OBSERVING REQUEST
University of Arizona Observatories

Year: 2015 **Term:** Jul–Dec **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 6 host galaxy fields. We are finding large halo-to-halo variance in the satellite populations of MW-analogs. Dwarf satellite populations are key to understanding the early stages of galaxy formation and the assembly of the stellar halo. However, models based on N-body simulations predict $\sim 3\times$ more satellites than observed, brighter than the Fornax dwarf galaxy (8 mags fainter than the MW), a well-known discrepancy called 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 2013-15A we have used Hectospec to take ~ 5000 spectra in the fields of 7 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 vs. the MW – more star formation, with a radial dependence of SF quenching; and 5 galaxies with only 1–3 satellites. We are following up confirmed satellites with Keck to measure their velocity dispersions and the satellite mass function. With refined selection against background, we can now survey each galaxy field in 2 configurations. We propose to cover 6 MW-analogs in the fall SDSS area in 2 nights on Hectospec.

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	MMT	f/5	Hectospec			2	dark	Sep–Nov	Sep–Dec	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 126115	00:03:58.99	+20:45:08.64	$M_r = -20.00$, D=32.5 Mpc
2	NSA 129237	01:21:47.76	+17:35:31.92	$M_r = -19.26$, D=38.6 Mpc
3	NSA 129387	01:24:03.91	+12:55:03.00	$M_r = -20.33$, D=37.3 Mpc
4	NSA 150307	22:55:41.76	-05:29:43.44	$M_r = -20.20$, D=39.4 Mpc
5	NSA 150340	22:57:19.44	-01:02:56.40	$M_r = -21.38$, D=40.0 Mpc
6	NSA 150578	23:04:56.64	+12:19:22.44	$M_r = -21.06$, D=33.3 Mpc

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

Background: The Milky Way is the most well-studied galaxy, and its two dozen dwarf galaxy satellites are a view into the process of galaxy and halo formation. 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 a 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. 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.

Studies of the typicality of the MW bright satellites using the SDSS find that our Galaxy is unusual, but not yet uncomfortably so. The faintest detectable satellite galaxies around MW-analogs in SDSS (spectra to $r < 17.7$) are similar to the Magellanic Clouds ($\Delta m = 2 - 4$). In SDSS, 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 ($\Delta m = 8$). Models predict a MW-mass galaxy should host > 14 satellites down to this luminosity limit, yet the MW has only 4 (Figure 2b). Models that match satellites to subhalos in rank order (most luminous dwarf in most massive subhalo, and so on) predict maximum circular velocities $v_{\rm max} \sim 40 - 50$ km s^{-1} (e.g., Busha et al. 2010). This is 2$\times$ larger than the $v_{\rm max} \sim 20$ 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 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), but 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 by finding more ultra-faint dwarfs at lower masses.

Possible Solutions: 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 LF, 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. Or, there may be a severe inefficiency or stochasticity in galaxy formation that 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, and 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 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).

Is the MW Typical? 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.

Our Survey: We have previously proposed to measure the luminosity function of several 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 6 host galaxies with 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 ~ 35 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.

Results: In our 2013A program we did a complete survey around NGC 6181 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 NGC 6181 field 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 1a), down to fainter than Fornax and very different (younger, star-forming) from the close-in Milky Way classical dwarfs. We also find that the satellites' offset from the mass-metallicity relation depends on distance from the parent, evidence that throttling of gas infall and star formation is an ongoing process (Figure 1b). This contrasts with the MW satellites, where simulations and observations imply that quenching happened quickly and long ago (Brooks & Zolotov 2012; Wetzel et al 2015).

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 are obtaining Keck long-slit spectroscopy (via co-Is 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). So far we find a range from 1 – 8 per host. We are working towards a total of 20 parent systems, to 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
Wetzel, A. et al. 2015, arXiv:1503.06799

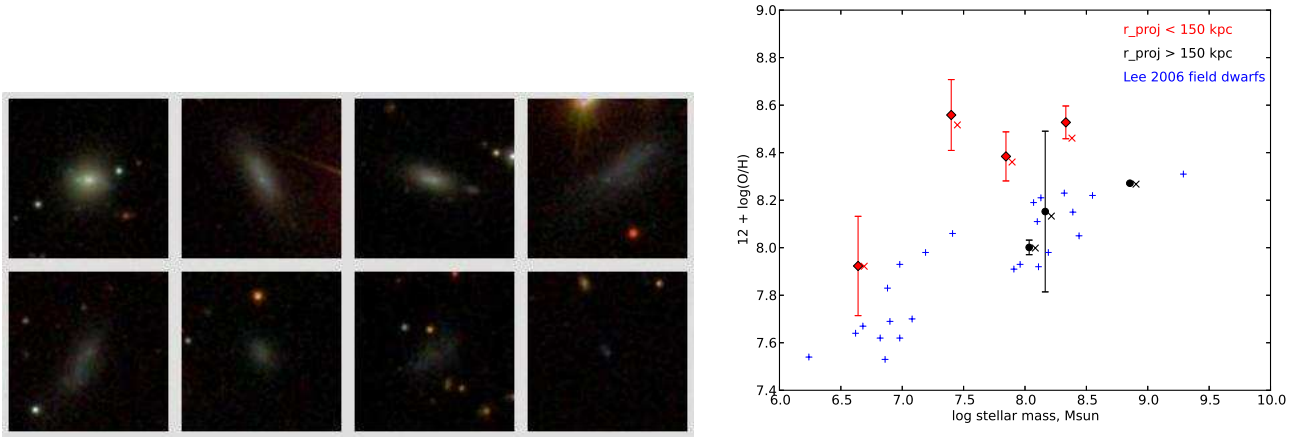

Figure 1: *Left:* SDSS color images of the eight faint satellites of NGC 6181 from our 2013A-15A Hectospec program. These galaxies have $M_r = -17$ to -12, from SMC-like to fainter than Fornax, and are at projected distances 46 to 270 kpc from the host. The number is similar to the MW or M31, but apart from the SMC analog, they are very different looking from the classical MW inner-halo dwarfs; these 8 all 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. *Right:* Mass-metallicity relation for the dwarf satellites from our spectra of [N II]/Hα. Satellites a, d, and f at large radius (black circles) are on the field dwarf mass-metallicity relation (Lee et al 2006, blue crosses), while satellites b, e, and g at small radius (red diamonds) are offset, with weaker Hα and higher metallicity, probably due to throttling of gas accretion. This shows that quenching depends on galactocentric radius, but is not quickly effective on all dwarfs inside R_{vir}.

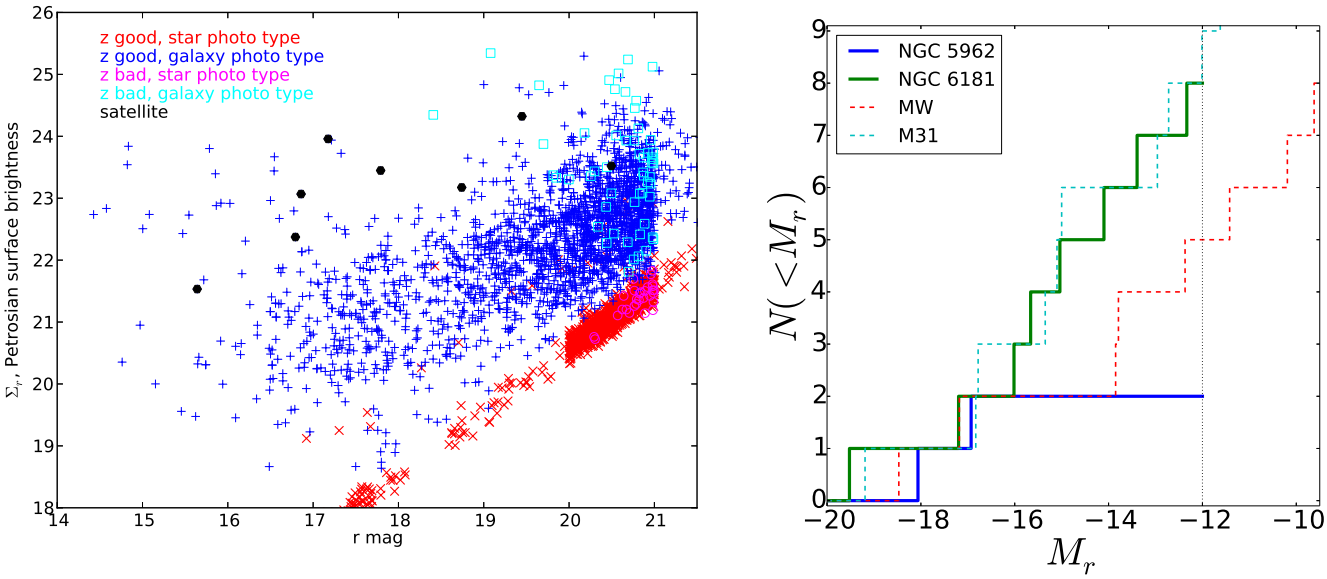

Figure 2: *Left:* Magnitude vs. surface brightness for our survey in the NGC 6181 field. Black circles are confirmed satellites at z=0.008, blue crosses are background galaxies, and cyan squares are redshift failures. The satellites (and all other low-z galaxies we find) are at fainter surface brightness than background galaxies. 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 1a); 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. In 2014B we completed two more hosts with somewhat worse weather.

Figure 2a 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 $> 10,000$ 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 ~ 7, yielding $\sim 200 - 300$ 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 satellites). With these cuts we can complete a field in 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 2 configurations; some require 3 due to field diameter and fiber collisions. Our goal is to survey 6 fields this semester, to bring the number of hosts with spectroscopic coverage up to ~ 14, with the goal of eventually reaching 20 hosts. 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-2014A Hectospec observations, with 1 hour exposure time per configuration, we had a 92% 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-14B we finished 5 galaxies and in 2015A we are surveying 3 more (these data are partially completed). We use a total exposure time of 1 hour, plus 0.33 hours for fiber setup and overhead per configuration. We request 18 hours total, or 2 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 fifth 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. We have a paper in near-final draft on the NGC 6181 survey. In 2014B we completed two more galaxies, attempting to reach lower surface brightnesses but reaching the limits of reliability of SDSS photometry. This proposal will $\sim$ double 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 ($\sim$ 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, PIs 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 1,2). 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, and testing the improved color-surface brightness satellite selection in another host. These data were about half completed due to weather and have been reduced and inspected for redshifts.

⋆ PI Weiner was allocated 3 nights of Hectospec time in 2015A for this project, finishing up some incomplete spectra in two hosts and completing 3 more hosts with improved selection. These data are partially taken through the Hectospec queue.

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 has been published together with a CANDELS photometric catalog in the field (P. Santini et al, 2015, ApJ, 801, 97).