OBSERVING REQUEST
University of Arizona Observatories

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

Physical properties of the brightest Lyα-emitting galaxy at $z > 5$ from deep optical spectroscopy

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Abstract of Scientific Justification

We serendipitously discovered the brightest galaxy known at $z > 5$ as part of an MMT program searching for quasars. J1414+5446 has $i_{\rm AB} = 23.2$ and extremely strong Lyα emission at a redshift of $z = 5.419$. We detected stellar continuum in a 40m. MMT spectrum, showing that J1414+5446 is uniquely suited for detailed studies of a galaxy near the epoch of reionization. We propose deep LBT/MODS spectroscopy to detect interstellar absorption features in the rest-frame UV continuum. We will use these features to probe outflowing gas powered by star-formation driven winds. The spectrum will also provide for detailed studies of the Lyα line profile, with moderate resolution and very high S/N, for a complementary tracer of outflows and neutral hydrogen absorption. By utilizing the MOS mode, we will also obtain redshifts for three candidate lensed arcs in the vicinity of the high-z galaxy and enhance the magnification model for a nearby lensing group (and its contribution to the observed flux of the galaxy). Finally, we will use LBT/LUCI JHK imaging to fill in the infrared SED and fit stellar population models to the galaxy. This data will form a picture of the star formation activity, gas outflows, and ionizing photon escape fraction at an epoch when star-forming galaxies are expected to have completed the reionization of the universe, but where observational constraints on key parameters — such as the escape fraction — are severly limited due to the faintness of known galaxies from deep surveys.

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	LBT	f/15	MODS			1	dark	Mar–May	Jan–Jun	yes	yes
2	LBT	f/15	LUCI			0.5	bright	Mar–May	Jan–Jun	yes	yes

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

no text past this line

A ⋆ appended to the proposal type indicates a continuation proposal; a ⋆ appended to the name of a proposer indicates the proposer is a (graduate) student; a proposer whose name is underlined is certified on the proposed telescope/instrument combination; if a ∗ appears within the PI or AO box in the observations summary table, the instrument is a PI instrument and/or Adaptive Optics are requested – signatures are required on the next page.

Target list (attach list if longer than 26 objects)

#	Object	RA	Dec	mag / color / type / redshift / comment / etc.
1	J1414+5446	14:14:46.82	+54:46:31.8	$z = 5.419$, $i_{\rm AB} = 23.2$, $z_{\rm AB} = 23.2$

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

Serendipitous discovery of the brightest LAE at $z > 5$ Observations of distant galaxies provide insight into the early stages of galaxy formation, as well as direct probes of the sources responsible for reionization. Among the most successful systematic searches for actively star-forming systems at high redshift are narrow-band imaging surveys that probe the class of Lyα emitters (LAEs), with various surveys having identified hundreds of such objects at $z > 5$, including many with spectroscopic confirmations. The strong Lyα emission from these galaxies implies moderately high star formation rates (SFRs) of $\sim 10\ M_\odot\ \mathrm{yr}^{-1}$; though this may underestimate the true SFR due to dust extinction and the complicated details of radiative transfer of the resonant Lyα line (which must escape both the galaxy and the dense surrounding medium at these redshifts). In any case, LAEs represent a significant fraction of the star-forming galaxies at $z \sim 6$, and shed light on the galaxy population that reionized the universe (Fan et al., 2006).

While searching the CFHT-W3 field (49 deg^2) in May 2012 as part of an MMT program to spectroscopically confirm faint, $z \sim 5$ quasar candidates, we discovered an extremely bright LAE at $z = 5.419$. J1414+5446 has $i_{\mathrm{AB}} = 23.2$ and $f_{\mathrm{Ly}\alpha} = 8 \times 10^{-16}$ erg s^{-1} cm^{-2}, making it by far the brightest LAE known at $z > 5$; surpassing a $z = 5.65$ object from the Wide-Field Imager Lyman-alpha Search (WFILAS, 0.72 deg^2, Westra et al., 2006) with $f_{\mathrm{Ly}\alpha} = 1 \times 10^{-16}$ erg s^{-1} cm^{-2}. From the CFHT imaging (0.9$''$ i-band, Fig. 1) and a 40m MMT Red Channel spectrum (Fig. 2), as well as archival HST F606W imaging, we have determined the following: 1) there is possibly a foreground galaxy, based on the g- and r-band detections in the CFHT imaging; 2) the galaxy lies $\sim 30''$ from the central galaxy of a known lensing group in the CFHTLS that includes three candidate lensed arcs, 2) the (unlensed) Lyα luminosity and Lyα-based star formation rate (SFR) are off the charts: $L_{\mathrm{Ly}\alpha} \sim 2.5 \times 10^{44}$ erg s^{-1}, SFR(Lyα) $>$ 260 $M_\odot$ yr^{-1}; and 3) even in a relatively shallow MMT spectrum we are able to detect the stellar continuum. J1414+5446 is either an exceptionally UV-luminous high-redshift galaxy, or if lensed, a more typical galaxy but one whose *brightness* makes it a unique target for a wide array of observations (although we estimate the lensing magnification from the group is a factor of $\sim$ 4–5 at most at the LAE position). *We propose combined MODS and LUCI observations at the LBT to conduct a detailed study of a rare, bright, reionization-epoch galaxy.*

Building the SED of an unusual galaxy We first propose a straightforward LBT/LUCI JHK imaging program to fill in the SED of this galaxy at longer wavelengths. We have already received *Spitzer* warm mission data at 3.6μm and 4.5μm. With full coverage from 0.5μm to 4.5μm we will measure the UV slope and the Balmer break of this galaxy. The photometric data will allow us to fit population synthesis models to the SED and constrain the stellar mass and age, as well as the amount of dust extinction.

Physical properties of a $z = 5.4$ galaxy The basic physical picture of Lyman-break galaxies (LBGs) based on observations at $z \approx 3$ is that they are compact ($r_{1/2} \sim 2$ kpc) and have moderately high SFRs ($\sim 50\ M_\odot\ \mathrm{yr}^{-1}$). The resulting high star formation surface densities should drive powerful winds of outflowing gas. Key questions are how much gas is ejected into the circumgalactic medium, and what the escape fraction of ionizing photons is from the galaxies; the latter being one of the crucial unknowns during the reionization epoch.

Using composite spectra of 81 LBGs at $z = 4$ with $z_{\mathrm{AB}} < 26$, Jones et al. (2012) confirm previous findings that the equivalent width of interstellar absorption features becomes greater with increasing Lyα emission; further, the Lyα-emitting fraction of LBGs increases at lower luminosities. They show that this trend increases with redshift; i.e., at higher redshifts the Lyα fraction increases and the mean ISM absorption line EW decreases. These trends hint that the covering fraction of neutral hydrogen decreases at lower luminosities and higher redshifts, allowing both Lyα and ionizing UV photons to escape more easily, exactly what is needed if faint galaxies are the primary source of reionization photons.

In detail, Jones et al. (2012) detect Si II λ1260, C II λ1334, Si IV $\lambda\lambda$1394, 1403, and C IV $\lambda\lambda$1548, 1550 in absorption in their composite spectrum, all of which will be available in a MODS spectrum of J1414+5446 (though with diminishing S/N for the longer wavelength transitions as they are in the OH sky line forest and a region of lower instrumental efficiency). Using the ratio of two Si II transitions at $\lambda = 1260$Å and $\lambda = 1527$Å they find that the absorbing gas is optically thick to UV photons near the systemic velocity $|v| < 200$ km s^{-1} but becomes more optically thin at higher velocities. They also detect fine-structure emission lines from Si II in their composite spectrum, providing another tracer of the kinematics and covering fraction of neutral gas. Further, the blueshift of the line center for various low-ionization absorption lines relative to the systemic velocity provides an estimate for the strength of the star-formation-driven outflows, as observed in a similarly bright, $z \sim 5$ galaxy (Frye et al., 2008).

Based on the trends outlines by Jones et al. (2012), for J1414+5446 we should expect very weak ISM absorption features, given its high redshift and extremely strong Lyα emission. If so, this may be an indication that the covering fraction of cool gas in galaxies at this epoch is low, allowing ionizing photons to escape. Because of its brightness, J1414+5446 is the best galaxy available at this redshift for obtaining constraints on ISM absorption features with low EW, allowing for a unique probe of the covering fraction near the reionization epoch.

High S/N study of Lyα at high redshift In the previous section we discussed tracers of cool absorbing gas *independent* of the Lyα line. Known galaxies at $z > 5$ are too faint for individual absorption line studies, and there are only marginally enough objects for meaningful composite spectra. Instead, much work has focused on the Lyα line, as its equivalent width, profile, and offset from systemic velocity all provide clues about the distribution of neutral gas around star-forming regions, providing constraints on galactic outflow models (Orsi et al., 2012). However, the details of Lyα radiative transfer are extremely complicated and the line profiles require detailed modeling (Verhamme et al., 2006).

With J1414+5447 we can study both the strong Lyα line emission and continuum properties *in the same galaxy*, due to its exceptional brightness. The shallow MMT spectrum already shows the Lyα line detected with extremely high S/N, but at low resolution. With four times greater resolution from LBT/MODS, we will be able to accurately model the Lyα line profile. Lyα line profile fitting can be used to estimate outflow velocities, extinction, and the escape fraction (Verhamme et al., 2008).

Diffuse Lyα emission provides a secondary channel for detecting gas ejected from star-forming galaxies into the circumgalactic medium, as that gas cools and re-radiates Lyα photons. The Lyα line itself can power strong winds (Dijkstra & Loeb, 2008). Such halos have been observed around high redshift quasars (e.g., Willott et al., 2012), but are generally too faint to be observed around galaxies. However, the strong Lyα emission in J1414+5446 again means that it is ideally suited for a search for diffuse Lyα by examining the extent of the Lyα emission along the slit direction in a 2D spectrum.

Constraining the group lens model J1414+5446 is $30''$ from the center of a lensing group identified as part of the CFHTLS (More et al., 2012). This group shows three candidate strong lenses, including two radial arcs and one lengthy tangential arc. A lensing mass model has already been developed for the group, but redshift information for the arcs will substantially improve the model. This will allow for further detailed study of the lensing group itself, as well as a refined estimate for the lensing magnification at the position of the J1414+5446 (which is currently estimated to be $\sim$ 4–5. We will target the lensed arcs with slits cut on MOS masks in order to obtain redshifts.

References

Dijkstra & Loeb 2008, MNRAS , 391, 457
Fan et al. 2006, ARA&A, 44, 415
Frye et al. 2008, ApJ , 685, L5
Kennicutt 1998, ARA&A, 36, 189
Jones et al. 2012, ApJ , 751, 51
More et al. 2012, ApJ , 749, 38
Orsi et al. 2012, MNRAS , 425, 87
Stanway et al. 2003, MNRAS , 342, 439
Verhamme et al. 2008, A&A , 491, 89
Verhamme et al. 2006, A&A , 460, 397
Westra et al. 2006, A & A, 455, 61
Willott et al. 2011, AJ , 142, 186

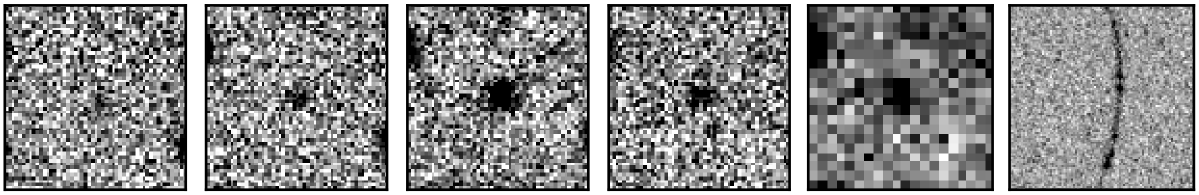

Figure 1: CFHT $griz$ images of J1414+5446 (10″). The measured fluxes are $g = 26.9 \pm 0.4$, $r = 25.4 \pm 0.2$, $i = 23.17 \pm 0.03$, and $z = 23.2 \pm 0.1$. We will examine the $\sim 2\sigma$ g-detection (indicating a foreground interloper) with MODS imaging. The fourth panel shows the $\sim 3\sigma$ LUCI detection from 2013A and the fifth panel shows an archival HST image of one of the nearby lensed arcs.

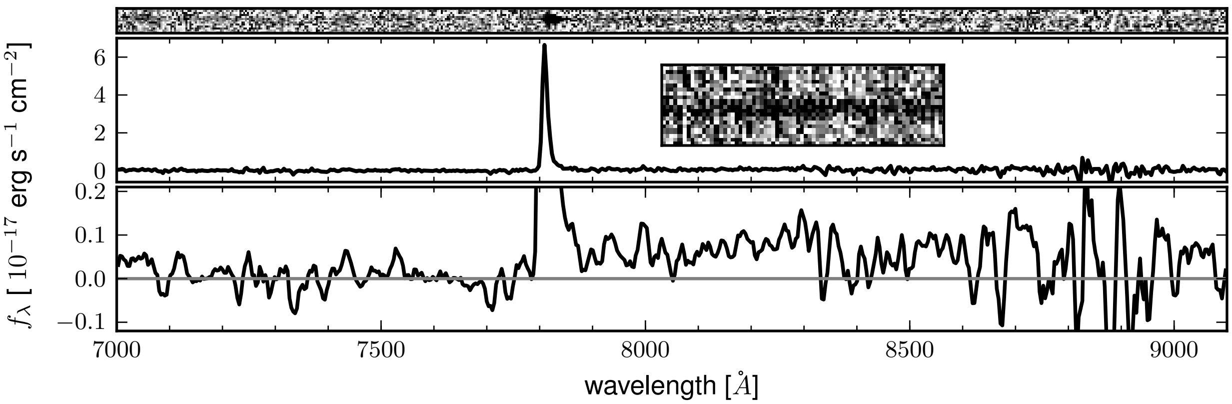

Figure 2: MMT Red Channel spectrum of J1414+5446. The upper panel shows the sky-subtracted 2D spectrum, the middle panel the extracted 1D spectrum, and the lower panel shows a zoom on the continuum detected redward of Lyα (also visible in the 2D image). The line is highly asymmetric due to absorption of the blue wing, as expected for a high-z LAE. The redshift measured from the centroid of the Lyα line is $z = 5.4189$. The line has a width of 190 $\mathrm{km\ s^{-1}}$ and a rest-frame $\mathrm{EW}_\lambda = 160$Å. The inset panel shows the continuum at ~ 8000Å from the stacked 2D LBT/MODS spectra obtained in 2013A, at $S/N \sim 3$ pixel^{-1}.

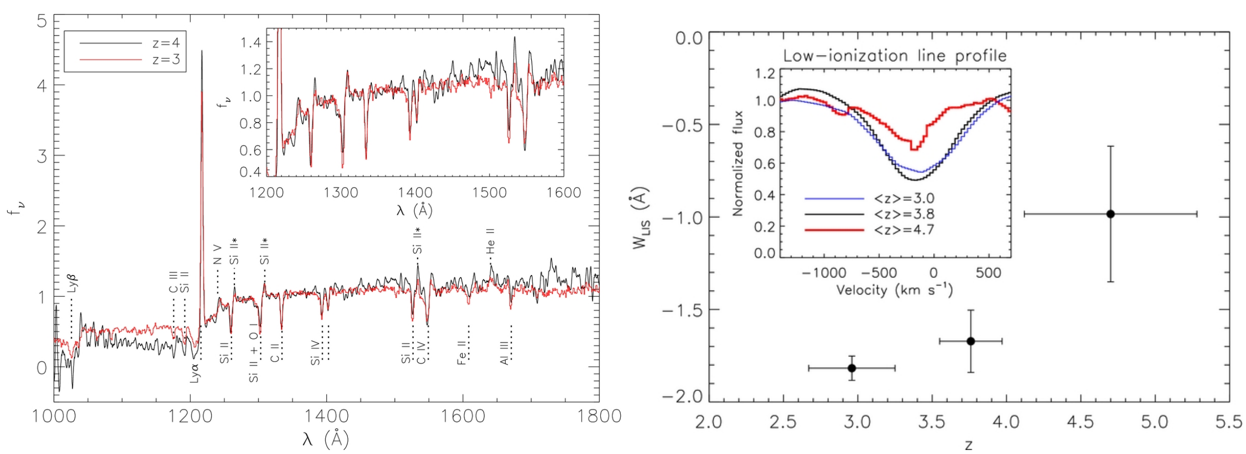

Figure 3: Figs. 4 and 11 from Jones et al. (2012). The left panel shows a composite spectrum of 81 galaxies at $\langle z \rangle = 3.9$ compared to a composite at $z = 3$. The $z = 4$ composite has $S/N \gtrsim 10$ in the continuum blueward of Lyα. The right panel highlights the trend of weakening interstellar absorption features with redshift. **We can achieve comparable S/N for the *single* bright $z = 5$ galaxy in this proposal.**

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**)*

This proposal consists of several components using the LBT to study this rare high redshift galaxy in detail:

LUCI imaging

Star-forming galaxies at $z \sim 6$ have colors $z_{\rm AB} - J \sim 1$ and $J - K \sim 1.5$ (Stanway et al., 2003). We initially estimated fluxes of $J \approx 22.2$ and $K \approx 21$ based on these colors and the optical photometry. Our J-band observations with LUCI from 2013A yield a flux of $J = 22.6 \pm 0.35$, slightly fainter than the original estimate. According to the LUCI ETC, $J = 22.5$ can be reached at 10σ in 1 hour (note that our 2013A observations were in very poor conditions with overhead clouds and $1.3''$ seeing, see next section). Similarly, in 1 hour $K = 21$ is reached at 7σ and $H = 21$ is reached at 9σ. Photometry at the $\sim 10\%$ level will be sufficient (in combination with our Spitzer imaging) to constrain SED models of the galaxy. Our total LUCI request is for 3 hours of imaging with ~ 0.5 hours for overhead.

MODS spectroscopy

We will use MODS in the dual grating mode with full coverage from 3000-10000Å in order to sample the rest-frame UV emission to $\sim$ 1560Å. Based on the MODS preliminary sensitivity specifications we estimate the continuum at rest-frame $\sim$ 1200Å will be detected at $\sim 10\sigma$ in a 10 hour integration. This would allow for detection of relatively low EW absorption features. We require dark time and good seeing conditions (if observed in queue mode) in order to maximize the S/N.

As detailed in the next section, in 2013A we designed two MOS masks for this target. Both masks included the high-z galaxy. The three lensed arc candidates were also divided between the two masks, and remaining positions were filled with group member galaxy candidates. Under poor conditions we detected the LAE continuum at $\sim 3\sigma$ in two hours, roughly consistent with our expectation that we could achieve $S/N \sim 10$ in 10 hours under good conditions. This is also sufficient for detection of emission lines from the lensed arc candidates, the faintest of which consists of multiple (5) emission knots with $R \sim 25$ (Fig.1), so that the summed flux is $R \sim 23.3$. Most of this emission can be covered by a single slit cut to match the extended arc profile.

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 proposal was awarded time in 2013A and 2014Afor both LUCI and MODS. Due to a combination of weather and the failure of the LUCI instrument for most of both semesters, the only LUCI data we have obtained is J/K imaging as part of backup observations during poor conditions. The data are poor quality. Nonetheless, we detect the galaxy at $\sim 3\sigma$ with a flux of $J = 22.6 \pm 0.4$ (Fig.1). This is within range of our original proposed estimate, and thus we are requesting the same amount of LUCI time in order to obtain higher S/N, multi-band detections of the galaxy.

We originally proposed for MODS time in longslit mode. However, further analysis of the galaxy showed that it lies behind a known lensing group from the CFHTLS. We thus modified our program to utilize two MOS masks, both of which included a slit for the high redshift galaxy, but which also contained two non-overlapping sets of slits for galaxies within the FoV. The primary goal was to obtain redshifts for three candidate lensed arcs associated with the lensing group. The arc redshifts would greatly enhance the lensing mass model for the group already developed by a team in Marseille. We also filled the masks with candidate group member galaxies to obtain velocity dispersion data. However, due to weather, only one mask was observed, for a total time of 2 hours. The seeing was mediocre ($\sim 1''$) and the telescope experienced collimation problems during the integration, contributing to image degradation (apparent by the distorted PSF in the acquisition image). We were thus unable to obtain sufficient S/N on the low surface brightness arcs, and the bright continuum from the high redshift LAE was only detected at $\sim 3\sigma$. We are thus requesting time in this proposal to reobserve the two masks. Under better conditions and with the full 10 hour exposure time we should reach $S/N \sim 10$ in the continuum of the high redshift LAE and obtain redshifts for the lensed arcs.

We have also been awarded Spitzer and HST time to observe this galaxy. The Spitzer observations are in hand, getting K-band imaging is crucial to filling out the SED just blueward of the 4000Å break. The HST data are scheduled for Cycle 22.

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)***

A Transformative Multi-Object AGN Reverberation Mapping Campaign: Photometric Component (2014A) – A large campaign to provide photometric data to complement multi-epoch spectroscopy with the SDSS telescope for the purposes of Over 60 epochs of g+i imaging obtained. First version of reduction pipeline has been released to the collaboration. Technical paper submitted, two more papers in preparation.

An LSST Pilot Survey: High redshift quasars from multiple-epoch imaging and the $z \sim 4$ luminosity function (2013B,2014B) – Four nights in 2013B; three telescope did not open, first night observed backup targets in poor conditions. Three nights in 2014B scheduled.

⋆ *Physical properties of the brightest Lyα-emitting galaxy at $z > 5$ from deep optical spectroscopy* (2013A/2014A) – One night in 2013B with LBT/MODS. Much of the run was lost to bad weather. Obtained two hours of observations with one mask. 1.5 nights in 2014B. No additional spectroscopy obtained due to weather. Obtained 0.5 hrs g-band imaging and some poor K-band imaging. Discovery paper is in preparation.

varBoötes: A Study of AGN Variability in the NDWFS Boötes Region (2012B/2013A/2014A) – Several epochs of imaging on Boötes obtained. Data quality is very good for most epochs. Some data is reduced and we have checked that the S/N at the faint limit is sufficiently high for variability studies. Project is now being folded into tests of target selection in SDSS-IV/eBOSS as well as quasar variability studies with the SDSS-III Reverberation Mapping campaign.

⋆ *The Faint QSO Luminosity Function at $z \sim 5$ From CFHTLS-W3* (2012BC/2014A) – Four nights in 2012 resulted in ~ 20 new quasars in the CFHT fields. One night in 2014 lost to weather. MMT data will be combined with two nights of Gemini data to provide the first measurement of the $z \sim 5$ QLF to $i \sim 24$. One paper published (from 2011 data on similar program), analysis for second paper started.
