4-2-2018

Mapping Star Formation from the Core to the Outskirts of Galaxy Clusters

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

Mapping Star Formation from the Core to the Outskirts of Galaxy Clusters

Abstract of Scientific Justification *(will be made publicly available for accepted proposals)*:
We propose for time to complete our u- and r-band imaging program of 30 low-redshift ($z \leq 0.03$) galaxy clusters using the CTIO Blanco 4m+DECam telescope/detector combination. These data will allow us to probe star formation from the cluster core to the infall region, and complete the acquisition of observations for the Ph.D. dissertation of Gihan Gamage (University of North Dakota). The deep u- and r-band data will allow us to explore relative changes in the luminosity function, dwarf-to-giant ratio, blue fraction, and galaxy morphological type as a function of cluster-centric radius for a statistically significant sample of 30 clusters. The large field-of-view of the telescope+detector will permit us to not only map star formation out to the infall region, but also to probe dwarf galaxies using a reasonable exposure time due to the low redshift of our target sample. The comparison of u- and r-band observations will provide the necessary leverage to look for enhancements/quenching of star formation as galaxies fall into the cluster environment from the low density field region.

Summary of observing runs requested for this project

Run	Telescope	Instrument	No. Nights	Moon	Optimal months	Accept. months
1	CT-4m	DECam	2	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: 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 obtain deep u- and r-band observations of a sample of 18 low-redshift ($z \leq 0.03$) galaxy clusters. Combined with our previous observations, we will compile a statistically significant sample of 30 galaxy clusters.

The proposed deep u- and r-band observations will help us map star forming galaxies over a significant fraction of cluster radius by comparing and contrasting the u- and r-band luminosity functions (LFs), dwarf-to-giant ratios, spatial distributions, and galaxy morphology. 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 CTIO proposal will allow us to use the Blanco 4m telescope to detect in the u- and r-band a large range in galaxy mass from giants to dwarfs, and to sample galaxies from the infall region at several virial radii to the cluster center. By tracking star formation from the infall region we will be able to map out changes in the star formation activity of galaxies as they fall into the cluster gravitational potential well. These targeted observations will allow us to probe to fainter magnitudes than that available from SDSS and the DES. We request Blanco 4m+DECam time to obtain deep u- and r-band images of 18 galaxy clusters to quantify SF as a function of galaxy luminosity and cluster-centric radius. Comparison of u- and r-band observations 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. Galaxy morphology will be measured as a function of cluster-centric radius using central concentration, asymmetry, the Gini and M20 parameters, the bulge-to-disk ratio, and our new statistic based on the Theil index.

[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

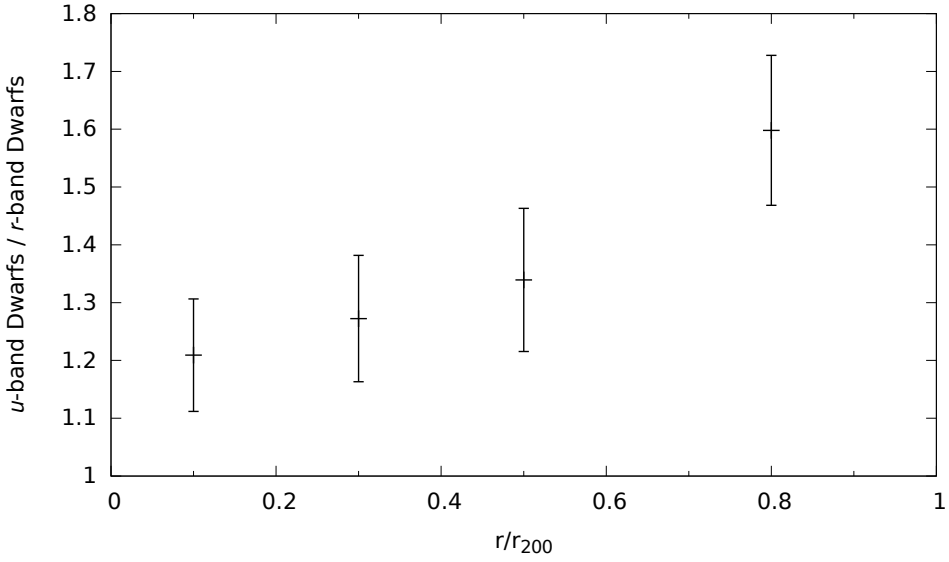

Figure 1: The ratio of background-corrected u-band dwarfs to r-band dwarfs as a function of cluster-centric radii (normalized to r_{200}) for a stacked sample of 15 galaxy clusters observed at CFHT from [11][12]. Dwarf galaxies are selected as having $-19.5 < M_r < -17.5$ ($-17.24 < M_u < -15.24$). The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

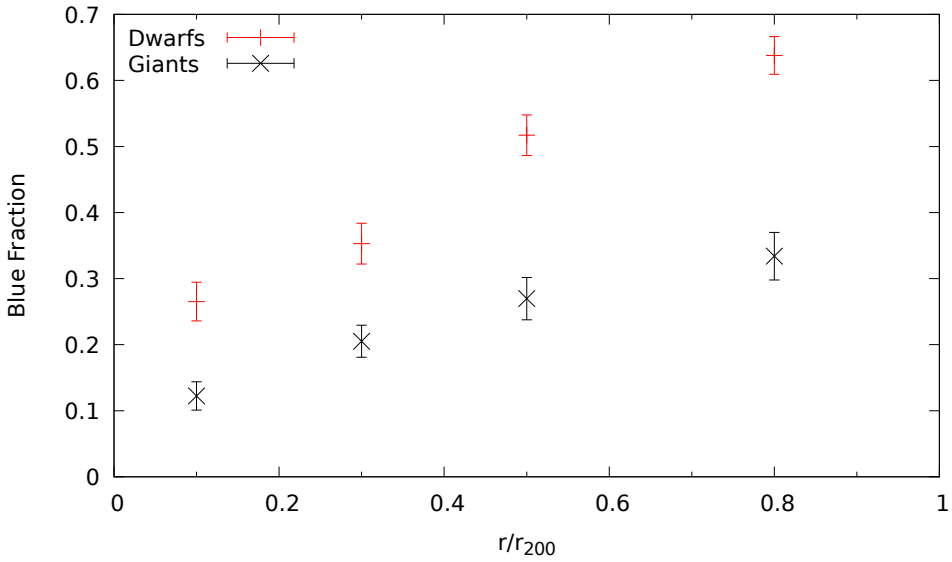

Figure 2: Blue fraction versus cluster-centric radii for dwarfs (dashed symbols) and giants ("X" symbols) for the CFHT 15 cluster sample from [11][12]. The fraction of blue dwarfs compared to blue giants increases with increasing radius.

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 over a large cluster-centric radius from the cluster core region to the infall area.

We propose to use deep u- and r-band images of 18 low-redshift galaxy clusters (combined with our previously obtained images of 12 galaxy clusters using Blanco+DECam during the 2017B semester) 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. 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 faint levels over a large cluster-centric radius for clusters at very low redshifts compared to what we are proposing. Thus our observations will reach fainter u-band magnitudes than SDSS and hence fulfill an important niche in mapping out the $u-r$ color distribution of local cluster galaxies. This combined sample of 30 galaxy clusters (18 proposed here and 12 obtained in 2017B) is a major data source for the Ph.D. dissertation of co-I Gihan Gamage at the University of North Dakota.

One of the questions that we will address from these data 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, morphological type, 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. Due to the large field-of-view of DECam on the Blanco 4m, the outskirts of the clusters will be used to sample the background field counts. In addition we will use publicly available fields, such as the DES, to sample the u- and r-band galaxy counts to faint magnitudes. Cluster galaxy membership will be assigned based on the red-sequence.

This proposal will allow us to obtain deep u- and r-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.

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?"*

The PI has access to internal university financial resources to support travel to CTIO 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.

$\boxed{\star}$ **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).

$\boxed{\star}$ **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).

$\boxed{\star}$ **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).

$\boxed{\star}$ **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: CT-4m/DECam

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).*

To acquire a statistically meaningful sample of galaxy clusters in order to probe star formation from the cluster center to the outskirts, we propose to obtain deep u- and r- band images for 18 low-redshift galaxy clusters. This sample, combined with our previous CTIO 4m+DECam observations of 12 clusters from January 2018, will provide us with 30 galaxy clusters in which to map out star formation as a function of cluster-centric radius for the galaxy population from giants to dwarfs. These observations will finish the data collection phase for the dissertation of Gihan Gamage.

Our 18 galaxy cluster targets are selected mainly from the Abell catalog based on the appropriate RA and Dec range for the 2018B observing semester at CTIO. To adequately sample dwarf galaxies in the u- and r-band, we have selected clusters that have a redshift $z \leq 0.03$. This will ensure that we can detect star forming dwarf galaxies using the CTIO Blanco 4m telescope in a reasonable amount of observing time. The large areal coverage of DECam will allow us to probe galaxies from the cluster core to the cluster infall regions, and use the outer areas as a reasonable sample of the background field galaxy population.

Our exposure times are tuned so that we can detect early-type dwarf galaxies, assuming $u-r \sim 1.5$, to the depth in the r-band that covers a significant fraction of the dwarf population ($M_r \sim -13$). Given the redshift range of our cluster targets ($z \leq 0.03$), we need to reach $m_u \sim 24.1$ (depending on redshift) for $m_r \sim 22.6$.

Based on our previous observing run with CTIO 4m+DECam, we need to integrate for approximately 49 minutes in the u-band (divided into seven 420 sec dithered exposures to compensate for bad pixels, chip gaps, and cosmic rays; actual integration time will depend on the redshift of the cluster). For the r-band, we will integrate for a total of 15 minutes, using five dithered exposures of 180 sec each. In total we require 64 minutes per cluster to image in the u- and r-band. In addition to observing 18 clusters, we will image standard star Landolt fields in order to calibrate the data.

Taking into account overhead for standard stars, target acquisition, dithering, and read-out time, we require a total of 19.7 hours or two nights to observe 18 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): 0 to -60

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