OBSERVING REQUEST
University of Arizona Observatories

Year: 2017 **Term:** Jul–Dec **Proposal type:** short-term

MMIRS Spectroscopy of Dwarf Star Forming Galaxies at $z \sim 2$

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CoI(s): Daniel Stark (SO)

Abstract of Scientific Justification

Star formation at high redshift $z > 2$ is increasingly dominated by low luminosity systems. Yet little is known about their metal content or stellar populations. Recent work has begun to hint at several intriguing aspects in the spectroscopic properties of intrinsically faint galaxy spectra at $z \simeq 2$. Low mass galaxies are commonly found to be in an 'extreme optical line emitting phase' reflecting very large specific star formation rates. The strength of UV and optical emission lines points to an intense radiation field, as might be expected if galaxies are undergoing a burst of star formation. In 2015B and 2016A, we have built a large sample of near-infrared spectra of young, low mass galaxies at $z \simeq 2$. Preliminary results reveal that these galaxies have relatively low metallicities ($Z \lesssim 0.3 Z_\odot$) and large ionization parameters which imply a hard radiation field. However, interpretation of more detailed physical properties and star formation history for the current sample is stunted because of the incomplete set of emission lines. *In 2016B we began to obtain complete line sets, but the bad weather prevented us from getting enough data.* Here we propose to obtain deeper MMT/MMIRS spectra with the goal of characterizing fainter emission lines which provide key diagnostics of the nature of this unique population. We have three objectives. First we will measure robust metallicities of these galaxies via either the 'direct' method or calibrations requiring the full suite of emission lines. Second, we will use the emission line catalog to characterize the shape of the ionizing spectrum. Third, we will investigate the star formation histories through comparison of star formation rates derived from Hα and far UV continuum. Taken together, these spectral constraints will provide much improved understanding of the evolution of young, low mass galaxies at high redshift.

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		MMIRS			2	bright	Oct	Sep–Nov	no	no

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

no text past this line

A $\star$ appended to the proposal type indicates a continuation proposal; a $\star$ 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	UDS	02:17:26.00	-05:12:13.0	H = 24.8

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 if student is PI on the cover page or if this is a 2nd-year or Thesis program. Send confirmation email to TAC chair in place of signature.)*

Student's Name	Advisor's Name	Advisor's Signature	2nd-yr	Thesis
Mengtao Tang	Daniel Stark		no	yes

Scientific Justification

Over the past decade, great strides have been taken in our understanding of star formation and feedback in bright L* galaxies at $z \simeq 2-3$ (e.g. Steidel et al. 2014, Shapley et al. 2015). These studies have revealed that large-scale outflows appear to play a fundamental role in governing the efficiency of star formation and the metal enrichment of the intergalactic medium (IGM). Additionally these observations are now demonstrating that the structure (covering factor, ionization state) of this outflowing gaseous medium likely regulates the transmission of ionizing radiation into the IGM (Steidel et al. 2010, Jones et al. 2013) and therefore helps determine the contribution of galaxies to the global ionizing background.

Yet limited to the brightest systems, these surveys provide an incomplete picture of early galaxy formation. Measurements of the luminosity function at $z \simeq 2$ demonstrate that more than 90% of the total UV luminosity density comes from the unexplored population of sub-L* galaxies (Alavi et al. 2016), and the dominance of such low luminosity galaxies becomes even more pronounced at yet earlier times (Bouwens et al. 2015). Understanding the baryonic evolution of early galaxies and their contribution to the enrichment and ionization of the IGM requires detailed understanding of the physics governing low luminosity galaxies.

Star Formation and Feedback in Low Luminosity Galaxies: The lower gravitational potential well in sub-L* systems may fundamentally alter the processes governing galaxy formation. For example, it is conceivable that supernova-driven outflows in these lower mass galaxies are more efficient at creating holes in the surrounding gaseous medium (e.g. Governato et al. 2010), allowing a larger fraction of the ionizing radiation and metals to escape into the IGM. Due to strong stellar feedback and photo-heating from the UV background, star formation is often thought to be bursty in low mass systems (e.g., Murray et al. 2005, Shen et al. 2014). The fluctuations in star formation are predicted to occur on a dynamical timescale and may play a fundamental role in modifying the dark matter distribution in dwarf galaxies (e.g., Pontzen & Governato 2012). Observationally, bursts of star formation should manifest themselves in powerful emission lines powered by young, metal poor massive stars. Unfortunately little is known about the outflows, metal content, or stellar populations of low mass galaxies. Such information can only be obtained through detailed spectroscopy, which has long proven very difficult for low luminosity sources at high redshift.

MMIRS Campaign in 2015B-2016: In the past several years, a large population of $z \simeq 1.5-2$ low mass ($\sim 10^8 M_\odot$) galaxies with very large equivalent width (EW) rest-frame optical emission lines ([OIII], Hβ) have been discovered (e.g., Atek et al. 2011, van der Wel et al. 2011). The equivalent widths of the optical lines require very large specific star formation rates, as would be expected from dwarfs undergoing bursty activity. The importance of this population increases with redshift, with recent estimates suggesting that half of $z \simeq 7$ galaxies are in an extreme emission line phase (Smit et al. 2015). With the identification of a large number of $z \simeq 2$ extreme emission line galaxies (EELGs) in low resolution WFC3/IR grism observations of the CANDELS fields, the time is now right for the first large spectroscopic campaign aimed at characterizing the metal content and gas physical conditions of this important and poorly-studied population.

With this as our goal, we initiated an MMT/MMIRS spectroscopic campaign targeting likely EELGs in five CANDELS fields at the end of 2015. During our 2015B and 2016 programs, we have completed the first step toward this objective, detecting multiple rest-optical emission lines in 60 EELGs via MMT/MMIRS (e.g., Table 1, Figure 1a). As shown in Figure 2a, the galaxies in our sample probe an unique parameter space, exhibiting large rest-frame [O III]λ5007 EW ($>$ 600Å) or Hα EW ($>$ 500Å) than more massive systems that are being studied in great detail via the MOSDEF survey (Kriek et al. 2015; EW $\simeq$ 110Å). Preliminary analysis of the subset of galaxies with the full suite of rest-optical line detections reveals a low metallicity population (<0.3 $Z_\odot$) and large ionization parameters (i.e., see position in BPT diagram in Figure 2b). *However, many of the EELGs observed in our 2015B and 2016 runs have incomplete set of emission line detections, which limits our ability to characterize their stellar populations, star formation histories and interstellar medium (ISM) conditions (i.e., metallicity, ionization parameter, electron temperature, and electron density).* In particular, the [O II], [O III]λ4363 and [S III] emission lines, which are important to such investigations, are absent in the current sample. We also require more stringent limits on the faint [N II]λ6584 or [S II] lines to determine the precise position of our targets in BPT diagram and hence the hardness of ionizing spectrum.

MMT Proposal for 2017B:. The progress described above hints at some important physical properties of low mass star forming galaxies at high redshift. The relatively low metallicity and high [O III]λ5007/Hβ ratios indicate hard radiation fields in $z \simeq 2$ EELGs, as is expected from the large equivalent width emission lines. However, due to the limited set of rest-optical line detections, several key physical properties constraining the stellar population and the ionization state of gas are still unclear. Time was awarded to follow-up a subset of $z \simeq 2$ low mass star forming galaxies to address this shortcoming in 2016B and 2017A. Complete emission line sets are expected to be obtained in $\sim 67\%$ of EELGs in the sample by the end of 2017A. **However, in 2016B program the weather was windy and the average seeing was $\gtrsim$2.0″, which prevent us from getting enough data.** Thus the rest EELGs in the sample still have incomplete emission line detection, especially for nine the most extreme line emitting galaxies ([O III]λ5007 EW > 1000Å) visible in the Fall, which are expected to occupy the most extreme parameter space and studies as analogs of galaxies in the reionization era. **Here we propose one final semester to cover targets in CANDELS/UDS field to finish this survey.** This will enable the first study of their detailed physical properties like robust metallicity and star formation history and will form a primary component of graduate student M. Tang's Ph.D thesis. We have three key objectives:

1. Robust Metallicity Measurement. Gas-phase metallicity is governed by gas accretion, star formation and gas outflow, providing valuable insight into the history of baryonic assembly. The EELGs appear to have low metallicities, offering unique insight into the stellar populations and evolution of metal-deficient galaxies. Particularly, galaxies in the most metal-poor phase may be analogous of the population in the early universe. We have developed a new method to select the most metal-poor galaxies via large Hα/[O III]λ5007 flux ratio ($\gtrsim$1; implies extremely low oxygen abundance), and identified six sources in the current EELG sample. We seek to obtain robust metallicity measurements for our EELG sample. However, recent works on the chemical abundance of $z \sim 2$ galaxies suggest that there is systematic offset of metallicities measured from nitrogen-based diagnostics between local and high redshift galaxies (Jones et al. 2015; Sanders et al. 2016). Robust measurements require the detection of a larger suite of optical emission line (e.g. Dopita et al. 2016) or the auroral [O III]λ4363 line (as well as [O II]λ3727, 3729, [O III]λ4959, 5007). We have already detected the faint [O III]λ4363 lines in several EELGs (Figure 1b), implying very low metallicities and demonstrating the feasibility of progress with deeper data. By building a larger sample with detections of faint emission lines [O III]λ4363, [O II] and [S II], we will secure robust metallicities for this unique population, complementing ongoing surveys of more massive star forming galaxies (i.e., MOSDEF).

2. Metal-Poor Massive Stellar Populations. If the low mass extreme emission line galaxies are dominated by young, metal-poor stellar population following a burst of star formation, we would expect a significant fraction of massive stars in these systems, powering a more intense radiation field than more massive star forming galaxies. Since EELGs appear to become dominant at $z > 6$, knowledge of their ionizing spectra is critical to assessing the contribution of early galaxies to reionization. Following our earlier work (i.e., Stark et al. 2014), we will use constraints on the full suite of rest-optical emission lines (including [O II], [S II], [N II], [S III]) to characterize the ionizing spectrum for young galaxies with extreme line emission.

3. Star Formation Histories of EELGs. Star formation rates (SFRs) determined by different indicators are valid for different timescales. While the far UV continuum luminosity probes SFR on ~ 100 Myr or longer, the Hα luminosity is sensitive to the SFR within the past ~ 10 Myr. High resolution spectroscopy provides robust measurement of Hα emission line separated from nearby emission lines ([N II]). We aim to observe Hα emission lines for the current sample and use Hα : Hβ ratios to correct for nebular dust attenuation. Comparison of the two different star formation indicators will enable investigation of the star formation history of the $z \simeq 2$ EELGs.

Reference: • Alavi et al. 2016, ApJ, 832, 56 • Atek et al. 2011, ApJ, 743, 121 • Baldwin et al. 1981, PASP, 93, 5 • Bouwens et al. 2015, ApJ, 803, 34 • Dopita et al. 2016, ApSS, 361, 61 • Governato et al. 2010, Nature, 463, 203 • Jones et al. 2013, ApJ, 779, 52 • Jones et al. 2015, ApJ, 813, 126 • Kewley et al. 2013, ApJ, 774, 100 • Kriek et al. 2015, ApJ, 218, 15 • Murray et al. 2005, ApJ, 618, 569 • Pontzen et al. 2012, MNRAS, 421, 3464 • Sanders et al. 2016, ApJ, 816, 23 • Shapley et al. 2015, ApJ, 801, 88 • Shen et al. 2014, ApJ, 792, 99 • Smit et al. 2015, ApJ, 801, 122 • Stark et al. 2014, MNRAS, 445, 3200 • Steidel et al. 2010, ApJ, 717, 289 • Steidel et al. 2014, ApJ, 795, 165 • van der Wel et al. 2011, ApJ, 742, 111

Programs	[O II]	[O III]λ4363	Hβ+[O III]	Hα	[N II]λ6584	[S II]
2015B+2016	30	3	59	50	9	10
visible in 2017B	10	1	20	16	4	6

Table 1: Total number of each emission line detection in 2015B and 2016 observing runs. The last row lists the number of detections in targets that visible in 2017B, in which there is still room to improve the detection of [O II], [O III]4363 and Hα+[N II]+[S II]. Faint [O III]λ4363, [N II]λ6584, and [S II] lines are detected in less than ten EELGs, while other galaxies do not show such feature due to the limit of exposure time. No EELG has had [S III] detection yet.

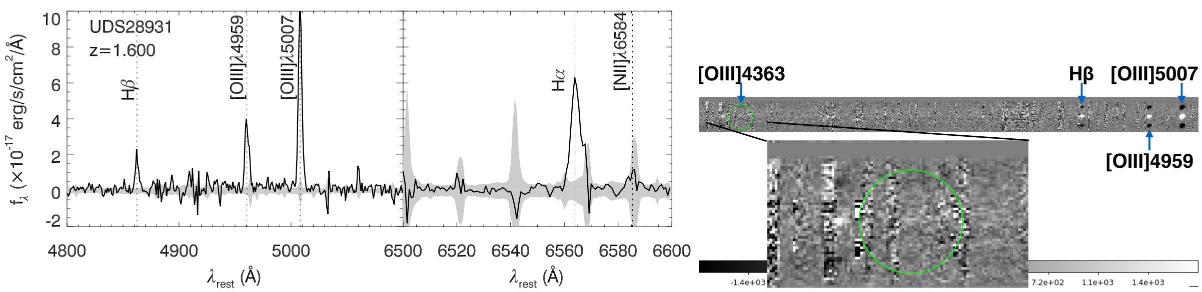

Figure 1: a. (left): An example 1-D rest-frame optical spectrum of EELG at $z = 1.600$ from 2015B MMIRS program. Strong optical emission lines (Hβ, [O III]λ4959, 5007 and Hα) are clearly shown in the spectrum. b. (right): 2-D spectrum of EGS11452 ($z = 1.672$) obtained from 2016A MMIRS run. Besides strongest lines Hβ and [O III] doublets, faint [O III]λ4363 is also detected (marked with green circles, see enlarged spectrum around rest-frame 4363Å below), which implies very metal-poor phase.

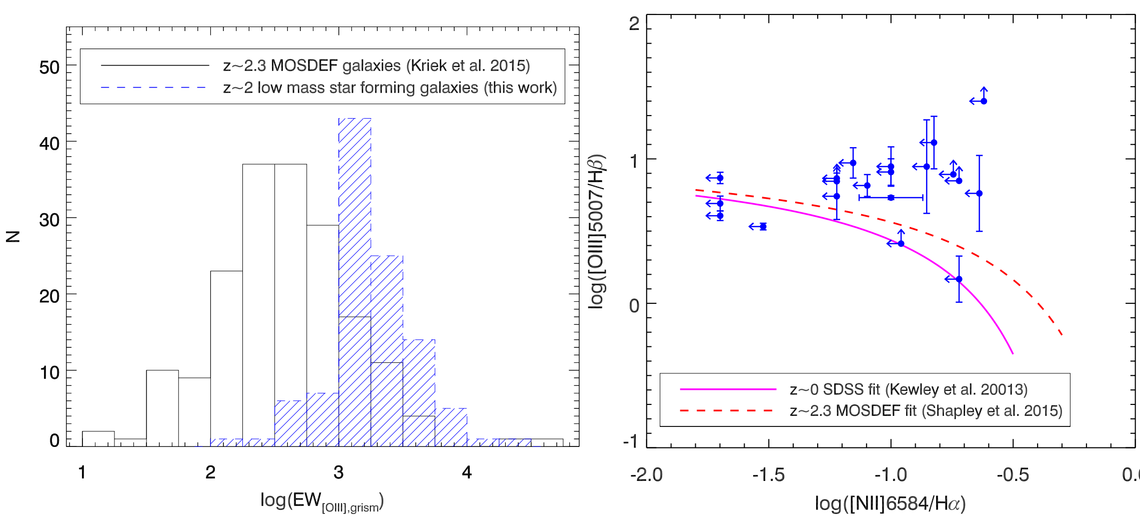

Figure 2: a. (left): Number distribution with [O III]λ5007 equivalent width (EW) from grism spectra. Our current sample (blue line filled region) have systematically larger [O III]?5007 EW than 'normal' massive galaxies from MOSDEF at similar redshift. b. (right): BPT diagram (Baldwin et al. 1981) for objects obtained in 2015B and 2016 with [O III]λ5007/Hβ and [N II]λ6584/Hα measurements (blue dots). Red dashed curve is the fit of $z \sim 2.3$ MOSDEF sample (Shapley et al. 2015). Magenta solid line represents the fit of $z \sim 0$ SDSS sample in Kewley et al. (2013).

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**)*

Requirements: We propose to use MMT/MMIRS to obtain deeper near-infrared spectra of EELGs at redshift $z \sim 2$ confirmed in the previous two observing runs. The key requirements of this program are listed below. First, we need to integrate long enough to secure detection on the relatively faint rest-optical emission lines ([O II]$\lambda 3727, 3729$, [O III]$\lambda 4363$, [N II]$\lambda 6584$, [S II]$\lambda 6717, 6731$). Second, the optical emission lines must be located in regions where the atmospheric transmission is near unity. And third, we need a high enough resolution to resolve [O II] and/or [S II] doublets to measure electron density and metallicity.

Sample Selection: We have identified EELGs at $z \sim 2$ in CANDELS fields visible on MMT. The EELGs are selected based on the presence of strong Hβ+[OIII] emission in the HST J_{125} band. The I_{814} and H_{160}-bands are used as a measure of the underlying stellar continuum. In order to select EELGs, candidates are required to be more than 50% brighter in J_{125} than in both I_{814} and H_{160} bands (van der Wel et al. 2011). We have examined available low resolution grism spectra from 3D-HST survey to confirm redshifts. We then identify the subset of galaxies which place optical lines in clean regions of the NIR sky spectrum.

In the 2015B and 2016 programs, we have identified 60 EELGs using MMT/MMIRS. The spectroscopic redshifts of most of the targets in UDS field (which will be visible in 2017B) are confirmed by strong Hβ+[O III] and/or Hα emission lines. We ultimately need to build a complete set of rest-frame optical emission lines for identified galaxies. For spectroscopically confirmed EELGs in UDS field, auroral [O III]$\lambda 4363$ lines and [S II] have seldom been detected due to the limit of integration time or the lack of spectra in relative bands. [O II] detection is also lack in one third of the identified EELGs. Better constraints need to put on [N II]$\lambda 6584$ lines for ionizing spectra investigation, while a subset of galaxies still need Hα to determine their SFR and [S III] to determine ionization parameter. We also need a sufficiently large sample to see how spectroscopic properties (metallicity, ionization parameter) vary with stellar mass and EW. The bad weather in 2016B program prevent us from obtaining enough data. In 2017A we expect to obtain full set of optical lines in 40 EELGs in EGS and GOODS-N fields. In 2017B we seek to detect [O II] in 5, [O III]$\lambda 4363$ in 14, Hα in 4, [N II] and [S II] in 16, and [S III] in 6 EELGs. Totally we aim to obtain deeper spectra and fainter emission lines of 20 EELGs with MMIRS in 2017B, including 9 galaxies with the most extreme emission line EWs. Together with 2015B - 2017A programs we will have full set of optical lines in 60 EELGs, The sample of 60 is chosen to ensure that we can robustly measure the mean and scatter in each mass and EW bin. The targets have typical magnitudes of H_{160}=24.8.

Instrument Justification: This program requires sensitive spectroscopic constraints within the zJ band ([O II]$\lambda 3727, 3729$, [O III]$\lambda 4363$) and K band (Hα, [N II]$\lambda 6584$, [S II]$\lambda 6717, 6731$, [S III]$\lambda\lambda 9069, 9531$) with MMT/MMIRS. We seek to observe 20 galaxies. This will be more efficiently completed using multi-object spectrograph. Therefore we propose MMIRS in MMT for our observations.

Detection of Emission and Absorption Lines: Based on the N2 metallicity, [O II] and [O III]$\lambda 4959, 5007$ fluxes of the existing sample, the expected fluxes of [O III]$\lambda 4363$ lines range from 1.5×10^{-18} erg s^{-1} cm^{-2} to 2.0×10^{-17} erg s^{-1} cm^{-2}. Using the MMIRS ETC, we estimate the integration time for 5σ detection of the relatively bright flux 1.0×10^{-17} erg s^{-1} cm^{-2} is 8 hrs (10 hrs including overheads) using J_zJ setup. The typical [O II]$\lambda 3727$ flux of EELGs with [O II] measurement is 4.6×10^{-17} erg s^{-1} cm^{-2}. It takes ~ 4 hrs to reach 5σ detection with zJ band. Combining with the typical Hα flux in our EELGs of 1.5×10^{-16} erg s^{-1} cm^{-2} and [N II]/Hα, [S II]/Hα ratio in Anders & Alvensleben (2003), the expected flux of each line of [N II] or [S II] doublets is $\sim 1.0 \times 10^{-17}$ erg s^{-1} cm^{-2}. Using $K3000\_Kspec$ setup it requires 5 hrs to obtain 5σ detection, and Hα lines would reach much larger S/N within the same exposure time. Considering typical ionization parameter for EELGs ($q \sim 1 \times 10^8$ cm/s), the expected flux of [S III] is $\sim 1.0 \times 10^{-16}$ erg s^{-1} cm^{-2}, which will reach S/N > 5 with 5 hrs exposure time.

The MMIRS mask has a size of 4×6.9 arcmin. Consider the spatial separation we estimate that we can place ~ 20 galaxies on each mask. Hence we require 1 for zJ and K band MMIRS observations, with a total of 18 hrs (including overheads). We thus request **2 nights with MMT/MMIRS** in 2017B.

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**)*

We recently completed the discovery phase of this program over 2015B and 2016A semesters, building a sample of 60 EELGs. Here we propose detailed study of these galaxies by obtaining the full suite of optical emission lines in these galaxies. The bad weather in 2016B prevented us from gathering enough data. Targets visible in the Spring will be followed up by the upcoming 2017A program, and the proposal 2017B focuses on targets visible in the Fall. With the upcoming results from 2017A, this is the final request for this project. If weather does not cooperate in 2017B, we may need one final request in 2018A to reach our desired sample size. We are not requesting time from non-UAO telescopes. This project is expected to be the primary component of Mengtao Tang's PhD thesis.

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: 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 accepted in MNRAS (James, Koposov, Stark et al. 2014). Four nights have been awarded in 2014B. Observations are scheduled for late October and December 2014.

⋆ Fourteen MMIRS nights awarded (2015B, 2016A, 2016B, 2017A) for follow-up of $z \simeq 2$ galaxies with extreme optical line emission. 2015B, 2016A data have already been reduced and analyzed. Data taken from 2016B were not enough owing to the poor weather condition. 2017A data will be obtained in April.

Summary: 17 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 accepted (James, Koposov, Stark et al. 2015) and another in preparation.

Magellan: One night awarded for June 2014 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.

Six nights awarded from Steward in 2014B-2015B to target $z \simeq 6-8$ galaxies with FIRE. Only three nights provided useful data owing to weather in 2015B. Graduate student Ramesh Mainali is writing paper on detection of nebular CIV. Draft is in advanced state and will be submitted in summer 2016.

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

One night allocated on MODS in 2015B to target rest-UV spectra of EELGs. MOS mode was not available so we had to change program and use longslit, reducing efficiency. Data under analysis and will be written up by M. Tang. Some imaging of gravitationally-lensed galaxies obtained and are included in recently submitted paper by R. Mainali. This paper also makes extensive use of LBT/MMT spectra obtained by the PI over 2012-2014.

Two nights allocated to R. Mainali in 2016A to target CIII] in a $z \simeq 7-8$ galaxies with confirmed redshifts. No data taken due to weather.

Summary: Four nights allocated with LUCI, but no data acquired. One night obtained with MODS; one paper submitted and another in preparation

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

Stark et al. 2014, MNRAS, 445, 3200
Bian, Stark, et al. 2014, ApJ
James, Koposov, Stark et al. 2015, MNRAS, 448, 2687
Mainali et al. 2016, MNRAS, submitted.

Other Information *Provide any additional program-related information including, for example, relation of current program to externally funded research, to the development of expanded capabilities for UA telescopes, or to individual timescales (e.g. PI is finishing postdoc appointment and this request would complete program). (**up to one page**)*