**OBSERVING REQUEST**
**University of Arizona Observatories**

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

# Lyman alpha, Lensing, and First Light


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**Abstract of Scientific Justification**

**We request 4 nights in 2015A to image four strongly lensed fields to finish our entire program of finding Ly-$\alpha$ galaxies to test for neutrality of inter-galactic gas at z=8.8**.

The redshift of reionization, its speed, and its homogeneity remain largely unknown. The Gunn-Peterson test places a lower bound ($z > 6$), while microwave background polarization provides an integral constraint implying $z \sim 10$. Ly-$\alpha$ galaxies provide a powerful tool to probe the *central phase* of reionization with neutral gas fractions of $\sim$50%, because the Ly-$\alpha$ photons scatter resonantly in a 50% neutral intergalactic medium (IGM), much like a lamp in fog. The observed Ly-$\alpha$ luminosity function (LF) should therefore decline substantially in neutral IGM. We pioneered this test, showing that the IGM is mostly ionized at z = 6.5 (Malhotra & Rhoads 2004, 2006).

**Magellan and Fourstar provide the best combination of telescope aperture and survey area to apply this test at $z \approx 9$, near the epoch of reionization.** In addition, we have designed an optimal survey that covers one blank (unlensed) field to a depth of $0.7L_*$, and six fields with strong gravitational lensing. The lensed regions will constrain the faint end of the luminosity function. The unmagnified parts cover a large volume, sampling bright end of the LF. For our overall program, we expect 20–22 Ly-$\alpha$ galaxies at $z \approx 9$, in an ionized IGM and 2–4 sources in neutral medium. Presently, there are *no* confirmed Ly-$\alpha$ emitters at $z > 7.6$ (from *any* search), and no narrow-band surveys with comparable depth and areal coverage.

So far, our COSMOS imaging has resulted in the deepest narrow-band image at 1.19$\mu$m and several good candidates for which we have succesfully obtained NASA Keck time for spectroscopic followup.


**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 | MAG1 | f/11 | FOURSTAR | | | 2 | grey | Jan | Jan-Feb | yes | no |
| 2 | MAG1 | f/11 | FOURSTAR | | | 2 | grey | Jun-Jul | May-Jul | yes | no |

**Scheduling constraints and unusable dates** *(up to 4 lines)*: Moon is too near one of our target fields on 2015 Jan 1–9, 26–31; Feb 1–4, 23–38; May 3–11, 30–31; Jun 1–3, 5–8, 26–30; Jul 3–5 & 24–28.

*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 | 0826 | 08:26:05.03 | +04:19:10.6 | Wong et al 13; good in Jan, ok to March |
| 2 | 2128 | 21:28:25.93 | +01:33:15.5 | Wong et al 13; 2nd halves, Jun-Jul |
| 3 | MACSJ0416 | 04:16:08.9 | -24:04:28.7 | HST Frontier field; 1st halves, January. |
| 4 | 1616 | 16:16:09.34 | +06:56:43.5 | Wong et al 13; Apr-Jul |

**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 |
|---|---|---|---|---|
| Alicia Gonzalez | James Rhoads | James E. Rhoads | no | yes |

## Scientific Justification

**Program Overview and Update:** This is a continuation of the FourStar narrowband Ly-$\alpha$ survey that the TAC supported in the 2013A, 2013B, and 2014A with a total of five nights, among which 2 were useful (one on Abell 370 in November 2013, one on COSMOS in February 2014) and 3 lost to weather. Our Carnegie partners have allocated time generously to the COSMOS field, which is now complete with 7 nights of on-sky integration (including data from programs led by Rhoads/Malhotra, Persson, Dressler, and Lee).

Our COSMOS stack is the deepest $1.19\mu m$ narrowband image ever. It achieves a $5\sigma$ limiting AB magnitude near 26.0, corresponding to $4 \times 10^{-18}\,\mathrm{erg\,cm^{-2}\,s^{-1}}$ for a pure emission line source. These limits are in line with our predictions in earlier proposals. Our stack is competitive in continuum sensitivity with the deepest near-IR broadband images of the field, including the HST-CANDELS J band imaging (see fig. 2). We have identified five top-grade $z = 8.8$ candidates, along with 19 lower confidence candidates, consistent with expectations. We have been allocated two nights of Keck+MOSFIRE (24 March 2014) through the NASA TAC, in highly competitive cycles. Unfortunately, $2''$ seeing on the first night prevented our spectra from reaching the faint flux levels needed, but brighter foreground line emitters were confirmed, validating our selection procedures. Our second MOSFIRE night is scheduled in early 2015.

The strong lensing portion of our program is intended to cover a total of six fields. Two are complete (Abel 370, from Arizona time; and Abell S1068, from OCIW time). One more should be observed under an OCIW program in late 2014, if conditions are good.

We ask now for four nights to complete the strong lensing field portion of the program. This will yield both intrinsically fainter galaxies that are lensed, and more of the brightest Ly-$\alpha$ galaxies from the large unlensed areas near field edges. It thus dramatically increases our power to measure the luminosity function shape. *Our OCIW partners have already exceeded their planned allocation of time to this joint program. Completing the full program now depends on suitable support from the Arizona Observatories.*

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**Lya galaxies are unique probes of the epoch of reionization.** In the last decade, the community has narrowed down the epoch of reionization to redshifts $6 < z < 11$ (e.g. Fan et al. 2002, Dunkley et al. 2009), and shown that faint star-forming galaxies can provide enough photons to power reionization (e.g. Yan & Windhorst 04, Malhotra et al. 05, Bouwens et al. 2007, 2011). There remain several outstanding questions. Was reionization quick, as seen in some simulations (e.g. Gnedin 2000)? Or did it happen twice (Cen 2003)? Or was it inhomogeneous (Messinger & Furlanetto 2009)? Whatever imprint reionization leaves on the intergalactic medium (IGM), or on the mass function of dwarf galaxies, it also provides invaluable information about the earliest star-formation in the universe.

We don't even know the exact redshift of reionization. The Gunn-Peterson effect in quasar spectra probes the late stages of reionization (e.g., Fan et al. 2002, 2006), while polarization of the cosmic microwave background gives us the total column density of free electrons and therefore a characteristic redshift of reionization (by assuming a single step function phase transition, Dunkley et al. 2009). New and powerful 21 cm experiments are being built to detect the signal from neutral gas before reionization, but they must overcome the challenges of foregrounds that are $10^5$ times brighter.

Before reionization, the neutral IGM scatters Ly-$\alpha$ photons like a fog. Reionization removes neutral hydrogen, leaving us a clear view of any Ly-$\alpha$ sources. Detailed modeling shows that the apparent Ly-$\alpha$ luminosity function in a neutral IGM is shifted towards faint fluxes by at least a factor of 3 (Santos 2004, Haiman 2002). The first statistical test of reionization using Ly-$\alpha$ emitters by Malhotra & Rhoads (2004) showed that the neutral fraction of the IGM is lower than 30% at z=6.5.

**Lya galaxies constrain the IGM neutral fraction.**
*(a) they probe the central phase of reionization at neutral fraction $\simeq 0.5$*
*(b) they probe local IGM around galaxies, thus providing a good measure of inhomogenieties in reionization*
*(c) the test is scalable to different redshifts and in the area covered*
*(d) the Ly-$\alpha$ reionization test can be carried out with current technology.* Wide field cameras and narrow-band filters are in use now. The narrow-band method of selecting Ly-$\alpha$ emitters is a well tested method. Unlike the 21cm searches, there are no foregrounds to worry about.

**Lya galaxies are detectable in the ideal redshift range.** Large surveys up to $z = 6.5$ suggest a modest ($\sim$30%) change in the Ly-$\alpha$ luminosity function from $z$=5.7 to 6.5 (Ouchi et al 2010, Hu et al 2010, Kashikawa et al 2011). This *might* indicate a small increase in neutral faction of the IGM (Kashikawa et al. 2011), but neither Ly-$\alpha$ line profile evolution (Ouchi et al 2010, Hu et al 2010) nor Ly-$\alpha$ galaxy clustering (McQuinn et al 2007) support neutral gas. Looking for small attenuation factors to test small neutral fractions runs into issues with systematics like galaxy evolution and field-to-field variations (Djikstra et al. 2007). *Therefore it is best to probe the central part of the reionization epoch, where the dimming of Ly-$\alpha$ is expected to be factor of 3, and we would see a dramatic change in the line profiles of Ly-$\alpha$ galaxies.*

Surveys at $z \approx 7$ have found and confirmed Ly-$\alpha$ selected galaxies up to z=7.3 (e.g. Shibuya et al. 2012, Rhoads et al. 2012), but in small numbers. Searches at $z = 7$ suffer especially from the declining sensitivity in optical CCDs. Another approach has been to look for Ly-$\alpha$ lines in continuum-selected i, z, and Y dropout galaxies (Pentericci et al 11; Schenker et al 11). This has had notable successes (including the current spectroscopic redshift record, Finkelstein et al 2013), but also has its own difficulties: First, about 40% of the Ly-$\alpha$ lines are expected to fall on top of bright airglow lines at moderate resolution. Second, the *expected* number of detections depends critically on photometric redshift probability distributions. Our approach avoids these issues, and so provides a crucial check on the spectroscopic Ly-$\alpha$ fraction studies.

**The Advantages of Our Survey:** (1) *We will probe the central redshift of reionization:* WMAP measurements of electron scattering optical depth imply $z_{reion} = 11.0 \pm 1.4$, with $z < 6.7$ ruled out at $3\sigma$ and $z < 8.2$ ruled out at $2\sigma$. We will carry out the Ly-$\alpha$ test at z=8.8, within the WMAP range where we expect $x_{HI} \approx 0.5$.

(2) *This survey is robustly designed to go deep enough to detect high redshift galaxies*: We have reached $0.7 \times L_*$ at $5\sigma$ for $z = 8.8$ Ly-$\alpha$ galaxies in COSMOS, thanks to our low-OH narrow-band filter and the large aperture and good seeing at Magellan.

(3) *We will get a statistically useful sample, including the faint and bright end of the luminosity function:* We will combine a deep field with 6 high-magnification fields, at 1/6th the exposure time per field. We should see $\sim 5$ lensed objects intrinsically fainter than our deep-field limit ($0.7L_*$). Simultaneously, the *unlensed* portions of these six fields will yield $\sim 8$ objects brighter than $1.6L*$. Together, the deep unlensed field and the six high-magnification fields will yield 20-22 Ly-$\alpha$ emitters at z=8.8, distributed widely in $L$, and thus enabling a high quality luminosity function measurement.

(4) *Spectroscopic followup is practical:* The narrowband filter pre-selects candidates with Ly-$\alpha$ emission in the dark part of the OH forest, maximizing our chances of getting conclusive spectra. Also, using well-studied enables collaborative followup to observe our objects with large telescopes outside the UAO system.

**Cluster Selection:** To date, we have observed two cluster fields (Abell 370 and Abell S1063), among a total of six. Our cluster targets are selected with the uniform goal of identifying the best gravitational telescopes in the sky. Two are from the lensing catalog of Wang, Zabludoff, Ammons et al (2013), with an initial selection based on SDSS luminous red galaxy surface density, and with followup spectra and deep Subaru imaging that yielded lens models with lensing masses $\sim 3 \times 10^{15} M_{\odot}$. The rest are HST Frontier Fields. The Frontier Fields have detailed public lens models, which we will use to translate our observations to luminosity function measurements. They also have deep imaging in multiple broadbands. Our narrowband observations are highly complementary with the HST broadband survey. We will be able to detect strongly lensed (and hence spatially extended) emission line galaxies that would not be detected in the Frontier Field observations themselves.[1] Pursuing our observations in the Frontier Fields will help enable collaborative access to spectra and other complementary data, just as it does in COSMOS.

To summarize, we have designed an optimal survey to determine the luminosity function of Ly-$\alpha$ emitters at z=8.8, using Magellan + FourStar. We have reached our target depth in COSMOS. We now wish to finish the complementary observations of strong gravitational lensing fields, of which we have observed just one so far. This will double our Ly-$\alpha$ sample and extend its luminosity range, dramatically improving our constraints on the shape of the Ly-$\alpha$ luminosity function at $z \approx 9$— in the era of Cosmic Dawn.

[1] The line flux limit for our lensing fields, $7 \times 10^{-18}\,\mathrm{erg\,cm^{-2}\,s^{-1}}$, corresponds to mag 28.7 in a broad band F125W filter. This is fainter than the expected HST Frontier Field depth for extended sources, and strongly lensed galaxies are extended at HST resolution (cf. Oesch et al 14).

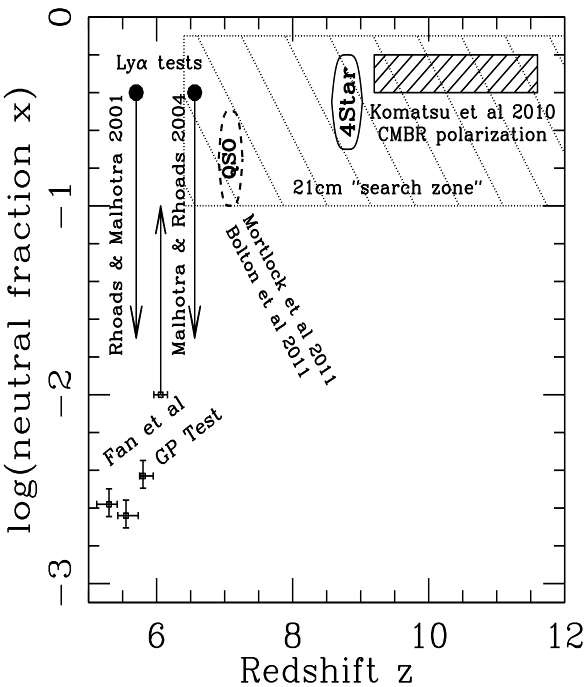


Figure 1: Our program in context (see "4Star"). We plot here a summary of observational constraints on reionization history. The Gunn-Peterson test results by Fan et al map the end of reionization, with several neutral fraction measurements at $z < 6$ and a lower bound on the $z \approx 6$ neutral fraction. Past work using Ly-$\alpha$ emitters provides complementary upper bounds at $z \approx 5.7$ and $6.5$. Recent results from the $z \approx 7.1$ quasar suggest some neutral gas at $z \approx 7$. Finally, polarization of the cosmic microwave background gives an estimate of the era when the IGM must have passed through a 50% neutral fraction. However, this is an integral constraint; what is really plotted is the redshift range where a step-function instantaneous reionization would match the data. *The point marked "4Star" shows the redshift and the range of neutral fractions probed by our proposed program. It fills a significant hole in the data, between the CMBR constraints and the current Ly-$\alpha$ and quasar constraints.* Our work will help plan more efficient 21cm experiments, which can be tuned to cover a more relevant portion of the redshift range from 6 to 12.

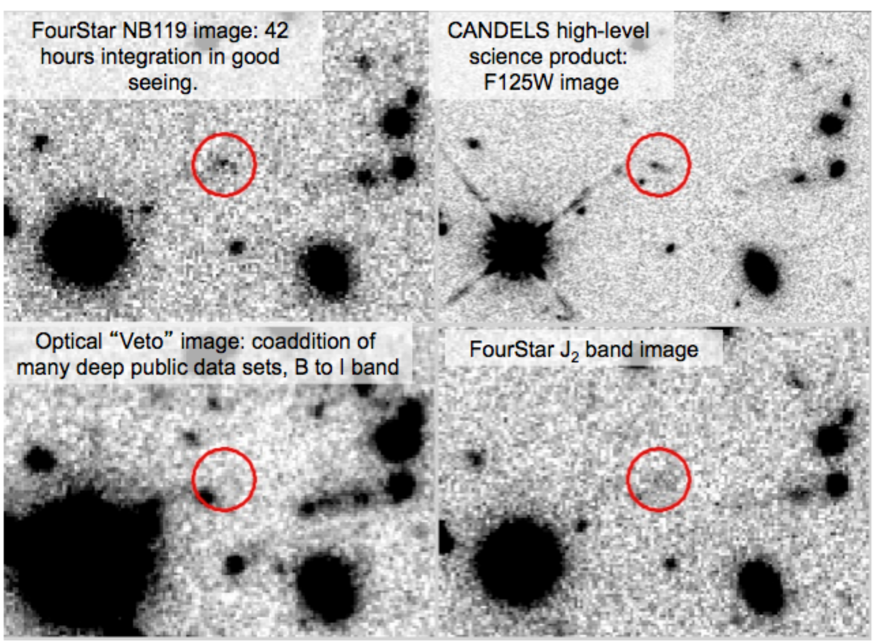


Figure 2: Results from our deep field in COSMOS: Postage stamps of a Ly-$\alpha$ candidate in the Narrow-band image $1.19\mu m$ image (top-left), CANDELS F125W image (top right), optical veto image (bottom-left) and J$_2$-band image (courtesy of the zFOURGE project, bottom-right). The position of Ly-$\alpha$ candidate is marked with circles. Candidates are selected to be (1) $6\sigma$ significant in the stacked narrowband image; (2) twice as bright in the narrowband as the broad band image (measured in bandpass-averaged $f_\nu$ units); (3) brighter in the narrowband than the broad band at the $3\sigma$ significance level; and (4) undetected in the combined optical image at the $2\sigma$ level. **In COSMOS, we have detected five top-grade $z = 8.8$ candidates, along with 19 lower confidence candidates, consistent with expectations;** and have been awarded NASA Keck+MOSFIRE time for followup spectroscopy. Our first two lensing fields, Abell 370 and Abell S1063, are fully observed and reduced, and candidate selection in those fields is now in progress.

**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)***

Our overall survey design consists of one deep, blank field and combined with six strongly lensed fields. This semester, we will concentrate on the lensed component, requesting four nights through the UAO TAC. Our colleagues at OCIW plan a similar request to their TAC. Together these requests could finish the lensed field observations if conditions are consistently good. If the intergalactic medium is ionized, our target depth and volume coverage should yield 20–22 Ly-$\alpha$ galaxies total, with about half in the deep field and the remainder in the lensed fields. In contrast, we expect only $\sim$ 2–4 galaxies if the IGM is $\gtrsim$50% neutral.

*FourStar provides the critical boost in NIR sensitivity and field of view that was needed to enable this science.* The high redshift of reionization demands a near-infrared instrument. The corresponding luminosity distance demands a 6–10m class telescope. The number density of sources demands a reasonably large field. No other NIR camera on any 6–10m class telescope provides a field of view to match FourStar.

We calculated our signal-to-noise ratios using on-sky performance numbers for the 1.19$\mu$m narowband filter on FourStar, and using PSF-fitting photometry (which maximizes signal-to-noise ratio for compact sources, including typical Lyman alpha galaxies, which have characteristic sizes $\leq 0.15''$). The observations are background-limited, with a background count rate $\approx 8.7e^-s^{-1}$. For a Gaussian PSF of width $\sigma$, the effective number of noise pixels is $N_{np} = 4\pi(\sigma/\mathrm{pix})^2 = 2.266(\theta_{\mathrm{FWHM}}/\mathrm{pix})^2 = 22.4(\theta_{\mathrm{FWHM}}/0.5'')^2$. The total noise is then $\mathcal{N} = \sqrt{N_{np} \times 8.7e^-s^{-1} \times t_{int}} = \sqrt{195 \times (t_{int}/s)} \times (\theta_{\mathrm{FWHM}}/0.5'')$.

For the signal, consider an emission line with flux $5 \times 10^{-18}\,\mathrm{erg\,cm^{-2}\,s^{-1}}$. This corresponds to AB=25.8 mag for this 137Å filter centered at $1.19\mu m$. Using the filter's zero point, $AB = 25.66 \leftrightarrow 1\,\mathrm{e^-\,s^{-1}}$, this corresponds to $\mathcal{S} = 0.35\mathrm{e^-\,s^{-1}} \times t_{int} \times (f/5 \times 10^{-18}\,\mathrm{erg\,cm^{-2}\,s^{-1}})$.

The net signal-to-noise ratio then becomes

$$\mathcal{S}/\mathcal{N} = 5 \times \left(\frac{f}{5 \times 10^{-18}\,\mathrm{erg\,cm^{-2}\,s^{-1}}}\right) \times \sqrt{\frac{t_{int}}{11.1\,\mathrm{hr}}} \times \left(\frac{0.5''}{\theta_{\mathrm{FWHM}}}\right) \quad .$$

For our deep field, which overlaps regions studied by the COSMOS and CANDELS projects, we have 42 hours on-sky integration with $\langle\theta_{\mathrm{FWHM}}\rangle \sim 0.7''$. Our realized sensitivity is consistent with the above equation.

For the lensed fields we here propose 7 hours on-sky narrowband integration per target, with a corresponding $5\sigma$ depth estimate of 6.3–$8.8 \times 10^{-18}\,\mathrm{erg\,cm^{-2}\,s^{-1}}$ in $0.5''$–$0.7''$ seeing. This depth is confirmed in our first two lensing fields completed (Abell 370 and Abell S1063).

To predict the numbers of high-redshift objects visible to these limits, we combine a Schechter luminosity function with the area-magnification curve appropriate to a high quality lensing field. Even without lensing, we would expect$\sim$ 8 bright Ly-$\alpha$ galaxies among the six fields (for a range of plausible assumptions about seeing and about the luminosity function parameters [Ouchi et al 2010; Kashikawa et al 2011]). With lensing, this expected number increases to $\sim$ 13, including objects intrinsically much fainter than those we can find in our deep field— down to intrinsic luminosities $\lesssim 0.2L_*$.

Our target fields all have significant HST and/or Subaru archival data. However, this does not in general provide J-band coverage over the full 11' FourStar field of view. Thus, in addition to the narrowband imaging, we will need about 2 hours of J band imaging per field. Our total request of 3 nights will allow us to image 3 lensed fields under optimum conditions.

Sullivan and Simcoe (2012; arxiv:1207.0817) measured an increase of $>$ 1mag in the interline y- and J-band sky background near full moon. *We therefore emphasize that we do need $\lesssim$9 day moon for this work. Also, nights when the moon is excessively near a target field may not be used with optimum efficiency. Such nights, when they fall in grey rather than bright time, are listed above under the "unusable dates" section.*

**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 will measure the Ly-$\alpha$ luminosity function at redshift $z \approx 9$ through a clever combination of deep FourStar narrowband imaging in one field and shallower observations of half a dozen strongly lensed lines of sight. Using this LF measurement, we will determine whether the intergalactic medium was neutral or ionized at redshift 9.

**We have built a collaboration between Arizona State University, the University of Arizona, and the Carnegie Observatories** to carry out this program. Our original plan was for an approximately even split between UAO and OCIW time. However, we are near a 30/70 split in time awarded to date.

In 2013A, the UAO TAC gave us two nights towards our deep field (in COSMOS). These were unfortunately lost to weather. Our OCIW co-Is — Alan Dressler, Eric Persson, and Andy Monson — obtained a total of 20 hours' integration on COSMOS from OCIW time, and Janice Lee shared an additional 9.6 hours of data from earlier semesters (Lee et al 2012).
In 2013B, the UAO TAC gave us two further nights, which we used to image our first lensed field (Abell 370).
In 2014A, the UAO TAC gave us one night, which we used for COSMOS imaging, and our OCIW collaborators observed COSMOS for an additional three nights.
In 2014B, we were not allocated time by UAO. Our OCIW collaborators allocated six half-nights for lensed fields (2/6 successful, on Abell S1063; 2/6 clouded out; and the final 2/6 upcoming.)

For 2015A, we are requesting four nights from the UAO TAC, to observe four more lensed fields. This could be our last request for this program, if the request is granted and conditions are good. Otherwise, we anticipate a further request in the one more semester to finish the lensed target component.

The outer regions of the lensed fields (observed 1 magnitude shallower than our deep field) will constrain the bright end of the luminosity function well, up to $3L_*$, while the strongly amplified regions will probe the faint end (down to $0.2L_*$). This "extended" LF measurement will provide powerful leverage, breaking the degeneracies between $L_*$, $\phi_*$, and $\alpha$.

We have collaborators who study other targets in the COSMOS field, have access to Keck+MOSFIRE or VLT+XShooter, and will be glad to include $z \approx 9$ objects in their observations. That will be one channel for spectroscopic followup of our COSMOS observations.

We were granted our full request for followup Keck+MOSFIRE spectroscopy by the NASA Keck TAC, both in Spring 2014 *and* in Spring 2015. The spring 2014 observations had $2''$ seeing and did not achieve sufficient depth for $z = 8.8$ galaxies, but we were able to confirm some foreground emission line sources. We look forward to our next MOSFIRE night in 2015A.

**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)***

We have made effective use of UAO facilities in past. UAO data have formed integral parts of four PhD theses with Rhoads (S. Finkelstein, E. McLinden) and with Malhotra (L. Xia, Z. Zheng) in the past five years. The PI (Rhoads) is an author on 15 published papers based on UAO data over the past five years, with another five submitted or in advanced stages of preparation.

Specific details for observing runs in the last 2–3 years:

⋆ Magellan + FourStar, PI=Rhoads, March 6-7 2013; first AZ run for this project: One night completely lost (dome closed); other fairly useless due to heavy cirrus clouds.

⋆ Magellan + FourStar, PI=Rhoads, November 24–25 2013; this project: Total of 1 night of useful data; we observed our first lensed field target (Abell 370).

⋆ Magellan + FourStar, PI=Rhoads, February 6 2014: One reasonably good night on COSMOS. Combined with about 35 hours of data from our collaborators, this yielded the images used to identify $z = 8.8$ galaxy candidates (see fig. 2).

Magellan + IMACS, PI = Rhoads, March 16-18th 2009; narrow-band imaging correspoding to z=6.9; good weather and good data! *Published in Hibon et al 2011, ApJ 741, 101*

⋆ MMT + Hectospec, PI=Malhotra, spring 2014: Gas metallicity of low-mass starburst galaxies. This project is essentially spectroscopy of the foreground emitter samples identified in the course of Ly-$\alpha$ surveys. The data are promising, and scientific analysis in in progress.

Magellan + IMACS spectroscopy, PI = Rhoads, December 30–31 2010; and February 8, 2011: 7 hours of data obtained, following up the candidates from Hibon et al 2011. One Ly-$\alpha$ galaxy confirmed at $z \approx 6.944$. *Published in Rhoads et al 2012, ApJ Lett 752, L28. This is currently (a) among the highest 15 spectroscopically confirmed redshifts, (b) the faintest $z \gtrsim 7$ galaxy spectroscopically confirmed, and (c) the most distant object discovered with Magellan.*

LBT+LUCIFER, 1 night allocated 2012 April 14–18, PI = McLinden. 3 $z \approx 3.1$ Ly-$\alpha$ galaxies observed in NIR. Published in McLinden et al 2014, MNRAS 439, 446.