OBSERVING REQUEST
University of Arizona Observatories

Year: 2015 **Term:** Jan–Jul **Proposal type:** short-term

Dynamics and Physics of Galaxy Satellite Systems

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Abstract of Scientific Justification
We propose to obtain Hectospec spectroscopy of satellite galaxies in a wide range on environments, including: two bright individual isolated systems (NGC3665 and NGC4151) selected from the SDSS Main Galaxy Catalog and three relaxed galaxy clusters (Coma, A2199, and A2107). The goals of this proposal are twofold; firstly, to probe dark matter via satellite galaxies and to study the environmental effects on galaxy properties in relaxed clusters. With regards to the isolated systems and the relaxed clusters, we plan to conduct an in-depth survey of the satellites in the inner regions aiming for high spectroscopic completeness down to low limiting magnitudes, which vary depending on the target. With these, and complimentary X-ray data, we will study the internal dark matter halo structure and dynamical state of the clusters. The kinematic status of these clusters revealed by the photometric and spectroscopic data will be studied through a series of massive N-body simulations. Additionally, galactic spectral features, including emission/absorption lines and the internal velocity dispersion, will be used to study the star formation and nuclear activity of the galaxies in these clusters. The wide area coverage, and available multi-wavelength data, for these clusters provide a unique opportunity to study the process of structure formation and its effects on galaxy evolution. *comment corresponds to number of requested nights: 2.5 nights in Semester A (assuming 8 hours of observing time a night. The observing time is a sum of the field exposure time plus the 20 minute overhead.)

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			2.5*	grey/dark	Jan–Jul	Jan–Jul	no	no

Scheduling constraints and unusable dates *(up to 4 lines)*: The following target list is listed in order of priority. The actual targets are the objects located close to those in the list. Targets 4, and 5 should be observed only after the first 3 objects are finished. The total observation time is 2.5 days in Semester A. Time allocated above, and in the target list on the following page, is a sum of the exposure time and 20 minutes overhead per field.

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	NGC3665	11:24:43.7	+38:45:46	z=0.007, S0 galaxy, t = 225 minutes
2	Coma Cluster/Abell 1656	12:59:48.7	+27:58:50	z=0.023, Cluster, t = 225 minutes
3	NGC4151	12:10:32.6	+39:24:21	z=0.003, SAB galaxy, t = 225 minutes
4	Abell 2199	16:28:38.0	+39:32:55	z=0.030, Cluster, t = 160 minutes
5	Abell 2107	15:39:39.0	+21:46:57	z=0.041, Cluster, t = 145 minutes

Approval for Instrument Use from PI: N/A

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

Scientific Justification

As previously stated, the aim of this study is twofold: to probe the dark matter halo surrounding individual isolated galaxies and to study the process of structure formation and its effects on galaxy evolution. Both require spectroscopic data, which will focus on either obtaining high spectroscopic completeness down to low limiting magnitudes (as is the case for satellites around isolated galaxies) or mapping the spatial and velocity distribution of galaxies around relaxed clusters. With these data, we also plan to use galactic spectral features to obtain information about star formation and nuclear activity in cluster galaxies.

Satellites Around Isolated Galaxies: Probing Dark Matter

There are two tracers of the dark matter halo potential: satellites and gravitationally lensed background galaxies. The latter can be used for very massive systems like galaxy clusters, but poses problems when studying less massive halos associated with individual galaxies. The distribution of satellites around the host provides us with important information on: the radial profile and triaxial shape of the dark matter halo associated with the host-satellite system, the halo mass function, the galaxy mass-to-light ratio as a function of mass, and the redshift evolution of dark matter halo properties (see [1] and [12] for discussion). Measurement of the radial profile and triaxiality of dark halos will help us understand galaxy formation and clustering on small scales. The mass function of galaxy-scale and cluster-scale dark halos directly obtained from observations will put strong constraints on the primordial matter density power spectrum and cosmological parameters. Additionally, the host-satellite connection can provide vital information on the theory of galaxy evolution.

Our two selected target isolated galaxies have distances of 12.7 and 29.7 Mpc for NGC4151 and NGC3665. With the SDSS data, we identify 11 and 19 confirmed satellites around NGC4151 and NGC3655, down to the SDSS limiting magnitude of $r = 17.77$. However, we will be able to significantly increase the number of observed satellites with the proposed lower magnitude limit of $r \lesssim 20$ of this survey, allowing us to detect objects as faint as $M_r \approx -11.5$ (at the redshift of our target host galaxies). NGC3665 and NGC4151 have magnitudes of $M_r = -20.4$ and -18.4; thus, the available range of magnitudes between the host and satellite galaxies (ΔM_r) will significantly increase to $\Delta M_r = 9$ and 7. In Figure 1 we present a panel from figure 6 of [9], which shows the satellite number density profile as a function of ΔM_r for the suggest models (solid lines) and SDSS data points. It is clear that the larger the value of ΔM_r, the higher the number of observed satellites. With this proposed survey we will increase ΔM_r by three orders of magnitude and thus obtain better constraints on the satellite, and therefore dark matter, distribution around our target host galaxies. In addition, NGC4151 has extensive HST coverage, which will allow us to carry out proper morphological classification of the observed satellites and further probe correlations between the properties of the host and satellite system [1].

Galaxy Clusters: Investigating Environmental Effects on Galaxy Evolution

Galaxy environment plays an important role in the evolution of galaxies (see [2] for a review). In galaxy clusters, the average morphology of galaxies changes with local density or clustercentric radius [6]. This finding also applies to other galaxy properties including star formation rates, colors, nuclear activity, and spectral features [10,13,19]. To explain the environmental dependence of galaxy properties in galaxy cluster environment, several physical mechanisms were proposed: ram pressure stripping, thermal evaporation, strangulation, viscous stripping, galaxy harassment, starvation and cumulative galaxy-galaxy hydrodynamic/gravitational interactions. This environmental dependence of galaxy properties seems to result from combined effects of several processes rather than from a single process; however, this is still a matter of debate (see [3] and [19] for a review).

To better understand the physical mechanisms responsible for the environmental dependence of galaxy properties, it is important to catch the change in galaxy properties that are still in action in this cluster environment. We therefore propose a spectroscopic survey of relaxed galaxy clusters with MMT/Hectospec to study in detail the change in galaxy properties, especially for low-luminosity galaxies that are sensitive to environmental effects.

We plan to observe three relaxed galaxy clusters: the Coma cluster, A2107 and A2199. These clusters are all located in the local Universe ($z < 0.041$). We propose to obtain high spectroscopic completeness for these clusters, which will significantly increase confirmed membership and allow for more in-depth studies of cluster dynamics and distribution of cluster members.

References and Figures

[1] Ann, H.B., et al. 2008, MNRAS, 389, 86 [2] Blanton, M. R., & Moustakas, J. 2009, ARA&A, 47, 159 [3] Boselli, A., & Gavazzi, G. 2006, PASP, 118, 517 [4] Clowe, D., et al. 2012, ApJ, 758, 128 [5] Donnelly, R. H., et al. 2001, ApJ, 562, 254 [6] Dressler, A. 1980, ApJ, 236, 351 [7] Fabricant, D., et al. 2013, PASP, in press (arXiv: 1308.4442) [8] Girardi, M., et al., 2008, A&A, 491, 379 [9] Guo et al., 2013, MNRAS, 434, 1838 [10] Hashimoto, Y., & Oemler, A., Jr. 1999, ApJ, 510, 609 [11] Hwang, H. S., & Lee, M. G. 2009, MNRAS, 397, 2111 [12] Hwang, H.S. & Park, C. 2010, ApJ, 720, 522 [13] Hwang, H. S., et al. 2012, A&A, 538, 15 [14] Jee, M. J., et al. 2012, ApJ, 747, 96 [15] Mahdavi, A., et al. 2007, ApJ, 668, 806 [16] Markevitch, M., et al. 2005, ApJ, 627, 733 [17] Moffat, J. W. & Toth, V. T. 2009, MNRAS, 397, 1885 [18] Okabe, N., & Umetsu, K. 2008, PASJ, 60, 345 [19] Park, C., & Hwang, H. S. 2009, ApJ, 699, 1595 [20] Rines, K., et al. 2013, ApJ, 767, 15

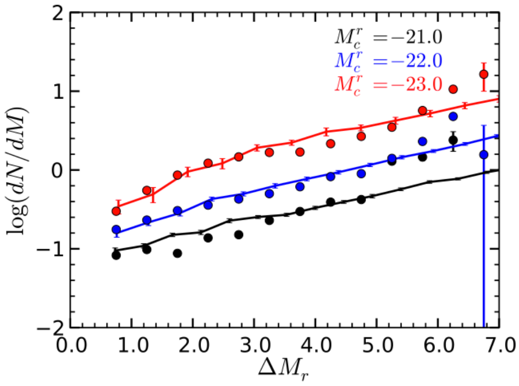

Figure 1: Satellite number density profiles as a function of M_r magnitude difference between the host and satellite galaxies for the model (solid lines) and SDSS data points shown in figure 6 of [9]. The black, blue and red colours correspond to the luminosity the central/host galaxy in bins of $M_r =$ -21.0, -22.0, and -23.0.

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**)*

NGC3665 and NGC4151: For both NGC3665 and NGC4151 we plan to use three Hectospec configurations; one 45 minute exposure to obtain high spectroscopic completeness down to $r = 17.77$ and two 60 minute exposures (each with different targets) to obtain high completeness down to $r = 20$. We will focus on the inner region of host-satellite systems, which will subtend $\sim$110 kpc and $\sim$ 260 kpc around NGC3665 and NGC4151 with the Hectospec FOV (centred on the target host galaxy). According to Taniguchi et al. (2007)'s survey of the COSMOS field, there are 270($\sim$1000) objects per square degree down to $r =$ 17.77(20) (photometric aperture of 2). Therefore, with the 1 degree diameter of the Hectoscpec, we expect 200(785) within the instrument's FOV. Many of these galaxies will be interlopers; however, there will also be satellites associated with the target host. With SDSS, we find that NGC3665 has 19 satellites and NGC4151 has 11 satellites. Our proposed faint survey will go 3 magnitudes deeper than SDSS, allowing us to observe the faintest systems down to $M_r = -11.5$. Such depth will allow for detailed analysis of the satellite distribution and thus better probe the dark matter distribution.

For objects with $r =$ 17.7(20) 45(60) minute exposure times are needed to achieve S/N=10. We require one bright (45m) exposure and two faint (60m) exposures to achieve the desired spectroscopic completeness. We propose to observe 600 target satellites, around each galaxy, to probe the satellite distribution. With 20 minute overheads, the total observational time requested is 7.5 hours ($= 4 \times 60 + 2 \times 45 + 6 \times 20$ minutes) to observe satellites around our two target isolated galaxies.

Relaxed Clusters: We plan to use two Hectospec configurations for A2107; one 45 minute exposure to obtain spectra for our bright sample and one 60 minute exposure for our faint sample. For A2199, we also plan to use two configurations, but each will be a 60 minute exposure to obtain completeness down to the same limiting magnitude. For the Coma Cluster, we will use three configurations; one 45 minute exposure to obtain high spectroscopic completeness for our bright sample and two 60 minute exposures (each with different targets) for our faint sample. With 20 minute overheads, the total observational time requested is 13.7 hours ($= 7 \times 60 + 4 \times 45 + 11 \times 20$ minutes) to observe five relaxed clusters.

For all targets, we will use Hectospecs 270 line mm^{-1} grating that provides a dispersion of 1.2 $\AA$ pixel^{-1} and a resolution of $\sim$6 $\AA$. The spectra cover the wavelength range 3650–9150 $\AA$ that includes all the main features of the ISM and stellar spectra ([OII]3727, D4000, Balmer series, [OIII]5007 and beyond).

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**)*

We received 2 nights in 2014A for this project (Park C. et al. 2014A). Among the two satellite systems and four clusters we proposed, we obtained the data only for one satellite system (i.e. two fields for NGC 3665) and for three clusters (i.e. two fields for A520, two fields for A2199, and one field for the Coma cluster). This is only $\sim 50\%$ complete compared to what we initially proposed. We are asking 2.5 nights in this semester to complete the project. We finished the reduction of the data taken in 2014A and are now analyzing the data.

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**)*

*Park C. et al. (2014A/B), 3 nights, under data analysis

Park C. et al. (2014B), 0.5 night, under data analysis