OBSERVING REQUEST
University of Arizona Observatories

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

Recalibrating Strong-line Metallicity Diagnostics for $z \geq 1$ Chemical Enrichment Studies with T_e-based Metallicities

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Abstract of Scientific Justification

The gas-phase metallicity of galaxies—and how it depends on stellar mass and SFR—is a key test of galaxy evolution models with gas accretion and star-formation "feedback." However, tracing the evolution of the stellar mass–metallicity–SFR relation has been problematic since local "strong-line" metallicity diagnostics are *not* valid for high-redshift galaxies. Specifically, numerous studies have now demonstrated that the interstellar gas properties of high-z galaxies are different from local star-forming galaxies.

To solve this problem directly, electron temperature (T_e) based metallicities at high redshifts are needed to empirically recalibrate strong-line metallicity diagnostics at $z \gtrsim 1$. This is difficult as it requires the detection of [O III]λ4363. We have completed a survey that has detected [O III]λ4363 in $\sim$100 star-forming galaxies at redshifts up to $z \sim 1$ (Ly et al. 2015a, 2016a). However, existing optical spectra miss Hα and [N II]λ6583 at $z \gtrsim 0.5$. These emission lines are used in almost *every* chemical enrichment study.

We propose MMT/MMIRS spectroscopy of five $z \sim 1$ [O III]λ4363-detected galaxies, to recalibrate strong-line metallicity diagnostics using T_e-based metallicities. Our study will be the first to recalibrate metallicity diagnostics for high-z galaxies using T_e-based metallicities. Our program efficiently uses telescope time by targeting galaxies that already have nebular emission-line measurements below rest-frame $\sim$5010 Å. Also, we have found that these galaxies have similar interstellar gas properties as $z \gtrsim 2$ galaxies. Our measurements will be incorporated within our existing framework for metallicity recalibration, which we are already finding to be more robust than previous calibrations. Given the importance of strong-line metallicity diagnostics, our new calibration will be frequently used in chemical enrichment studies.

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	f/5	MMIRS			1	bright	Oct–Nov	Sep–Dec	no	no

Scheduling constraints and unusable dates *(up to 4 lines)*: Avoid scheduling before Oct 10. Optimal period for queue scheduling is Oct 15 to Nov 30.

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	DEEP23	02:27:05.71	+00:25:21.54	z=0.7661; z'=22.6; $F(\mathrm{H}\alpha) = 2.8 \times 10^{-16}$ (cgs)
2	DEEP24	02:27:30.46	+00:31:06.04	z=0.7214; z'=22.6; $F(\mathrm{H}\alpha) = 5.5 \times 10^{-16}$ (cgs)
3	DEEP25	02:26:03.72	+00:36:21.98	z=0.7888; z'=23.5; $F(\mathrm{H}\alpha) = 5.9 \times 10^{-16}$ (cgs)
4	DEEP26	02:26:21.49	+00:48:06.64	z=0.7744; I=21.8; $F(\mathrm{H}\alpha) = 4.5 \times 10^{-16}$ (cgs)
5	DEEP28	02:29:02.03	+00:30:07.83	z=0.7315; z'=21.9; $F(\mathrm{H}\alpha) = 8.7 \times 10^{-16}$ (cgs)

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

Scientific Justification

The physical processes driving galaxy evolution—gas accretion, star formation, and supernova feedback—can be understood by their effects on the interstellar gas (Lilly et al. 2013). Theoretical modeling of these processes (e.g., Davé et al. 2011) are effectively tested by measuring the correlation of gas metallicity (Z) against stellar mass ($M_\star$) and/or star formation rate (SFR), for galaxy samples that span cosmic time. The SDSS has shown how Z, as measured from rest-frame optical nebular emission lines, increases with $M_\star$ (e.g., Tremonti et al. 2004; Andrews & Martini 2013). While efforts have been made at higher redshifts to constrain the $M_\star$–Z–(SFR) relation (e.g., Erb et al. 2006), such measurements have been questioned. Specifically, these high-z studies use "strong-line" metallicity diagnostics (e.g., R_{23}, McGaugh 1991; [N II]λ6583/Hα, Pettini & Pagel 2004, hereafter PP04) that were calibrated with *local* galaxies and H II regions. However, these calibrations are *now* believed to be *invalid* at high redshifts due to significant differences in the interstellar medium (ISM) properties. For example, Baldwin–Phillips–Terlevich (BPT) diagnostics ([O III]/Hβ vs. [N II]/Hα; Baldwin et al. 1981; Veilleux & Osterbrock 1987) have shown that $z \gtrsim 1$ star-forming galaxies occupy a region in the BPT diagram that is substantially offset from $z \sim 0$ galaxies (e.g., Rigby et al. 2011; Ly et al. 2014; Shapley et al. 2015). Also, this problem is well noted when metallicities determined using the [O III]/[N II] and [N II]/Hα flux ratios, which are known to agree at $z \sim 0$ (PP04), *disagree* for $z \sim$ 1–2 galaxies (e.g., Zahid et al. 2014; Steidel et al. 2014). The difference in the gas properties between high- and low-redshift galaxies is the **greatest source of uncertainty** in measuring the evolution of the $M_\star$–Z relation and understanding gas flows in galaxies.

Solution. What is needed to resolve this outstanding problem is electron temperature (T_e) based metallicities at higher redshifts to *empirically* recalibrate strong-line metallicity diagnostics. Such measurements require detections of the weak [O III]λ4363 emission line. To address the lack of [O III]λ4363 measurements at $z \gtrsim 0.2$, we have (1) completed a deep optical spectroscopic survey with MMT and Keck called "Metal Abundances across Cosmic Time" ($\mathcal{MACT}$; Ly et al. 2016a), and (2) mined the DEEP2 Survey (Ly et al. 2015a). $\mathcal{MACT}$+DEEP2 has the largest [O III]λ4363-detected sample at $z \gtrsim 0.2$: 94 galaxies at $z \lesssim 1$, with 57 galaxies at $z \geq 0.5$. The combined sample spans ~3 dex in stellar mass (≈10^7–10^{10} $M_\odot$) and ≈1.5 dex in oxygen abundance (≈0.04–1 $Z_\odot$) at $z \sim 1$. We have, for the first time, measure the evolution of the $M_\star$–Z relation at $z \lesssim 1$ with T_e-based metallicities (Ly et al. 2016b). The only limitation that prevents using the $\mathcal{MACT}$+DEEP2 [O III]λ4363-detected samples to recalibrate diagnostics at $z \sim 1$ is the lack of Hα and [N II]λ6583 measurements. These lines are redshifted out of optical spectra at $z \gtrsim 0.5$, but are repeatedly used to estimate abundances (Note: The PP04 [N II]/Hα calibration has ~800 citations).

We propose a **one-night** MMT/MMIRS survey to complete the rest-frame optical spectral coverage for a sample of five $z \sim 1$ [O III]λ4363-detected galaxies from DEEP2. This will yield a total sample of 19 galaxies with near-IR spectra. Our observations will detect Hα and [N II] at high significance. Combined with *flux-calibrated* optical spectra than span [O II]λ3727 to [O III]λ5007, and T_e-based metallicities, we will have the most reliable recalibration of strong-line metallicity diagnostics for higher redshift galaxies.

Why $\mathcal{MACT}$+DEEP2? Ideally, detecting [O III]λ4363 in $z \gtrsim 2$ galaxies would address the issue at high redshifts; however, this is very difficult with existing capabilities. For example, Trainor et al. (2016) yielded S/N < 3 measure of [O III]λ4363 from stacking deep Keck spectra for 60 $z \sim 2.5$ galaxies. Even with a few $z \gtrsim 2$ [O III]λ4363 detections, the sample size is *insufficient* to recalibrate strong-line diagnostics.

Ly et al. (2015a, 2016b) demonstrated that $z \sim 1$ [O III]λ4363-detected galaxies have similar ISM properties as $z \sim 2$ galaxies (see Figure 1), suggesting that these galaxies are low-z analogs for typical galaxies at $z \gtrsim 1$. Thus, our program efficiently uses MMT by targeting known [O III]λ4363-detected galaxies at $z \sim 1$ that show many similarities to $z \gtrsim 1$ galaxies, and already have flux-calibrated spectra below rest-frame ~5010Å.

Our program will extend our *new* metallicity calibration (see below) to $z \sim 1$, and expand the high-z [O III]λ4363-detected sample with complete rest-frame optical spectra. This observing program will have an immediate impact for chemical enrichment studies. The $\mathcal{MACT}$ survey already has complete rest-frame optical spectra from MMT/Hectospec for ~500 galaxies at $z \lesssim 0.5$ (Ly et al. 2016a). With our new strong-line metallicity calibration, we will construct the low-$M_\star$ end ($M_\star \sim 10^6$–10^9 $M_\odot$) of the $M_\star$–Z relation. **Given the importance of strong-line metallicity diagnostics, our new calibration will be frequently used in chemical enrichment studies.**

New insights on strong-line metallicity calibration

While recent $z \sim 0$ efforts (e.g., Brown et al. 2016; Cowie et al. 2016; Dopita et al. 2016) have introduced new metallicity calibrations, we note that these calibrations do not hold for $z \lesssim 0.5$ [O III]λ4363-detected galaxies from $\mathcal{MACT}$ (Ly et al., in prep). In fact, these calibrations yield metallicities that disagree more with $12+\log(\mathrm{O/H})_{T_e}$ than those derived from Pettini & Pagel (2004). Given these circumstances, we have recently developed a new strong-line metallicity calibration that is valid for *both* local H II regions and $z \lesssim 0.5$ [O III]λ4363-detected galaxies from $\mathcal{MACT}$.

Our new metallicity calibration is based on our recent extensive compilation of published (dating back to 1980's) spectroscopic measurements and diagnostics for ∼200 local H II regions with [O III]λ4363 detections at $\geq 3\sigma$ (Ly et al., in prep). Derived properties (e.g., T_e, O/H, gas density) are determined consistently using the latest atomic data, which minimizes systematics (published T_e-based metallicities can differ by as much as 0.3 dex due to different methodologies over three decades; see Figure 2 in Nicholls et al. 2013). Our sample spans blue compact galaxies and metal-rich late-type spiral galaxies. We have found that a tight planar relation exists between $12+\log(\mathrm{O/H})_{T_e}$ and emission-line flux ratios (R_{23}, [N II]/Hα) using principal component analysis (PCA). This new calibration, illustrated in Figure 3a, is an improvement (0.18 dex vs. 0.25 dex) over the PP04 calibrations (see Figure 3b).

The greatest problem for previous calibrations is the low-metallicity ($12+\log(\mathrm{O/H}) \lesssim 8.0$) galaxies. Figure 3b illustrates that these galaxies have a wide range of [N II]/Hα flux ratios. This poses a significant problem for high-z galaxies if their gas properties are similar to those seen in metal-poor galaxies. One explanation for this large dispersion is that the N/O abundance ratios are enhanced, resulting in higher [N II]/Hα ratios. This explanation has been considered to explain the offset in the BPT diagram at $z \gtrsim 1$ (e.g., Amorín et al. 2010; Masters et al. 2014). Fortunately, our new calibration can account for the [N II]/Hα behavior in low-metallicity galaxies at $z \lesssim 0.5$.

References

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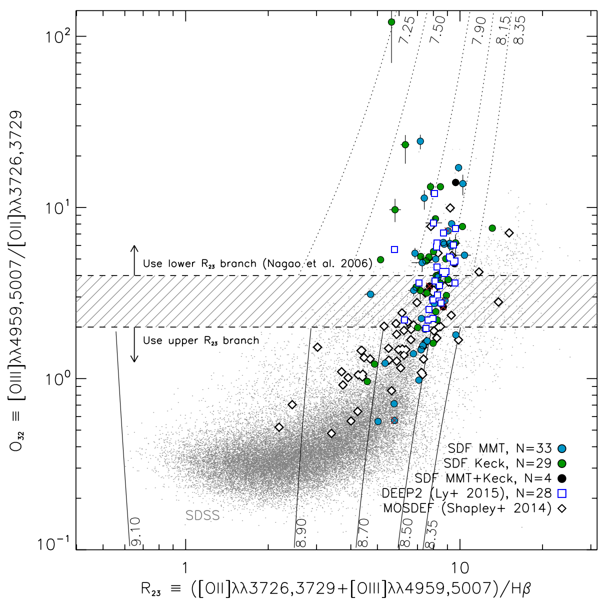

Figure 1: Emission-line diagnostics for metallicity (R_{23}) and ionization parameter (O_{32}). Our [O III]λ4363-detected galaxies (squares for DEEP2 and circles for $\mathcal{MACT}$/SDF) lie along a "ridge" consisting of high-R_{23} and high-O_{32} values. Typical $z \sim 2$ galaxies (diamonds; Shapley et al. 2015) are found along this same "ridge," suggesting that $z \approx 0.2$–1 metal-poor galaxies are analogous to $z \gtrsim 2$ star-forming galaxies.

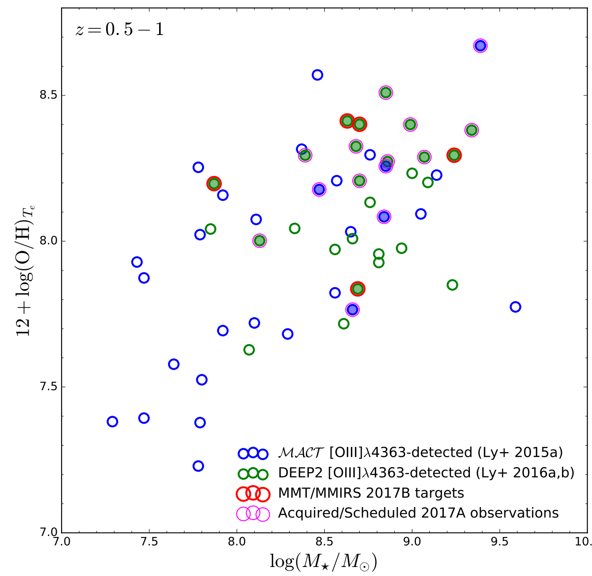

Figure 2: The T_e-based $M_\star$–Z relation at $z = 0.5$–1 (Ly et al. 2015a, 2016b). Filled points indicate where spectroscopy will detect [N II] at S/N≥ 3. Red (magenta) circles indicate our MMIRS targets (ongoing 2017A Gemini program). **This figure illustrates that our metallicity recalibration program will span $\approx$1 dex in metallicity and $\approx$1.5 dex in stellar mass.** MMIRS spectroscopy will extend our calibration analysis toward $\log(M_\star/M_\odot) < 8.0$, and increase our sample sizes by $\approx$50%–100% at $12+\log(\mathrm{O/H}) \lesssim 8.0$, $12+\log(\mathrm{O/H}) \gtrsim 8.3$, and $\log(M_\star/M_\odot) > 9.2$.

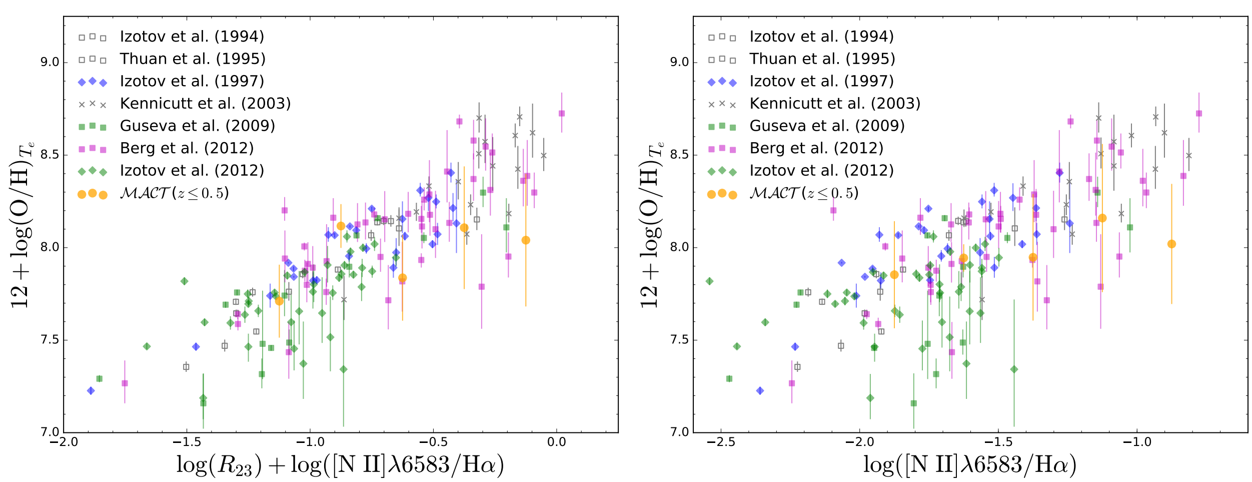

Figure 3: $12+\log(\mathrm{O/H})_{T_e}$ vs. the [N II]/Hα and/or R_{23} flux ratios for 155 local H II regions with [O III]λ4363 detections. Our new strong-line metallicity calibration (left), determined from principal component analysis (PCA), yields a tighter relation against T_e-based metallicity than the calibrations of PP04 (right). We overlay the $z \lesssim 0.5$ $\mathcal{MACT}$ [O III]λ4363-detected sample as orange circles (binned along the x-axis), which follows this new relation.

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)***

Overview. Our primary goal is to obtain spectroscopic measurements of Hα and [N II]λ6583 for a sample of $z \approx 0.6$–1.0 star-forming galaxies with detections of the [O III]λ4363 emission line (i.e., T_e-based metallicities are available). Our program will target five [O III]λ4363-detected galaxies with the MMT/MMIRS spectrograph. It will extend our current metallicity recalibration analyses from $z \lesssim 0.5$ to $z \sim 1$, and produce the largest sample of [O III]λ4363-detected galaxies at $z \gtrsim 0.5$ with complete rest-frame spectra.

The Sample. Our primary targets have been selected from two optical spectroscopic surveys, $\mathcal{MACT}$ (Ly et al. 2016a) and DEEP2 (Newman et al. 2013). $\mathcal{MACT}$ has obtained spectra for ~1900 emission-line galaxies using the MMT and Keck-II in the Subaru Deep Field (SDF; Kashikawa et al. 2004; Ly et al. 2007). These galaxies were selected using a set of narrowband filters that detect redshifted nebular emission lines. The spectroscopy has detected (S/N $\geq$ 3) [O III]λ4363 in 66 $z = 0.05$–1 galaxies. DEEP2 is a magnitude-limited ($R_{\rm AB} < 24$) survey that has obtained Keck-II spectra for ~50,000 galaxies at $z \sim 0.7$–1.4. We have searched the recent DR4 public release and found 28 $z \approx 0.8$ galaxies with [O III]λ4363 detections at S/N $\geq$ 3 (Ly et al. 2015a). In both samples, the optical spectra cover [O II]λ3727 to [O III]λ5007. The combined [O III]λ4363-detected sample of 94 galaxies is the largest to date at intermediate redshifts, and spans a broad range of galaxy properties: ≈2.5 dex in stellar mass and ≈1.5 dex in metallicity (see Figure 2). This program will target five of 57 galaxies at $z \sim 0.8$ that are only visible during the Jul-Dec observing period.

Instruments, Setups. MMT/MMIRS is the ideal spectrograph for our program, as it will provide moderate spectral resolution ($R \sim 1200$ for $0\farcs8$ slit) that separates [N II]λ6583 from Hα (~35Å apart at $z \approx 0.8$), and allow for the detection of faint nebular emission lines between the OH skylines. We will use the J grism with the zJ filter (0.95–1.5 μm) filter. These atmospheric windows will cover Hα+[N II] at $z \approx 0.5$–1.25. Observations with this grating will provide ample spectral coverage of Hα+[N II] to [S II]$\lambda\lambda$6717,6731 (≈340 Å at $z = 1$). Because the surface density of our galaxies is low, we will conduct longslit spectroscopy.

Integration Times, Observing Mode. Our exposure times are driven by the need to detect [N II]λ6583, which is our weakest line. It is expected to be at ~0.03–0.05 of the Hα flux, based on $12+\log({\rm O/H})_{T_e}$ and R_{23} (see Figure 3a). Hα fluxes are estimated from the Hβ flux (i.e., Case B recombination) with corrections for reddening from the Hγ/Hβ Balmer decrement (See Target list for Hα fluxes). For reference, the average Hα flux of our 2017B targets is 5.5×10^{-16} erg s^{-1} cm^{-2}. Using the MMIRS ETC, we estimate that we will detect an emission line with a flux of 2×10^{-17} erg s^{-1} cm^{-2} at S/N=3 in 1 hour with the J-zJ grism-filter combination.

We indicate in Figure 2 the galaxies where we will be able to detect [N II] with MMT/MMIRS. Our selected targets require less than 3 hours (on-source). For bright targets, we require a minimum of 30 min in order to have multiple observations dithered observations and given the overhead to align the longslit (≈10 min).

The optimal integration time for MMIRS at ~1 μm is 300s to minimize the variation of the OH background so that proper OH subtraction can occur. Thus, we will take between 6×300s and 36×300s exposures. We will use ABA′B′ dithering mode to enable clean background subtraction and avoid bad pixels. Since our targets are faint, slit alignment is difficult. Thus, we have decided to orient the 7′ slit to pass through a nearby bright object. This approach is better than using blind offsets, and will allow us to monitor the sensitivity and observing conditions with a bright object on the slit. Recent experience with Gemini for this project has confirm that this technique for slit alignment is the best option.

Sample Size, Requested Time. In order to recalibrate the strong-line metallicity diagnostics at $z \gtrsim 0.5$, we need a large enough sample to perform the PCA in a robust manner, and span both metal-poor and metal-rich galaxies. Our previous PCA analysis suggests that we need about ≈20 galaxies in total. With existing/forthcoming measurements for 14 galaxies, this observing program will need to target five additional galaxies. With ≈0.5–3 hr for each target (two targets require 0.5 hr each, two targets require 1 hr each, and the fifth target requires 3 hr), we will need **6 hours** of on-source integration. Accounting for overhead (e.g., long-slit alignment, telluric star calibration, comps and flat calibration, readout, slew time ABA′B′ dithering), we need **8.7 hours** or **one night**. Our five targets are in the DEEP2 Field #4, which is observable from Oct 10 to Nov 30.

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**)*

Previously, we have been awarded two MMT/Hectospec nights (PI: Malhotra; UAO-S13) in the 2014A semester for the $\mathcal{MACT}$ survey. Data from this observing run have been reduced and analyzed by PI Ly, and we have published two papers: one describing the survey and the spectroscopic data in the *Astrophysical Journal Supplements* (Ly et al. 2016a) and a science paper in the *Astrophysical Journal* (Ly et al. 2016b). The analysis included flux calibrating data from two instruments (MMT/Hectospec and Keck-II/DEIMOS) and combining emission-line measurements from both instruments. Analysis for a few other papers are underway.

Here, we are requesting one night to extend $\mathcal{MACT}$ with near-IR spectroscopy. This proposal targets our [O III]λ4363-detected galaxies only available in the Aug-Dec observing period. **Should weather permit, our request will complete the project.**

Our metallicity re-calibration project has been allocated time on Gemini North (Band 1 - highest priority) in the 2017A semester. This on-going project has acquired near-IR spectra for seven galaxies and will target an additional seven galaxies later this year. This MMIRS program will complete our program by targeting an additional five galaxies that are only observable in the Aug-Dec observing semester (Note: none of these targets have near-IR spectra). As demonstrated in Figure 2, our proposed MMIRS program will extend our analysis toward $\log(M_\star/M_\odot) < 8.0$, and increases our sample sizes by ≈50%–100% at $12+\log(\mathrm{O/H}) \lesssim 8.0$, $12+\log(\mathrm{O/H}) \gtrsim 8.3$, and $\log(M_\star/M_\odot) > 9.2$.

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**)*

See “Summary of Time Requested and Awarded” section for past use.

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**)*

PI Ly is an Affiliate Assistant Astronomer at SO, and a Professional Observer for the MMT. While the functional duties of the PI is with MMT, significant amount of discretionary time is available to the PI to maintain active research. The proposed research is a high-priority science project for the PI. This project will likely involve UofA astronomy undergraduate students, as PI Ly is mentoring three students on research. PI Ly has sufficient grant funds to support this program (e.g., student salary, journal publication). As one of the queue observers for the MMT, PI Ly has experience with MMIRS queue observing and is familiar with its capabilities.