OBSERVING REQUEST
University of Arizona Observatories

Year: 2015 **Term:** Aug–Dec **Proposal type:** short-term

A Chance Alignment: Confirmation of a Massive Compact Lensed Elliptical Progenitor at $z \sim 1.8$

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CoI(s): Katherine Whitaker (NASA - Goddard), Keren Sharon (U. Michigan)

Abstract of Scientific Justification

Galaxy bimodality is a well-established empirical fact for massive galaxies, yet we still do not understand how and when the population of quiescent ellipticals emerges. To match observed galaxy properties, physical quenching mechanisms must stop star-formation, destroy most rotation, and shrink galaxy sizes to build up a realistic quiescent galaxy population. Proposed models include gas-rich major mergers, bulge growth via disk instabilities, and formation in the early, dense Universe. Each mechanism would have unique timelines of transformation, which will be imprinted on the stellar populations and structures of recently quenched galaxies. However these observable signatures will fade within $\sim$1 Gyr, rendering quenching, or recently quenched, massive galaxies the optimal laboratory for testing quenching mechanisms. Using HST imaging from the SGAS cluster lensing survey, we have identified a rare strong-lensed massive ($\log M_*/M_\odot = 10.5$) red galaxy at $z\sim1.8$. 0851-E is already structurally similar to quiescent, massive galaxies and appears to be in the process of quenching. Using MMIRS on the MMT, we propose to obtain a deep YJ spectrum of 0851-E centered on its rest-frame Balmer/4000Å break. These observations are only possible for this unique galaxy due to lensing magnification and interpretations will benefit from excellent structural measurements of 0851-E from source plane reconstructions of its four images. From this spectrum, we will calculate a spectroscopic redshift, measure stellar absorption features to assess stellar populations, and derive an absorption line velocity dispersion and dynamical mass for 0851-E. These measurements will test the quenching timeline for this unique galaxy at a key moment in its own history and that of the Universe, shedding light on the life and death of massive distant galaxies.

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	grey	Dec–Dec	Nov–Dec	yes	yes

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	0851-E	08:51:40.03	+33:30:49.86	$H_{AB} = 20.7$, $z \sim 1.8$ lensed galaxy

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

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

Background: *The Challenge of Forming Compact Quiescent Galaxies*

Surveys of the Universe at $1 < z < 3$ are critical for understanding galaxy formation. During this epoch, both the star formation history and number density of quasars peaked (e.g. Hopkins & Beacom, 2006). Simultaneously, a population of galaxies with quenched star formation emerged (Kriek et al., 2006). These quiescent galaxies have not only grown rapidly in number and mass over the last 11 Gyr ($z < 3$), but they have also undergone dramatic structural evolution (Daddi et al., 2005). Quiescent galaxies of the same stellar mass were significantly smaller in the past, with smaller radii by a factor of $\sim$5 at $z\sim$2. The tension in the observations arises because the sizes of star-forming galaxies are larger than quiescent galaxies (e.g. a factor of $\sim$4 at $\log \mathrm{M/M_{\odot}}$=10.5 at $z\sim$2 (Fig. 1). We know that the progenitors of quiescent galaxies must be drawn from equivalently massive star-forming galaxies, yet these two populations look nothing alike.

Quenching Mechanisms: *The Possible Pathways to Forming a Present-Day Massive Elliptical*

All quenching models must explain the ceased star-formation and the creation of *smaller*, bulge dominated galaxies, for which the progenitors appear to be rotating disks (e.g. Wisnioski et al. 2015). Several groups (e.g. Barro et al. 2013, Williams et al. 2014) have identified a significant population of compact star-forming galaxies (the extreme tail of the size distribution of the star-forming population), which could quench without structural transformation. These compact star-forming populations are reproducible with cosmological simulations, where they are either driven by violent disk instabilities (Ceverino et al., 2015), or have very early formation times when the universe was far denser (Khochfar & Silk, 2006; Wellons et al., 2015). One troublesome implication is that only the smallest star-forming galaxies are able to shut down at $z > 2$, which are by far in the minority. Alternatively, it may be that gas-rich mergers dramatically change the galaxy structures. These mergers can induce radial gas inflows that fuel a central starburst and trigger the quenching of star formation through black hole feedback (e.g. Hopkins et al. 2008, Wellons et al. 2015). Furthermore, while the central starburst is still heavily enshrouded in dust, in extreme cases the galaxies would be detectable as strong submillimeter sources.

All of these scenarios have *unique* transitional timelines, which will be imprinted on stellar populations and structures. Comparisons between stellar ages and scaling relations when those stars formed could possibly eliminate early formation from "normal" star-forming progenitors. Stellar absorption features, particularly the Balmer lines, can be used to assess the strength of the most recent burst of star-formation, thereby testing a gas-rich merger hypothesis. Time is of the essence for this galactic archeology: spectral age indicators are powerful for the first $\sim$1Gyr in an aging stellar population, but change only gradually afterward. This is an important point for identifying optimal test cases - massive galaxies observed during or recently after quenching. The fundamental limitation is in fact not in identifying representative samples, which is now possible with a vast array of deep extragalactic multi-wavelength surveys, but in reaching the necessary signal-to-noise (S/N) and spectral resolution to robustly quantify these observational signatures.

A Unique Target - 0851-E: *A Massive Lensed Galaxy Shutting Down at the Peak of Cosmic Star Formation*

In this context that 0851-E, a strongly lensed, massive, transitioning galaxy at $z\sim1.8$ is exciting target. Here we propose to use MMT-MMIRS to obtain an accurate redshift, spectroscopically constrain the age of the stellar population, and solidify its mass. These observations will help to constrain the quenching timeline and responsible physical mechanisms for this unique, but representative lensed galaxy.

Cosmic Microscopes: *Magnified and Spatially-Resolved Distant Galaxies through Gravitational Lensing*

The brightening and magnification effects from strong gravitational lensing are a powerful tool that enables studies of distant galaxies with better signal-to-noise (S/N) and higher spatial resolution than is normally possible with current instrumentation. Over the last decade, these unique laboratories have provided insights into the formation and evolution of "typical" galaxies at $1 < z < 5$, which are most commonly low-mass, blue star-forming galaxies (e.g. Rigby et al., 2011). With the advent of Herschel and the South Pole Telescope submillimeter observatories, we have now also gained access to populations of strongly lensed submillimeter galaxies identified from wide-field surveys (e.g. Negrello et al., 2010; Vieira et al., 2010) and behind massive clusters (e.g. Egami et al., 2010).

What has remained largely elusive are strongly lensed "red and dead" massive galaxies at $z{\sim}2$. Although these galaxies comprise 50% of the massive ($\log \mathrm{M}/\mathrm{M}_{\odot} > 11$) galaxy population at $z{\sim}\ 2$ (Whitaker et al., 2011), they are still quite rare ($\sim$1 every 10 arcmin^2). This makes the serendipitous discovery of a quiescent galaxy in a favorable alignment with a foreground lensing structure unlikely. Furthermore, distant red galaxies (both quiescent and star-forming, if the latter has significant amounts of dust obscuration) are extremely faint in the observed optical bands with extremely red near-IR colors (Franx et al., 2003), making both deep *and* wide-field NIR imaging a requirement for their detection.

The SGAS Survey: *Serendipitous discovery of 0851-E*

The Sloan Digital Sky Survey Giant Arcs Survey (SGAS) is a large Cycle 20 HST program (107 orbits; PI Gladders) imaging 37 fields of strong-lensed clusters. Until the next generation of space telescopes, this combination of HST's exquisite image quality and the magnification boost of strong lensing is the only opportunity to probe scales < 500 pc at z=1–3. While SGAS is aimed at understanding the morphology and fundamental size scales of star formation in distant galaxies, we have also made the fortuitous discovery of a red lensed galaxy at z=1.8 within one of the SGAS clusters, SDSSJ0856+3331, hereafter target 0851-E.

0851-E Basics: *Structurally quiescent, stellar populations appear to be in the process of quenching*

An analysis of the SED of 0851-E, combining four HST images (F390W, F814W, F125W and F160W) with two Spitzer/IRAC images, and using a preliminary lensing models, reveals that this particular candidate is indeed quite intriguing. With a magnification boost of $\sim$10 and 4 images of this galaxy from sub-structure lensing within SDSSJ0851+3331 (Fig. 2), we measure that 0851-E has a demagnified stellar mass estimate of $\log \mathrm{M}/\mathrm{M}_{\odot}$=$10.5^{+0.3}_{-0.3}$ from a preliminary lensing model by Co-I Sharon. While 0851-E appears to have a strong Balmer-break, indicative of a significantly evolved stellar population, there is also a significant amount of ultraviolet radiation from recent star formation. It falls in the transition region between the bimodal color-color distributions of quiescent and star-forming galaxies. What makes 0851-E even more interesting is that it is compact for its stellar mass, with a tentative effective radius of $1.5^{0.7}_{0.4}$ kpc and a concentrated light profile with a Sérsic index of 3.7. We have caught a galaxy on the brink of shutting down at the peak epoch of star formation, with similar galaxy structural parameters to the enigmatic quiescent population. This galaxy is already compact, but the question remains at what stage did this occur?

The Interpretation of 0851-E Requires Spectroscopic Follow-up

Spectroscopic Redshift: Key for Lens Modeling and Stellar Mass Estimates

The proposed NIR spectrum of 0851-E will provide a spectroscopic redshift, breaking key degeneracies in the photometric redshift modeling due to a sparsely sampled SED (see Fig. 2, lower panel). A critical step for interpretation of the observations is computing an accurate lens model, as many intrinsic properties of the background galaxies depend on their magnification. MMIRS has multi-object capabilities with $0.4''$ slits, so given good seeing conditions we will also acquire spectroscopic redshifts for other objects in the field, thereby improving the currently uncertain model and the interpretation of 0851-E itself.

Spectroscopic Estimation of Stellar Populations:

Next, we will analyze the stellar populations of 0851-E. Without the magnification boost, we stress that such an analysis is otherwise inaccessible. The shape of the Balmer/4000Å break, together with the prominent Hδ, G-Band, Hβ stellar absorption features and [OIII], will be used to diagnose if this galaxy has a significantly old stellar population with a frosting of recent star formation, or if it is on the verge of joining the recently quenched population for the first time.

Stellar Dynamics can test SPS Stellar Mass Estimates:

The stellar mass and size of 0851-E implies a measurable stellar velocity dispersion of 200^{+20}_{-50} km/s. We will confirm this by fitting broadening of stellar absorption features. Comparing the dynamical mass to the derived stellar mass will be important for testing SPS models and the massive, compact nature of 0851-E.

References

• Ceverino, D., et al. 2015, MNRAS, 447, 3291 • Daddi, E., et al. 2005, ApJ, 626, 680 • Egami, E., et al. 2010, A&A, 518, L12 • Franx, M., et al. 2003, ApJ, 587, L79 • Hopkins, A. M., & Beacom, J. F. 2006, ApJ, 651, 142 • Khochfar, S., & Silk, J. 2006, ApJ, 648, L21 • Kriek, M., et al. 2006, ApJ, 645, 44 • Negrello, M., et al. 2010, Science, 330, 800 • Rigby, J. R., et al. 2011, ApJ, 732, 59 • Vieira, J. D., et al. 2010, ApJ, 719, 763 • Wellons, S., et al. 2015, MNRAS, 449, 361 • Whitaker, K. E., et al. 2011, ApJ, 735, 86

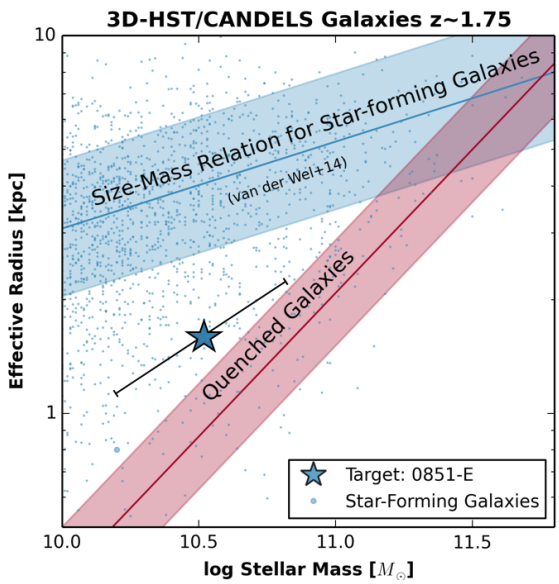

Figure 1: Size versus stellar mass relation for $z\sim1.8$ galaxies in the 3DHST/CANDELS fields. The compact structure of 0851-E best resembles that of already quiescent galaxies at this redshift, however the UV slope of its SED suggests some residual star formation (see Fig. 2). The large error bar is due to the uncertain lens model, conservatively assuming a range of magnification from 5–20. Spectroscopy will verify the galaxy's redshift and inferred mass and constrain age and composition of its stellar populations.

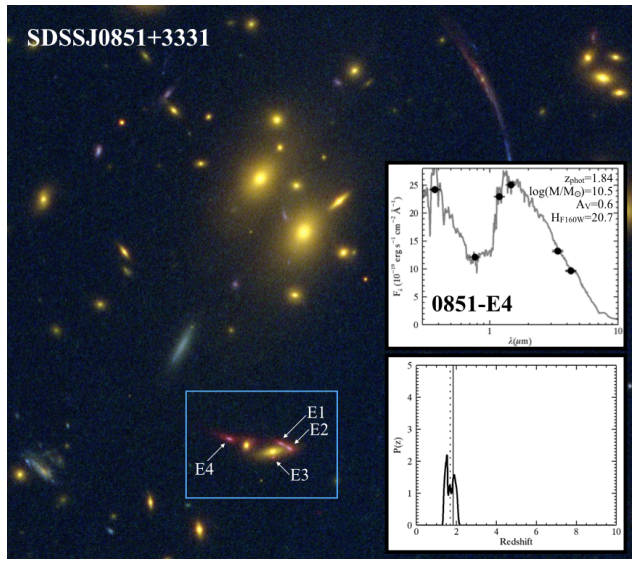

Figure 2: Color image (F390W, F814W, F125W, F160W) of cluster SDSS0851+3331 with 0851-E images highlighted. Top inset: spectral energy distribution for 0851-E4. Strong UV flux indicates the presence of a young population of stars, however the fraction and age of the overall stellar population remains unconstrained. Bottom inset: Probability distribution for the photometric redshift of 0851-E4. Photometric measurements constrain the redshift between $1.5\lesssim z\lesssim2$, which changes the stellar mass estimates by $\sim$0.3 mag due to the uncertain lens model.

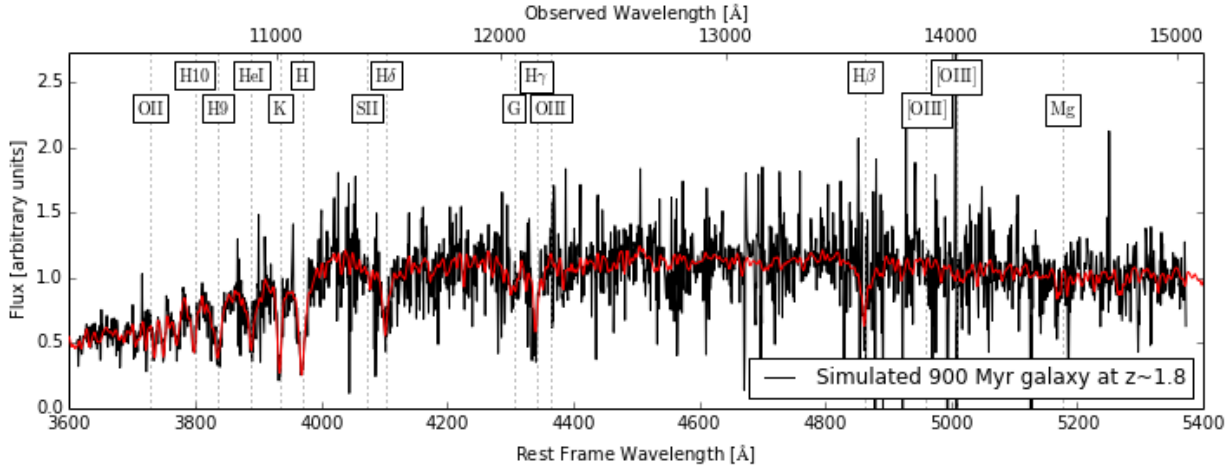

Figure 3: Top: Simulated 10 hour exposure calculated using the MMIRS signal-to-noise calculator using a J_JK_short slit, 0.8" seeing and a 0.8" *short* longslit (corrected for the spectral slope of an A0 star) and degraded slightly to account for the barely resolved extent of the galaxy. Observable spectroscopic features are labeled.

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 propose to observe 0851-E4 (the forth image - see Fig. 2) with MMIRS using a 0.8" long slit, masked to 10" to minimize scattered light from within the instrument. The J_YJ grism provides the perfect balance of spectral resolution and wavelength coverage - catching the Balmer/4000Å break at $z \sim 1.8$ as well as several Balmer absorption features, which would be present after ceasing a dramatic episode of star formation for $\sim$1Gyr. Detection of such lines would indicate that indeed the galaxy is in the process of quenching.

In the case of exceptional seeing, we will switch to multi-slit mode of MMIRS (because these slits are 0.4"), including other lensed galaxies in addition to 0851-E4 to measure redshifts and improve the overall lens model for SGAS cluster SDSS0851+3331.

Our observations will be split into 600 second exposures, offset by an ABA'B' dither pattern, to increase the S/N of the final exposures and to account for sky variations and detector defects. We will observe A0V stars before and after each observing block, to correct for telluric features. Use the signal-to-noise calculator, we estimate that we will reach our goal of $S/N\sim10$ with a total of $\gtrsim$10 hours of on source integration (see Fig. 3), when optimally extracting 1D spectrum in spatial direction. This S/N will be sufficient to reliably measure the strength of absorption features and, if the velocity dispersion is as high as predicted, to measure the broadening of stellar absorption features. We request two nights to reach the required depth, however the target is accessible at the end of the night during November and December 2015B. However if night splitting were advantageous, we could achieve proposed depths in 1.5 nights (with overheads for acquisition and calibration frames). Grey time is requested due to the faint nature of 0851-E4 and wavelength coverage, particularly in the Y-band.

Given the unique nature of this galaxy, this is a stand-alone program with respect to spectroscopy. We do not anticipate applying for additional time.

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 request 2 nights (or 3 half nights) for the completion of this project in 2015B.

PI Bezanson has extensive experience with spectroscopy and in collaboration with Co-I Whitaker will perform data reduction and analysis. Bezanson will make dynamical measurements and Whitaker will lead the analysis of the stellar population of 0851-E. Co-I Sharon is already leading the lensing model for 0851-E and the SDSSJ0856+3331 cluster.

Discovery of 0851-E was made possible by the SDSS Giant Arcs Survey (PI: Mike Gladders, HST Cycle 20 Program 13003), together with the complementary Spitzer program (PI: Jane Rigby). PI Bezanson and Co-I Whitaker will share the spectroscopic redshifts measured as a result of this proposal with the SGAS collaboration (M. Gladders, J. Rigby, K. Sharon, M. Bayliss, E. Wuyts), in order to achieve the highest quality possible lensing model. We note that the main science goals of this proposal are complementary but unique from that of the original SGAS/HST proposal.

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**)*

PI Bezanson: 3 nights of Hectospec time were allocated in 2014B to collect deep spectroscopy of massive galaxies (down to shallower depths than the current proposal) in the COSMOS field to probe their dynamical and stellar populations. Of these three nights approximately 7 hours of the required data were collected in good conditions ($\sim$25% completion) in November 2014. All data have been fully reduced and data analysis, including the modeling of stellar populations and galaxy kinematics is underway. Even at these shallow depths approximately 130 out of 600 observed galaxies yield reliable dynamical fits. A three-night extension is being requested in 2015B to fully probe massive galaxy bimodality with sufficiently high S/N spectra.

Co-I Whitaker: has no experience with SO facilities but has lead a number of large studies of massive galaxies at $1 < z < 3$.

Co-I Sharon: has no experience with SO facilities but is an expert in lens modeling and is leading the lens modeling of the SDSSJ0856+3331 cluster.

From: **McLeod, Brian** bmcleod@cfa.harvard.edu
Subject: Re: MMIRS on the MMT
Date: March 27, 2015 at 8:24 AM
To: Bezanson, Rachel - (rbezanson) rbezanson@email.arizona.edu

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Hi Rachel
Yes
Brian

On Thursday, March 26, 2015, Bezanson, Rachel - (rbezanson) <rbezanson@email.arizona.edu> wrote:

> Dear Brian,
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> My name is Rachel Bezanson and I'm a Hubble fellow studying galaxy evolution at the University of Arizona. I'm currently investigating the feasibility of spectroscopic followup of a lensed, high-z (z~1.8) compact massive galaxy (H_AB ~ 20.7). The galaxy is exciting because it is both quite compact (and looks like dead galaxies at that redshift), but may not have fully quenched its star-formation. Without a spectroscopic redshift and better sampling of the SED and/or spectral age diagnostics, modeling its stellar populations is degenerate. I was wondering if it is possible for me to submit a proposal (through the UA TAC) to use MMIRS for this program? My target is up in the late fall (November-December).
>
> Best regards,
>
> Rachel