OBSERVING REQUEST
University of Arizona Observatories

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

Towards an understanding of quenching in galaxies at high-redshift

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Abstract of Scientific Justification

Passive (early-type), massive ($M/M_\odot > 10^{10}$) galaxies at $z > 1.5$ are nearly all much more compact than their local counterparts of similar mass, suggesting that the quenching mechanisms at these early epochs must be related to compactness. Recent evidence suggests that compact star-forming galaxies, their likely progenitors, at $z \sim 3$ experience more extreme feedback than normal-sized galaxies of similar mass (Williams et al. 2014), but this link between stellar density and quenching has yet to be fully investigated. We propose near-infrared spectroscopy with LBT/LUCIFER to study the kinematics, ionization state and metallicity of the gas in a sample of compact, spheroidal star-forming galaxies, and a control sample of normal-sized star-forming galaxies. These galaxies have been selected from the CANDELS dataset and already have existing rest-frame UV spectroscopy to complement the proposed observations. With the proposed dataset, we will discover if the compact galaxies are more evolutionarily advanced, if they truly experience stronger feedback than more extended galaxies, and study if they energize their ISM sufficiently to prevent future SF.

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	N1.8	LUCIFER			2.5	bright	Feb–Mar	Jan–Apr	yes	no

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

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	COSMOS Field	10:00:28.6	+02:12:21.0	40 star-forming galaxies with $1<z<3.7$

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

The assembly of the Hubble Sequence of galaxies is one of the most widely studied, yet poorly understood phenomena in galaxy evolution. Early-type galaxies (ETGs) have been passive, i.e. with no star formation, since at least z$\sim$2 (Renzini 2006), and thus they are relics of the early evolutionary processes that form and quench galaxies and subsequently transform them over cosmic time. Quenched galaxies with spheroidal morphology have been identified as early as z$\sim$3 (e.g. Franx+03, Daddi+05, Cimatti+08, van Dokkum+08, Guo+12), and found to be up to 5 times smaller than their local counterparts of similar mass ($>10^{10}M_{\odot}$), hence up to a factor of 100 higher in stellar density (Cassata+13). Quenched galaxies at $z > 1.4$ are dominated by compact ones at (see Figure 1) implying that at the peak of star-formation activity in the universe, quenching preferentially affects compact galaxies (Bell+12). This trend continues toward higher redshift, showing that compact galaxies are in fact the first systems to quench, suggesting that high stellar density must be a key physical parameter that controls quenching.

Recently, Williams+14a found evidence that the interstellar medium (ISM) in compact star-forming galaxies (SFG) is characterized by faster outflows, higher turbulence, patchier neutral gas than in normally sized SFG of similar mass and star formation rate (SFR). This suggests that more extreme feedback takes place in the compact systems. They also found that the forming stellar populations of compact SFG have older age and higher metallicity, indicative of an accelerated evolution (Williams+14 a,b). Although a causal link between the compactness and energized ISM, rapid evolution and quenching could not be established, there are compelling reasons to suspect stronger feedback among compact galaxies at high redshift, and here we propose to conduct further investigations. At intermediate redshift ($z\lesssim1$), Tremonti+07 discovered powerful outflows ($>$1000 km/s) in rare compact, "post-starburst" galaxies (selected to have strong Balmer absorption, typical of A-type stars, concluding that the outflows are the relics of the winds launched during the star-formation (SF) phase. There is evidence the quenching is initiated by the high surface density of SF on short timescales ($\sim$20 Myr; Diamond-Stanic+12), although such powerful outflows are typically attributed to feedback from AGN (Tremonti+07). Clarifying where the outflowing gas goes, and what its properties are, hold important clues to re-constructing the process of quenching.

Studying the kinematic properties and ionization state of gas in high-redshift galaxies is challenging. Accurate gas-phase kinematics require both optical spectroscopy, which at high redshift samples the diagnostic–rich rest–frame UV, and NIR spectroscopy to measure the systemic redshift, metallicity, stellar kinematics, dust obscuration. NIR spectroscopy is also required to probe the nebular gas ionization condition through the BPT diagram, as shown in z$\sim$2 galaxies by Steidel+14. The samples for which both these data exist small (Law+12, Steidel+10), and do not lie in fields rich with multi-wavelength *HST* photometry, which are vital to provide accurate measures of morphology, SFR, stellar mass, continuum dust obscuration and stellar age, both integrated and spatially resolved at the sub–kpc scale.

Here, we propose NIR spectroscopy to study kinematics, ionization state, and metallicity of the gas in a sample of spheroidal, compact z$\sim$2 SFGs and a control sample of normal-sized ones from the HST/WFC3 CANDELS survey. These samples already have deep rest-frame UV spectroscopy from existing surveys (Le Févre+14), as well as all CANDELS ancillary data. Combining our existing data with the proposed NIR spectroscopy will allow us to study our galaxies with vastly improved accuracy over our existing measures, which rely on very crude and noisy diagnostics and systemic redshifts from UV lines only. From NIR spectroscopy we will access robust metallicity diagnostics and further investigate the evidence that compact SFGs are more metal rich than normal SFGs of comparable mass and SFR. We will measure the Balmer decrement, which gives independent estimates of dust obscuration and breaks the age-reddening degeneracy, allowing us to improve the age–dating of the stellar populations. We will also probe the general ionization conditions of the nebular gas via the BPT diagram (Baldwin, Phillips & Terlevich 1981) and study if these conditions differ between compact and non–compact SFGs, another crucial independent assessment of the difference in the physics of feedback in these two types of galaxies. Thus we will determine if compact galaxies are more evolutionarily advanced, if they truly experience stronger feedback than more extended galaxies, and if they really energize their ISM sufficiently to stop and prevent future SF. In turn, this will help us put our investigations of a causal link between high stellar density and feedback strength on a much more rigorous ground.

The aim of this proposal is to accurately measure different quantities, listed below, and to check for systematic differences between galaxies with a spheroidal component and galaxies without.

Outflows We plan to identify possible outflows in our galaxies by estimating the offset between the redshift defined by the UV ISM lines as SiII $\lambda1260$, OI$\lambda1303$, CII $\lambda1334$, CIV $\lambda1549$, SiII $\lambda1526$, that we already identified in the VUDS spectra, and the systemic velocity, derived by Hα. The resolution of the HK-spec grism (R$\sim$ 2000), in combination with the VIMOS spectra in the optical will allow us to identify offsets larger than 200 km/s. Ultimately, we will test the hypothesis that galaxies with spheroidals are being quenched, therefore they show stronger/faster outflows than the control sample.

Star-formation activity We will measure the Balmer decrement at least via the Hα/Hβ ratio, and for the most star–forming galaxies in the sample also we will also detect Hγ. The Balmer decrement is a very robust indicator of the dust content, and once the line fluxes corrected for dust extinction we will have a direct estimate of the star-formation activity of each galaxy from the Hα luminosity. Once the dust content and the SFR fixed, we will also derive much more robust SED fitting parameters as ages and stellar masses. We will then check if the galaxies with spheroidal components have suppressed SFR with respect to the galaxies in the control sample.

AGN contribution We will apply the BPT diagram by Kewley et al. (2006) to disentangle normal star–forming galaxies and AGN: we will measure with great accuracy the OIII/Hβ ratio; and we will be able to at least put an upper limit to the luminosity of NII $\lambda6584$, that lies for all galaxies within the K-band. Again, we will check if galaxies with a spheroidal component show any AGN contribution with respect to galaxies in the control sample. More generally, we will check for any correlation between the presence of an AGN component and stronger winds.

Metallicity We will estimate the gas phase metallicity, measuring with great precision the R$_{23} = (OIII\lambda4959 + 5007 + OII\lambda3727)/H\beta$ and O$_{32} = (OIII\lambda4959 + 5007)/OII\lambda3727$ parameters (similarly to Maiolino+08). We will then test if galaxies with higher ages or suppressed star–formation activity, are also more metal poor than galaxies that form stars on a longer timescale.

Lyα escape fraction By simply comparing Lyα and Hα luminosities (corrected for dust via the Balmer decrement) we will have a direct measurement of the Lyα escape fraction, that is thought to be correlated to the dust/ISM geometry/content/dynamics. For example, we will test if $f_{esc}(Ly\alpha)$ is higher in the presence of stronger winds and/or in galaxies with less dust content.

References

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Baldwin et al. 1981, PASP, 93
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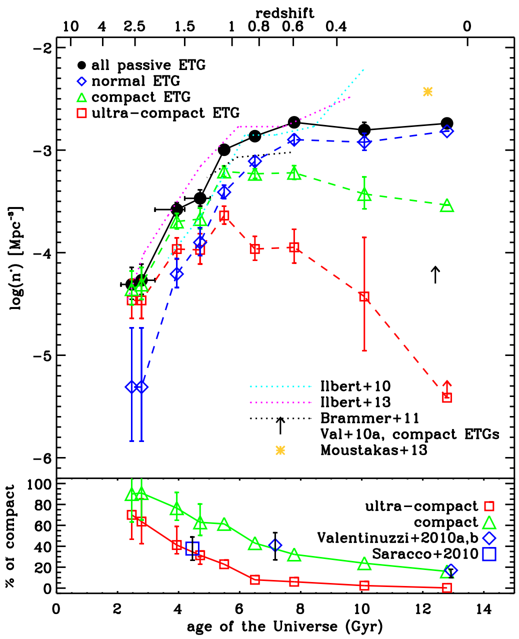

Figure 1: Top panel: The evolution in number density of ETGs over cosmic time. At $z > 1$, compact ETGs dominate. Bottom panel: The percent of all ETGs which are compact. Nearly 100% of the first ETGs are compact, making them ideal objects for studying the quenching mechanisms at high redshift. Figure: Cassata+13.

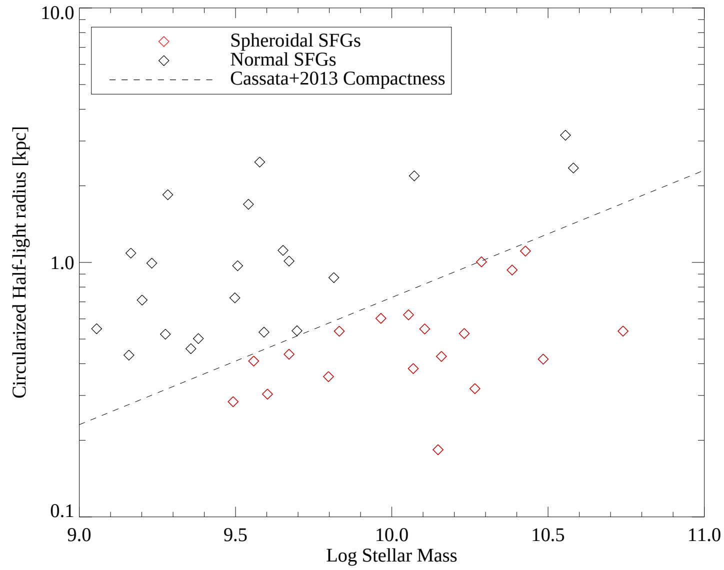

Figure 2: Parent sample of 2<z<2.5 SFGs that will be observed with this program. In red are SFGs which are identified as spheroidal and compact in stellar density ($> 3\times10^9 M_\odot \mathrm{kpc}^{-2}$) and black are normal SFGs. The dashed line represents the lower $1-\sigma$ of the mass-size distribution of local ETGs (Cassata+2013). Sizes are measured from the high-resolution HST H-band imaging from CANDELS. Our proposed targets, which include galaxies from each class, are drawn from these samples.

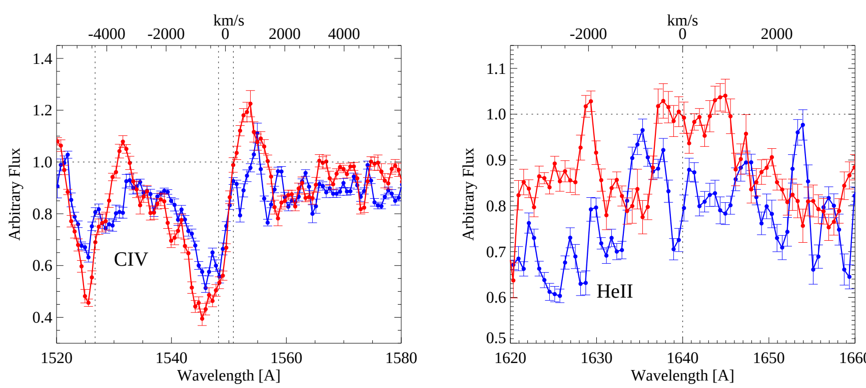

Figure 3: Metallicity dependent features in stacked spectra of z∼3 compact (red) and normal (blue) SFGs. Left panel: P-Cygni profile of CIV$\lambda\lambda$1548,1550Å from the winds of massive stars. Both absorption and emission components increase equivalent width with increasing metallicity (Rix+04, Leitherer+10). Right panel: Emission of HeIIλ1640Å is produced by metal rich massive stars and is also observed in compact SFGs but undetected in the normal sample. Figure: Williams+14a

Experimental Design & Technical Description

We propose to observe a sample of 40 SFGs, at 1<z<3.7 with one pointing of LUCI on LBT, in order to start building a sample with both rest frame optical and UV spectroscopy, with the aim of exploring the phenomenology of compact galaxies. Our main sample, whose redshifts allow us to observe all required lines to address all the science questions outlined above, include 20 galaxies at 2<z<2.5. The sample is selected from the area covered by CANDELS observations in the COSMOS field, and the galaxies in the sample all have a high-quality optical spectrum from the VUDS survey (Le Fèvre et al. 2014) in which the continuum is detected with S/N$\sim$ 10 per resolution element. Of the galaxies in the main sample, roughly 1/3 have a prominent spheroidal component in their optical rest-frame (as inferred from the CANDELS H-band imaging), while the remaining 2/3 have disk-like or irregular morphologies, and will be used as a control sample. Moreover, the galaxies with spheroidal components have also smaller physical sizes than the ones in the control sample (see Figure 3). If the correlations of spectral properties with compactness are clear, as they were among 19 Lyman-Alpha Emitters in Law et al. 2012, and 12 compact SFGs in Williams et al. 2014a, we expect to be able to detect the trends with this sample.

With our proposed observations we will detect OII3727, Hβ4861, OIII4959+5007 and Hα6563 with S/N of $\gtrsim$ 10 per spectral element in the optical rest-frame of these galaxies. The VUDS optical spectra provide an extremely accurate spectroscopic redshift ($\Delta\ z/(1+z) \sim 0.00072$, corresponding to $\sim$ 200 km/s). We will measure at least one of the above emission lines for our entire sample (between 1<z<3.7) in order to accurately measure their systemic redshifts. The systemic redshift derived will allow us to accurately measure gas kinematics from the entire sample. For the highest redshift galaxies with 3<z<3.7, we will still be able to measure metallicities. For the main sample at 2<z<2.5, we will detect all specified lines, allowing us to carry out the studies of star-formation activity, AGN contribution, metallicity, and Lyα escape.

Our proposal requires spectra from 2 filters. We will use the N1.8 camera in spectroscopic mode with the zJspec filter, central wavelength 1.175μm with the 200 lines/mm grating to target OII3727 at z>2 and OIII or Hβ at z<2. We will use the N1.8 camera with the HKspec filter, central wavelength 1.93 μm with 200 lines/mm grating, to detect the remainder of the lines at z>2. We will use slit widths of 0.75", that gives the best trade-off between the (highest possible) spectral resolution and (the lowest possible) slit loss. In this configuration we will get R$\sim$2000. We run all the simulations that we discuss below with the LUCI exposure time calculator (ETC) for airmass=1.75, 1.6mm water vapor, typical seeing of 0.8", default sky brightness of 18 Vega magnitude per square arc second, and detector integration times of 300.

In order to estimate the expected line fluxes, we converted the SFR derived from the SED fitting to Hα fluxes according to Kennicutt (1998) and then we applied typical line ratios (OIII/Hα $\sim$ 1, H$\beta/H\alpha$ $\sim$0.3 and OII/Hα $\sim$0.5), and we included the effect of dust assuming a typical E(B-V)=0.15. According to the LUCI ETC, with one hour integration we will detect Hα with a S/N of at least 10 per resolution element (corresponding to $\sim$3 spectral pixels) for all galaxies in our main sample (expected Hα fluxes in our sample range from $F_{H\alpha} = 4\times10^{-17} erg/s/cm^2$ and $F_{H\alpha} = 7\times10^{-17} erg/s/cm^2$). This configuration will provide a resolution R$\sim$2000, corresponding to FWHM$\sim$200 km/s. However, the precision with which the position of the line is known is far better than the FWHM: we estimate that the position of Hα will be known within an uncertainty of $\sim$50 km/s. This, combined with the same figure for the optical VUDS spectra, will allow us to identify winds faster than 250 km/s.

We will also identify Hβ and OIII4959+5007 in with HKspec. Since the Hβ line is expected to be 3 times fainter than Hα we estimate that we need to integrate for 4 hours to detect Hβ with a S/N of at least 10 per resolution element (corresponding to $\sim$3 spectral pixels) for all galaxies in our sample (the expected Hβ fluxes in our sample range from $F_{H\beta} = 1.2 \times 10^{-17} erg/s/cm^2$ and $F_{H\beta} = 4 \times 10^{-17} erg/s/cm^2$). This sets our request for 4 hours in HK. With similar arguments, we estimate that we will detect the OIII line with S/N of 10–25 per resolution element. Finally, we will use the zJspec filter to measure OII at 2<z<2.5. As this line is fainter, to achieve similar S/N we will integrate for 8 hours, and detect the OII line with S/N of 7.5–20 per resolution element. Thus, we are requesting 4 hours (science only) time for the HKspec, and 8 hours (science only) in zJspec, to carry out our study. With our overhead estimates ($\sim$1.3 hours per 4 hour science image), we request a total of 16 hours. NIR observations can be carried out on bright time. Between February and March 2015 the COSMOS field is observable at airmass better than 2 for 7 hours per night.

Summary of Time Requested and Awarded *The TAC needs to understand the scope of this project — (1) tell us how many UAO nights you've already had for this project, how many you request this time, and (a good guess of) how many you need to complete the project; (2) if a substantial amount of observing for this project comes from non-UAO telescopes, tell us about that observing, and how the UAO part fits in; (3) if you are collaborating with people who have telescopes, especially if you are part of a large collaboration, tell us who is leading the project, and how UAO time and your participation fit in. (**up to one page**)*

This is a new project and therefore no time, including at UAO, has yet been dedicated for this project. With this proposal we aim to begin building a sample of these galaxies so that we can start to explore the phenomenology of compact galaxies. We plan to supplement these observations with future observations through UAO from GOODS-South, where there are large samples of galaxies with high-resolution imaging from CANDELS for which ancillary rest-frame UV spectroscopy already exists.

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**)*

The PI has no allocations through UAO facility for this project or any other projects.