OBSERVING REQUEST
University of Arizona Observatories

Year: 2015 **Term:** Aug–Dec **Proposal type:** short-term

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

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CoI(s): Mengtao Tang (SO), Ramesh Mainali* (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 outflows, 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. The outflowing gas (traced in absorption) appears highly ionized. The weak low ionization absorption lines in these systems point to a low covering fraction of neutral gas, which may play a significant role in allowing ionizing radiation to escape. However, these results are currently based on a handful of systems. Here we propose to use LBT/MODS and MMT/MMIRS to characterize the optical (rest-UV) and near-infrared (rest-optical) spectroscopic properties of a large sample of young, low mass galaxies at $z \simeq 2$. We have four objectives. First we will determine whether high ionization UV nebular emission lines (He II, CIV) are common. These features are rarely seen in massive star forming systems and require a significant output of very energetic radiation whose origin is unknown. Second, we will characterize the ionizing radiation field through comparison of UV and optical lines to photoionization models. Third, we will measure the kinematics, covering fraction, and ionization state of the outflowing gas. And fourth, we will estimate the metal content of the low mass systems. Taken together, this information will provide a much-improved picture for the formation and growth 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			4	bright	Oct	Sep–Nov	no	no
2	LBT		MODS			1	dark	Oct	Sep–Nov	yes	no

Scheduling constraints and unusable dates *(up to 4 lines)*: We prefer dark time for the optical LBT/MODS observations. Grey time will also be fine if the dark time is unavailable.

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	UDS	02:21:20	-04:30:00	H = 24-25.5

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
Mengtao Tang	Daniel Stark		no	no
Ramesh Mainali	Daniel Stark		no	no

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. Shapley et al. 2003, Steidel et al. 2014). 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 inter-galactic 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. 2014), and the dominance of such low luminosity galaxies becomes even more pronounced at yet earlier times (Schenker et al. 2013). 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 very low mass systems (e.g., Murray et al. 2005, Shen et al. 2013). 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.

Dwarf Star Forming Galaxies at High-Redshift: In the past several years, the first handful of detailed studies targeting high redshift galaxies with low stellar masses ($\sim 10^7$ M$_\odot$) have begun to emerge. The rest-frame ultraviolet spectra show strong nebular emission lines from high ionization species (CIV, He II), which are rarely seen in more massive star forming systems (e.g., Stark et al. 2014). These features require an extreme radiation field, as might be expected from a very young stellar population formed via a burst of star formation. While samples are very small, initial results reveal that the outflowing gas (traced by UV absorption lines) tends to be much more highly ionized than in more luminous systems (Erb et al. 2010), likely reflecting the intense ionizing field produced by the young, metal poor stars.

A related development is the discovery of a large population of $z \simeq 1.5-2$ low mass ($\sim 10^8 M_\odot$) galaxies with very large equivalent width rest-frame optical emission lines (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. Over 200 extreme emission line galaxies (EELGs) have recently been identified through the impact of the powerful emission lines on broadband photometry in the CANDELS multi wavelength imaging (Figure 1a), opening the door for a major spectroscopic campaign targeting low mass galaxies at high redshift. 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 (Figure 1b; Smit et al. 2015). The first attempt at ground-based near-infrared spectroscopy (which probes the strong rest-optical lines; Figure 2) suggests that at least a subset of the galaxies have low gas-phase metallicities and low dynamical masses (Maseda et al. 2014). No optical (rest-UV) spectroscopy has been obtained for this sample to date, hence constraints on the outflowing gas and UV emission lines are absent.

This Proposal. The progress described above hints at several important differences in the spectra of low mass galaxies. The extreme UV and optical emission lines reflect much more intense radiation fields and larger specific star formation rates than are seen in more massive star forming galaxies, The highly ionized outflowing gas may allow ionizing radiation to more easily escape through the circumgalactic medium.

However owing to the very small existing samples, it is unclear whether the presence of high ionization emission lines (CIV, He II) and weak low ionization absorption lines are common.

Here we propose to characterize the optical (rest-UV) and near-infrared (rest-optical) spectroscopic properties of a large sample of low mass extreme line emitting galaxies identified in the CANDELS fields. The (re)-installation of the near-infrared spectrograph MMIRS in MMT in 2015B provides an excellent opportunity for a major spectroscopic campaign. We will combine MMIRS observations of the rest-optical lines with LBT/MODS constraints on the rest-UV emission and absorption lines. We will target low mass galaxies in the one CANDELS field that is visible in the Fall semester. We have four key objectives which we describe in more detail below:

1. **Extreme UV Emission Lines.** The nebular UV lines seen in the low mass $z \simeq 2$ galaxies (Figure 3) may provide our only means of spectroscopically studying reionization-era galaxies with GMT (see Stark+ Magellan proposal). But to date, there are still very few galaxies showing these lines at moderate redshifts, precluding an accurate measure of the equivalent width distribution. Using MODS, we propose to provide the first constraints on the strength of UV nebular emission lines (CIV, He II, OIII], CIII]) in the extreme optical line emitting galaxies. Comparison of the UV line strengths to optical line properties (metal content, ionization parameter) will provide new insight into the physical conditions which support strong UV line emission. These observations will play a major role in guiding future surveys targeting UV lines in young, metal poor galaxies in the reionization era.

2. **Ionizing Spectra and Stellar Populations.** Steidel et al. (2014) has recently demonstrated that the ionizing spectrum in 'normal' massive star forming galaxies at $z \simeq 2-3$ requires much hotter stars than are typically found in evolutionary synthesis models. If the low mass extreme emission line galaxies are dominated by young stellar populations following a burst of star formation, we would likely expect an even more intense radiation field, as hinted by the preliminary results described above. We will use rest-optical and rest-UV emission line strengths (from MMIRS and MODS respectively) to characterize the radiation field of extreme line emitting galaxies.

3. **Outflows in Low Mass Galaxies.** The combination of optical and near-infrared spectroscopy promises new insight into feedback in extreme line emitting systems. We will use MODS spectra to trace the outflowing gas in absorption. The neutral gas kinematics and covering fraction will be traced through measurement of low-ionization absorption lines (OI+SiIIλ1303, CIIλ1334), while the hotter outflowing material will be probed through measurement of high-ionization absorption lines (CIV, Si IV). Rest-optical lines detected in MMIRS will provide the systemic redshift that is necessary to map the kinematics of the absorbing gas and will allow us to search for broad wings and asymmetric line profiles that may probe outflowing gas (e.g. Genzel et al. 2014). With these data, we will test the Erb et al. (2010) assertion that outflowing material is more highly ionized in young, lower mass galaxies.

4. **Metal Content.** Gas-phase metallicity is governed by gas accretion, star formation, and gas outflow, providing valuable insight into the history of baryonic assembly. MMIRS observations will provide optical lines ratios which we will use to characterize the metallicity distribution via standard calibrations. Based on the results of Maseda et al. (2014), we expect to build a sizeable sample of some of the most metal poor galaxies known at high redshift and to detect the auroral [OIII]4363 line in the brighter systems, providing a direct measure of the metallicity that is still rare at high redshift.

Reference: • Bouwens et al. 2010, ApJ, 709, 133 • Erb et al. 2010, ApJ, 719, 1168 • Forster-Schreiber et al. 2010, ApJ, 706, 1364 • Genzel et al. 2014, ApJ, 796, 1 • Governato et al. 2010, Nature, 463, 203 • Hopkins et al. 2011, MNRAS, 417, 950 • Maseda et al. 2013, ApJL, 778, L22 • Maseda et al. 2014, ApJ, 791, 17 • Reddy & Steidel 2009, ApJ, 692, 778 • Shapley et al. 2003, ApJ, 588, 65 • 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 • Stinson et al. 2013, ApJ, 667, 170 • van der Wel et al. 2011, ApJ, 742, 111

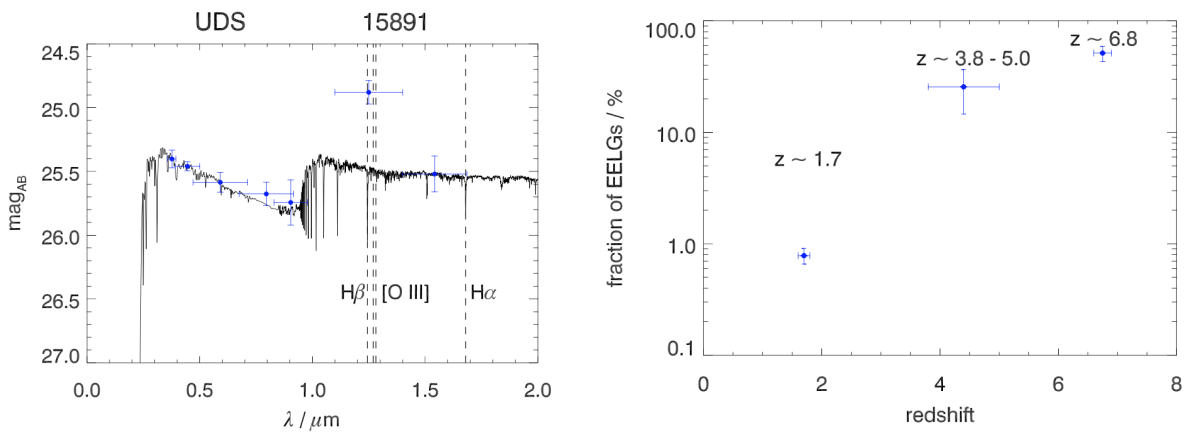

Figure 1: a. (left:) An example SED of a EELG at $z \sim 1.7$ from van der Wel et al. 2011. It is fitted without J_{125} band data and clearly shows J band excess. b. (right:) The fraction of EELGs evolved with redshift. Fraction at $z \sim 1.7$ is calculated from van der Wel et al. 2011; fraction at $z \sim 6.8$ is directly from Smit et al. 2015.

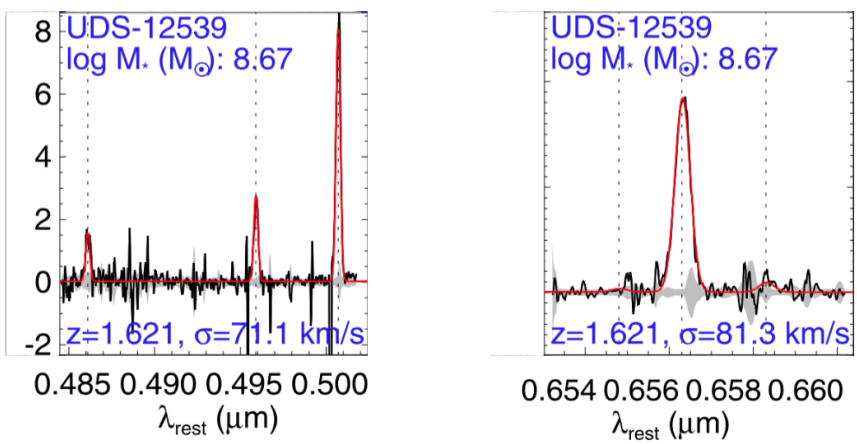

Figure 2: Example rest-frame optical spectrum of EELGs at $z \sim 1-2$ from Maseda et al. 2014. Optical emission lines (left: Hβ, [OIII], right: Hα) are clearly shown in the spectrum.

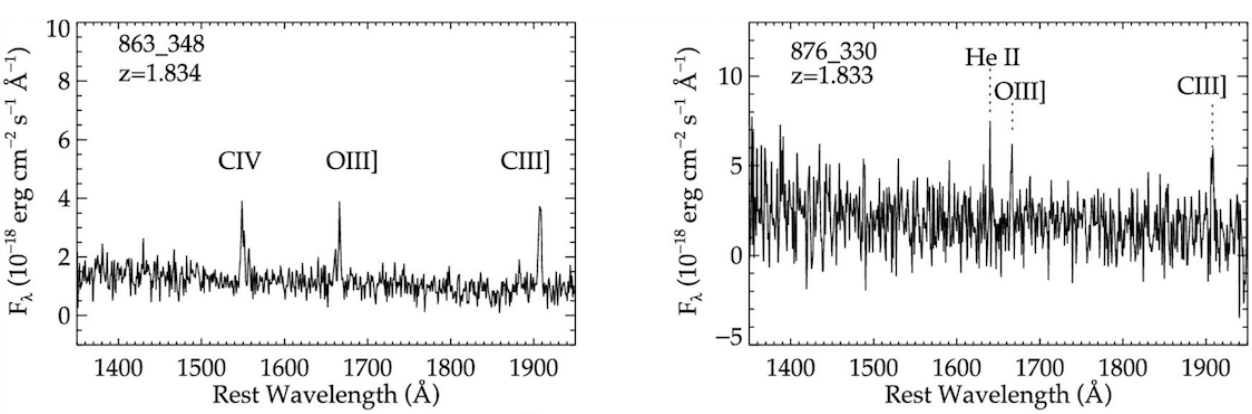

Figure 3: Example rest-frame UV spectra of low-mass (left: $\log M_*/M_\odot = 7.46$, right: $\log M_*/M_\odot = 7.80$), gravitationally lensed galaxies from Stark et al. 2014. Strong UV emission lines (HeII, CIV, OIII], CIII]) are shown in the spectra.

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 and LBT/MODS to obtain deep near-infrared and optical spectra of extreme optical emission line galaxies at redshift $z \sim 1.7$. The key requirements of this program are listed below. First, we need to integrate long enough to secure detection on the relative faint rest-frame optical emission lines (Hβ) and UV metal lines (CIV, He II, CIII], OIII]). Second, the UV and optical lines must be located in regions where the atmospheric transmission is near unity, which forces us to select galaxies with redshifts which place the relevant lines in the optical channel (avoiding the gap between the blue and red channels of MODS), or the J and H-bands of MMIRS. And third, we need a sufficiently large sample in order to obtain reliable statistical measures of the nature of the extreme line emitting population.

Sample Selection: Following van der Wel et al. (2011), we have identified EELGs at $z \sim 1.7$ in the four CANDELS fields visible from MMT and LBT. 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 grism spectra (which are too low resolution for our science goals) from 3D-HST to confirm redshifts. We then identify the subset of galaxies which place optical lines in clean regions of the NIR sky spectrum. The targets have typical magnitudes of H_{160}=24.0-25.5.

The total sample size is close to 200 over the four fields visible from the northern hemisphere. In the field that is up in 2015B, there are 41 extreme line emitting galaxies with no previous spectral constraints. We ultimately need a sufficiently large sample to see how spectroscopic properties (absorption line properties, UV emission line strengths, metal content) vary with stellar mass, and sSFR. For the near-infrared MMIRS component of this proposal, we seek to separate the galaxies into 4 mass/sSFR bins. To estimate average near-infrared spectroscopic properties, we require 10 galaxies per bin. Since no optical spectra exist on this sample, we seek to make a smaller first step with the MODS component of this proposal, obtaining a total sample of 20 systems with optical spectra. We will carefully choose these 20 objects to make sure they are representative of the parent sample.

Instrument Justification: This program requires sensitive spectroscopic constraints within the J band (Hβ, [OIII]) and H band (Hα, [NII]) with MMT/MMIRS and in the optical (UV metal lines, absorption lines) with LBT/MODS. We seek to observe ~ 40 galaxies. This will be more efficiently completed using multi-object spectrograph. Therefore we propose MMIRS in MMT and MODS in LBT for our observations.

Detection of Emission and Absorption Lines: Based on the J band magnitude (containing both continuum emission and optical emission lines: Hβ, [OIII] doublet) and H band magnitude (purely dominated by continuum emission) of EELGs at $z \sim 1.7$, we estimated the emission line flux taking standard line ratios for metal poor galaxies (consistent with those found in Maseda et al. 2014). For a typical object (J mag = 24.5, H mag = 25.3), the line fluxes are 4×10^{-17} erg/s/cm^2 for Hβ, 7×10^{-17} erg/s/cm^2 and 2×10^{-16} erg/s/cm^2 for [OIII] doublet. Using the MMIRS ETC, we estimate that these limits can be achieved in 5 hours using the J_zJ setup. The H-band will contain Hα and [NII]. We expect [NII] to be faint in metal poor galaxies, but based on the Hα strengths (predicted from Hβ using case B recombination), we expect to achieve a useful limit in 4 hours using the H_H setup. We estimate the rest-UV line fluxes from the equivalent widths in our earlier work. Given the typical magnitude of our sample, we estimate integration times of 4 hrs with MODS will yield continuum detections that allow us to place robust limits on the absorption lines and emission lines in the rest-UV.

The MMIRS mask has a size of 4×6.9 arcmin. We estimate that we can place 15-20 galaxies on each mask and hence we require 3 masks and a total of 32 hrs (including overheads) for the J and H-band MMIRS observations. For MODS, we estimate that we can place 8-12 objects per mask. To achieve our desired sample sizes, we thus request **4 nights with MMT/MMIRS and 1 night with LBT/MODS** in 2015B.

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 first request for this project. We are not requesting time from non-UAO telescopes. This project is expected to be the primary component of Mengtao Tang's 2nd Year project and will turn into a significant component of his PhD thesis. The results from the 2015B allocation will stand on their own and should be publishable. But we expect to request more MMT time to build up a very large spectroscopic database of low mass galaxies in GOODS North, the EGS, and COSMOS.

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.

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.

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 accepted (James, Koposov, Stark et al. 2015).

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. Further two nights awarded in February 2015. Several papers in preparation by graduate student Ramesh Mainali.

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.

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