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

**Year:** 2017 **Term:** Jul–Dec **Proposal type:** short-term$^\star$

# Extreme Feedback: the Drivers of Galactic-scale Outflows at High Redshift

**P.I.:** Christina C. Williams (SO; *ccwilliams@email.arizona.edu*; 520-621-2054)
**CoI(s):** Kyoung-Soo Lee (Purdue University), Mauro Giavalisco (University of Massachusetts-Amherst)

**Abstract of Scientific Justification**

Stellar feedback in galaxies not only ionizes and enriches the interstellar gas, but also drives galactic-scale outflows which can expel materials into the circumgalactic medium and beyond. How stellar feedback processes impact the subsequent star-formation and evolution as a function of galaxy properties is crucial to understanding key galaxy statistics such as luminosity functions and the mass-metallicity relation. Out to intermediate redshift, outflow velocity is observed to increase with star-formation rate and surface density, exceeding the escape velocity at the highest end. If a similar relation holds at high-redshift, strong outflows may provide a viable mechanism to form passive galaxies early in cosmic time, as seen in observations, without invoking AGN feedback. Observationally, the nature of outflows at high-redshift remains unclear; specifically, how they correlate with other galaxy properties. Large scatter observed in local analogs of high-redshift galaxies suggests that probing a wide dynamic range in galaxy parameters may be the key to discerning any intrinsic trend. We propose to dramatically improve outflow measurements at the highest SFRs and SF surface densities to enable a robust investigation of the physical connection between outflow and global properties of galaxies. Our target galaxies are drawn from two of the deepest spectroscopic surveys in the COSMOS field and are specifically chosen to have the highest SFRs in the regime previously under-explored in existing studies. With the extensive dataset already in our possession, the only missing information is their systemic redshifts to make direct measurements of outflow velocities.

**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 | | | 2 | bright | Jan–Jan | Dec-Jan | no | no |

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

*no text past this line*

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

**Target list (attach list if longer than 26 objects)**

| # | Object | RA | Dec | mag / color / type / redshift / comment / etc. |
|---|---|---|---|---|
| 1 | COSMOS field | 10:00 | +02:12 | $\sim$100 LBGs at z$\sim$2-4 ($R < 23.7$) |

**Approval for Instrument Use from PI:** See attached email from Brian McLeod

**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**

Massive stars produce a copious amount of ionizing radiation and then quickly end their lives as supernovae. The energy and momentum imparted by these processes not only ionize and enrich the gas in the interstellar medium (ISM) but also can expel materials into the circumgalactic and intergalactic medium (CGM and IGM) thereby slowing down the subsequent star formation in the galaxy. How this 'stellar feedback' impacted the evolution of different galaxies is crucial to understanding key galaxy statistics such as galaxy luminosity functions and the mass-metallicity relation (Dave+ 2011a,b).

One key observable of stellar feedback is *outflows*, commonly observed in star-forming galaxies as blueshifted absorption lines relative to stars, produced by neutral and ionized gas in the outflowing ISM. Propagation of Ly$\alpha$ photons is also thought to depend sensitively on the physical conditions of the ISM (Verhamme+ 2006) as the Ly$\alpha$ emission line is almost always redshifted relative to stars and the velocity offsets of the two quantities appear correlated (Steidel+ 2010, Erb+ 2014). At low and intermediate redshift, the outflow velocity is observed to increase with star formation rate (SFR) and stellar mass of the galaxy, exceeding the galaxy's escape velocity at the highest end (Heckman+ 2000, Martin 2005, Rupke+ 2005, Weiner+ 2009, Bradshaw+ 2013, Heckman+ 2015, 2016). The column densities of the absorbing gas implies that the amount of gas being removed by outflows is comparable to the galaxy's SFR if not larger (Heckman+ 2015).

Galactic outflows are expected to play an increasingly more important role in galaxy formation at high redshift. Compared to their lower-z counterparts, high-z galaxies are typically forming stars at higher rates; they are also smaller in size and mass, and thus have lower escape velocities. If outflows in high-z galaxies obey a similar scaling relation to that at low redshift, it can help elucidate several key aspects of high-redshift galaxy formation which are not well understood. Specifically, current state-of-the-art theoretical models are unable to form massive non-star-forming galaxies as early as $z \sim 4$ (e.g., Guo+ 2011), which are observed (Marchesini+ 2009, Ilbert+ 2013). Furthermore, massive galaxies at high redshift span a broad range of UV luminosities (Lee+ 2012), suggesting that SF is being suppressed in at least some of them. Many ultra-UV-luminous galaxies do not show a detectable level of AGN signature in their spectra (Lee+ 2013). Stronger outflows in galaxies forming stars at the highest rates may offer a viable mechanism to form passive galaxies early without AGN feedback.

Observationally, the nature of outflows at high redshift remains unclear. We do not know the range of typical solid angles in which outflows are launched (bipolar, isotropic, or somewhere in between), and how that compares with observations at lower redshift. Furthermore, anisotropic outflows measured along specific sightlines will result in significant scatter in measured line-of-sight velocities, which, when combined with a relatively small dynamic range in galaxy parameters, may wash away any intrinsic correlation. The fact that existing studies found only a weak or no dependence of outflow velocities on other parameters may be in part due to this effect (Steidel+ 2010, Erb+ 2012, Rubin+ 2014, Kornei+ 2012). In contrast, at low-z, Heckman+ (2015, 2016) studied local analogs of high-z Lyman Break Galaxies (LBGs) and found that their outflow velocities correlate strongly with both SFR and SFR surface density (SFR per unit area). Indeed, we found observational evidence that outflow velocities of high-z SF galaxies are larger at the highest values of these parameters (Fig. 2; Lee+ 2013, Williams+ 2015), in line with the Heckman et al's findings. However, our studies are based on indirect measures of the outflow velocity – computed as $\Delta(v_{\rm Ly\alpha} - v_{\rm ISM})$ – and also on small samples, and thus the significance of the observed correlations remain poorly constrained.

We propose to dramatically improve the outflow measures at the highest SFRs and SF surface density in order to make a robust physical connection between outflows and global properties of galaxies and thereby investigate the physical nature of outflows at high redshift. To that end, we will use MMT/MMIRS to detect nebular emission lines (primarily H$\alpha$, but also [O III], [O II], H$\beta$) of $\sim 60-70$ galaxies at $z > 2$ in the COSMOS field as means to determine their systemic redshifts. Our target galaxies are normal star-forming galaxies observed with the highest UV luminosities (and thus UV-based SFRs) in the regime previously under-represented in existing studies (Fig. 2, 3). High-quality UV spectroscopy of our targets exists from the zCOSMOS deep (Lilly+ 2007) and VVDS UltraDeep survey (VUDS: Le Fevre+ 2015), from which we have measured their ISM redshifts, and in a subset of our sample, Ly$\alpha$ emission line redshifts. Morphological (size, compactness, Sersic profile) and stellar population parameters (e.g., reddening, stellar mass, dust-corrected SFR) are also available from deep and extensive *HST*/ground-based datasets (Cassata+

2007, Ilbert+ 2015).

We will measure systemic redshifts of these targets primarily using H$\alpha$ emission line. The majority of our targets lie at $z = 2.0 - 2.5$ where H$\alpha$ falls into the K-band. Given the brightness of our targets, their line luminosities are expected to be the highest among sources at similar redshift. In Fig. 3c, we show a zCOSMOS deep spectrum of one of our targets. The strong ISM absorption features apparent in the spectrum are produced by outflowing gas-phase ISM. Galaxies' outflow velocities will be measured as the offset between the centroids of ISM absorption lines and of the nebular emission line. In Fig. 2c, we show a mock LBG spectrum with realistic noise to illustrate the precision of ISM-based redshift estimation from multiple ISM features. Typical integration for the zCOSMOS spectra and typical brightness of our sample galaxies are assumed. By combining the outflow measurements with existing rest-UV spectroscopy and multi-wavelength data, we will place robust constraints on the relationship between outflow velocities and other parameters of the same galaxies.

**Outflow Velocity and Star Formation:** The proposed observations will primarily focus on measurements of outflow velocity for galaxies in the high-luminosity regime previously under-represented in existing surveys. The ranges of galaxy parameters spanned by our primary targets are illustrated in Fig. 3b. These galaxies fill the glaring gap present in existing measurements (Fig. 2b), and thus will provide critical constraints needed to determine how outflow velocity correlates with the level of star formation (SFR, SF surface density, specific SFR). Correlations with other galaxy parameters (size, stellar mass) will also be explored. Measured correlation will place limits on the geometry of galactic outflow. If the opening angle of the outflow is large ($\Omega \approx 4\pi$), which is a possibility for extended clumpy galaxies, outflow measurements would depend less on the viewing angle and thus a tighter scaling is expected. Conversely, small opening angles ($\Omega << 1$) – e.g., bipolar ejection perpendicular to stellar disk as observed in lower-z galaxies (Chen+ 2010) – will result in larger scatter. Even for the latter case, a large sample at the highest end as proposed here will allow determination of the 'maximum velocity' (when outflow is parallel to the line-of-sight) at fixed SFR and SF surface density.

**Ly$\alpha$ Photons and Outflows:** It is widely accepted that galactic outflows give rise to both blueshifted ISM absorption lines and redshifted Ly$\alpha$ line. While the two velocities should be related by a simple scaling in a uniformly expanding shell model (Verhamme+ 2006), existing observations hint at a more complicated relationship (Steidel+ 2010). The resonant scattering nature of Ly$\alpha$ photons implies that their propagation depends sensitively on the column density, geometry, and kinematics of the gas and dust in the medium. In turn, simultaneous measurements of outflows and Ly$\alpha$ properties can shed light on whether and how the geometry and dynamics of the ISM affect the emergent Ly$\alpha$ properties such as line profile, redshift of the centroid, and equivalent width. Several recent studies reported evidence that strong outflow in a clumpy medium may aid easier escape of Ly$\alpha$ photons, resulting in a high Ly$\alpha$ escape fraction, $f_{\rm esc}$, in some massive/luminous galaxies (Mallery+ 2012, Matthee+ 2016). These constraints, when used jointly, can inform sophisticated Ly$\alpha$ radiative transfer codes to construct a more realistic picture of the ISM that is consistent with a full range of observations (e.g., Dijkstra & Kramer 2012, Verhamme+ 2012). Among 328 galaxies in our UV-bright primary sample, 91 galaxies showing clear Ly$\alpha$ emission will be our highest priority targets.

The proposed study will provide a unique insight into the physical conditions of the ISM, star formation and feedback processes in ultra-luminous galaxies at high redshift, thereby possibly identifying an evolutionary path to their transformation into massive quiescent galaxies.

**References** • Ando+ 2006, ApJ, 645, 9 • Cassata+ 2008, ApJS, 172, 270 • Chen+ 2010, AJ, 140, 2 • Dave+ 2011a, MNRAS, 415, 11 • Dave+ 2011b, MNRAS, 416• Erb+ 2012, ApJ, 759, 26 • Erb+ 2014, ApJ, 795, 33 • Guo+ 2011, MNRAS, 413, 101 • Heckman+ 2000, ApJS, 129• Heckman+ 2015, ApJ, 809• Ilbert+ 2013, A&A, 556, 55 • Kornei+ 2012, ApJ, 758, 135 • Lee+ 2012, ApJ, 752, 66 • Lee+ 2013, ApJ, 771, 25 • Le Fevre+ 2015, A&A, 576, 79 • Lilly+ 2007, ApJS, 172, 70 • Mallery+ 2012, ApJ, 760, 128 • Marchesini+ 2009, ApJ, 701• Marchesini+ 2010, ApJ, 725• Martin 2005, ApJ, 621, 227 • Matthee+ 2016, MNRAS, 458, 449 • Rupke+ 2005, ApJS, 160, 115 • Stark+ 2010, MNRAS, 408• Steidel+ 2010, ApJ, 717, 289 • Verhamme+ 2006, A&A, 460, 397 • Weiner+ 2009, ApJ, 692, 187 • Williams+2015, ApJ, 800, 21

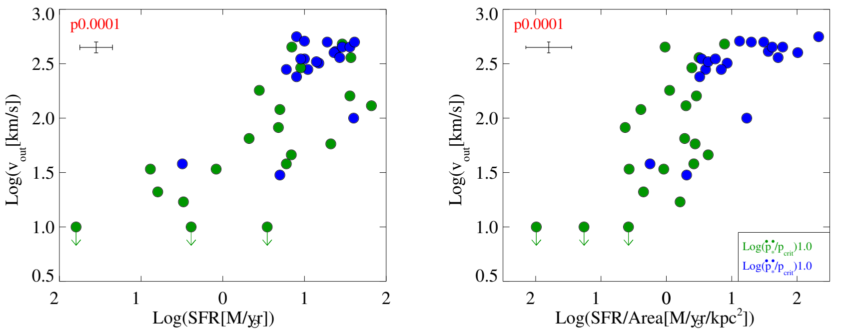


Figure 1: Correlation of outflow velocity at $z \sim 0$ with SFR (left) and SFR surface density (right). Both correlations are significant. Blue/green points show the strong/weak outflows (computed as winds accelerating and decelerating at 1 kpc, respectively. Heckman+ 2015).

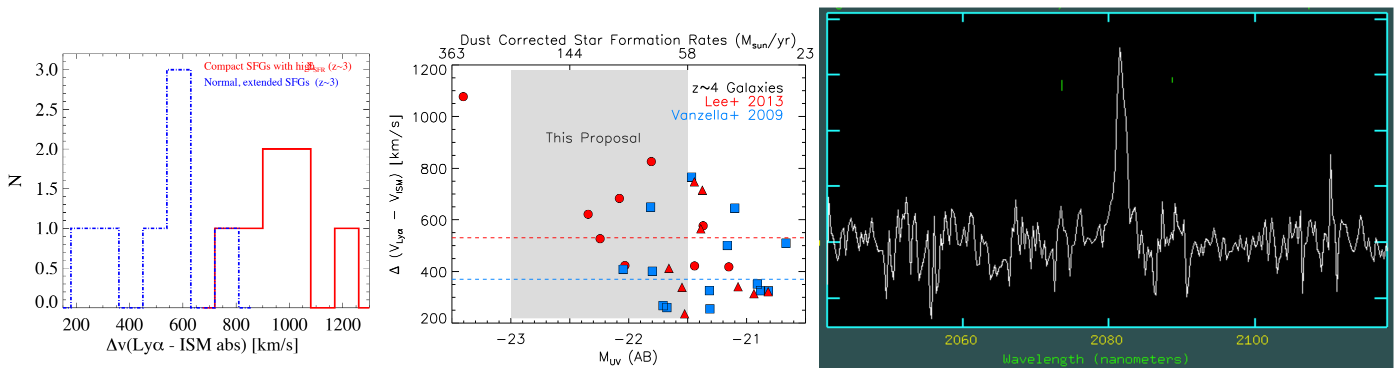


Figure 2: **a):** Velocity offsets between Ly$\alpha$ and ISM absorption lines are observed to be larger in stacked spectra of compact SFGs with high surface density of SF (red) compared to normal, extended SFGs (Williams+2015). **b):** Relationship between rest-frame UV magnitude and velocity offset between Ly$\alpha$ emission and interstellar absorption lines (Lee+ 2013). We will fill in the glaring gap in the explored UV luminosity range. **c):** H$\alpha$ detected in one of our 2016C MMIRS spectra (z=2.168).

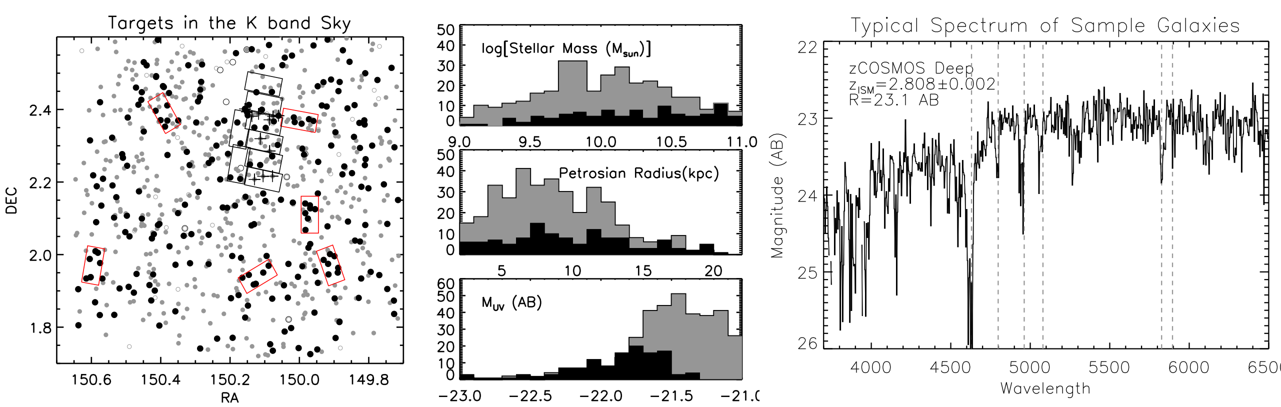


Figure 3: **a):** Sky distribution of our targets. Black (grey) points are positions of primary (secondary) targets; filled (open) circles mark those whose H$\alpha$ (H$\beta$, [O III], [O II]) falls into the $K$-band. Red and black boxes indicate tentative MMIRS pointings and existing MOSDEF pointings, respectively. Crosses mark sources observed with MOSDEF (DR1). **b):** Histograms of galaxy properties for primary and secondary targets. Characteristic UV absolute magnitudes of SFGs is $M^*_{\rm UV}$ ~-21. **c):** Example spectrum of our sample galaxies with 5Å resolution.The galaxy has $R = 23.1$ AB, and ISM redshift of $z = 2.808 \pm 0.002$ tracing the outflowing gas-phase ISM: dashed lines mark Ly$\alpha$, SiII, OII+SiII, CII, SiII, and CIV (left to right). Measurement of systemic redshift is critical to determine the true outflow velocity.

**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**)*

We request MMIRS observations to measure systemic redshifts of $\sim 70$ UV ultraluminous but otherwise normal star-forming galaxies. Using the offsets between the redshifts already determined from the ISM absorption lines, and those from our proposed detections of nebular emission, we will be able to directly determine line-of-sight outflow velocities of individual galaxies.

**Precision of Outflow Measurement:** The uncertainty in outflow measurement will be dominated by random errors in the ISM redshift determination. We have already determined them from the zCOSMOS deep survey and VUDS survey; typical integration time for these surveys on VLT is 4.5 hr and 14 hr, respectively. A zCOSMOS spectrum of one of our sample galaxies is shown in Fig. 3c, while a simulated spectrum (binned to have resolution of 5Å) assuming the typical zCOSMOS integration time and brightness of our sample is shown in Fig. 2c to illustrate the accuracy of ISM-based redshift determination. It can be seen that the individual line centroid can be measured within 5Å of accuracy. Assuming 3 (4) ISM lines are detected (which is realistic at the sample brightness based on our experience with DEIMOS), this error translates to $\Delta z \approx 0.0022$ $(0.0020)$ or $\Delta v \approx 196$ $(170)$ km/s.

**Target Selection:** Our targets are selected from the zCOSMOS deep and VUDS spectroscopic survey with these criteria: $z \geq 2$ and $r^+, i^+ < 23.7$ AB in the Subaru bands. Sources with broad emission lines (Ly$\alpha$ or C IV) and those detected in the X-ray data (Civano+ 2016) are excluded as AGN dominated systems. Of these, primary targets are brighter ($r^+/i^+ \leq 23.2$ AB), consisting of 328 galaxies, while the secondary sample consists of 788 galaxies. We further require that H$\alpha$ emission falls into the $K$ band. 250 of 328 primary targets have one or more nebular emission (H$\alpha$, O [III], [O II], H$\beta$), and 241 have H$\alpha$ in the $K$ band. 615 out of the 788 secondary targets have one or more nebular emission line, and 584 have H$\alpha$. The sky distribution of these sources is shown in Fig. 3a (black/grey denote primary/secondary). To observe these rare sources (particularly, primary targets which are the most important for this study) with high efficiency, the wide field of view makes MMIRS ideal for this program.

**Why Not MOSDEF?:** In Fig. 3a, we show the MOSDEF footprints (black boxes) and 12 of our targets already observed with MOSDEF (crosses), of which 3 are our primary targets. The observing strategy and sensitivities of the MOSDEF survey are optimized for more populous, less-luminous sources. The proposed study cannot be carried out with the MOSDEF dataset.

**Time Request:** Since target galaxies span a wide range of extinction with large uncertainties (mostly estimated based on the UV slope), we conservatively estimate SFRs directly from the $r^+$ or $i^+$ band magnitudes (essentially assuming no extinction for the most pessimistic case). Using the Kennicutt (1998) calibration, we convert the SFRs to H$\alpha$ luminosities. We predict that the faintest line flux for our sample ($i^+ = 23.7$) is ~2.2e-17 erg/s/cm$^2$ for H$\alpha$. The majority of our targets are expected to have brighter line fluxes. Using both observed Magellan/MMIRS data from Guaita+2013 and the MMIRS ETC, we conservatively estimate that we can achieve S/N of 10 in the line with 4 hr of on-source integration even if there is overlap with sky lines, and also at the red end (for $z > 2.4$). Our science goal is to discern a trend between outflow velocities vs SFR and SF surface density. Since the analysis is statistical in nature, the program requires ~30-40 rare, UV-bright galaxies (i.e., the primary sample). Tentative pointings in Fig. 3a indicate that we can observe ~10 targets (6 primary and 4 secondary) per mask. Our program requires 6 pointings to measure H$\alpha$-based redshifts of ~35-40 primary and ~20-30 secondary targets. To complete the program, we need 4 pointings with 4 hours per pointing, we request 16 hours of science integration. With 48 x 300sec exposures (7-17sec overhead per exposure) and conservative estimate of 25 min for calibrations, alignment, and acquisition per pointing, we request 19 hours (total) to complete the program.

**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 is a resubmission of a program that was accepted for semester 2016B, in which we only observed about 30% of our program due to bad weather. We plan to complete the project in the time proposed here for semester 2017B.

**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**)*

This proposal is a resubmission of a program that was accepted for semester 2016B, in which we only observed about 30% of our program due to bad weather. We plan to complete the project in the time proposed here for semester 2017B.

The PI and co-Is had an accepted program for a different project through UAO with Hectospec/MMT In semester 2015B. We were awarded two out of three nights requested for a project to obtain rest-frame UV spectroscopy in the 1 deg$^2$ CFHTLS D1 field to study protocluster candidates. Due to bad weather, only 3 hours of data were observed. The program could not be completed, however we reduced the 3 hours of spectra.

The PI has an accepted program for a different project through UAO with LUCI/LBT from semesters 2015A and 2017A. The observations were completed in February 2017, and the PI has completed a reduction of the first semester of LUCI spectroscopy. Reduction of the second semester of data and analysis of the reduced data is underway.

**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**)*

The PI will begin a National Science Foundation postdoctoral fellowship at Steward Observatory this fall, and the data from this program is an integral component of the science that was outlined in the fellowship proposal.

**McLeod, Brian** <bmcleod@cfa.harvard.edu> Mar 27 (7 days ago)

to Christina

Hi Christina,

No updates on our end.  Hope you have better luck with the weather this time around.

...

Brian

On Mon, Mar 27, 2017 at 1:57 PM, Christina Williams <ccwilliams@email.arizona.edu> wrote:

> Dear Brian,
>
> I'm a postdoc at University of Arizona, and last semester (2016C) I used MMIRS to conduct a survey of star-forming galaxies at z~2-4 (see attached email below, of my previous request to use MMIRS for that semester). We had some success in obtaining spectra, but bad weather prevented us from completing our program, so I plan to resubmit this proposal. I'm writing to let you know my intention to re-propose, and to ask if there are any updates or additional things I should know about MMIRS for the coming run.
>
> Thank you!
> Christina
>
> On Wed, Mar 30, 2016 at 5:31 AM, McLeod, Brian <bmcleod@cfa.harvard.edu> wrote:
>
>> Hello Christina,
>>
>> I don't need any more information - you are welcome to use MMIRS.
>>
>> If you have any questions about the instrument feel free to ask.
>>
>> Brian
>>
>> On Tue, Mar 29, 2016 at 7:51 PM, Christina Williams <ccwilliams@email.arizona.edu> wrote:
>>
>>> Dear Dr. McLeod,
>>>
>>> My name is Christina Williams, I'm a postdoc at University of Arizona and I'm interested in proposing to use MMIRS to study bright star-forming galaxies at z~2-4. The main objective of the proposal will be to detect rest-frame optical emission line(s) that will provide accurate systemic redshifts for the galaxies, and allow us to use existing rest-frame UV spectroscopy to study the detailed properties of outflows in bright star-forming galaxies. In particular, we will study the relationship between star-formation rate and star-formation rate density with outflow velocity in different ISM phases, as well as how the properties of Lyman-alpha are affected by outflow velocity.
>>>
>>> Please let me know if there is anything you need to know about this proposal, and if there's any information about MMIRS that I should know that isn't available on the website.
>>>
>>> Thank you!
>>> Christina