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U-band Measurement of Star Formation in Cluster Galaxies

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NOAO Observing Proposal *Standard proposal* **Panel:** *For office use.*
Date: April 2, 2018 **Category:** Clusters of Galaxies

U-band Measurement of Star Formation in Cluster Galaxies

Abstract of Scientific Justification *(will be made publicly available for accepted proposals)*:
We propose to obtain deep U-band observations of 14 low-redshift ($z \leq 0.06$) galaxy clusters using the WIYN 0.9m+HDI telescope/detector to complete our survey to probe star formation of galaxies in high-density environments. These observations, combined with previously obtained data of 11 clusters observed using the same telescope+detector, will give us a statistically significant sample for the Ph.D. dissertation of co-I Gihan Gamage. Clusters are selected from 57 clusters in which we have obtained deep B- and R-band data using the KPNO 0.9m+MOSA. U-band data will allow us to explore relative changes in the luminosity function for the U- and R-band as a function of cluster-centric radius. The large field-of-view of the telescope+detector will permit us to map out the spatial distribution of star forming galaxies from the core region to the outskirts. Comparing U-band observations with our R-band data will provide the necessary leverage to look for enhancements/quenching of star formation as galaxies fall into the cluster. These observations allow us to probe ~ 2 mag fainter than SDSS.

Summary of observing runs requested for this project

Run	Telescope	Instrument	No. Nights	Moon	Optimal months	Accept. months
1	KP-0.9m	HDI	7	darkest	Aug - Jan	Aug - Jan
2						
3						
4						
5						
6						

Scheduling constraints and non-usable dates *(up to six lines)*.

Investigators *List the name, status, and current affiliation for all investigators. The status code of "P" should be used for all investigators with a Ph.D. or equivalent degree. For graduate students, use "T" if this proposal is a significant part of their thesis project, otherwise use "G".*

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CoI: Sandanuwa Kalawila **Status:** G **Affil.:** University of North Dakota
CoI: Madina Sultanova **Status:** G **Affil.:** University of North Dakota
CoI: Dean Smith **Status:** P **Affil.:** University of North Dakota
CoI: Elijah Mathews **Status:** U **Affil.:** University of North Dakota
CoI: Haylee Archer **Status:** G **Affil.:** Northern Arizona University

Scientific Justification *Be sure to include overall significance to astronomy. For standard proposals limit text to one page with figures, captions and references on no more than two additional pages.*

A fundamental goal in the study of galaxy clusters is to understand how galaxies evolve, and to explore what impact the high-density environment has on their evolution [1]. It is well established that galaxy type is correlated with local density such that the central cluster region is dominated by E/S0 galaxies, while the outskirts of clusters contain a larger fraction of spiral systems [2]. Due to this dichotomy, galaxy clusters are believed to be built-up from the infall of galaxies from low-density regions outside the cluster [3]. Since clusters have deep potential wells, they attract matter from surrounding less-dense regions and serve as sites for enhanced galaxy interactions [4].

The objective of this proposal is to map out the impact of the high-density galaxy cluster environment on the star formation (SF) of infalling galaxies from giants to dwarfs. Since galaxy clusters contain a large amount of hot gas (as evidenced by their X-ray emission), galaxies traveling through the hot intracluster medium will be subjected to compression shocks (ram-pressure) that will tend to either compress the gas in galaxies and trigger SF, or strip gas from individual galaxies (especially dwarf galaxies), resulting in a quenching of SF [5][6]. It is also possible that infalling galaxies experience both mechanisms over a short timescale, resulting in a burst of SF followed by quenching. Characterizing this process in terms of the effect on the SF rate of infalling galaxies will provide valuable insights into the impact of the cluster environment on the galaxy population. Some studies indicate that the central regions of clusters are devoid of star-forming galaxies (e.g., [7][8][9]). A SF-density relation has been proposed in which ram-pressure stripping of gas has quenched SF in galaxies located in high-density regions [10]. Since this effect is not well-studied for galaxies ranging from giants to dwarfs over a large cluster-centric radius, we propose to supplement our existing B- and R-band observations of 57 low-redshift galaxy clusters [1] with deep U-band data for a statistically significant sample of 25 galaxy clusters with $z \leq 0.06$. Since we have previously obtained U-band observations for 11 clusters, we propose to finish our study by acquiring U-band images of the remaining 14 clusters. These data will be used for the Ph.D. dissertation of co-I Gihan Gamage (University of North Dakota). The deep U-band observations will help us map star forming galaxies over a significant fraction of cluster radius by comparing and contrasting the U, B, and R-band luminosity functions (LFs), dwarf-to-giant ratios, spatial distributions, and galaxy morphology. For example, we have recently studied the distribution of star forming galaxies for a sample of 15 clusters selected from the CFHT archives by measuring the ratio of the number of net dwarf galaxies (background-subtracted) in the u-band to that measured from the r-band [11][12]. We found that this ratio increases with cluster-centric radius, where the radius is normalized to r200 (Figure 1). Also, the fraction of u-band dwarfs ("blue fraction") compared to giant galaxies was found to increase with cluster-centric radius (Figure 2). This KPNO proposal will leverage our previous observations by exploring the low-redshift end of our galaxy cluster sample. This allows us to use the WIYN 0.9m to detect in the U-band a large range in galaxy mass from giants to dwarfs. These data will enable us to probe ~ 2 magnitudes fainter than SDSS (see Figure 3). We request WIYN 0.9m+HDI time to obtain deep U-band images of 14 galaxy clusters to quantify SF as a function of galaxy luminosity and cluster-centric radius. Comparison of the acquired U-band observations with our previous B- and R-band measurements of the same clusters, will enable us to track relative changes in the LF (e.g. faint-end slope) as a function of bandpass over a large range in cluster-centric radius (normalized to r200). An enhancement/truncation of SF in infalling galaxies should be indicated by a cluster-centric dependent change in the relative ratio of U-band versus R-band selected galaxies.

An added benefit of this study is the comparison of local U-band LFs with cluster LFs at much higher redshifts. Since high-z LFs are often observed in the equivalent rest-frame U-band, local U-band LFs will provide a robust template in which changes in cluster evolution can be measured.

[1] Barkhouse, W. A., Yee, H. K. C., & Lopez-Cruz, O. 2009, ApJ, 703, 2024

[2] Dressler, A. 1980, ApJ, 236, 351

[3] Kravtsov, A. V., & Borgani, S. 2012, ARA&A, 50, 353

[4] Park, C, & Hwang, H.-S. 2009, ApJ, 699, 1595

[5] Taranu, D. S. et al. 2014, MNRAS, 440, 1934

[6] Lian, J. et al. 2016, ApJ, 832, 29

[7] Lewis, I., et al. 2002, MNRAS, 334, 673

[8] Rines, K., et al. 2005, AJ, 130, 1482

[9] Cedres, B., et al. 2009, AJ, 138, 873

[10] Quadri, R. F., et al. 2012, ApJ, 744, 88

[11] Rude, C. 2015, Ph.D. thesis, University of North Dakota

[12] Rude, C., et al. 2018, MNRAS, in preparation

[13] Lopez-Cruz, O., Barkhouse, W. A., & Yee, H. K. C. 2004, ApJ, 614, 679

[14] Barkhouse, W. A., Yee, H. K. C., & Lopez-Cruz, O. 2007, ApJ, 671, 1471

[15] Yee, H. K. C. 1991, PASP, 103, 396

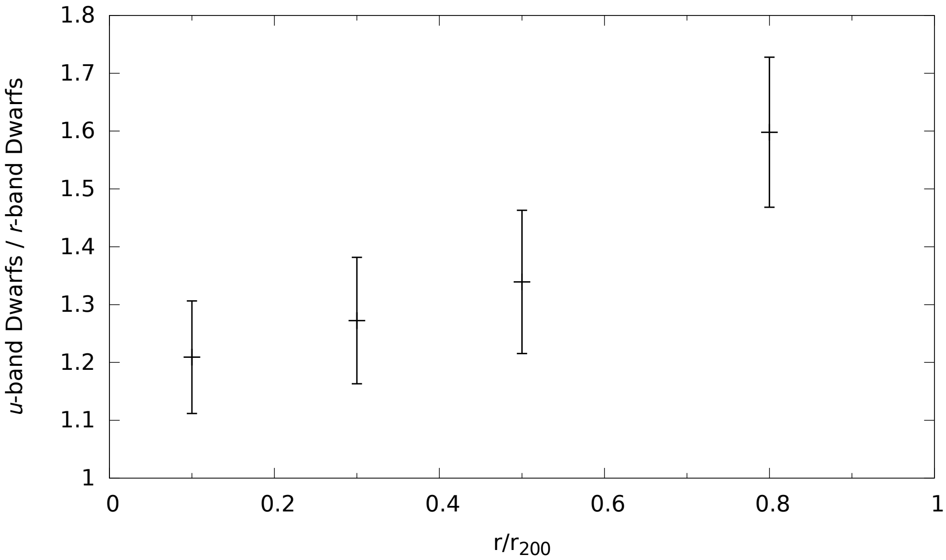

Figure 1: The ratio of background-corrected u-band dwarfs to r-band dwarfs as a function of cluster-centric radii (normalized to r_{200}) for a stacked sample of 15 galaxy clusters observed at CFHT from [11][12]. Dwarf galaxies are selected as having $-19.5 < M_r < -17.5$ ($-17.24 < M_u < -15.24$). The number of u-band detected dwarf galaxies compared to the r-band increases with increasing radius.

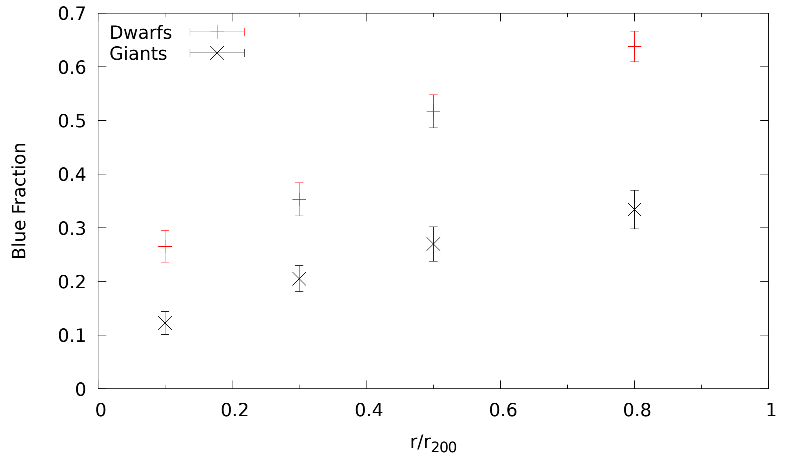

Figure 2: Blue fraction versus cluster-centric radii for dwarfs (dashed symbols) and giants ("X" symbols) for the CFHT 15 cluster sample from [11][12]. The fraction of blue dwarfs compared to blue giants increases with increasing radius.

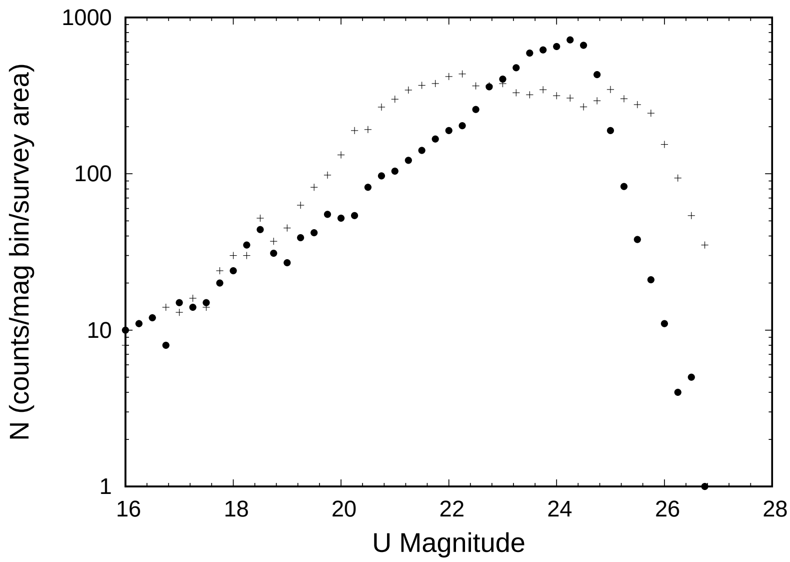

Figure 3: Differential galaxy counts versus U-band magnitude for Abell 2152 from SDSS ("+" symbols) and observations obtained with the WIYN 0.9m+HDI (solid circles). The turnover in the number counts for SDSS is 22.2 mag, while the turnover for the 0.9m data is 24.3 mag (based on 4.5 hours of integration time).

Experimental Design *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. (limit text to one page)*

Galaxy clusters are one of the most massive, mainly virialized structures in the universe, and as such they play an important role in developing a complete understanding of how galaxies evolve in high-density regions. The importance of dynamical processes (such as ram-pressure and galaxy-galaxy tidal interactions) to galaxy star formation activity needs to be fully explored for a large range in galaxy mass from giants to dwarfs. Several studies have probed the star formation rate of giant cluster galaxies, but little in comparison has been done for the combined population that includes dwarf galaxies.

We propose to use deep U-band and R-band images of 25 low-redshift galaxy clusters to map out the relative change in the $U - R$ color of galaxies as a function of cluster-centric radius. The goal is to explore whether galaxies, especially dwarf galaxies, undergo an enhancement or burst of star formation as they enter the cluster environment. Since we have already acquired and fully reduced/analyzed our clusters using R-band observations with KPNO 0.9m+MOSA (see [1][13][14]), it is relatively cheap to acquire deep U-band observations of a statistically significant sample of our previously observed clusters in order to use $U-R$ color as a signature of star formation activity. Although several studies have been published regarding the use of $U - R$ color to track star formation of cluster galaxies (e.g., WINGS survey and SDSS-related projects), most of these surveys do not probe to very faint levels over a large cluster-centric radius for clusters with very low redshifts compared to what we are proposing here. Since we have previously acquired U-band observations for 11 clusters, we are requesting time to observe an additional 14 clusters to complete our sample of 25 clusters in total. Our analysis of U-band images taken with the WIYN 0.9m+HDI demonstrates that we can reach $\sim$ 2 magnitudes fainter than SDSS in a reasonable amount of observing time.

One of the questions that we will address is whether dwarf galaxies, as they fall toward the cluster central region, have their gas first compressed (triggering star formation) and then quenched as interstellar gas is swept out of dwarf galaxies via ram-pressure stripping. The spatial distribution of $U - R$ color as a function of galaxy mass and luminosity will help us to better discriminate between these various star formation histories. In particular we will measure and compare the U- and R-band luminosity functions, dwarf-to-giant ratios, and blue fractions measured in several radial bins scaled by r200 to compensate for variations in cluster optical richness. The construction of luminosity functions requires the use of a control or background field. The outskirts of the clusters will be used, when appropriate, to sample the background field counts. In addition we will use publicly available deep field surveys, such as the DES fields, to sample the U and R-band galaxy counts to faint magnitudes. Cluster galaxy membership will be assigned based on the $B-R$ red-sequence [13]. Thus this proposal will allow us to obtain deep U-band data to compare/contrast using $U - R$ color the cluster galaxy population (including dwarf galaxies) within individual local clusters, as well as examining any cluster-to-cluster differences.

We note that in addition to studying star formation, observing time on the WIYN 0.9m telescope is extremely valuable as a method to help teach students the process of collecting data and operating a professional-grade telescope+detector.

Proprietary Period: 18 months

Use of Other Facilities or Resources *(1) Describe how the proposed observations complement data from non-NOAO facilities. For each of these other facilities, indicate the nature of the observations (yours or those of others), and describe the importance of the observations proposed here in the context of the entire program. (2) Do you currently have a grant that would provide resources to support the data processing, analysis, and publication of the observations proposed here?"*

This observing proposal is in part based on the use of deep R- and B-band data obtained previously using the KPNO 0.9m+MOSA. These prior data have been reduced and analyzed, resulting in several publications (see [1][13][14]). In addition, the DES fields will be used as a background control field.

The PI has access to internal university financial resources to support travel to KPNO and to cover publication costs. Data reductions will be performed using IRAF, PPP [15], and Terapix software, with which the PI has extensive experience in using.

Previous Use of NOAO Facilities *List allocations of telescope time on facilities available through NOAO to the PI during the last 2 years for regular proposals, and at any time in the past for survey proposals (including participation of the PI as a Co-I on previous NOAO surveys), together with the current status of the data (cite publications where appropriate). Mark with an asterisk those allocations of time related to the current proposal. Please include original proposal semesters and ID numbers when available.*

Mohr et al: *SZE+Optical Studies of the Cosmic Acceleration*, 2005B-0043, NOAO CTIO 4m (survey proposal, 45 nights, data acquired for 45 nights, data reduction completed via the Dark Energy Survey pipeline, an additional 15 nights awarded for November 14-28, 2008 to compensate for bad weather and instrument problems).

Publications: High et al. 2010, Optical Red-shift and Richness Estimates for Galaxy Clusters Selected with the Sunyaev-Zel dovich Effect from 2008 South Pole Telescope Observations, ApJ, 723, 1736; Zenteno et al. 2011, A Multiband Study of the Galaxy Populations of the First Four Sunyaev-Zeldovitch Effect Selected Galaxy Clusters, ApJ, 734, 10.1088/0004-637X/734/1/3; Buckley-Geer et al. 2011, The serendipitous observation of a gravitationally lensed galaxy at z = 0.9052 from the Blanco Cosmology Survey: The Elliot Arc, ApJ, 742, 48; Suhada et al. 2011, The XMM-BCS galaxy cluster survey I. The X-ray selected cluster catalog from the initial 6 deg^2, A&A, 537, 39.

⋆ **Barkhouse et al:** *Probing Star Formation in Cluster Dwarf Galaxies via H-alpha Imaging*, 2015B-0065, NOAO KPNO 4m. A total of three nights were awarded for January 2016. One and a half nights were productive, yielding observations for four galaxy clusters. The last half of the observing run (1.5 nights) was not usable due to poor seeing and bad weather. The data has been reduced and preliminary object detection and photometry has been completed. These observations serve as the main data source for the Ph.D. dissertation of Sandanuwan Kalawila (University of North Dakota).

⋆ **Barkhouse et al:** *Mapping Star Formation via U-band Observations of Low-Redshift Galaxy Clusters*, 2017A-0292, NOAO WIYN 0.9m. A total of four nights were awarded for March 27-30, 2017. 1.5 nights were lost due to bad weather. Five clusters were observed to the target depth. These observations are part of the data source for the Ph.D. dissertation of Gihan Gamage (University of North Dakota).

⋆ **Barkhouse et al:** *Probing Star Formation in Cluster Galaxies using Deep U-band Imaging*, 2017B-0068, NOAO WIYN 0.9m. A total of four nights were awarded for November 18-21, 2017. One night was lost due to bad weather and instrumentation problems. Six clusters were observed to the target depth. These observations are part of the data source for the Ph.D. dissertation of Gihan Gamage (University of North Dakota).

⋆ **Barkhouse et al:** *Uncovering Star Formation from the Galaxy Cluster Core to the Infall Region*, 2017B-0103, NOAO CTIO 4m+DECam. A total of two nights were awarded for January 16-19, 2018. 18 clusters were observed to the target depth in the u- and r-band. These data are part of the Ph.D. dissertation of co-I Gihan Gamage (University of North Dakota).

Observing Run Details for Run 1: KP-0.9m/HDI

Technical Description *Describe the observations to be made during this observing run. Justify the specific telescope, the number of nights, the instrument, and the lunar phase. List objects, coordinates, and magnitudes (or surface brightness, if appropriate) in the Target Tables section below (required for queue and Gemini runs).*

We propose to obtain deep U-band images of 14 galaxy clusters in order to quantify star formation as a function of cluster-centric radius for the cluster galaxy population from giant to dwarf systems. These 14 galaxy clusters will be selected from the 57 clusters in which we have previously obtained deep B- and R-band observations using the KPNO 0.9m+MOSA (see [1][13][14]). The primary target galaxy clusters for this proposal will be based on the appropriate RA range for the 2018B observing semester. To adequately sample dwarf galaxies in the U-band, we have selected clusters that have a redshift $z \leq 0.06$. This will ensure that we can detect star forming dwarf galaxies using the WIYN 0.9m telescope in a reasonable amount of observing time. These observations will complete our research project and serve as a data source for the Ph.D. dissertation of co-I Gihan Gamage.

Our exposure times will be tuned so that we can detect early-type dwarf galaxies, assuming $U - R \sim 1.5$, to the depth in the R-band measured from our previous KPNO 0.9m+MOSA observations ($M_R \sim -15$). Given the redshift range of our cluster targets ($z \leq 0.06$), we would need to reach $m_U \sim 23.5$ (Johnson filter; depending on redshift) for $m_R \sim 22$. Note that we need to probe ~ 2 magnitudes deeper in U than the available data from SDSS. Based on our previous WIYN 0.9m+HDI observations, we require 4.5 hours of integration time per cluster in order to reach U-band depths of ~ 2 mags fainter than SDSS (Figure 3). This total integration time will be divided into 900 sec dithered exposures in order to minimize saturation effects and correct for bad pixels, and cosmic rays.

In addition to the 14 clusters, we will acquire standard star observations of Landolt fields in U and R in order to calibrate the data (note that the only images taken in the R-band will be for standard star observations).

Taking into account overhead for standard stars, target acquisition, focusing, dithering, and read-out time, we require a total of 140 hours or seven nights to observe 14 galaxy clusters.

Instrument Configuration

Filters: U, R	Slit:	Fiber cable:
Grating/grism:	Multislit:	Corrector:
Order:	λ_{start}:	Collimator:
Cross disperser:	λ_{end}:	Atmos. disp. corr.:

R.A. range of principal targets (hours): 15 to 10

Dec. range of principal targets (degrees): -5 to +65

Special Instrument Requirements *Describe briefly any special or non-standard usage of instrumentation.*

NOAO observing proposal LaTeX macros v3.0.