OBSERVING REQUEST
University of Arizona Observatories

Year: 2014 **Term:** Aug–Dec **Proposal type:** short-term

Arclet Redshift Census in the Field of MACS0647

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Abstract of Scientific Justification

We propose to undertake a redshift census of galaxies in the field of the massive lensing cluster MACS0647.7+7015. This cluster is made famous for lensing a candidate star forming galaxy at z=10.8, and despite the attention there is little known about many of the galaxies in the cluster and the hundreds of objects behind it, and no spectroscopic confirmation for any multiply-imaged galaxies. We request 1 dark night to do multi fiber spectroscopy with Hectospec with the goal to measure redshifts and galaxy properties for ~ 80 galaxies with r_{AB}<22 mags and also for fainter emission line objects to r_{AB}<24. We expect to identify emission line galaxies in Lyα for z = 2.6-6.1, [OII]3727,3729 for z<1.3, in [OIII]4959,5007 for z<0.7, and Hα for z<0.3. This program complements our photometric redshift catalogs based on 17 HST filters, and our HST/Cy21 GO-13317 program on WFC3/IR G141 grism spectroscopy in the center of the cluster still in the process of acquisition (PI: Coe). We will plan to make extensive use of this ancillary data to make secure redshift measurements of galaxies guided by the photometric redshift and grism redshift information. With this program we will be able to get detailed redshift information crucial to constrain the cluster mass and also to study the physical characteristics/conditions in the lower-luminosity z=1-5 galaxies boosted in brightness by the lensing effect. Hectospec provides the unique capability to study the dynamics of the cluster members out to the far-field for this powerful lens with its highly elongated total mass of visible plus dark matter. Note this program was approved in 2015A yet only 1 of 3 masks was acquired owing to poor weather. With this one mask we made a rare spectroscopic confirmation of a 24th mag (AB) arclet at z=1.0 (Figs. 2, 3), showing that Hectospec is well-matched to this problem.

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	Hectospec			1	dark	Dec	Nov-Dec	no	no

Scheduling constraints and unusable dates *(up to 4 lines)*: The ideal month to observe this target is December. If scheduling requirements are such that this observation is scheduled in November, then the primary target will be below 2 air masses starting at 10 pm MST.

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	MACS0647.7+7015	06:47:50.2700	+70:14:55.00	Galaxy cluster, z=0.591

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
Greg Walth	Eiichi Egami		no	no

Scientific Justification

Gravitational lensing is a powerful tool, enabling one: 1) to probe objects at earlier cosmic times because their images are brighter, and 2) to measure the total mass of visible plus dark matter of the dark matter. Galaxy clusters are the largest ∼virialized objects in the universe; they are also extended spatially on the sky, allowing for hundreds of galaxies in the background, or 'arclets' to be observed simultaneously. The cluster deflects and reorients the image shapes of background galaxies into directions which trace our the gravitational field of the cluster. Although predicted in the 1930s by Fritz Zwicky, it would not be until the early 1990s that clusters were viewed as laboratories for studying the lensing effect (Tyson 1990). In that same decade, the highest redshift objects were turning up as star forming galaxies strongly-lensed by galaxy clusters, such as multiply-imaged objects or 'image families' at $z = 4.04$, $z = 4.88$, and $z = 5.12$ (Frye et al. 1998, Frye et ao. 2002), and another image family at $z = 4.92$ (Franx et al. 1997). Since then dozens of ground-based campaigns have been undertaken aimed at discovering and studying arclets in the fields of massive lensing clusters (Frye et al. 2002, 2007, 2008). More recently, the first arclet survey in the field of a massive lensing cluster has been undertaken from space (Frye et al. 2012).

Important questions relating to galaxy clusters are: what is the distribution of the total mass of baryons plus the dark matter? How do the intermediate and high redshift galaxies in the background evolve over cosmic time? The discovery of the first cases of cases of galaxies image families has led to a paradigm shift in our understanding of the cluster mass. For the well studied cluster Abell 1689 (A1689; z=0.18), for example, there were zero examples of image families prior to imaging with HST. Immediately following our HST Advanced Camera for Surveys Key Project, collaborators and the PI discovered 30 image families and the joint analysis of these data has led the most robust mass maps ever constructed for which the mass distributions are found to be inconsistent with an isothermal mass (Broadhurst et al. 2005). This field has since been extended to include searches for halo substructures. Given the improved mass estimates, a formalism has recently developed to use the positions of image families to constrain the underlying cosmology (Gilmore et al. 2009; Jullo et al. 2010). At this point we simply lack the data to make strong cosmological constraints on the $\Omega_M - \Omega_\Lambda$ plane using image families. To build up the numbers, recently, I and collaborators have undertaken the first arclet redshift census *from space*, in the field of A1689. We found 43 galaxies (3/4 new to the literature!), including a giant arc (F12_ELG1 at $z = 0.79$) for which we were able to follow the emission lines along the 4.2 arcsec arc and map them onto their exact locations on the source plane (Frye et al. 2012). Many of these extraordinary cases of lensed galaxies were discovered by first undertaking galaxy redshift surveys from the ground where there are the largest light buckets available for the spectroscopy.

This Proposal

We request one night on MMT/Hectospec to initiate a new redshift survey of galaxies in the field of MACS J0647.7+7015 (MACS0647). MACS0647 is a galaxy cluster at $z = 0.591$ showing spectacular giant arcs, myriads of small but distorted arclets, and cluster members. This cluster was thrust into the spotlight owing to the discovery of a strong z≈10.8 galaxy candidate MACS0647-JD identified by Coe et al. (2013) as a part of the Cluster Lensing and Supernova survey with Hubble (CLASH), a collaboration on which PI-Frye and Co-I Coe are members (Postman et al. 2012). Bolstered by this discovery, we secured an HST grant (HST Cy21/GO-13317 PI: Coe) to obtain slitless spectroscopy of the MACS0647 field using the ACS G141 grism. The data acquisition is now complete (as of March, 2015), with the final set of data consisting of 12 orbits, split into three different epochs. Based on the first epoch data we are able to rule out the presence of a strong emission line source interloper for the z=10.8 galaxy candidate (Pirzkal et al. 2015). Despite the excitement over this cluster, there is remarkably little known about the galaxy population at z<10.8. **The goal with these proposed observations is to obtain detailed redshift information on the many dozens of objects at intermediate redshifts in and behind the cluster, many of which have redshifts of z∼1-2 near to the star formation density peak of the universe.** To aid with the redshift identification and assist with the analysis of galaxy properties, we will plan to make use of the deep HST imaging ranging from 0.2 - 1.6 microns.

Observations using Hectospec on MMT of MACS0647 enable an efficient redshift survey of arclets that would be infeasible using long-slit spectroscopy. We will achieve the first high spectral resolution (2-6 Å FWHM) observations of arclets in this field, which cannot be approached by the multi-band photometry or

the grism spectroscopy (45 Å per spatial pixel resolution). We will be able to spectrally-resolve redshifted common emission line features such as the [OII]3727,3729 doublet, and Hα from [NII]6583, which are valuable for making spectral classifications of galaxies as well as measuring physical conditions in the ISM. We will also be able to detect continuum and continuum features. This is because while grism observations have high sensitivity to the detection of compact emission features that are characteristic of ELGs, the background subtraction is notoriously difficult, leading to very few detections of stellar continuum or continuum breaks (although breaks can be detected in heroic coaddition efforts, Rhoads et al. 2008). Our goals for this short term program are the following:

- to produce a redshift catalog based on the spectroscopy of faint galaxies in the field of MACS0647 to ABmag $<$21, and to fainter limiting magnitudes in the cases of strong ELGs
- to measure [OII] SFRs for the cluster members at $z\approx$0.591 for comparison with Hα SFRs in the NIR, where available. We will also measure a new cluster velocity dispersion and and map out distribution of the cluster members out to the far-field.
- to study the background galaxies which will include Lyα emitters (z=2.6-6.1), [OII] emitters ($z<$1.3), [OIII] emitters ($z<$0.7), and Hα emitters ($z<$0.3). We will use the rich ancillary dataset 17 HST filter bandpasses and low resolution HST grism observations (still proprietary) to measure SEDs, derive stellar ages, stellar masses, star formation rates, and dust extinction.

The aim of our arclet redshift survey is to undertake a redshift survey of galaxies in the field of MACS0647. When combined with the deep HST photometry as well as the expected single emission line grism data, Hectospec spectroscopy can be used to study the physical characteristics and physical conditions in the arclets as well as the kinematics and star formation histories of the cluster members. MMT/Hectospec is required to enable the first detailed study of all galaxies above the flux limit ($i_{AB}<$22) in the field. **Note this program was accepted in 2015A but was truncated to only 1 of 3 masks owing to poor weather. In that single mask, acquired through thin cirrus, we made the secure redshift measurement of a faint 24th mag (AB) arclet (see Figs 2 & 3)!** This program is well-matched to Hectospec, and all masks are already made. We request one additional night to complete the program.

References: Broadhurst et al. 2005, 621, 53 • Coe et al. 2013, ApJ, 762, 32 • Franx et al. 1997, 486, 75 • Frye & Broadhurst 1998, ApJ, 499, 115 • Frye et al. 2002, ApJ, 568, 558 • Frye et al. 2007, ApJ, 665, 921 • Frye et al. 2012, ApJ, 754, 17 • Gilmore et al. 2009, MNRAS, 396, 354 • Geller et al. 2012, ApJ, 143, 102 • Jullo et al. 2010, Science, 329, 924 • Pirzkal et al. 2015, ApJ, *accepted*, astro-ph/150205681 • Postman et al. 2012, ApJS, 199, 25 • Richard et al. 2011, MNRAS, 413, 643

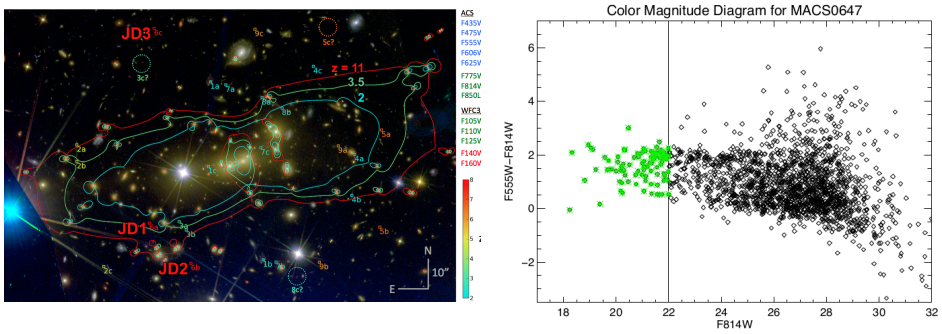

Figure 1: **Left**: image of our target MACS0647, with critical curves marked for z=2, z=3.5 & z=11. **Right:** the CMD for MACS0647, indicating the 90 galaxies as yet unpublished redshifts in the field. We expect to get to i_{AB}=21-22 mags for continuum detections and i_{AB}=24 mags for the emission line galaxies.

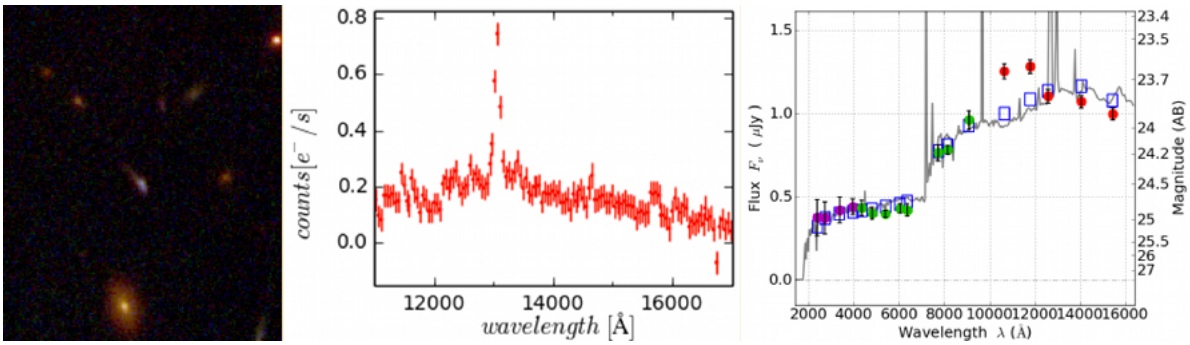

Figure 2: **Left:** HST ACS gri image of one faint blue arclet in the field of MACS0647. **Middle:** HST WFC3/IR G141 grism spectrum of this arclet with one strong emission line at ∼1.31 microns (and fainter [SII]$\lambda\lambda$6715,6730 emission redward). **Right:** SED fit to the HST UV-NIR photometry shows this galaxy image to be well fit by an ELG at z=0.98. Although our primary targets have i_{AB}<22, this faint arc with i_{814}=24.1 mags is predicted to show strong [OII] at ∼7400 Å if the rest equivalent width is high, as is found for the more 'extreme' ELGs (Frye et al. 2012, Atek et al. 2011). See Fig. 3 below for the answer!

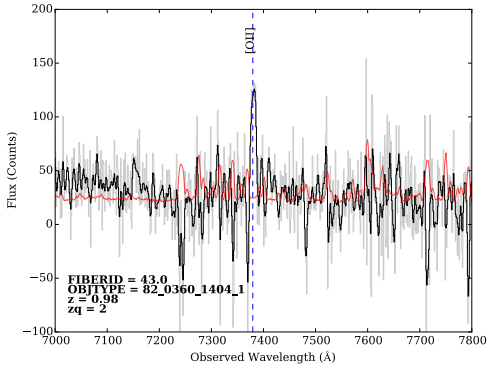

Figure 3: Spectrum of the blue arclet shown in Fig. 2 taken in a 2 h exposure with our approved 2015A Hectospec time. This 24th mag (AB) lensed source shows a strong emission line at λ≈1.31 μm (Fig. 2b) and has an estimated photometric redshift of z≈1 (Fig. 2b,c). We detect a strong emission line at 7400 Å, thereby obtaining a rare spectral confirmation of an extremely faint source in the precious redshift range at which the prominent nebular emission lines are split between the optical and the NIR. This was accomplished in only 2 h of our 1 night of approved time owing to poor weather. **We request 1 additional night to complete this program which is successful so far and is well-matched to MMT/Hectospec.**

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)***

Our goal is to obtain redshifts and emission line measurements for all galaxies in the field of MACS0647 (z=0.591) with i_{AB}<22 mags, and also redshifts of emission line galaxies (ELGs) with r<24 mags. Our target is a CLASH cluster, and as such as PI-Frye is a CLASH team member, there is access to a vast ancillary dataset including deep HST imaging from 0.1 Å to 4.5 microns and deep HST grism spectroscopy which was completed in February, 2015 (PI: Coe Cy21 GO: 13317). To achieve a high success rate for these observations, we will use these ancillary data to estimate the redshifts and predict the expected positions of any emission lines and/or continuum breaks. The grism spectroscopy consist of between zero and one emission lines all taken at low ∼45 Å/pix resolution. These detections will need to be corroborated by the detection of two or more emission lines at optical wavelengths. Hectospec is ideally suited for this type of spectroscopic program, and the field of view is excellent for galaxy cluster fields for which far-field spectroscopy aids with the weak lensing analysis of this prominent CLASH cluster.

Our observing plan will consist of two parts: 1) measurement of cluster member redshifts, and 2) measurement of background arclet redshifts, as follows:

- For the cluster members, 1h integrations are required in each of two configurations using the 600 grooves mm^{-1} grating to spectrally resolve the [OII]3727, 3729 doublet which falls in the middle of the spectral bandpass for z=0.591. This is based on the computation that a 1 h Hectospec exposure with 600 grooves mm^{-1} grating in seeing 0.6-0.8$''$ can reach a 5σ flux limit of $\sim 3 \times 10^{-17}$ ergs cm^{-2} s^{-1} at about 6600Å, sufficient to detect [OII] at z=0.591. The total integration time amounts to 1 h per configuration, or 2 h using the 600 gpm grating.

- For the arclets, 3 h integrations are requested in each of two configurations using the 270 grooves/mm grating to make use of the extended wavelength range to measure redshifts for the faint arcs which typically have less secure photometric redshifts . We arrive at this number as follows: the SHELS Survey (Geller et al. 2012) used 0.75-2.0 h integrations to obtain 96% redshift completeness to $R(Vega)$<20.6 mag. This corresponds to R_{AB}=20.8 mag, or i_{AB}=20.5 mag, assuming a mean $(R - i_{AB})$=0.3 mag. Since the mean exposure time for SHELS was 1 h, we are requesting 3 h to reach our limit of i_{AB}<21.5 mag. Based on the dozens of arclets well spread out over ∼few arcmin, and minimum Hectospec spacings of 20 arcsec, we see that we need two configurations to cover our full sample, or 6 h using the 270gpm grating.

The total science exposure time amounts to 8 h, which including overheads amounts to 1 night of observing which in Nov-Dec is ∼10.5 h assuming 18° twilight. We are aware that multifiber instruments require preparatory work to select targets and make the masks using the fiber configuration program, xfitfibs. As this program was approved in 2015A, we have already completed the mask-making activities.

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 program and as such was approved for one night in 2015A using MMT-Hectospec, but was truncated after one mask owing to poor weather. Our one mask was rich with results, such as enabling the spectroscopic measurement of a 24th mag (AB) arclet. We are requesting one night to complete this survey which will make a significant contribution to the galaxies with known redshifts in this famous cluster. We assigned this proposal as short term.

(2) The galaxy targets are supported by an extensive ancillary dataset coming from PI-Frye's membership with the CLASH collaboration, including deep UV through mid-IR data as well as HST grism data on MACS0647 by Co-I Coe (HST Cy21/GO-13317) which is proprietary and still in progress. **Curiously, there is still very little in the way of spectroscopic redshifts yet known for this cluster, perhaps on account of its high declination**. Thus the UAO time fits in by providing the critical spectroscopic redshifts which are necessary to produce a spectroscopic catalog of emission lines and to measure galaxy properties and physical conditions of our targets. For each bright galaxy, photometric redshift estimates are made as well as more complex derived information, such as multi-color fits to the spectral energy distributions (SEDs).

(3) This MACS0647 program is designed to produce a spectroscopic catalog of galaxies in and behind the cluster to i<22-24 mag. On collaborators, Co-I Coe is PI of the HST grism observations and is leading the overall HST grism portion of the project. PI-Frye is tasked by the group to lead the ground-based spectroscopic redshift census. the UAO time will be used to measure redshifts and get basic information on galaxy properties, including corroborating single emission line detections in the grism data and the secure identification of arclets, including the image families. This program fits into the larger aim to provide quantitative information on the physical characteristics of the massive lensing cluster MACS0647 and the background to enable the study of the assembly of total mass. Lensing analysis of this cluster is important as we want to characterize the total mass of dark plus visible matter in the cluster lensing what is at the moment the highest redshift galaxy at z=10.8 (Pirzkal et al. 2015). The PI plans to present these data and analysis in refereed papers.

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**)*

MMT-Hectospec 2015A: The PI was awarded one night on MMT-Hectospec to carry out a redshift survey of arclets in the field of MACS0647+7015. Only 2 h of time was used on-source to observe one cluster field owing to poor weather. The spectroscopy for this one mask has been reduced and is yielding results that are even better than expected (see Figs 2-3 of this proposal), so that we request one night to complete this program and write refereed papers.

LBT/LBC run in 2015A: The PI was awarded one night to acquire multi-band photometry of new massive, dark-matter dense galaxy clusters to characterize their lensing strengths. We obtained all of our observations in seeing of $1 - 1.6''$, adequate to carry out the full science program to identify the cluster members photometrically and pick out the more interesting background arcs/arclets. The observations were completed in March, 2015, and are now being reduced.

LBT-LUCI1 run in 2014B: The PI was awarded two 1/2 nights of shared-rick DD time to an enhanced AO observation rare for being in an extragalactic field. We attempted to detect the faint multiple images of a supernova (likely type II) at z=1.5 which is lensed by a foreground galaxy cluster MACS1149+22 into four images with angular separations of $<1.5''$ from each other and from a bright cluster elliptical at z=0.5 situated in the center of the cross. We obtained only 21 min of on-source imaging at Ks for this so-called 'SN Refsdel' owing to poor weather and intermittent instrument issues which was not adequate to make the detection.