OBSERVING REQUEST
University of Arizona Observatories

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

Dwarf Satellite Populations around Milky Way-like Galaxies: Luminosity Functions and Star Formation

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Abstract of Scientific Justification

We propose to continue our survey for dwarf satellites around Milky Way-like galaxies, with refined selection methods allowing us to cover 15 fields, 3x the existing sample, to measure the variance among satellite populations of MW-analogs. Satellite populations are key to understanding the early stages of galaxy formation and the assembly of the stellar halo. However, the luminosity function of the MW satellites and their properties do not agree with model predictions. Models based on N-body simulations predict $\sim 3\times$ more satellites brighter than the Fornax dwarf galaxy (8 mags fainter than the MW) than observed, a discrepancy that has received much attention as the "missing satellites problem." Model predictions for satellite velocity dispersions also disagree with the data. No other MW-like systems currently have studies of satellite properties down to $\Delta m = 8$, except M31, which is $\sim 2\times$ as massive as the MW and may have a different evolutionary history. We are measuring the LF and properties of satellites down to the scale of the Fornax dwarf around MW-analog disk galaxies, using wide-field spectroscopy to find satellites among the much more numerous background galaxies. In 2013-14 we have used Hectospec to take ~ 5000 spectra in the fields of 3 MW-analog disk galaxies. We found several faint satellites and developed cuts to reduce the stellar and distant galaxy backgrounds. So far, we find 1 galaxy with 8 satellites (2x more than the MW) and with different properties (more star formation); and 2 galaxies with only 1-2 satellites. We are now following up confirmed satellites to measure their velocity dispersions and the satellite mass function. With refined selection we can now survey each galaxy field in 1 or 2 configurations. We propose to cover 15 MW-analogs in the spring SDSS area in 3 nights on Hectospec.

Summary of observing runs requested for this project

								Scheduling		Sharing	
Run	Telescope	Cage	Instrument	PI	AO	Nights	Moon	Optimal	Acceptable	Poss.	Adv.
1	MMT	f/5	Hectospec			3	dark	Apr–May	Mar–Jun	yes	yes

Scheduling constraints and unusable dates *(up to 4 lines)*: None

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	NSA 33446	08:12:57.84	+36:15:16.56	$M_r = -20.5$, D=37.7 Mpc
2	NSA 135440	08:42:39.84	+14:17:08.16	$M_r = -20.5$, D=32.8 Mpc
3	NSA 16235	09:17:39.84	+52:59:34.80	$M_r = -19.8$, D=36.2 Mpc
4	NSA 32	09:42:03.36	+00:20:11.23	$M_r = -20.5$, D=30.0 Mpc
5	NSA 16559	10:19:33.12	+58:12:20.88	$M_r = -20.3$, D=34.5 Mpc
6	NSA 159593	11:18:21.36	+45:44:53.52	$M_r = -20.3$, D=36.1 Mpc
7	NSA 101649	11:28:00.72	+29:30:39.96	$M_r = -20.1$, D=36.9 Mpc
8	NSA 140458	11:55:57.36	+06:44:57.37	$M_r = -20.7$, D=36.0 Mpc
9	NSA 161174	12:11:10.08	+20:10:32.52	$M_r = -19.8$, D=36.3 Mpc
10	NSA 141465	12:28:50.64	-01:56:21.05	$M_r = -20.6$, D=35.4 Mpc
11	NSA 142722	12:59:27.12	+14:10:16.32	$M_r = -20.9$, D=30.0 Mpc
12	NSA 163136	13:11:36.96	+22:54:55.80	$M_r = -20.6$, D=37.6 Mpc
13	NSA 94340	13:53:17.76	+33:29:27.24	$M_r = -20.0$, D=34.7 Mpc
14	NSA 94217	13:56:55.92	+29:09:51.84	$M_r = -20.6$, D=34.6 Mpc
15	NSA 145879	15:09:49.44	+00:28:12.31	$M_r = -20.3$, D=30.2 Mpc

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Approval for Instrument Use from PI: ______________________________

(have instrument PI signature appear on, or attach PI e-mail to, ***all*** *copies)*

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

Our home galaxy, the Milky Way, is in many respects the most well-studied galaxy in the Universe. From a cosmological and galaxy formation perspective, one of the most informative components of the Milky Way is its population of over two dozen dwarf galaxy satellites. These include the Magellanic Clouds, the classical dwarf spheroidals, and the recently discovered ultra-faint dwarfs. A wide variety of precise measurements of the mass distribution and ages exist for the Milky Way satellites that are not possible in more distant systems (e.g., Walker et al. 2007, Simon & Geha 2007, Brown et al. 2012). These satellites and their old stellar populations are a probe of galaxy and star formation at early times in low mass objects, and they are the key to understanding the formation of the Milky Way's stellar halo, which contains many stellar streams and kinematic remnants likely from disrupted dwarfs.

However, the Milky Way satellite population constitutes a small, and perhaps biased, sample from which it is difficult to extrapolate generic properties. For example, do host galaxies with similar luminosity, morphology, and mass as the Milky Way harbor a similar population of satellites? Applying our detailed knowledge of the Milky Way satellites to broader questions of galaxy formation and dark matter properties requires an improved understanding of satellite populations in the context of cosmology/structure-formation models.

Several studies have considered the question of how typical is the Milky Way (MW) in terms of its bright satellite population, by studying the faintest detectable satellite galaxies around MW-analogs in the Sloan Digital Sky Survey (spectra to $r < 17.7$). The SDSS can spectroscopically detect satellites similar to the Magellanic Clouds, which are 2 and 4 magnitudes fainter than the MW itself ($\Delta m = 2 - 4$) . These studies find that our Galaxy is unusual, but not yet uncomfortably so. MW-analogs on average have only ~ 0.3 satellites with $\Delta m < 4$, vs two for the Milky Way. The average result is also remarkably consistent with simulations (Tollerud et al. 2011, Busha et al. 2011, Liu et al. 2010).

The next two most luminous satellites around the Milky Way are the disrupting Sagittarius dSph ($\Delta m = 6$) and the Fornax dSph ($\Delta m = 8$). Under the assumption that luminosity correlates positively with mass, theoretical models predict a MW-mass galaxy should host more than 14 satellites down to this luminosity limit, yet the MW has only 4 (Fig. 2). Furthermore, models that match satellites to subhalos in rank order (most luminous dwarf is in most massive subhalo, and so on) predict these galaxies should have maximum circular velocity $v_{\rm max} \sim 40 - 50$ km s^{-1} (e.g., Busha et al. 2010). This is a factor of two larger than the strongly constrained $v_{\rm max} \sim 20$ km s^{-1} for Fornax (Strigari et al. 2010). So the existing satellites are not just too rare, but too low mass to live in the expected halos. If we instead simply count the number of simulated objects more massive than $v_{\rm max} = 20$ km s^{-1}, theory predicts 25 to 75 satellites more massive than Fornax (Springel et al. 2008; Diemand et al. 2008), whereas we observe only 3 such objects. The discrepancies exist at these below-SMC subhalo masses, i.e., the classical dwarf spheroidals, and cannot be resolved with more discoveries of ultra-faint dwarfs at lower masses.

Thus the Milky Way has more LMC/SMC-like satellites than normally observed in similar galaxies, gaps in luminosity between the satellites at the bright end of the luminosity function, and far fewer dwarf satellites than expected. M31 has a similar shortfall in the number counts, though not a luminosity gap. There are several proposed solutions to this now refined version of the "missing satellites" problem (e.g., Boylan-Kolchin et al. 2012; Brooks & Zolotov 2012). The Milky Way satellite population may not be representative of a typical MW-mass galaxy. Alternatively, there may be a severe inefficiency or stochasticity in galaxy formation which begins below the scale of the Magellanic Clouds, which upsets rank order and allows many massive halos to remain dark. Or the effect of baryonic physics due to star formation feedback could cause puff-up, subsequently tidal stripping, and thus decrease the masses of dwarf satellites. More extremely, the underlying dark matter halo population could be modified due to non-standard cosmologies such as Warm Dark Matter that would decrease the number of satellites at these mass scales.

Matching the MW satellite luminosity function in ΛCDM is possible, but requires that the dwarfs live in halos 5x more massive than observed. Further, different simulations disagree on how much supernova feedback can reduce dwarf masses. The discrepancy sets in for subhalos with $M_h \sim 10^{10}\ M_\odot$ and $V_c \sim 50$ km/s, larger than expected to have severe feedback effects on mass or SF (Boylan-Kolchin et al. 2011).

All of the work on this subject has assumed that the MW and M31 are entirely typical. Dwarfs fainter than the SMC are essentially unprobed around field galaxies; there is a 3 magnitude gap between the SMC and Fornax, and it's not at all clear if we will find this or something entirely different in other galaxies. A first analysis using SDSS data alone (Strigari & Wechsler 2012) has shown that the Milky Way is consistent with having a typical number of satellites down to Fornax, but the error bars from this study are much too large to be conclusive in this magnitude range. A theoretical analysis (Purcell & Zentner 2012) has shown that scatter could resolve the MW-SDSS discrepancy. To progress and determine whether or not these are viable solutions requires measuring the luminosity, properties, and mass functions of a statistically significant number of satellites around MW-analog systems. It's critical to determine whether the MW and M31 satellites are typical before building our models of galaxy formation to fit them.

We have previously proposed to measure the luminosity function of five Milky Way-analog systems to the scale of the Fornax dSph using the MMT/Hectospec. Here we propose to use improved target selection derived from our previous data to be 10x more efficient, covering 15 host galaxies with 1-2 fiber configurations per host. Hectospec can measure redshifts down to $r = 21$ in 1 hour, 3.3 mag fainter than SDSS, and below the luminosity of Fornax ($M_r = -13$) for the hosts in our sample at $\sim 35\,\mathrm{Mpc}$.

Identifying true satellites requires a large investment of spectroscopic time over a wide field. Photometric redshifts at these distances are insufficiently accurate or reliable to distinguish satellites from background galaxies. In our 2013A program we did a complete survey to avoid biases in the satellite distribution. We accepted a high fraction of stars and background galaxies to do an unbiased census of satellites and test the reliability of star/galaxy separation and color cuts. This was 2/3 completed, and in 2014A we completed the survey with more efficient selection against stars and high-z galaxies. We obtained ~ 3200 spectra to $r = 21$ inside the virial radius, and found 8 true satellites (Figure 1), down to fainter than Fornax and very different (younger, star-forming) from the close-in Milky Way classical dwarfs.

The Hectospec spectra yield velocities for association with hosts, and measurements of absorption/emission properties, which we can study as a function of radius from the central galaxy. In the MW the dwarfs inside R_{vir} are all gas-poor and fairly old, except the Magellanic Clouds, while in NGC 6181 all 8 of the dwarfs are star forming, one also with Balmer absorption (youngish, A stars). We have obtained Keck long-slit spectroscopy (via co-I Geha and Tollerud's institutional access) to measure masses of the satellite galaxies. The velocity dispersions of faint dwarfs are often below 10-20 km/s, so moderately high resolution, high throughput single object spectroscopy is the only way to measure them. This is prohibitively expensive without Hectospec to winnow the sample down to a small number of confirmed satellites.

If our hosts have satellite luminosity functions similar to the MW, we expect ~ 4 satellites brighter than $\Delta m = 8$ (Fornax) within their virial extents (200-300 kpc), with a large spread in luminosity. For satellite LFs closer to those from simulations, we would find tens of satellites per field (unlikely). With a total of 20 parent systems, we will quantify the mean and variance in dwarf satellite numbers for the first time, and show whether the MW satellite LF is typical vs. satellite systems outside the Local Group. We will also observe whether the radial division between non-starforming dwarf spheroidals and starforming dwarf irregulars is normal or atypical. We will use the spectroscopically detected dwarfs and background to train better photometric redshifts for studies with SDSS imaging around a larger set of MW-analogs, and to develop better color cuts for future spectroscopic surveys. Followup observations of velocity dispersions for detected dwarfs will establish their luminosity-mass relations. These test the matching of subhalo masses against dwarf luminosities, and the proposed solutions of inefficiency/stochasticity in star formation, versus supernova-driven feedback causing virial mass reduction in dwarfs.

Boylan-Kolchin, M. et al. 2011, MNRAS, 415, L40
Boylan-Kolchin, M. et al. 2012, MNRAS, 422, 1203
Brooks, A. & Zolotov, A. 2012, arXiv:1207.2468
Brown, T. et al., 2012, ApJ, 753, 21
Busha, M. et al. 2011, ApJ, 743, 117
Busha, M. et al. 2010, ApJ, 710, 408
Diemand, J. et al. 2008, Nature, 454, 735
Liu, L. et al. 2010, ApJ, 733, 62
Purcell, C. & Zentner, A., 2012, JCAP, 12, 007
Simon, J. D. & Geha, M., 2007, ApJ, 670, 313
Springel, V. et al. 2008, MNRAS, 391, 1685
Strigari, L. et al. 2008, Nature, 454, 1096
Strigari, L. & Wechsler, R. H. 2012, ApJ, 749, 75
Tollerud, E. et al. 2011, ApJ, 738, 102
Walker, M. et al. 2007, ApJ, 667, 53

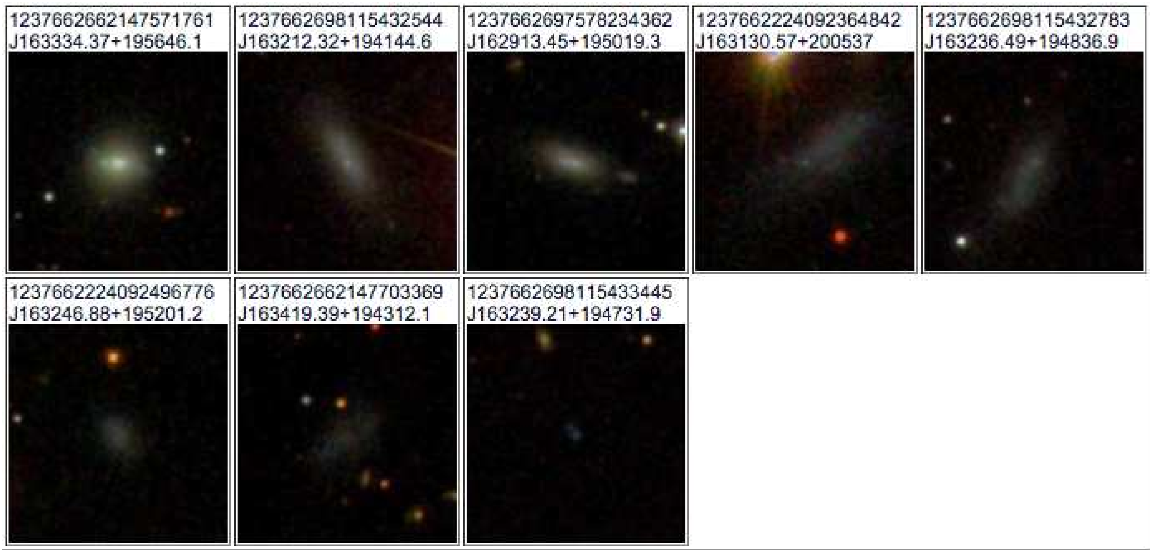

Figure 1: SDSS color images of the eight faint satellites of NGC 6181 from our 2013A-14A Hectospec program. These galaxies have $M_r = -17.1$ to -12.1, ranging in brightness from SMC-like to fainter than Fornax, and are at projected distances 46 to 270 kpc from the host. The number of these satellites is similar to the MW or M31, but apart from the SMC analog, the satellites are very different looking from the classical MW inner-halo dwarf satellites; all of the 8 have some star formation even though inside R_{vir}. The sixth object is about the magnitude and radius of Fornax but has weak star formation.

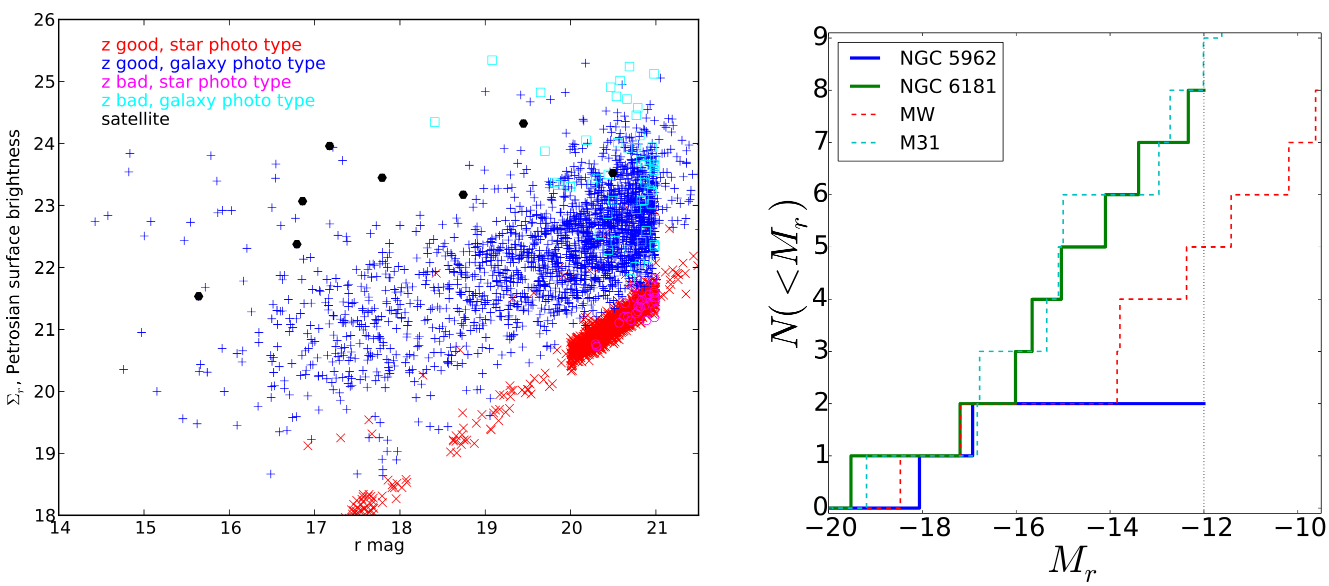

Figure 2: *Left:* Magnitude vs. surface brightness for our survey in the NGC 6181 field. Black circles are confirmed satellites at z=0.008, blue crosses are background galaxies, and cyan squares are redshift failures. The satellites (and all other low-z galaxies we find) are at fainter surface brightness than most galaxies, because they are intrinsically faint and there is a known luminosity-SB relation. Using SB plus color selection allows us to be $\sim 10\times$ more efficient in target selection. *Right:* Luminosity functions for NGC 6181 and NGC 5962 from our surveys. NGC 6181 (green solid line) has as many satellites as M31, but NGC 5962 (blue solid line) has only two satellites from SDSS (with two dubious redshifts from MMT not yet confirmed), illustrating the large variance in satellite populations.

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)***

Milky Way-Analog Sample: Our goal is to find faint satellites around galaxies of similar mass to the Milky Way, whose populations have not been substantially affected by environment or interactions. We selected a sample of host galaxies from the SDSS: isolated primary disk galaxies, which have no neighbor with a luminosity $\geq$ the MW within 0.4 Mpc. We use a magnitude for the MW of $M_r = -20.4$ and consider primaries within ± 0.5 magnitudes of this value. These primaries are selected to be sufficiently nearby that we can observe satellites 1 mag fainter than the Fornax dSph ($M_r = -13$), but have a physical virial radius (250 kpc) within a field-of-view about $1°$.

In 2013A we targeted one host, NGC 6181, selecting down to $r = 21$, or $\Delta m \sim 8$, with no pre-selection on color, and using SDSS star/galaxy separation only to $r < 20$ where it was known to be good, yielding ~ 4100 targets. We accepted a large contamination to insure completeness. We found all unresolved objects were stars or (a few) quasars. This program was 60% completed, and finished in 2014A with improved target selection (gri color cuts, and removing stars). We found 8 confirmed satellites (Figure 1); only two had pre-existing SDSS redshifts. In 2014A we also surveyed two other hosts: one had no satellites and one had two possibles, which we are following up to get higher S/N spectra.

Figure 2 shows that surface brightness is a powerful discriminator between low-z faint and higher-z bright galaxies. We have investigated color and surface brightness cuts using a sample of more than 10,000 spectroscopic redshifts down to $r = 21$. Using a sample of $> 10,000$ spectroscopic redshifts down to $r = 21$ from our data plus redshifts from the SDSS and GAMA surveys, we derive combined cuts in $g - r$, $r-$WISE $W1$, $u - g$ vs $r - i$, and surface brightness vs. r mag, taking photometric errors and non-detections into account. These reduce the number of targets by a factor of $\sim 7 - 10$, yielding $\sim 80 - 200$ high probability targets per host. *All* known galaxies with $z < 0.02$ and $17 < r < 20.5$ meet these color cuts; all but two meet the surface brightness cuts (and these are not satellite galaxies). With these cuts we can complete a field in 1 or 2 Hectospec configurations, vs. the 13 configurations we used on the first system.

Strong pre-selection beyond these simple color cuts, e.g, with photometric redshifts, is largely inaccurate at present at these very low redshifts. The SDSS $ugriz$ color-space occupied by dwarf galaxies out to 50 Mpc is degenerate with galaxies at moderately higher redshifts. With more satellites, we will use machine learning classification techniques, combining colors with other parameters (e.g. surface brightness and radial profile) to statistically distinguish satellites from background. However, we still need larger samples of confirmed satellites to train the classification. These will improve photometric training sets and refine our selection for future surveys to observe a large sample of MW hosts.

Most fields can be covered to $r < 21$ at $\sim 90\%$ completeness in 1 configuration and some require 2 due to field diameter and fiber collisions. Our goal is to survey 15 fields to bring the number of hosts with spectroscopic coverage up to ~ 20. We will measure the mean number of satellites per host to $M_r = -12$, the variance among hosts, and the satellite properties (star formation, spectral indices).

Time Required: From our 2013A Hectospec observations, with 1 hour exposure time per configuration, we had a 95% redshift success rate for blue and red objects to r=21 AB. At D=35 Mpc the 1.5" diameter Hectospec fiber subtends 250 pc, a good match to the diameters of faint dwarfs. In 2013A-14A we finished 3 galaxies and in 2014B we are surveying 2 more, one in Stripe 82 with deeper imaging (these data have not yet been taken). We use a total exposure time of 1 hour, plus 0.33 hours for fiber setup and overhead per configuration. We request 24 hours total, or 3 nights. Dark time is necessary for these faint objects.

The accuracy of redshifts from Hectospec is typically 30 km/s (based on galaxies with repeated observations in our previous data), sufficient for an unambiguous association of satellites with the central galaxy. We are following up the confirmed satellites with Keck/DEIMOS and ESI spectroscopy (via our Yale co-PIs) to measure their velocity dispersions and stellar population parameters from absorption line indices.

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**)*

This is the fourth UAO proposal for this project. The first proposal in 2013A obtained 2/3 of its data on NGC 6181, found several satellites, and has allowed us to make the selection much more efficient. In 2014A we completed NGC 6181 and added two more MW-analog galaxies, and found that NGC 6181 has many satellites but the other two have few. In 2014B we will complete a fourth galaxy to a fainter satellite magnitude limit using deeper imaging from Stripe 82, and will test our probabilistic color-surface brightness selection on a fifth galaxy – these data have not yet been taken. This proposal will quadruple the number of galaxies by more efficient selection of satellite candidates, to measure the variance among systems.

The overall project goal is to determine the 'intrinsic' distribution of satellites around a Milky Way (MW) mass dark matter halo, of which the MW itself is a single realization. Our aim is to detect faint satellites around several Milky-Way analogs, developing selection techniques that will allow us to eventually measure the luminosity function photometrically for 100 Milky Way-analogs and satellite velocity functions with spectroscopic followup for a subset (~ 10) of these systems. The complete spectroscopic sample provided by this first stage of the project will allow us to more effectively preselect possible dwarf satellites for followup around further sets of hosts, with either Hectospec or other facilities, reducing the time required for identifying a complete satellite sample. We will compare these results to a complementary suite of numerical simulations being run specifically for this project. This proposal is part of an ongoing collaboration between PI Weiner, and Co-Is Geha, Tollerud and Wechsler. In order to carry this program through we need: imaging from SDSS; wide-field low-resolution spectroscopy for satellite identification (the present proposal); and followup high resolution, high throughput single object spectroscopy (Keck/ESI, PI Geha, Tollerud). We are also supplementing these observations with WIYN/Hydra fiber spectroscopy at brighter magnitudes (Hydra has lower efficiency and only 72 fibers). Wechsler provides important theoretical expertise on the relation and matching of luminosity to dark matter mass, and is pursuing a parallel simulation program of MW analogs.

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**)*

⋆ PI Weiner was allocated 3 nights of Hectospec time in May-June 2013 for the first proposal of this project, targeting the NGC 6181 field. This program was 60% completed due to weather. The data have been reduced and redshifts measured (Figure 1). We found a handful of satellites, which are being followed up at Keck, and have used the catalog to refine the target selection for this proposal to increase efficiency. A paper on the survey and the confirmed satellites is in draft.

⋆ PI Weiner was allocated 3 nights of Hectospec time in May-June 2014 for this project, finishing the NGC 6181 field and targeting two more MW-analog galaxies with improved target selection for 3x greater efficiency. These data are reduced; we found a total of 8 dwarf satellites in NGC 6181, but the other hosts have respectively 0 dwarfs, and 2 possible dwarfs with poor spectra that we are trying to confirm with Keck/DEIMOS.

⋆ PI Weiner was allocated 3 nights of Hectospec time in Sep-Nov 2014 for this project, targeting a host galaxy in the deeper SDSS Stripe 82 imaging to a greater spectroscopic depth with a complete sample, and testing the improved color-surface brightness satellite selection in another host. These data have not yet been taken.

PI Weiner was allocated 2 night of MMT/Blue Channel time in June 2011 and Feb 2012 for long-slit spectroscopy of IR-luminous galaxies with Herschel PACS far-IR spectroscopy. The data have been reduced and we are finding correlations between optical emission extent and far-IR line strength.

PI Weiner was allocated 1.5 nights of Magellan/IMACS time in December 2010 for redshift surveys in the UKIDSS/UDS and COSMOS/Ultravista fields that are receiving deep imaging in the CANDELS HST survey, sharing slit masks with J. Rhoads (ASU). These spectra were taken in good conditions and have been fully reduced and redshifts identified by M. Cooper. The team has published a paper from this data reporting the discovery of a $z = 6.9$ Lyman-alpha emitting galaxy (J. Rhoads et al. 2012, ApJ, 752, L28). The redshift catalog is being published together with a CANDELS photometric catalog in the field (P. Santini et al, submitted).