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 (MACS0647). 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 behind it, and no spectroscopic confirmation for any multiply-imaged galaxies, or image families. We request 1 dark night to do multi fiber spectroscopy with Hectospec with the goal to measure redshifts and galaxy properties for the $\sim$ 80 galaxies in the field with r_{AB}<21 mags and also for fainter emission line objects to r_{AB}<22. 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 for the arclets crucial to constrain the cluster magnification 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.

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	Jan	Jan-Feb	no	no

Scheduling constraints and unusable dates *(up to 4 lines)*: The ideal month to observe this target is January. If scheduling requirements are such that this observation is scheduled in February, then the primary target will fall below 2 air masses 2.5 h before morning twilight.

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 work has since been extended to include searches for halo substructures, and also a formalism to constrain the dark energy equation of state given the identification of multiple image families in a mere 40 clusters (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. 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 program (HST Cy21/GO-13317 PI: Coe) to obtain slitless spectroscopy of the MACS0647 field using the ACS G141 grism. The data acquisition is still in progress, and the final set of data will consist of 12 orbits, split into three different epochs. Despite all the excitement over this cluster, there is remarkably little known about the galaxy population at z<10.8. Our goal 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 will enable an efficient redshift survey of arclets that would be infeasible using long-slit spectroscopy. We will achieve the fist high spectral resolution (2-6 Å FWHM) 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 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 and is currently not possible to obtain from the grism data. 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 $z\approx0.591$ 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 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}<21) in the field.

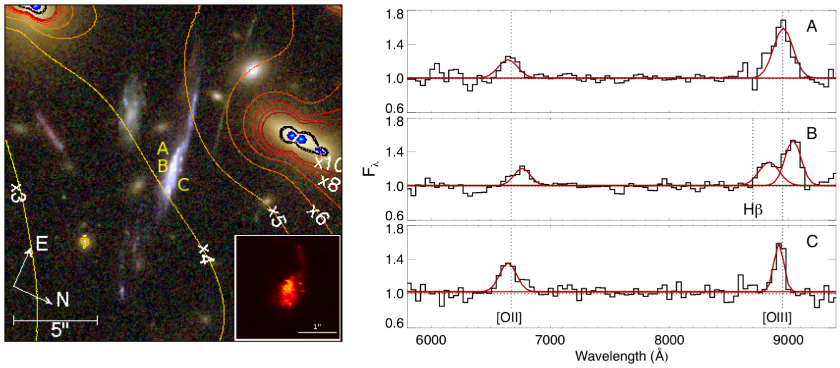

Figure 1: **Left:** i_{775} image of the giant arc at z=0.790 in the field of the cluster A1689. The positions of 3 emission lines sources within this single galaxy are labeled as 'A,' 'B,' and 'C,' and are traced back to their exact locations on the source plane (inset). **Right:** flux-normalized HST/ACS grism spectra of sources A, B and C. With these data plus spatially-resolved follow-up spectroscopy we have measured a ∼solar gas-phase oxygen abundance and elevated metal line ratios in the direction of the tail indicative of a relatively recent galaxy interaction (Frye et al. 2012).

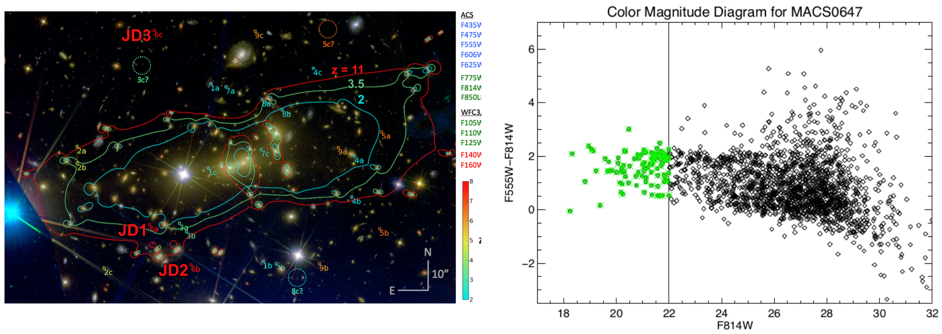

Figure 2: **Left**: Image of our target MACS064, with the critical curves marked for z=2, z=3.5 and z=11. **Right:** Color Magnitude Diagram for MACS0647, indicating the 90 galaxies as yet unpublished redshifts in the field. We expect to get to i_{AB}=21 mags for continuum detections and i_{AB}=22 mags for the emission line galaxies.

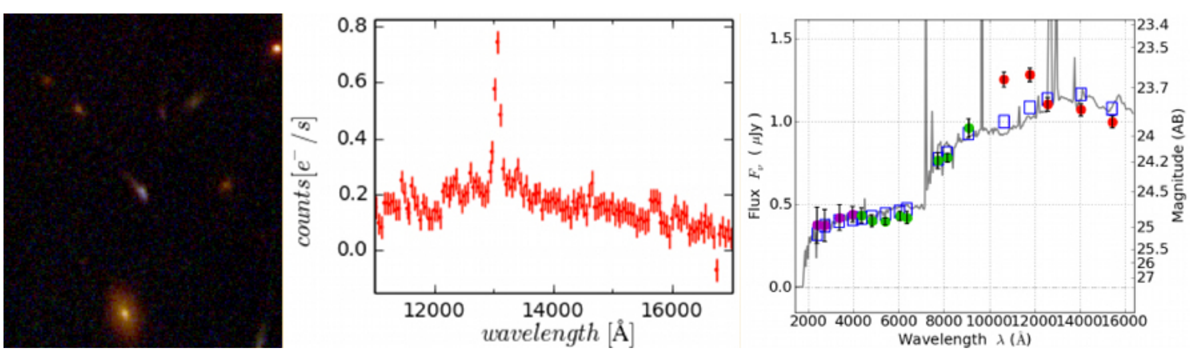

Figure 3: **Left:** HST ACS gri image of one faint blue arclet in the field of MACS0647. **Middle:** HST WFC3/IR G141 grism spectrum of this arclet with one strong emission line at ∼1.3 microns. **Right:** SED fit to the HST UV-NIR ancillary photometry shows this galaxy image to be well fit by an ELG at z=0.9. Although our primary targets have i_{AB}<21, this faint arc with i_{814}=24.1 mags is predicted to show strong [OII] at ∼7600 Å which may be detected if the rest equivalent width is high, >100 Å as is found for the more 'extreme' ELGs (Frye et al. 2012, Atek et al. 2011).

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}<21 mags, and also redshifts of emission line galaxies (ELGs) with r<22 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 still in the process of data acquisition (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 will typically 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 a second emission line at optical wavelengths. Hectospec is ideally suited for this type of spectroscopic program, and the field of view is ideal for galaxy cluster fields.

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 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 Jan-Feb 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.

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 a new proposed program and as such there have not yet been any nights awarded for this project. We are requesting one night, which is sufficient to initiate a redshift survey of galaxies and make a significant contribution to the galaxies with known redshifts in this famous cluster. We assigned this proposal as short term as it is a 'stand alone' project.

(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. 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<21 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. The PI plans to present these data and analysis in refereed papers.

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 • Postman et al. 2012, ApJS, 199, 25 • Richard et al. 2011, MNRAS, 413, 643

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)***

The PI took advantage of one TBA observing opportunity using LBT to observe a galaxy protocluster candidate with R. Green on 24-25 Dec, 2012. Both nights of observing were lost due to storms save for a total of $\sim$20 min which was shared between the users present. We did acquire a total of 10 min of NIR imaging in a single band in 2.2-2.5$''$ seeing, which was adequate to identify the cluster members in this submillimeter-selected galaxy protocluster but insufficient to result in a refereed publication.