OBSERVING REQUEST
University of Arizona Observatories

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

Spanning the Gap: Dissecting Galaxy Bimodality and Quenching with a deep survey of galaxy absorption lines at $z \sim 0.5$

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Abstract of Scientific Justification

Perhaps the most fundamental property of galaxy populations is the fact that galaxies are bimodal: they are either star-forming or quiescent. However the physical process(es) by which galaxies quench their formation of stars and transition between the two populations remains elusive. The efficiency of quenching appears to depend on galaxy (1) mass and (2) environment: massive galaxies are more likely to be quenched as are those in dense environments. This proposed program will extend detailed studies of local galaxies to shed light upon the quenching process 5 Gyr in the past. This survey will obtain deep, medium resolution spectra for a mass-limited sample of galaxies down to $\log M_* = 10.5\, M_\odot$ (less than the mass of the Milky Way) in the UltraVista/COSMOS field. Building from a high quality photometric catalog and HST/ACS imaging across the entire field, this sample will allow for absorption line studies of galaxy dynamics, scaling relations, and stellar populations at $z \sim 0.5$, with unprecedented flexibility with respect to galaxy morphology, quiescence, and environment. Specifically, the survey will provide accurate ages and stellar population indicators to dissect galaxy bimodality, accurate dynamical masses, and precise environmental measurements. Armed with improved understanding of the distribution of stellar populations in galaxies, and therefore of what it means to be "quenched", and the most accurate measurements of the properties that correlate with quenching, we will be much closer to answering the question of how, when, and why star formation ceases in galaxies outside of the local Universe. Finally, this survey will serve as an intermediate-redshift bridge to future higher-z spectroscopic galaxy studies with multi-object Near-IR spectrographs both on the ground and on the upcoming JWST.

Summary of observing runs requested for this project

								Scheduling		Sharing	
Run	Telescope	Cage	Instrument	PI	AO	Nights	Moon	Optimal	Acceptable	Poss.	Adv.
1	MMT	f/5	Hectospec			3	dark	Jan–Mar	Jan–Apr	yes	yes

Scheduling constraints and unusable dates *(up to 4 lines)*: None

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	UltraVista Cosmos Field	10:00:00	+02:15:00	$I(AB)$=19–21.5, $0.4 < z < 0.6$ galaxies

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

Galaxy bimodality, or the fact that galaxies generally fall into one of two categories: star-forming and quiescent, is perhaps the most fundamental characteristic of galaxy populations. The separation between the two classifications of galaxies extends to a multitude of their properties: in addition to their stellar populations (and therefore colors), star-forming and quiescent galaxies differ in shape (disks vs. spheroidals), size (disks are generally larger at fixed mass), dynamics (rotation versus dispersion supported) as well as their evolution through cosmic time. Although this bimodality has been demonstrated to exist as early as $z \sim 4$ (e.g. Muzzin et al., 2013), the fraction of quenched galaxies at a given stellar mass ($f_q(M_\star)$) grows with time; requiring migration between these two populations. This migration of star-forming galaxies to the red sequence, dubbed "quenching", appears to depend on both galaxy *mass* (more massive galaxies have higher f_q) and the *environment* in which a galaxy lives.

The physical mechanism(s) responsible for causing galaxies to stop forming stars and maintain their quiescence (while also altering structural and dynamical properties) is still elusive. One possibility is the importance of AGN feedback: with a combination of strong "quasar-mode" feedback to stop formation and "radio-mode" feedback to keep remaining gas from cooling and forming new stars. Others have suggested the importance of a halo mass threshold ($\log M > 12$) above which gas is shock heated and cold flows no longer penetrate to central galaxies, which are starved into quiescence (e.g. Dekel & Birnboim, 2006)

This Proposal: A unique spectroscopic survey of massive galaxies at z ~ 0.5

We propose to conduct a deep, mass-limited, and "color-blind" spectroscopic survey that will incorporate absorption-line measurements for ~ 1000 galaxies at $0.4 < z < 0.6$. This survey will probe the observational trends in galaxy quenching and minimize several key uncertainties that are not being addressed by any ongoing photometric or spectroscopic survey at $z \gtrsim 0.1$. The current survey will obtain deep ($S/N > 10\text{Å}^{-1}$), medium resolution spectra for a mass-limited sample of galaxies down to $\log M_* = 10.5\,M_\odot$, probing the mass at which galaxy quenching is most active, in the UltraVista/COSMOS field. This survey will build from a high quality photometric catalog (Muzzin et al., 2013) and will boast an unprecedented, yet necessary, flexibility with respect to galaxy morphology, quiescence, and environment.

First, we will measure the details of stellar populations from spectroscopic features across the full range of galaxy morphologies to dissect the simple bimodality - allowing for trends in **ages, metallicity, and star formation histories**. Additionally, absorption line kinematics, in combination with galaxy structures measured from existing HST/ACS imaging, will be used to measure **dynamical masses**-calibrating notoriously uncertain stellar mass estimates and therefore more accurately assessing the importance of quenching as a function of galaxy mass. Additionally, uniformly selected galaxies across the wide ($1.62\ \mathrm{deg}^2$) field, with excellent spectroscopic redshifts galaxies will allow for further assessment of the efficiency of galaxy quenching across a **range of environments**. Finally, the large proposed sample size will both representatively span the range of galaxy populations and will allow for the assessment of trends within subsamples. For example, any 2D phase space can be divided into $\sim 3 \times 3$ bins and scaling relations in bins of ~ 100 galaxies (e.g. low, middle, and high mass and bluest, average, and reddest colors) can be investigated.

Similar broad and deep spectroscopic surveys only exist in the local universe

Large surveys of the local universe, such as the SDSS, have provided a wealth of imaging and spectroscopic data for hundreds of thousands of galaxies, compiling a complete census of galaxy dynamics, structures and star formation histories since $z \sim 0.1$ (Fig. 1a). No such spectroscopic survey exists at higher redshifts. Current high-z surveys that select galaxies uniformly provide excellent redshifts and some information about stellar populations at $z > 0.1$ - particularly from emission lines. However, these surveys are far too shallow (e.g. DEEP2 (Newman et al., 2012), TKRS (Wirth et al., 2004)), and/or low resolution (e.g. VVDS-deep/VVDS-wide (Le Fèvre et al., 2004; Garilli et al., 2008), zCosmos (Lilly et al., 2007) and PRIMUS (Coil et al., 2011)), to measure reliable absorption line velocity dispersions for anything but the brightest galaxies (Fig. 1b). On the other hand, smaller dynamical surveys have been conducted of high-z galaxies selected to be uniform in a specific observable property, such as morphology (e.g. Treu et al., 2005).

Stellar Populations and Metallicities

The uniform spectroscopy across galaxy types in the SDSS revolutionized our understanding of galaxy stellar populations (e.g. Kauffmann et al., 2003). By identifying spectral features (such as the strength of the

Balmer break, D4000, and equivalent widths of Balmer lines, namely $H\delta$), we can pin down galaxy ages and break photometric degeneracies in star-formation histories (see Fig. 1a). This allows for the study of individual galaxies and trends with such properties as stellar mass and answering questions like: how dead are quenched galaxies? How rapid is the quenching of star-formation (by comparing current star-formation rates to stellar age). Assembling this information for galaxies at a lookback time of 5 Gyrs and comparing it to similar trends in the local universe will contribute dramatically to our understanding of the intertwined processes of star-formation and quenching.

Dynamics and Dynamical Masses

Nearly all high-redshift galaxy studies rely on estimates of stellar masses from photometric data. Inherent in these measurements are a number of uncertain, and hotly debated, assumptions about stellar populations such as the relative contribution of TP-AGB stars to the integrated light of a galaxy (Kriek et al., 2010) and the stellar initial mass function (e.g. Conroy & van Dokkum, 2012). The systematic error in the mass estimates for galaxies could be as high as $0.1-0.2\,\mathrm{dex}$, even assuming that stellar populations at high-z are consistent with those in the local Universe. With high S/N spectroscopy, one can measure stellar absorption line kinematics that can be used, in conjunction with galaxy structural parameters, to measure dynamical masses. The comparison between dynamical and stellar mass estimates can provide an important test of the accuracy of stellar masses at $z > 0.1$. Until now, these comparisons have only been made for biased samples of the most massive high-z galaxies (e.g. van de Sande et al., 2013; Bezanson et al., 2013a), however this survey will probe a unique range in stellar mass - potentially probing evolution in the slope, in addition to the normalization, of this correlation. Furthermore, dynamical measurements can be used to examine the evolution of scaling relations, such as the Faber-Jackson relation and the Fundamental Plane, and shed light on the dark matter fractions of galaxies.

"Mass" versus "Environmental" Quenching

The large area of the sky will allow for environmental studies of the galaxies in this survey - progressing beyond simple field versus cluster designations. At $z \sim 0$, it has been suggested that galaxy quenching depends on both the mass of the dark matter halo and whether a galaxy is a central or satellite (e.g. Peng et al., 2010). Many spectroscopic studies of $z > 0.1$ cluster environments exist, however quenching of galaxies in group and field environments requires the large area approach of this survey and excellent spectroscopic redshifts are required to identify physical associations (e.g. number of galaxies within a fixed volume).

AGN in Massive Galaxies

Emission line spectroscopy, in addition to the extraordinary multi-wavelength ancillary data in the COSMOS field (e.g. Radio from VLA, IR from Spitzer, X-ray from XMM and Chandra), will allow for studies of AGN occurrence rates in massive galaxies at $z \sim 0.5$ and investigate correlations with stellar populations and the possible ties to galaxy quenching. Furthermore, it will probe the impact of AGN emission on massive galaxy photometry, and specifically on colors and photometric estimates of quiescence.

Providing a Bridge to Future Higher-z Spectroscopic Galaxy Surveys

In the future, large spectroscopic galaxies surveys will probe further into the $z \gtrsim 1$ Universe. This has begun with current generation near-IR multi object spectrographs (e.g. with MOSFIRE on Keck) and will continue with the next generation of 30-meter class telescopes and the JWST. In this context, a detailed understanding of galaxy evolution, provided by the proposed deep, large spectroscopic surveys, will provide a crucial link - bridging the gap between today and the 9-10 Gyrs past where these surveys will pick up.

References

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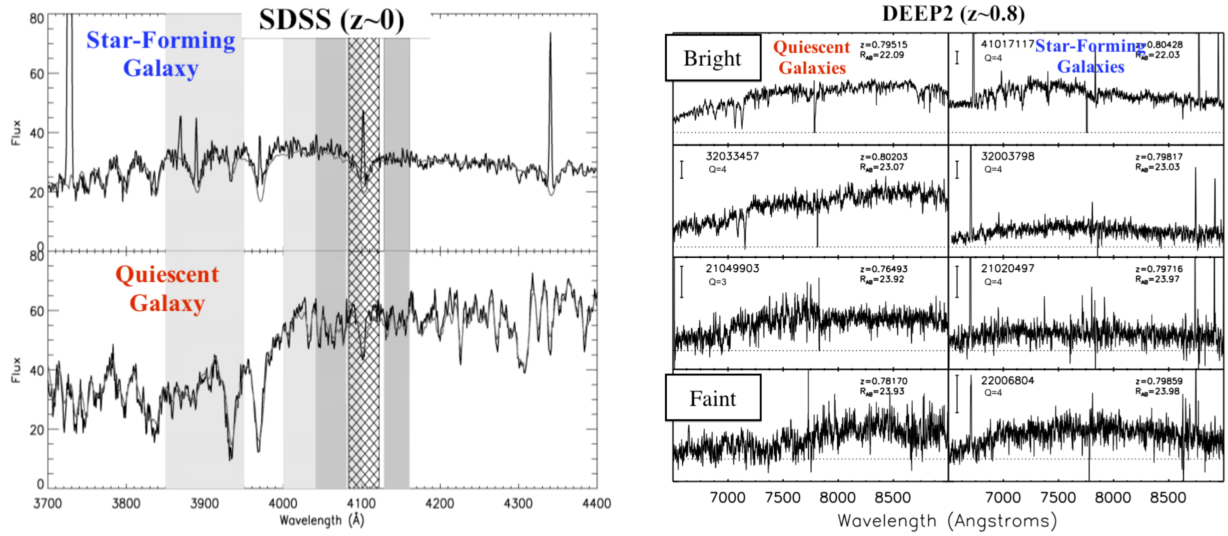

Figure 1: *(a)*: Spectra from the SDSS (Kauffmann et al., 2003) with high S/N, suitable for dynamical and stellar population studies. *(b)*: State of the art spectra of Red and Blue Galaxies at $z \sim 0.8$ in the DEEP2 Survey (Newman et al., 2012). With short exposure times, the continuum disappears for all but the brightest galaxies. This proposed survey will provide SDSS quality spectra (left) for a mass-limited and representative sample of $z \sim 0.5$ galaxies across the full range of galaxy structural and stellar population properties.

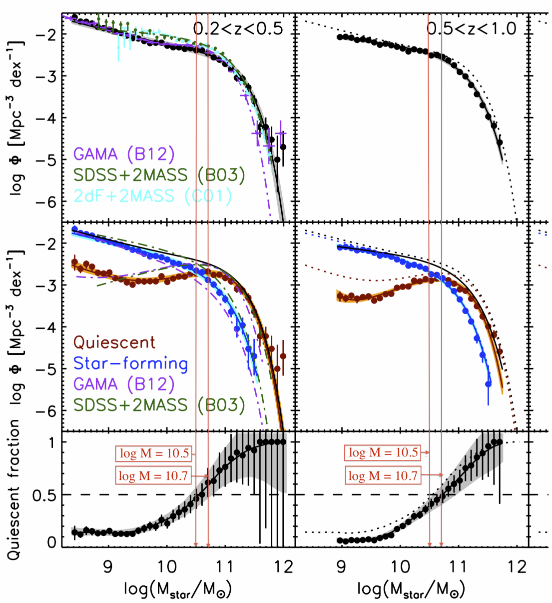

Figure 2: The observed mass function of galaxies in the UltraVista field (Muzzin et al., 2013), separated (based on photometry) into star-forming and quiescent galaxies from $0.2 < z < 1$. Bottom panels at each redshift show the quenched fraction of galaxies as a function of stellar mass.

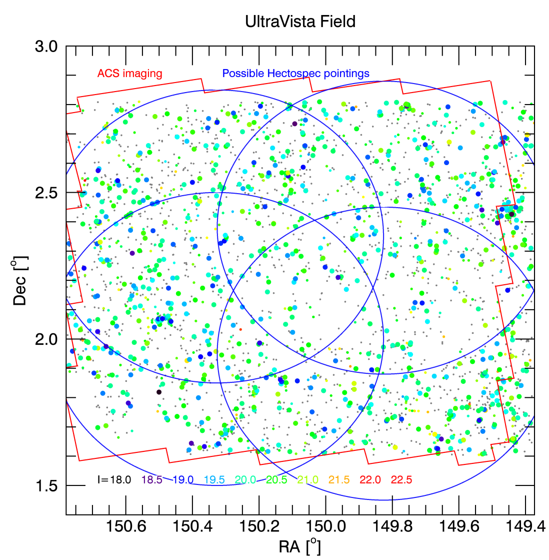

Figure 3: Galaxies in the UltraVista field with $0.4 < z \leq 0.6$ (grey = low mass galaxies, small circles $\log M_* > 10.5$, larger circles $\log M_* > 10.7$). Massive galaxies are color-coded by magnitude ($I \lesssim 20.4$, generally blue and green dots, should achieve desired depth in ~ 5hr.)

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)***

UltraVista Photometric Catalog

Spectroscopic targets will be selected from the existing UltraVista Catalog (produced by Co-I Muzzin et al., 2013), which combines photometric data in 30 bands (including GALEX, Subaru, CFHT, UltraVista, and Spitzer imaging) allowing for excellent photometric redshifts (as well as spectroscopic redshifts in the field), well-sampled SEDs for derived colors and stellar mass estimates, and optimally derived star-formation rates from combined UV and IR luminosities. Finally, HST/ACS imaging exists over nearly the whole field (necessary to characterize morphologies). There are 3004 galaxies within the $0.4 < z \leq 0.6$ in the full catalog, 1300 of which are above the ultimate mass limit ($\log\, M_{*} > 10.5$) and 776 above the initial $\log\, M_{*} > 10.7$ limit. The full survey area (1.62 $\deg^2$) is well matched to the Hectospec field of view. We will sample the field with four pointings (see Fig. 3 for a rough design), however we will use multiple iterations of each - repeating the faintest few hundred galaxies (begun in 2014B) in multiple configurations and varying brighter galaxies to reach target S/N for roughly 1000 galaxies. This will be particularly helpful in crowded areas.

Mass (Not Magnitude!) Limits and Spanning Galaxy Colors

The unique aspect of this survey lies in the combination of its depth, allowing for absorption line measurements, and uniform sampling of the mass-limited galaxy population, which spans across the range of galaxy bimodality. M_{*}/L for redder galaxies are higher than for blue galaxies, therefore magnitude limits impose strong selection biases against dead galaxies. Instead, we adopt stellar mass limits to accurately represent the galaxy population. Since quenching occurs preferentially in more massive galaxies, we must probe down to a mass at which galaxies exhibit a range in stellar populations. The proposed (continued) observations will fully sample the $\log\, M_{*} > 10.5$ galaxy population at which quenching is likely to be most active - (quenched fraction $\sim 40 - 50\%$) (Muzzin et al., 2013) (see Fig. 2).

Configuration and Wavelength Coverage

Optimal rest-frame wavelength coverage for studying the stellar populations of galaxies is roughly $3500 - 5000$Å (sampling the Balmer break, OII, Balmer lines etc.), whereas absorption line kinematics are best measured above $\lambda_{\rm rf} \sim 4000$Å (Balmer lines can produce strong template mismatch errors). At $z \sim 0.4(0.6)$, this corresponds to an observed wavelength range of $4900 - 7000$Å ($5600 - 8000$Å) , which is well-suited the 270 groove/mm grating, with spectral coverage of $3650 - 9200$Å.

Required S/N and exposure time

Fabricant et al. (2013) demonstrated the feasibility of measuring velocity dispersions from MMT/Hectospec spectra at slightly lower redshifts (though extending to $z \sim 0.6$), shorter exposure times ($\sim$ 1hr), and larger uncertainties ($\sim 30 - 50$km/s). Given the goal of testing stellar masses, we require uncertainty in dynamical mass ($\propto \sigma^2 R$) to be $< 0.1\,$dex, therefore $< 0.05\,$dex uncertainties in velocity dispersion. In previous work, we found that $\lesssim$10% errors can be obtained from spectra with $S/N \gtrsim 10$Å (e.g. Bezanson et al., 2013b). For that similar dataset of Keck DEIMOS spectra, we fit S/N as function of I magnitude and exposure time. After correcting for aperture size and resolution differences find that the exposure time to reach $S/N \geq 10\text{Å}^{-1}$ should follow: $\mathrm{t[hr]} \sim (7 \times 10^{-13}) 10^{0.6\,\mathrm{I}}$, which is consistent at ~ 0.75hour to the S/N versus R plot in the Hectospec manual. We expect galaxies $\mathrm{I} < 20.4$ to reach this depth in $\sim 5hr$, divided into 20 minute exposures. In the initial 30 hours of observing time (split amongst four configurations), we expect to reach $I = 20.7$ or 90% completeness for $\log\, M_{*} > 10.7$ galaxies. With additional 3 nights re-observing faint galaxies and adding brighter ones to the new configurations, galaxies down to $I \sim 21.2$ ($\sim 99\%$ of $\log\, M_{*} > 10.5$) should reach the required S/N.

Scheduling Note

We understand that scheduling this program within the queue depends strongly on a number of constraints such as the availability of Hectospec during dark time, limited observability, etc. We emphasize that this survey is cumulative; if less than the required time is available this semester, any additional data will still be valuable and will provide insights about more massive samples. We will eventually co-add spectra to reach the ultimate survey depths.

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**)*

Our current request is for 3 nights of observing time with Hectospec, building on our previous allocation of three nights in 2014B. Assuming that observations in 2014B and the proposed observations in 2015A are completed as planned, this will achieve the stated goals of this proposal and no additional telescope time will be necessary.

Reduction and data analysis will primarily be undertaken by PI Rachel Bezanson, in collaboration with Co-I Ben Weiner, who has extensive experience with Hectospec data and the in-house reduction pipeline designed by Richard Cool.

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 Rachel Bezanson:

⋆ 3 nights of Hectospec time were allocated in 2014B to collect deep spectroscopy of massive galaxies (down to the mass of the Milky Way) in the COSMOS field to probe their dynamical and stellar populations. Data have not yet been collected. The current proposal will complete the survey to lower mass limits to fully sample the regime of galaxy quenching.

Co-I Ben Weiner has extensive experience using UAO facilities and publishing results (MMT experience abbreviated list follows):

- 3 nights of Hectospec time were allocated for May-June 2014 for a second proposal of the dwarf satellite survey, to finish the NGC 6181 field and target two more MW-analog galaxies with improved target selection for 3x greater efficiency. These data have not yet been taken.
- 3 nights of Hectospec time in May-June 2013 for the first proposal of a survey of dwarf satellites around Milky Way analogs, targeting the NGC 6181 field. This program was 60% completed due to weather. The data have been reduced and redshifts measured. We found a handful of satellites, which are being followed up at Keck, and have refined the target selection for this proposal to increase efficiency. A short paper on the confirmed satellites is in preparation.
- 2 night of MMT/Blue Channel time in June 2011 and Feb 2012 for long-slit spectroscopy of IR-luminous galaxies with Herschel PACS far-IR spectroscopy. The data have been reduced and we are finding correlations between optical emission extent and far-IR line strength.
- 1 night of MMT/Blue Channel time in Jan 2012 in a special call, for followup of SDSS QSOs that have a BOSS galaxy close to the line of sight, to search for Mg II absorption. The data reduction is in progress.