OBSERVING REQUEST
University of Arizona Observatories

ENG249¡ 0 **Year:** 2015 **Term:** Aug–Dec **Proposal type:** long-term⋆ **Proposal ID:** L

Galaxy Cluster Survey with 10 nm Narrow Band Photometry

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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 acquired data in 16 bands for 9 cluster fields selected from the CLASH and Frontier Fields clusters from an observing run in spring, 2015, and preliminary results show that with a 20 minute total exposure in each band, we reach a 10σ magnitude limit of $\simeq 20 - 21$. From these observations combined with data from the Cluster Lensing And Supernova survey with Hubble (CLASH) and SDSS 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 continue the observing run in the fall to get deeper images, and acquire data on additional CLASH fields such as MACSJ1720+35, Abell 2261, RXJ2129+0005 and MACSJ2129. The long term goals from this proposal are to obtain a catalog of approximately 1000-2000 galaxies with redshifts per cluster field and to investigate the possibility of determining cluster masses with velocity dispersions.

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”		90Prime				Grey	Aug–Dec	Aug–Dec	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	MACSJ1720+35	17:20:17	+35:36:27	z=0.391, Galaxy Cluster
2	Abell 2261	17:22:00	32:08:00	z=0.225, Galaxy Cluster
3	RXJ2129+0005	21:29:40	+00:05:21	z=0.234, Galaxy Cluster
4	MACSJ2129	21:29:39	+00:04:59	z=0.589, 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
Pao-Yu Wang	Philip Mauskopf		no	no

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 CLASH and Frontier Fields galaxy clusters using the Bok 2.3 m telescope with measurements in 16 filter bands, each 10 nm wide, from 490 - 650 nm. Figure 1 shows a preliminary image of the cluster field Abell 370 ($z = 0.288$) using only the filter band at 650 nm. The 10σ limiting magnitudes in the fields are between 20 and 22 and the total number of galaxies detected per 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.

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.

Now that we have demonstrated this technique during the engineering run at the Bok telescope we are proposing to perform a survey of galaxy clusters at redshifts $z \leq 0.6$ with the exiting narrow band filters and extended to higher redshifts with more filters and deeper integrations. In addition to producing catalogs of 1000-2000 galaxies with redshifts for each cluster field, long term goals for this project are to investigate the possibility of determining cluster masses with velocity dispersions and measuring the spectrum of diffuse stellar emission from clusters using cross correlations of different images.

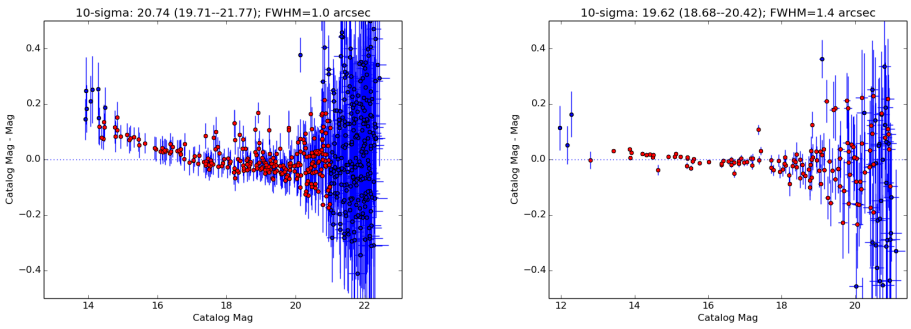

Figure 1: Galaxies photometry from 640nm filter (left) and 490nm filter (right). The magnitude limit spams from 19 to 20.7

References

[1] M,. Postman et al. 2012, ApJS 199, 23

[2] S. Jouvel, O. Host, O. Lahav, S. Seitz, A. Molino, D. Coe, M. Postman and L. Moustakas *et al.*, Astron. Astrophys. **562**, A86 (2014) [arXiv:1308.0063 [astro-ph.CO]].

[3] N. Benitez, E. Gaztanaga, R. Miquel, F. Castander, M. Moles, M. Crocce, A. Fernandez-Soto and P. Fosalba *et al.*, Astrophys. J. **691**, 241 (2009) [arXiv:0807.0535 [astro-ph]].

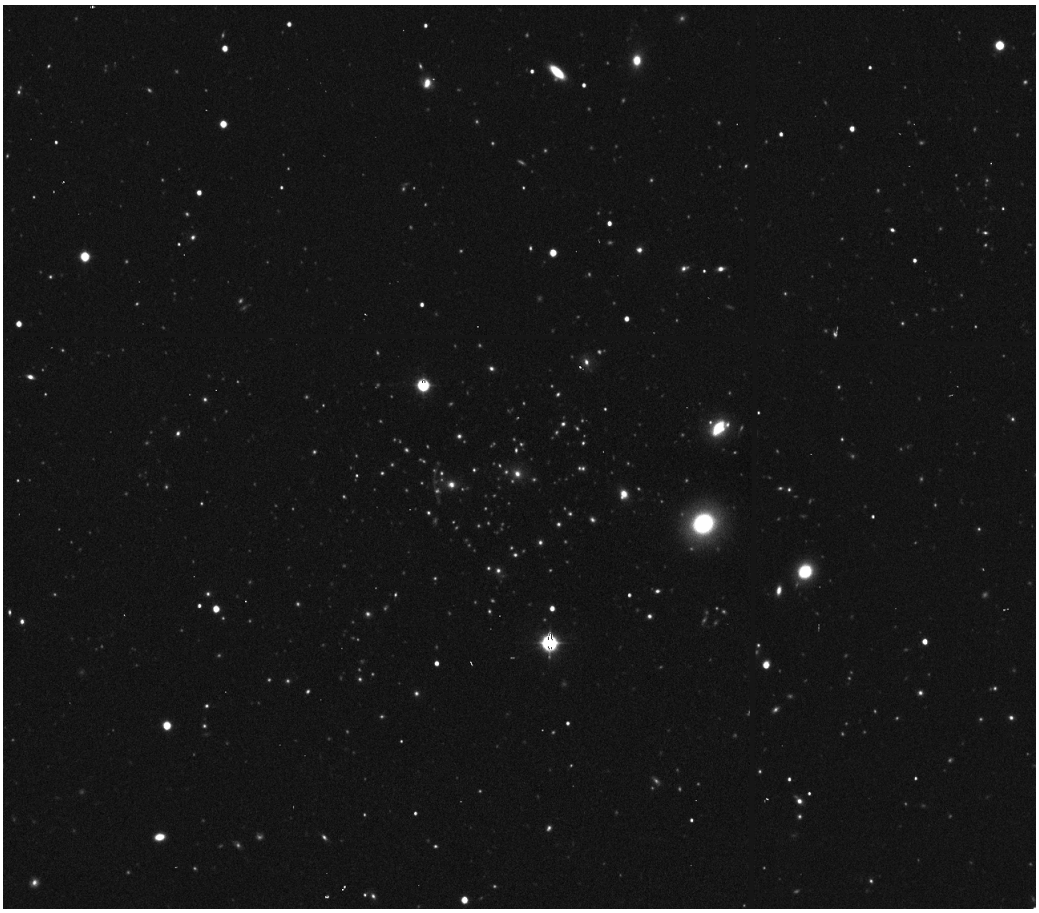

Figure 2: Image of Abell370 from 640nm filter

[4] N. Benitez *et al.* [J-PAS Collaboration], arXiv:1403.5237 [astro-ph.CO].

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 have installed 16 bandpass filters at the Bok telescope, each 50mm in diameter and 5mm thick in the first observing run in spring, 2015. 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 observe the target cluster fields in each of the 16 filter bands. 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 ~ 16 45-minute exposures per cluster or 4 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.

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 long term proposal for UAO and we obtained 11 nights of data in spring, 2015 for engineering tests. These tests were successful and we obtained science data for 9 clusters. We are requesting ten (10) nights on the Bok 90", allowing us to observe an additional 4-6 galaxy clusters in the 16 narrow filter bands. To complete the full survey of CLASH and FF clusters observable from Kitt Peak would require an additional 10 nights each in fall and spring 2016 to extend the wavelength coverage with more filters and optimize the integration depths for the different clusters post-analysis.

(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**)*

We obtained 11 nights of data in spring, 2015. Currently images from all of the clusters have been processed, sources have been extracted and we are in the process of photometric calibration and catalog production. We have developed software to do the first-order redshift fitting.