OBSERVING REQUEST
University of Arizona Observatories

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

Uncovering a New Population of Chemically-Pristine Galaxies

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Abstract of Scientific Justification

Chemically pristine galaxies provide a valuable fossil record of the first phases of galaxy formation and the early enrichment of the IGM. The near-pristine gas in these galaxies provides constraints on the primordial light element abundances predicted by big bang nucleosynthesis. In spite of considerable observational efforts, I Zw 18 and SBS 0335-052W have for several decades retained the record as the most metal poor star forming galaxies known. While emission line studies with SDSS have increased the number of extremely metal poor (XMP) galaxies, such searches are biased to objects with high surface brightness. As a result, samples of the lowest metallicity galaxies remain too small for generalized conclusions about their formation and light element abundances. Recently a blind HI imaging survey has uncovered Leo P, a galaxy with near-pristine gas with much lower surface brightness and more irregular morphology than previous XMPs. Motivated by the presence of Leo P in SDSS imaging, we have developed a search algorithm to identify star forming dwarf galaxies with low surface brightness and similarly low metallicity, which we name ‘Blue Diffuse Dwarf’ (BDD) Galaxies. MMT spectra of 12 out of 100 galaxies in our sample confirm that the galaxies are indeed comprised of very metal poor gas (James et al. 2014c) and, in addition to this, have star-formation properties that may bridge the evolutionary gap between irregular and blue compact dwarf galaxies. However, our comparative analysis is severely hindered by low number statistics. Here we propose to use MMT Blue Channel Spectroscopy to measure the chemical and physical properties of a larger subset of the population in order to (i) continue to find systems with metallicities in the range of Leo P and I Zw 18 and (ii) provide essential constraints this new population of BDD galaxies.

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		BCS			4	dark	Mar – May	Jan–Jun	no	no

Scheduling constraints and unusable dates *(up to 4 lines)*:

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	obj2	211.024994	31.015499	g=18.678400
2	obj4	216.384995	52.587601	g=20.803699
3	obj6	177.529999	62.489700	g=18.396299
4	obj11	208.992996	8.993370	g=18.663601
5	obj16	171.794998	39.254299	g=17.878201
6	obj18	140.363007	7.364640	g=16.528799
7	obj20	247.802994	46.884800	g=18.046700
8	obj26	214.559998	43.380501	g=19.012199
9	obj30	251.453003	46.791302	g=17.634300
10	obj34	221.352005	-6.123420	g=18.746599
11	obj36	225.598999	39.000401	g=19.097099
12	obj39	237.895996	8.031420	g=18.541401
13	obj45	198.119003	-3.389790	g=18.008600
14	obj47	182.266006	36.891102	g=19.182100
15	obj51	175.727005	42.099400	g=16.501200
16	obj52	156.123001	43.231899	g=16.554100
17	obj54	234.654007	13.516500	g=16.958700
18	obj56	214.460999	6.838870	g=17.156200
19	obj59	240.557999	53.866600	g=17.425900
20	obj64	202.537994	32.287800	g=17.871401
21	obj66	218.524002	49.770401	g=17.656700
22	obj72	238.352005	40.389599	g=17.955500
23	obj89	153.828003	12.992800	g=18.077000
24	obj115	241.072006	58.843899	g=17.093500
25	obj116	188.621002	64.101501	g=17.611900
26	obj122	186.427002	26.809601	g=16.522301

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

Metal-poor Galaxies: The lowest metallicity galaxies provide a unique fossil record of the early universe. Exploration of their pristine environments is critical for our understanding of early galaxy formation and the properties of low-metallicity stars, along with providing critical constraints on theories of stellar evolution, the early enrichment of the pre-galactic medium, and studies of primordial elements. While distant galaxy searches have now extended back to 400 Myr after the Big Bang (e.g., Coe et al. 2013), very limited constraints can be extracted from these faint systems. Measurement of the chemical abundance patterns and minimum metallicity in the most unenriched galaxies in the local universe therefore provides a valuable means of constraining the early star formation, complementing the ongoing high-z searches.

Unfortunately metal-poor objects are very rare, especially those belonging to the class of extremely metal-poor (XMP) galaxies (defined as having 12+log(O/H)<7.65, less than one tenth solar). For many decades, I Zw 18 (1/50$Z_\odot$, Izotov & Thuan 1999) and SBS 0335-052W (1/41 $Z_\odot$, Izotov et al. 2005) have held the record for the lowest metallicity. Currently only 129 XMPs exist within the literature (see Morales-Luis et al. 2011 for a complete compilation). This is in part due to their intrinsic low-luminosity, as can be seen from the well-known luminosity-metallicity relation (Fig. 2). However, given the large number of feeble galaxies predicted from the local galaxy luminosity function, very low-metallicity galaxies should be much more common than indicated by the small number of known XMP galaxies.

The Search for XMPs: The discovery of XMP galaxies has thus far focused primarily on surveying emission-line galaxies (see Skillman et al. 2013 for a review). While such surveys have increased the number of XMPs, they have provided a very low yield. For example, of one million SDSS DR-7 spectra, there are only 15 candidates with 12+log(O/H)<7.35 within the Local Volume (Izotov et al. 2012). The low yield from these spectroscopic surveys is partly due to their design - they require objects to have high surface brightness H II regions for detectability and abundance analysis. Based on the relationship between luminosity and metallicity shown in Figure 2, it is natural to expect many lower surface brightness XMP galaxies to be missing from these surveys (e.g., Berg et al. 2013).

Recently, a new record-breaking galaxy has been brought to light: Leo P (Giovanelli et al. 2013). Using blind H I 21 cm line imaging, this nearby dwarf irregular galaxy was discovered during a survey identifying mini-halo candidates. Follow-up spectroscopic observations by Skillman et al. 2013 unveil this object as one of the most metal poor star forming galaxies ever observed, with 12+log(O/H)=7.17. Its diffuse morphology and low-surface brightness ($M_B = -8.94 \pm 0.30$) are atypical of most XMPs (see comparison in Figure 1), and set it apart from the other current low-metallicity record holders. The accidental discovery of Leo P summons the question - *are we missing a large population of low surface brightness XMPs?*

Finding Leo P Analogs in SDSS: As Leo-P is detectable in the SDSS images (as a set of blue blobs embedded into low surface brightness emission), we undertook a systematic search in the Sloan source catalog for similarly faint, nearby star-forming systems, not yet associated to any known galaxies and without an SDSS spectrum. The main requirements of our search are as follows: (i) Presence of at least one point source with "blue" color (HII region); (ii) Overdensity of multiple faint sources or the presence of extended emission; (iii) Various data quality cuts to reject defects related to bright stars, very large galaxies, etc. This search yielded a few hundreds of candidates (including Leo P and many known nearby star-forming dwarf galaxies). After removing all known sources from the list and selecting the best cases, we have a list of ~ 100 low surface brightness star forming dwarf galaxies. A small subset of these can be seen in Figure 1.

A New Population of Blue, Diffuse, Metal-Poor Dwarf Galaxies in SDSS: The population of objects identified with this search algorithm is unlike any population studied to date. We show example postage stamps of nine of our galaxies in Figure 1. Like Leo P (also shown in Fig. 1), each galaxy is blue, extremely diffuse, and irregular, with typically only one or two H II regions. Their morphologies alone suggest that they are ideal candidates to be young, pristine galaxies. Previous SDSS emission line surveys for XMPs reveal compact, bright objects (Fig. 1, bottom panel); rather different from the diffuse objects within our sample. In January, we were granted 3 nights of MMT time to obtain spectroscopic observations of $\sim$20 objects within this sample. However, due to a combination of bad weather for two nights and restricted RA, we were obtained spectra of only 12 targets. Within this small sample, we were able derive metallicities for eight objects and two galaxies were found to be within the XMP range (James et al. 2014c, see also Fig. 2) - *one of which has an oxygen metallicity comparable to the three most metal-poor galaxies known to-date*. Such statistics clearly illustrate how efficient our sample selection has been in discovering XMP galaxies.

In addition to low-metallicity gas, the MMT spectra also revealed that the galaxies as have young stellar populations ($<$10 Myr) and, despite their low surface brightnesses, are actively forming stars (James et al. 2014c). As such, this new population appear to be non-quiescent dwarf-irregular galaxies, or the diffuse counterparts to BCDs and as such may bridge the gap between these populations (Fig. 3). However, the comparisons between our sample and different dwarf galaxy populations are currently hindered by low-number statistics and we were unable to fully characterise this new population.

Based on the success of this primary run, we have further selected 28 targets which would be most suitable for MMT spectroscopic observations in 2015A. The SDSS photometry indicates g-band magnitudes between $\sim$17–19, and typical diameters of $\sim$10–40 arcseconds.

This Proposal: Here we propose to utilize the MMT blue-channel spectrograph to obtain an optical spectrum of each target in order to further characterise the nature of this new population. The optical spectra will enable us to quantify their metal content, characterize the primary sources of ionization, and constrain their past star formation history through their chemical fossil record. As we find more galaxies with metallicities as low as I Zw 18, we will use the optical spectra to constrain the primordial light element abundances.

As demonstrated by the spectra obtained during our first run (e.g. James et al. 2014c, their figure. 2), the blue channel spectrograph (with 300 l/mm grating) provides an ideal wavelength range, allowing us to observe all the necessary lines needed to derive accurate metallicities. The most reliable determination of elemental abundances are via relative strengths of emission lines from H II regions, including weak, temperature-sensitive transitions such as [O III] λ4363 and density-sensitive ratios (e.g. [S II] $\lambda\lambda$6716, 6731) - commonly known as the 'direct' method. To this end, the detection of auroral lines, and the consequent determination of the H II region electron temperature ($T_{\rm e}$) is essential. In addition to this, the blue-channel spectrograph is sufficiently blue to detect the (blended) [O II] $\lambda\lambda$ 3727+3729 doublet, from which we can derive O^+/H^+ and thus remove the need for uncertain ionization correction factors.

During our our first run with MMT blue spectrograph, we obtained optical spectra of 12 galaxies within our sample. Our observations show that [O III] λ4363 is significantly detected within eight of these targets, enabling us to accurately measure their gas-phase metallicity (Fig. 2). Although the spectra are shallow ($\sim$20–40 min), we have been able to measure $T_{\rm e}$'s of 11,000–40,000 K, and metallicities of 7.45 $<$12+log(O/H)$<$ 8.0. In Figure 2 we show the eight galaxies within the local metallicity-luminosity relationship. It can be seen that we are readily approaching the XMP range; in fact one galaxy (KJ 53) is classified as one of the most metal-poor galaxies known to-date. In this proposal, we will use MMT to continue targeting sources in our SDSS sample in order to ultimately constrain this population.

Program Goals: The observations proposed will also access a suite of emission lines which hold further information about this new, unexplored population. Other than deriving the oxygen abundance within the galaxies (our primary goal) we intend to explore the following:

- **Sources of ionization:** We will use the ratio of [N II] λ6584/Hα vs [O III] λ5007/Hβ to assess the hardness of the radiation field within each galaxy and investigate the presence of shock-ionized emission within them. Understanding the sources of ionization and the ionization processes within XMPs is essential for studies of primordial galaxies and for galaxy evolution.
- **Star formation history from chemical fossil record:**The [N II] λ6584 emission will allow us to determine the N/H abundance, which we will assess in relation to O/H. The N/O ratio is of great interest because it serves as a clock to indicate the time since the most recent burst of star-formation. Our sample will provide a constraint on the N/O vs. O/H relationship at low-metallicity, where nitrogen transitions from acting as a primary to a secondary element (see Berg. et al. 2012, their figure 6).

References: Berg et al. 2012, ApJ, 754, 98 • Berg et al. 2013, ApJ, 775, 128 • Coe et al. 2012, ApJ, 762, 32 • Giovanelli et al. 2013 • Izotov et al. 2005, ApJ, 632, 210 • Izotov & Thuan 2009 A&A 734, 82 • Izotov et al. 2012, A&A 546, 122 • James et al. 2014c, MNRAS, submitted, pre-print available at: `www.ast.cam.ac.uk/~bjames/BDDs_mnras_submit.pdf` • Morales-Luis et al. 2011, ApJ, 743, 77 • Skillman et al. 2013, AJ, 146, 3

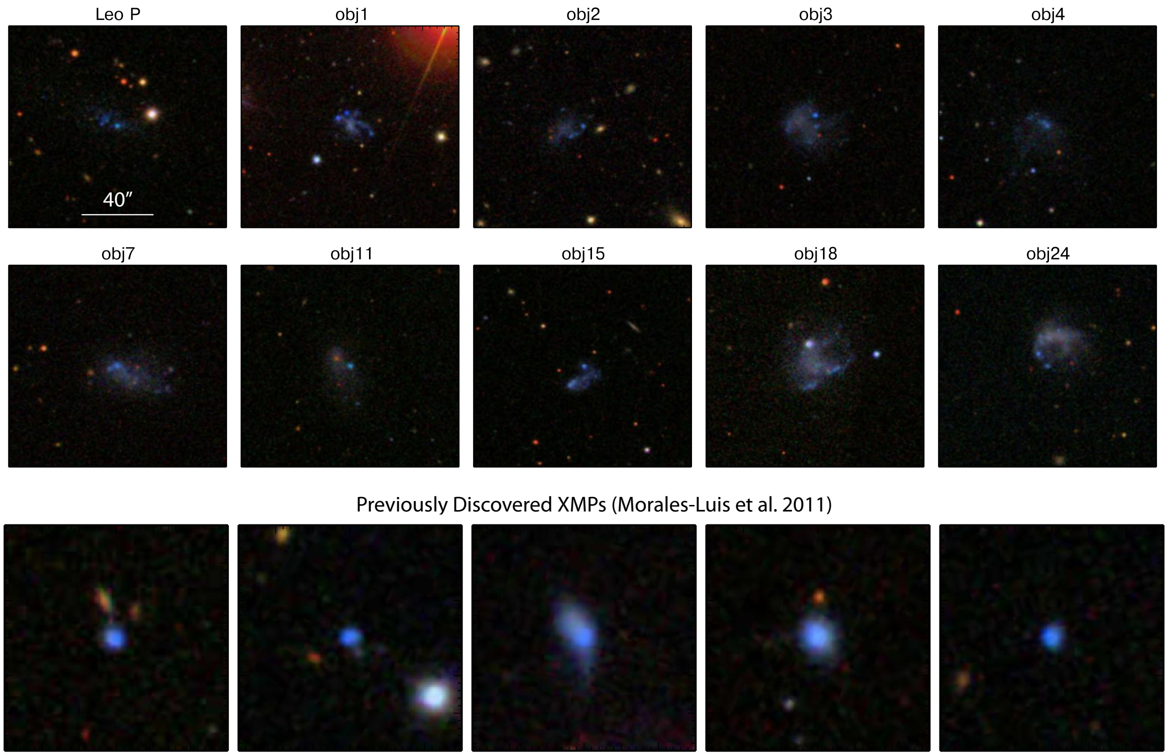

Figure 1: *Top-panel:* SDSS postage stamps of 9 galaxies within our sample, illustrating their blue and diffuse nature. We also include the SDSS image of Leo P (top left panel), the recently discovered XMP galaxy, on which our unique selection criteria were based. *Bottom-panel:* a selection of higher surface brightness XMPs discovered via SDSS spectroscopic search by Morales-Luis et al. 2011. Their bright, 'blobby' morphology is very different from our the new population shown in the panel above.

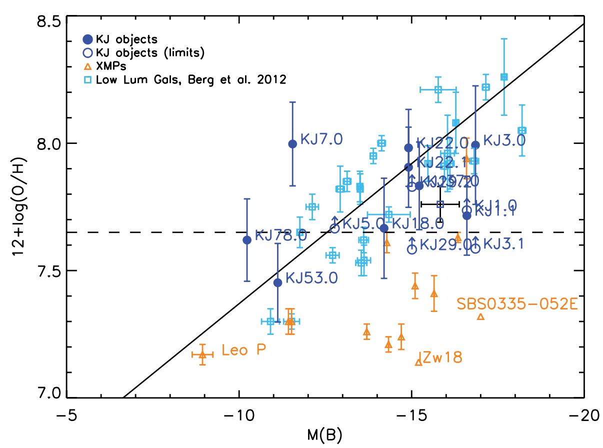

Figure 2: *B*-band luminosity – oxygen abundance relationship for dwarf star-forming galaxies, (adapted from Berg et al. 2012 and shown in James et al. 2014c). The 12 objects from our primary MMT run are shown in dark blue circles. From only 8 direct-method metallicities, 2 are can be classified as XMPs (illustrated by the dashed horizontal line at 0.1 Z⊙) - illustrating the effective nature of our search for XMPs. The solid line represents the M(B)–12+log(O/H) regression from Berg et al. 2012.

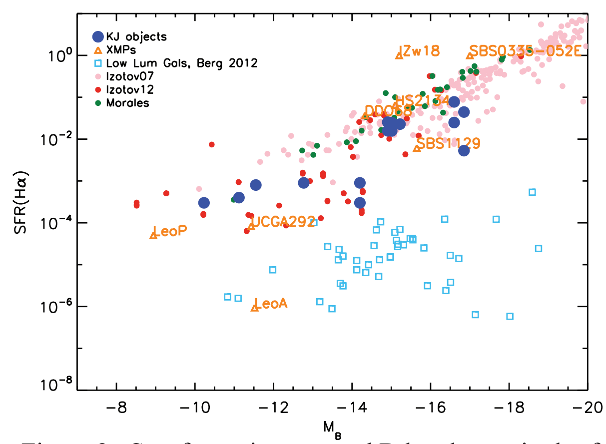

Figure 3: Star-formation rate and B-band magnitudes for our population of diffuse dwarfs (dark blue) and other dwarf galaxy populations - known XMPs (orange & green), BCDs (pink & red), and low-luminosity dwarf irregular galaxies (light blue), as shown in James et al. 2014c. Our new population may bridge the gap between starbursting BCDs and inactive dIrr galaxies - however, spectroscopic observations of more galaxies within our sample are needed to confirm this.

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)***

We request 4 nights with the MMT Blue Channel Spectrograph to continue characterising a new population of XMP candidate galaxies selected in SDSS. We have several goals.

First and foremost we seek to measure the gas-phase metallicity distribution function of this population. To robustly assess the metallicity, we require detection of the [OIII]λ4363 auroral line (sensitive to electron temperature), the [OII]$\lambda\lambda$3727+3729 and [OIII]λ4959, 5007 emission lines, and the [SII]λ6717,6731 doublet (sensitive to electron density).

Secondly, in addition to measuring the metallicity, we aim to use these galaxies to understand how star formation proceeds in low metallicity environments. To do so, we will first assess the hardness of the ionizing radiation field using the BPT diagram ([N II] λ6584/Hα vs [O III] λ5007/Hβ), enabling unique constraints to be placed on the (massive) stellar population. And second, since nitrogen is produced on longer timescales than oxygen, constraints on the N/O ratio will provide unique insight into the past formation history of extremely low metallicity galaxies.

Third and finally, we intend to fully characterise the 'extremely diffuse' galaxies within our sample. Without prominent H II regions, their blue diffuse morphology and weak emission lines, make them highly intriguing targets because their nature remains unknown. We will obtain deeper spectra of this sub-sample, in order to calculate distances and place constraints on their gas-phase properties.

Instrument Set-Up and Lunar Phase: To achieve the goals described above, we need spectral coverage spanning a wide enough wavelength range to detect emission lines ranging from [OII]λ3727 to [SII]$\lambda\lambda$6717, 6731. The 300 line/mm grating with the MMT Blue Channel Spectrograph covers this wavelength range simultaneously, enabling more reliable flux ratios than would be obtained if we had to split up the blue and red observations. While the resolution is not sufficient to resolve the [OII] doublet, we will be able to just resolve [SII]$\lambda\lambda$6717, 6731 (e.g. Fig. 3) providing a necessary constraint on the electron density.

As we require detection of multiple emission lines in the blue (the [OII] doublet at 3727Å and the [OIII]λ4363 auroral line), our observations are most efficiently conducted in dark time. If it were to prove easier to schedule, our program could be completed (albeit less efficiently) in grey time.

Sensitivity Requirements: The faintest line is likely to be the auroral [OIII]λ4363. We expect [OIII]λ4363 equivalent widths in the range 1-10 Å. Based on the continuum surface brightness of the HII regions in our galaxy population, we predict the line fluxes for [OIII]λ4363 will be moderately in excess of 2×10^{-17} ergs cm^{-2} s^{-1}. From experienced gained from our primary-run with the MMT Blue Channel Spectrograph, we should reach typical 5σ emission line flux limits of 2-3$\times10^{-17}$ erg cm^{-2} s^{-1} in 1 hr of science integration at 4363 Å. We therefore require no more than 1-2 hrs of integration per target. Integration times will be adjusted from source to source depending on the continuum surface brightness. For example, we intend to acquire deeper spectra ($\sim$2 hours integration) of the more diffuse objects, in order to fully constrain distances and/or metallicities.

Sample Selection for 2015A: The current search algorithm yields a population of roughly 100 galaxies. Optical spectra of 12 galaxies confirms their metal poor nature, with two objects classified as extremely metal poor. Our goal here is to continue extending this sample to fainter and hopefully lower metallicity galaxies. To reliably sample the metallicity distribution function in three luminosity bins (see L-Z relation in Figure 2), we require metallicity measurements of $\sim$ 50 galaxies and if successful, our 2014b observations will yield a maximum of $\sim$25 galaxies. We therefore list a further 28 galaxies from our sample (chosen to be visible in 2015A) in the Observing Table.

Accounting for overheads for target acquisition and readout, **we request 4 nights with MMT** to complete the proposed program.

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 third request for spectroscopy of these targets. Our first request was successful in being awarded three nights of MMT spectroscopy. However, due to bad weather conditions (complete loss of 2 of the 3 nights) and a restricted RA range (all 3 nights were scheduled together) we were only able to obtain shallow spectra of 12 galaxies (a total integration time of 11 hours). In order to observe 12 galaxies within this restricted time, we were forced to compromise S/N levels and could only observe targets for a maximum of 2x20 min exposures. Results from this first night have recently been submitted to MNRAS (James et al. 2014c). We were granted 4 nights of MMT spectroscopy to target blue diffuse candidates that are visible during the 2014B semester. The runs are scheduled for late October and December of this year. Unfortunately many of our best candidates are only visible in the spring. Due to the large nature of the statistics required to fully characterise this large population, we request one final allocation of 4 nights in 2015A to make up for the poor weather during our 2014A run. In reflection of the nature of this first run, we request to split the requested 4 nights into 2 runs, with the hope of facing less restricting circumstances.

Lick spectra of 5 objects were obtained during an observing run focused on other science. We are not pursuing this program further with Lick (we require the larger aperture of MMT to extend to fainter sources) or any other facility.

Previously we proposed to obtain deeper imaging of this population with LBT, Blanco/DECam, and DCT in the hope that these systems would be in the local group. Deep imaging (from DECam and DCT) has been obtained for 5 systems.

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)***

MMT: Eight MMT nights have been obtained with the Blue and Red Channel Spectrograph between 2011C and 2012C with the goal of obtaining a large spectroscopic sample of gravitationally lensed galaxies in SDSS. Through this program, 26 new gravitationally-lensed galaxies have been confirmed. The catalog paper describing the spectroscopic survey and some of the first science results is now accepted in MNRAS (Stark et al. 2013b). The discovery of this population is motivating detailed investigations with other facilities. Time has been awarded to follow-up these sources with Keck AO-assisted near-IR IFU spectroscopy and moderate resolution optical echelle spectroscopy.

$\star$ Three MMT nights awarded in 2014A for exploration of a new population of nearby metal poor galaxies. Two nights were cloudy. One night of useful data taken. Observations have resulted in discovery of one of the most metal poor galaxies known (see MMT proposal). First paper describing the new sample has recently been submitted (James, Koposov, Stark et al. 2014). Four nights have been awarded in 2014B. Observations are scheduled for late October and December 2014.

Summary: 11 nights awarded, catalog paper describing survey published in MNRAS (Stark et al. 2013). Detailed follow-up underway. First data taken for new program targeting blue diffuse dwarf galaxies in Jan 2014. One paper submitted.

Magellan: Two nights were awarded with Magellan/FIRE in 2012B to follow up lensed galaxies. Conditions were cloudy and no data were acquired.

Two nights were awarded with Magellan/FIRE in 2013A to obtain the first detection of CIII] at $z \gtrsim 6$. Clouds and poor seeing prevented acquisition of any useful data on the primary program. In short gaps in the clouds, we were able to obtain constraints on rest-optical emission lines in one of our reionization-era analogs. Results are included in Stark et al. (2014a).

One night awarded for June to target metal poor reionization-era analogs with FIRE. Data taken and are part of a paper in preparation by Steward graduate student Ramesh Mainali.

Two nights awarded from Steward in November 2014 to target $z \simeq 6-8$ galaxies with FIRE. Results from time allocated to Carnegie have been discussed above and shown in Figure 2. Several papers in preparation.

Summary: 5 nights allocated for various programs. No useful data taken for primary program owing to poor weather conditions. One clear night in June. Two scheduled for November. One paper published, and several more are in preparation.

LBT:

Two nights are allocated with LUCI in 2013B to observe bright lensed galaxies at $z \simeq 2-3$. Program could not be completed because LUCI was broken. Instead we acquired $\simeq$ 3 hrs of imaging of gravitationally-lensed galaxies from Stark et al. (2013) using MODS in cloud and poor seeing (1.5-2$''$). Data will be written up in a paper by Ramesh Mainali.

$\star$ Two nights allocated in 2014A with LUCI to target CIII] in a $z \simeq 7$ galaxy with confirmed redshift. No data taken owing to instrument problems.

Summary: Four nights allocated with LUCI, but no data on primary science programs yet acquired.

Bibliography (papers from proposals led by PI on Steward facilities in last two years):

Stark et al. 2013, MNRAS, 436, 1040
Stark et al. 2014a, MNRAS in press, arXiv:1408.1420
Bian, Stark, et al. 2014, submitted to ApJ
James, Koposov, Stark et al. 2014, submitted to MNRAS
