OBSERVING REQUEST
University of Arizona Observatories

Year: 2015 **Term:** Jan–Jul **Proposal type:** engineering

Galaxy Cluster Cosmology with Low Resolution Spectroscopic Imaging

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Abstract of Scientific Justification

We propose to characterize the galaxy population of a sample of massive galaxy clusters by obtaining images of these clusters with a set of narrow band filters ($\Delta\lambda = 10$ nm) designed to bracket the rest frame 400 nm spectral feature in the cluster galaxies. These measurements fill in the gap between standard (e.g. UGRIZ) photometric imaging and multi-object spectroscopy and have the potential to rapidly provide information on redshifts and galaxy types for a large number of galaxies with a relatively small telescope. We have tested this technique by making observations of the galaxy clusters MACS1720+3536 and RXJ2129+0005 with a set of 12 narrow band filters on a dedicated 28" telescope. From these observations combined with data from the Cluster Lensing And Supernova survey with Hubble (CLASH) observations we estimate that we are able to measure the redshifts of several hundred galaxies in each clusters to an accuracy of $\Delta z = 0.003\ (1 + z)$ as well as constraining their SED and galaxy type. We propose to install a similar set of filters which we will provide on the Bok 90" telescope and observe the galaxy clusters MACS0717+3745 and MACS1149.5+2223. These galaxy clusters are members of the Hubble Space Telescope (HST) Frontier Fields program and have some of the deepest photometric and spectroscopic data publicly available as well as lensing models.

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	90"	PF	90Prime			10	grey	Jan–Mar	Jan–Jul	no	no

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	MACS0717+3745	07:17:34.0	+37:44:49.0	z=0.545, Galaxy Cluster
2	MACS1149.5+2223	11:49:36.3	+22:23:58.1	z=0.543, Galaxy Cluster

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
Ian Chute	Philip Mauskopf		yes	no
Pao-Yu Wang	Philip Mauskopf		no	yes

Scientific Justification

Galaxy clusters can provide information about the distribution of matter on the largest scales through cluster redshift surveys, about galaxy formation in high density environments and about the distant universe through lensing magnification of background galaxies. The Cluster Lensing and Supernova survey with Hubble (CLASH: Postman, et al., 2012) consisted of deep imaging of 25 galaxy clusters in 16 passbands with the Hubble Space Telescope (HST). Currently the Frontier Fields program has begun a large observing program with HST and the Spitzer Space Telescope (SST) of deep imaging of 6 galaxy clusters in photometric bands from 0.4 - 5 microns. Some of the goals of this programs are i) to measure the profiles of dark matter in galaxy clusters using gravitational lensing, ii) to detect type Ia supernovae out to redshifts of $z \simeq 2.5$, iii) to use the gravitational lensing of the cluster to probe high redshift galaxies at $z > 7$ and iv) to study the structure and evolution of the galaxies in the clusters (Coe, D., Bradley, L., & Zitrin, A. 2014).

Estimating the redshifts of the galaxies in these fields can be done with photometric redshift fits to the 16 passbands giving uncertainties of a few percent. Higher precision redshifts can be obtained with measurements of X-ray spectral lines or with optical high resolution multiobject spectroscopy (MOS) of the galaxies. Galactic spectra from three of the frontier fields clusters, MACSJ0416.12403, MACSJ0717.5+3745, MACSJ1149.5+2223 have been measured with MOS instruments on Keck and Gemini (Ebeling, Ma and Barrett, 2014). These redshifts are necessary to unambiguously identify cluster members and improve the mass modelling from the lensing measurements. The velocity dispersion can also be measured from the distribution of redshifts of the galaxies in the cluster giving an independent mass estimate that can be compared with the lensing mass.

However, for now imaging with the depth and precision of the frontier fields and follow up spectroscopy is only possible on a small sample of clusters. Using galaxy clusters as a cosmological probe requires a larger survey with on order 1000s of clusters covering a wide range of redshifts. The largest catalogs of galaxy clusters are from photometric surveys such as SDSS (e.g. Geach, Murphy and Bower, 2011) with photometric redshifts of the cluster galaxies with accuracy of a few percent. This redshift accuracy is good enough to constrain cosmological parameters if the masses of the clusters can be measured. For the most massive clusters, the velocity dispersion corresponds to a dispersion in redshift of the cluster galaxies of approximately 0.3%. This is the same redshift accuracy required to measure the baryon acoustic oscillation signal from large scale structure.

Several groups have demonstrated the ability to measure galaxy redshifts with similar precision in non-cluster fields using either combinations of 10 nm wide filters (Benitez, et al., 2009, Benitez, et al., 2010) or low resolution prism-based MOS instrumens (Coil, et al., 2011). We propose to use a set of 16 narrow band filters covering wavelengths from 490 - 650 nm combined with archival broad band photometric data to measure redshifts and galaxy types of galaxies in the frontier fields clusters MACSJ0717.5+3745, MACSJ1149.5+2223 with an accuracy of 0.1% using the Bok 2.3 m telescope. While narrow multiband imaging is not as fast as low resolution MOS, it is relatively simple to implement with existing imaging systems such as 90Prime. There are several advantages to targeting galaxy clusters rather than non-cluster fields including

1. there is a relatively high density of galaxies so that the observing efficiency is high for narrow band imaging
2. the cluster galaxies typically will have spectral energy distributions similar to elliptical galaxies with strong 400 nm break features and therefore will allow higher precision redshift estimates

We have demonstrated this technique on lower redshift galaxy clusters using a dedicated 0.7 m telescope with measurements in 12 filter bands, each 10 nm wide, from 490 - 610 nm. Figure 1 shows a preliminary three color image of the cluster field MACSJ1720.5+3536 ($z = 0.391$) using only the filter bands at 532 nm, 540 nm and 550 nm. Even with this narrow range in wavelength, it is possible to separate the cluster member galaxies (orange) from the foreground stars and galaxies (white). The 10σ limiting magnitudes in the fields are between 19 and 20 and the total number of galaxies detected per square degree field is approximately 500-1000. We are now in the process of making redshift estimates from the point source catalog data.

We have performed simulations of the effectiveness of the redshift fitting using a combination of SDSS ugriz bands and our 12 narrow band filters shown in Figure 2a. We simulate the spectral energy distribution of a typical elliptical galaxy, redshift it by different amounts and then observe it with the filter set, add noise and then fit a redshift and galaxy type using the LePhare photoz software. The brightness of the source is normalized to 19th magnitude in r-band for all redshifts. The results of the fit are shown in Figure 2b.

For the higher redshift clusters proposed here, we will need deeper integrations to detect the cluster member galaxies with high signal to noise and the Bok telescope provides the necessary increase in sensitivity. Because the target fields will have extremely high quality imaging and spectroscopic data, we will be able to characterize the precision of the redshift estimates from different combinations of broad and narrow band filters for both cluster members and foreground galaxies. In addition, by comparing the spectral data with the high resolution images, we will be able to determine the ability to spectrally characterize galaxy types.

The goals of this proposal are therefore:

1. to demonstrate the ability to measure cluster redshifts with multiple narrow band filter measurements. Explore the possibility of measuring dynamical mass - compare with lensing mass estimates.

2. to demonstrate the ability to perform a census of galaxy types in cluster fields. Compare spectral type identification from narrow band filter measurements with high resolution magnitude 29 imaging from HST.

3. to obtain wider field images of the area surrounding the cluster including adjacent 'blank' fields to probe the surrounding cluster environment and demonstrate the ability to characterize galaxy redshifts in non-cluster fields.

This method can be used with the Bok telescope or other comparable or smaller telescopes to perform a survey of galaxy clusters at redshifts $z \leq 0.6$ and could be extended to higher redshifts with deeper integrations.

References

[1] M,. Postman et al. 2012, ApJS 199, 23
[2] D. Coe, L. Bradley, & A. Zitrin 2014, arXiv:1405.0011
[3] H. Ebeling, C.-J. Ma & E. Barrett 2014, ApJS , 211, 21
[4] J. Geach, D. N. A. Murphy & R. G. Bower 2011, MNRAS , 413, 3059
[5] N. Benitez, et al. 2009, ApJ , 691, 241
[6] N. Benitez, et al. 2009, ApJ , 692, L5
[7] A. Coil, et al. 2011, ApJ , 741, 8

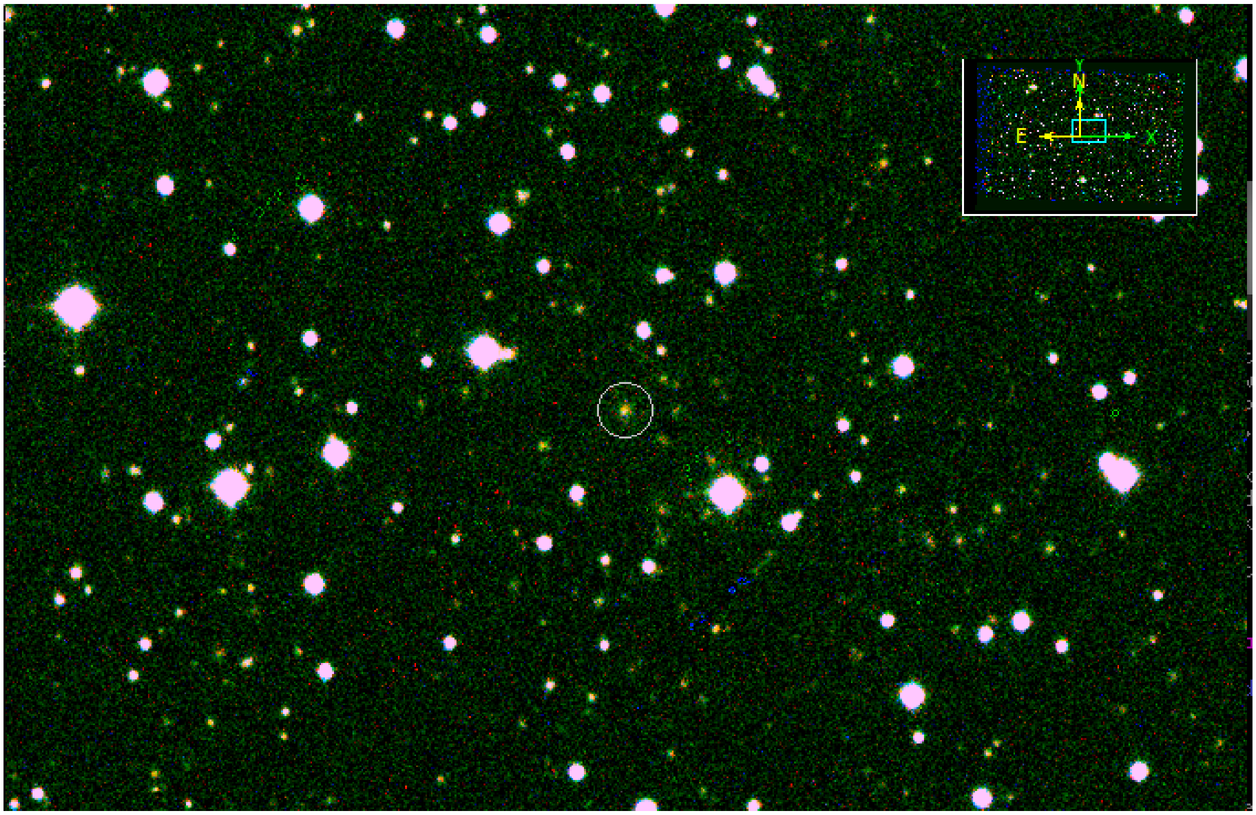

Figure 1: Three color image of the cluster MACSJ1720.5+3536 taken with a 28” telescope with a set of 10 nm wide narrow band filters. The colors used in this image correspond to the filters with short wavelength edges at 532, 540 and 550 nm. The galaxy in the center is the BCG of the cluster and the field of view is approximately 8’ $\times$ 12’. The full field is shown in the inset at the top right.

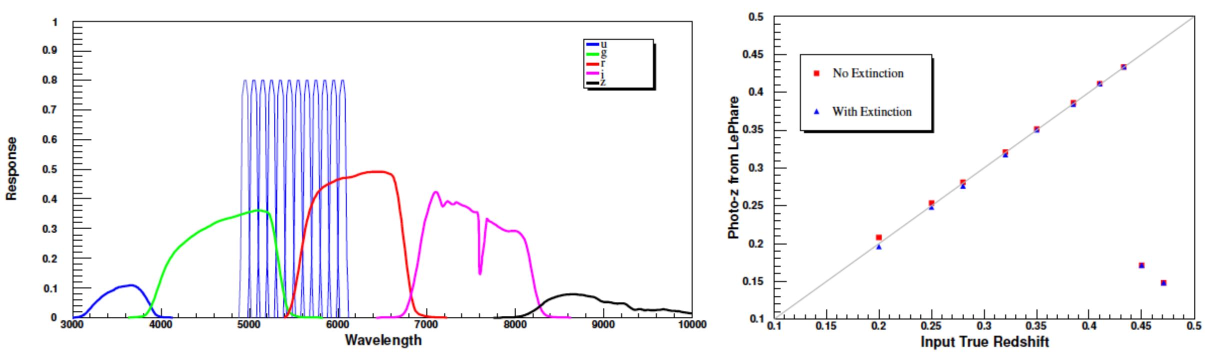

Figure 2: a) Response of the filters used for the measurements in Figure 1 along with the profiles of the ugriz filters used in the Sloan Digital Sky Survey. The 12 narrow band filter profiles are computed from laboratory measurements taking into account the f/3.1 beam of the telescope. b) Results of photometric redshift fitting to simulated data from elliptical galaxies as a function of redshift. Data was generated from a galaxy template model and observed in the filter bands in Figure 2. Then noise was added and the LePhare software was used to compute redshift and galaxy type. The dispersion in the points from the curve between redshift of 0.2 and 0.4 is approximately 0.1%.

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 intend to install 16 bandpass filters, each 50mm in diameter and 5mm thick. Each filter has a bandwidth of 10-12 nm as measured in a f/3.1 beam and the full set of filters covers the wavelength range from 490 - 650 nm. In consultation with Ed Olszewski we have designed a filter holder to hold four 50mm filters aligned to cover the 90Prime instrument. The 50mm filters have already been tested and utilized on a 28" telescope and will be provided for the Bok 90" telescope.

We will install and test the filter holder and filters complete the testing phase during the first night to work out any potential engineering complications. During this phase, we will take flats and dark images with the 90Prime and filters installed.

After completion of the testing phase, we will observe the two target fields for MACS0717+3745 and MACS1149.5+2223. The integration time for each of the 16 filters is ~ 45 min. Using four filters simultaneously, we observe each target field with four exposures. After swapping out filters, we again observe until the entire targets fields have been observed with each of the 16 filters. Overall, we would need ~ 32 45-minute exposures or 2.5 nights of on-target integration. We request 10 nights to account for installation, testing and overhead.

Overhead time would include initial focusing and collimation, taking darks and flats, slewing and pointing to target field, and swapping out filters. We assume normal telescope operations, 2 arcsec seeing, 8 hour nights, and partial moon.

For the long-term program, we would need 30 nights to observe the target galaxy clusters in 40 bandpass filters.

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**)*

(1) This is an initial proposal for UAO and therefore we have not been awarded any prior UAO nights. We are requesting ten (10) nights on the Bok 90", allowing us to both install the filters and filter wheels and then observe the galaxy clusters in the 12 narrow filter bands. Potential future observations of galaxy clusters would require additional time but is not needed at this time.

(2) We have previously utilized a semi-autonomous 28" Centurion telescope operating at Polaris Observatory (California) as a proof-of-concept for this project. The preliminary observations from the 28" telescope have verified the effectiveness of the observing methods and filters for this project and the Bok 90" will allow for a more robust scaled-up version.

(3) Co-I Rich (UCLA) is the primary operator for the 28" Centurion telescope and has significant involvement with the data acquisition. PI Mauskopf (ASU) has coordinated the target selection and data analysis of the 28" telescope with Co-I's Butler (ASU) and Wang (ASU).

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**)*

There has been no prior use of Steward Observatory facilities within the past 2 years.