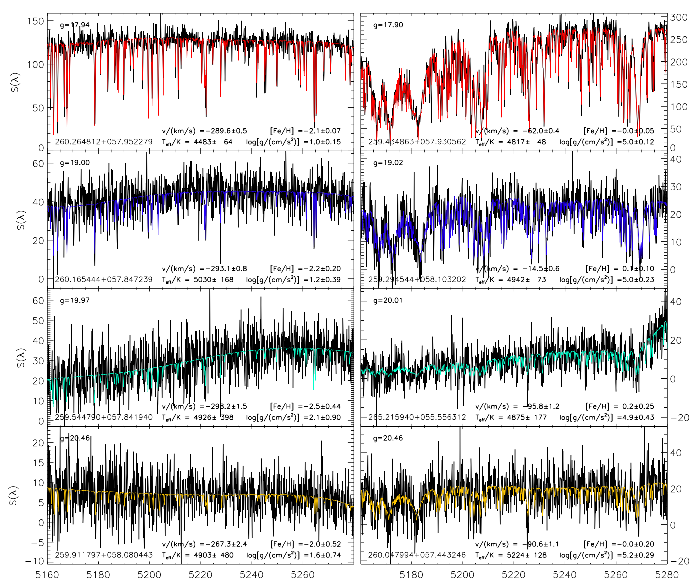

Figure 2: Sky-subtracted Hectochelle spectra (black) for probable members of Draco (left) and probable foreground stars (right) spanning magnitudes $18 leg \leq 20.5$. Overplotted with colored curves are best-fitting model spectra. Text in the figures lists, among others, derived velocity, temperature, gravity, and abundance.

Experimental Design & Technical Description *Describe your overall observational program. How will these observations contribute toward the accomplishment of the goals outlined in the science justification? If you've requested long-term status, justify why this is necessary for successful completion of the science.* ***(up to one page)***

Based on years of experience with MMFS on Clay, and Hectochelle on MMT, and now M2FS on Clay, to get good velocities and abundances to V=20-21 one needs 4×45 min per field. As we discussed in the scientific justification, our Carina project is asking for 3 nights from Steward and 3 nights from Michigan.

We will be working at the $\lambda5180$ Mg triplet echelle order in order to get the best abundances and velocities for these red giants. This requires dark time, especially for Sextans, for which the Moon can get close and/or occult. For stars fainter than 20th mag, dark time is extremely important for both objects. Each half magnitude is important because the number of stars per half-mag bin keeps increasing substantially.

It needs to be said that over the past few years, Michigan has given substantially more than half the time to our joint projects, while in the north, the UA MMT time has equalized things.

It also needs to be said, as we did at the top of the proposal, that MMFS is a PI instrument with seven of us as "builders" (in the SDSS sense). Members of this group designed and built the instrument, commissioned the instrument, provide plate-drilling software, are present at all observing runs (taking data mostly for other people), and are designing reduction software (and consulting with other observers on the same).

The observing program described here is part of our decade-long work with the MMT and Magellan, although it is a stand-alone continuation from where the original pioneering work led us. If we have a full allocation and clear weather, this particular project wil be complete, with of course the caveat that it may lead to new observing projects.

Summary of Time Requested and Awarded *The TAC needs to understand the scope of this project — (1) tell us how many UAO nights you've already had for this project, how many you request this time, and (a good guess of) how many you need to complete the project; (2) if a substantial amount of observing for this project comes from non-UAO telescopes, tell us about that observing, and how the UAO part fits in; (3) if you are collaborating with people who have telescopes, especially if you are part of a large collaboration, tell us who is leading the project, and how UAO time and your participation fit in. (**up to one page**)*

Michigan will submit a proposal for 3 nights of Magellan time (ie, to combine with the 3 we are requesting).

Mateo and Olszewski have collaborated since the late 1980s, and over the past decade the ratio of Michigan Magellan time at Magellan is larger than that of Steward time. Mateo built the Magellan instrument we will use, and all of us support it. Walker has collaborated with us for a decade, and while he was at CFA was able to contribute substantial MMT time. Walker's startup package at Carnegie-Mellon included $100k to purchase an echellete grating for M2FS, which we will commission in late 2014 or early 2015. This is a true collaboration, with each of us equally contributing observing work and reduction/analysis work.

Previous Use of Steward Facilities *List **all** allocations of telescope time for the present project and allocations for other projects on facilities available through UAO during the past 2 years, together with the current status of the data (cite publications where appropriate). Mark those allocations related to the present proposal (i.e, precede text with* `\related` *command). **(up to one page)***

Since Fall 2012 we have had the following time:

Hectochelle: Fall 2012 (SAO time only)- about 50% successful Feb 2013 (2 UA nights and several SAO bright nights)- about 75% successful May 2013- 3 SAO bright nights. Oct 2013- 2 Steward nights and 1 SAO night. Spring 2014- 5 Steward nights, approx 2/3rds clear, data reduced.

Blue Channel: 3 nights in Fall 2012 completely weathered out. 3 nights in Jan 2014 for spectra of nearby dIrr galaxies. One clear night, excellent data reduced and analyzed. Paper about to be submitted. Fall 2014 time has not yet occurred.

Magellan M2FS: Fall 2013- 3 Michigan nights in total dedicated to Mateo/Olszewski science, Nov 2013, Feb 2014, Sept 2014.

Recent publications, since 2010, based on UAO time and UM/SAO time:

1) Belokurov et al, 2013, "Precession of the Sagittarius Stream," arXiv1301.7069- precursor paper to MMT observations of Oct 2013.

2) Sand et al, 2012 "Tidal Signatures in the Faintest Milky Way Satellites: The Detailed Properties of Leo V, Pisces II and Canes Venatici II", ApJ, 756, 79. From older LBT data.

3) Mateo et al "Spectroscopy of the Crater Globular," about to be submitted based on M2FS data. From M2FS data.

4) Walker et al, "Bayesian analysis of resolved stellar spectra: application to MMT/Hectochelle Observation of the Draco Dwarf Spheroidal," responding to referee, will post on astro-ph once accepted. From MMT Hectochelle data.

5) James et al, "Uncovering Blue Diffuse Dwarf Galaxies," submitted to MNRAS. From Blue Channel time.

LaTeX 2$_\varepsilon$ UAO Observing Proposal class, 'soprop.cls' v1.3 (2007 Aug 01 [RAJ]).