1 Scientific Justification

1.1 Background: AGN, Star Formation, and Brightest Cluster Galaxies

Defining the connections between AGN and star formation feedback and the formation and evolution of the most massive galaxies, and the growth of the central supermassive black holes in these galaxies is one of the highest priority tasks in the study of galaxy evolution today. The Brightest Cluster Galaxies (BCGs) inside galaxy clusters with large X-ray luminosities are interesting galaxies for studying the role of of feedback in the growth of galaxies because they are the most massive galaxies known, probably owing to their prime location at the bottom of a gigantic potential well, and many of them are apparently forming stars and feeding a central AGN.

A surprising fraction of these cluster galaxies appear to be forming new stars at the rate of $10 - 100$ $M_\odot$ yr^{-1} (e.g. McNamara & O'Connell 1989, Cardiel et al. 1995), in the midst of a massive, red, and aging population of stars.[1] Spitzer IRAC and MIPS have confirmed the presence of significant amounts of warm, dusty gas (Egami et al 2006ab; Donahue et al 2007; Quillen et al 2007.) And, the mid-IR luminosities are consistent with the interpretation of the Hα radiation and the UV and optical colors as signatures of recent star formation (Donahue et al. 2007; O'Dea et al. in prep.)

In addition, the jets from AGN in the centers of many of these BCGs have been carving vast bubbles in the hot intracluster gas (see McNamara & Nulsen 2007 for a review). Such bubbles were first detected in a nearby X-ray cluster (Böhringer et al. 1993) by ROSAT high resolution X-ray imaging, but the spatial resolution and sensitivity of the Chandra X-ray observatory has revealed that many X-ray clusters have such bubbles (e.g. McNamara et al. 2000; 2000, Birzan et al. 2004). These X-ray cavities nearly always appear to be filled with radio-emitting plasma, suggesting that the radio source generates particles with a total kinetic energy that far exceeds the radio energy (see review by McNamara & Nulsen 2007).

The presence of these AGN blown bubbles were seized upon by theorists to solve another problem: the cluster cooling-flow problem. The cooling-flow problem, in a nutshell, arose when astronomers realized that rate at which the intracluster gas was radiating (L_x) in the centers of clusters of galaxies was so rapid that the enthalpy of the gas ($5kT/2$) would be depleted in less than the age of the universe. In some cases, this radiative cooling time was much shorter. If this gas cooled, the upper layers of the nearly hydrostatic atmosphere would slump slowly toward the core. However, the results of a couple of decades of searches for this cooled gas, and the star formation that was expected to accompany further cooling, were disappointing. Recent high-resolution X-ray spectra from XMM, showed a lack of emission lines from species such as FeXVII and OVII (e.g. Peterson et al. 2003). The conclusion was that the gas was not isothermal: it is cooler! However, the gas somehow loses some but not all of its thermal energy.

With the AGN bubbles showing a surprisingly large amount of kinetic energy being expelled, AGN feedback has become the in most promising potential solution to the long-standing cooling flow problem in clusters. Properly tuned, with self-adjusting accretion providing the fuel, and as yet-unidentified processes distributing the energy, an AGN could stabilize the cool core of an X-ray cluster, and dramatically slow the rate at which gas can

[1] All quantities in this proposal are derived using concordance cosmology values of $H_0 = 70$ km/s/Mpc, flat geometry and $\Omega_\Lambda = 0.7$.

cool and condense to form stars.

One intriguing feature of these systems is that the presence of an Hα emission-line nebula and/or a radio source is strongly correlated with the presence of low entropy, X-ray emitting gas in the central 50 kpc of the cluster (Figure 2). Intracluster gas entropy is a fundamental clue to assessing the history and the processes of feedback in the ICM. We can estimate gas entropy from the quantity $K = kT/n_e^{2/3}$. The X-ray temperature (kT) and the gas density n_e are inferred from X-ray spectra and emissivities respectively. With XMM and Chandra X-ray data, we can now derive temperature and electron density profiles for clusters of galaxies, and thus produce entropy profiles (e.g. Donahue et al. 2005; 2006). Cluster simulations show that while the cluster temperature is largely determined by the depth of the gravitational potential well, the X-ray luminosity of the cluster is determined by the distribution of entropy in the gas and the shape of the potential well. As gas falls into the dark matter potential well, it organizes such that low entropy gas sinks to the center and high entropy gas buoyantly rises. If the gas parcels have higher entropy on average, the resulting stable configuration is puffier and therefore less luminous than a configuration that starts out with parcels with low entropy. Gentle motions about the cluster are adiabatic processes that do not change the entropy (and hence the quantity K). But radiative losses can reduce gas entropy, and shocks can increase it. For bremsstrahlung emission, the cooling time can be written in terms of K and metallicity. Therefore a map of the entropy of the gas is like a map of the cooling times in the gas. High entropy gas (> 100 keV cm^2) has a long cooling time, and therefore retains the imprint of galaxy feedback. Low entropy gas ($< 20 - 50$ keV cm^2) can cool in a relatively short time ($< 10^9$ yrs). The fact that this gas is commonly found in the cores of clusters means that (lacking an obvious sink of gas) this gas must somehow be stabilized by on-going feedback (e.g. Voit & Donahue 2005).

•Spitzer Studies of BCGs With Star Formation

Quillen et al. (2007) describes a recent project to obtain Spitzer IRAC and MIPS observations for a sample of 63 BCGs in clusters of galaxies. These galaxies were selected for their high Hα luminosities. Most of these galaxies exhibit starburst, or starburst+AGN mid-IR spectrophotometric properties in the mid-IR. However, as shown in O'Dea et al. (2008, in prep) their IR luminosities are higher than one would expect based on their H-α luminosities, if one simply applied a Kennicutt (1998) relation for a starburst or a normal, star-forming galaxy. All of the clusters that appear in the Quillen et al. sample and in our X-ray cluster sample have extremely low central entropies ($K < 10 - 20$ keV cm^2).

The mid-IR luminosity of a starburst is an indicator of emission from dust that has reprocessed stellar luminosity from the UV to the IR. Some physical processes that are not related to star formation but that can also contribute to the mid-IR luminosity are the reprocessing of optical luminosity and the thermal conduction of heat from the X-ray emitting gas to the dust (Donahue et al. 2007).

•The Need for a BCG Control Sample

Spitzer data on BCGs with feedback signatures are abundant in the Spitzer data archive, but similar data on BCGs with no apparent feedback are scarce. In order to isolate and study the IR signatures of star formation and feedback in BCGs, we need more data on BCGS without star formation and feedback. To this end, we have measured the X-ray gas properties (gas temperature, entropy, and X-ray luminosity) of a sample of over 140 nearby X-ray clusters with excellent observations by the Chandra X-ray Observatory (Figure 1).

We then identified those clusters with centers that have been observed by the Spitzer Space Telescope. While clusters with low central entropies and $z < 0.1$ have been fairly well-studied by Spitzer, very few observations exist for clusters with similar X-ray luminosity, but somewhat higher central entropies (Figure 3). We propose here to observe 6 single BCGs residing in clusters with similarly high X-ray luminosities, but a broad range central entropies. We will obtain similar quality observations to those that already exist in the archives. This sample is required to provide a solid scientific comparison sample for the other, more exotic BCG observations in the cluster archive. The redshift range is chosen to be close enough to detect interestingly faint IR emission while far enough to fit into a typical IRAC and MIPS field of view.

We have chosen a sample of BCGs that reside in luminous ($L_x > 10^{44}$ erg/s, bolometric), that have single (not double) BCGs. These BCGs exhibit no obvious sign of star formation or AGN activity, and have fairly stringent 3σ upper limits on their Hα luminosities of $\sim 1 - 5 \times 10^{39}$ (Crawford et al. 1995; Donahue, private communication), and faint limits or detection (Abell 2142) near the flux limit from the NVSS and FIRST radio surveys at 20 cm. Radio luminosity upper limits were computed using the same assumptions as found in Birzan et al. (2004). There were a few existing BCGs in this redshift range with MIPS observations, but all 3 of these were double BCGs that appeared to be interacting.

With these observations, we will establish the norms of a typical BCG without obvious evidence for star formation and AGN feedback in a sample of 6 luminous X-ray clusters, selected to have very similar X-ray luminosities and temperatures but a wide range of central entropies from $K_0 = 10$ keV cm^2 to 250 keV cm^2. We removed BCGs with Hα emission and/or radio emission. This exclusion primarily removed BCGs in clusters with $K_0 = 20$ keV cm^2, a subsample we argue has been covered extensively by existing Spitzer observations. The resulting list of clusters (and their BCGs) is presented in Tables 1 and 2. The K_0 and z of both the archival BCG targets and the ones we propose are plotted in Figure 2. Sloan Digital Sky images for 5 of the 6 target BCGs are presented in Figure 3.

2 Technical Plan

We will obtain IRAC and MIPS 24 and 70 micron observations of 6 Brightest Cluster Galaxies (BCGs) at redshifts of $z = 0.035 - 0.09$. We have produced AORs that provide for an exposure time of 100 seconds/pixel in all 4 IRAC bands (3.6, 4.5, 5, 8 microns) and 140 and 120 seconds/pixel in the two shortest wavelenght MIPS bands (24 and 70 microns). These exposure times will allow an extended source sensitivity of 1σ of 0.00877, 0.0131, 0.0531, and 0.00682 MJy/sr in each of the 4 IRAC bands respectively, and of 0.0606 and 1.3 MJy/sr in the 24 and 70 micron bands. We assessed the 70 micron background at the location of each target using Spot, and we found that half of the targets have low background (at 70 microns, this corresponded to 5.5-7.6 MJy/sr) and half have medium background (11.7-14.2 MJy/sr). The point source sensitivies, 1σ are $3.6 - 8.0$ μJy for the IRAC bands, 49 μJy at 24 microns, and 6.2 mJy at 70 microns. Our sensitivity estimates were constructed with the assumption of medium background, using the on-line sensitivity tool called SENS-PET.

Very similar observation times have been used to obtain excellent photometry of BCGs of similar near-IR properties (see Donahue et al. 2007), so we are confident these AORs will produce equivalently deep, and most importantly, comparable sensitivity data to data already in the archive. For comparison, the 70 micron flux for the BCG in Abell 2597 was 90 ± 4 mJy and 6.0 ± 0.8 mJy at 3.6 microns (Donahue et al. 2007). These data will allow us to accurately measure the stellar light contribution from these sources, as well as assess the contribution from any AGN or warm dust that may be present. If not present, we will be able to place interestingly sensitive upper limits in this sample, compared to the detections of warm dust discovered by Spitzer in BCGS in the low-entropy cores of clusters of galaxies.

We are submitting final AORs for this program.

We are following IRAC and MIPS Best Observing Practices for all of the observations.

The data for these six galaxies will be primarily analyzed by Donahue and Cavagnolo. Donahue has previous Spitzer data analysis experience with very similar data. Voit will provide theoretical guidance for the interpretation of the data.

3 Legacy Data Products Plan

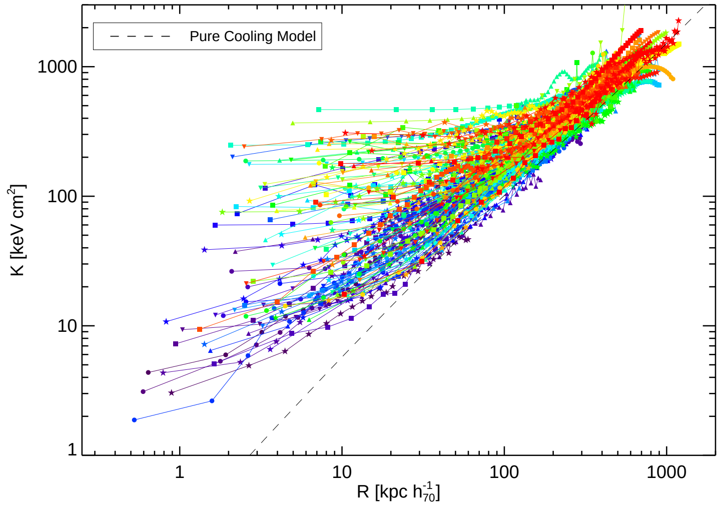

Figure 1: A plot of the X-ray gas entropy as a function of radius, for our complete X-ray cluster sample of over 140 galaxies. The color code is by cluster mean temperature, where blue represents the coolest clusters and red is the hottest clusters. The entropy in a gravitational potential decreases with radius if it is stable to convection. Note that the scatter of gas entropy at 100-200 kpc is very small, while the scatter in the core is over a factor of 10. Spitzer has primarily observed BCGs in low redshift clusters with low central entropy (< 20 keV cm^2). We are proposing to obtain key comparison observations of BCGs in clusters with a range of central gas entropies.

4 Figures and Tables

Table 1: BCG and Cluster Properties

Name	z	L_x 10^{44} erg s^{-1}	K_0 (keV cm^2)	$L_{H\alpha}$ 10^{38} erg s^{-1}	L_{Radio} 10^{39} erg s^{-1}
Abell 119	0.0442	1.39	240-260	< 2	< 1.3
Abell 401	0.0745	8.39	154-158	< 2	< 3.7
Abell 2142	0.0898	75.9	75-83	< 80	< 5.5
Abell 2063	0.0351	4.27	51-52	< 12	4.5
Abell 1650	0.0843	20.4	20-30	< 5	< 4.8
Abell 2107	0.0411	3.0	5-10	< 20	< 0.8

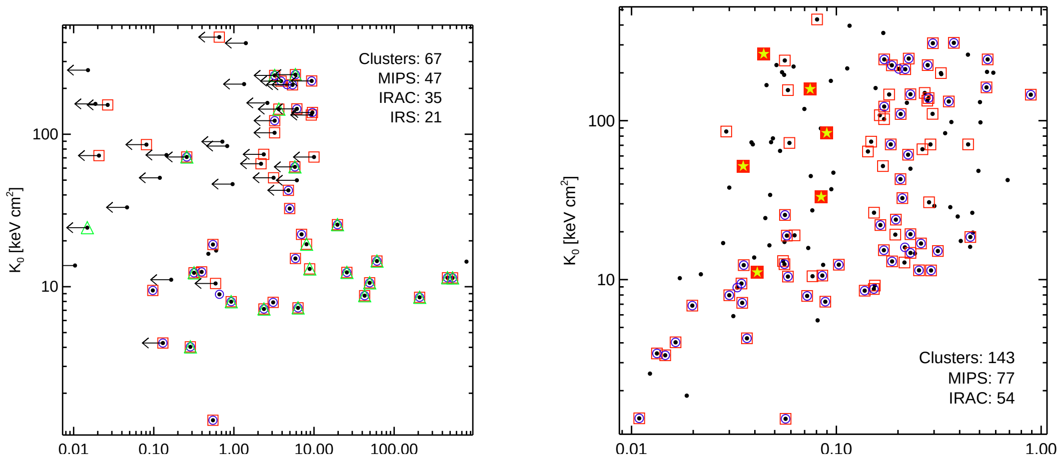

Figure 2: On the left, a plot of Hα luminosity as a function of central entropy, for the clusters in our complete X-ray cluster sample with Hα measurements available. Note that Hα only appears in clusters with low central entropy. These clusters are the ones with central cooling times shorter than about 3×10^8 years. On the right, a plot of the best-fit central hot gas entropy for 143 clusters as a function of redshift (where $K(r) = K_0 + K_{100}(r/100\ \mathrm{kpc})^{\alpha}$). Existing Spitzer observations are indicated indicated by shapes and color coding. Red squares indicate existing MIPS observations, green circles indicate IRS, and green triangles identify IRAC observations. Note that our selection of 6 targets (plotted as red boxes with yellow stars) span a range of parameter space not sampled by archived observations. (Four MIPS observations of BCGs in the same range are of merger systems.)

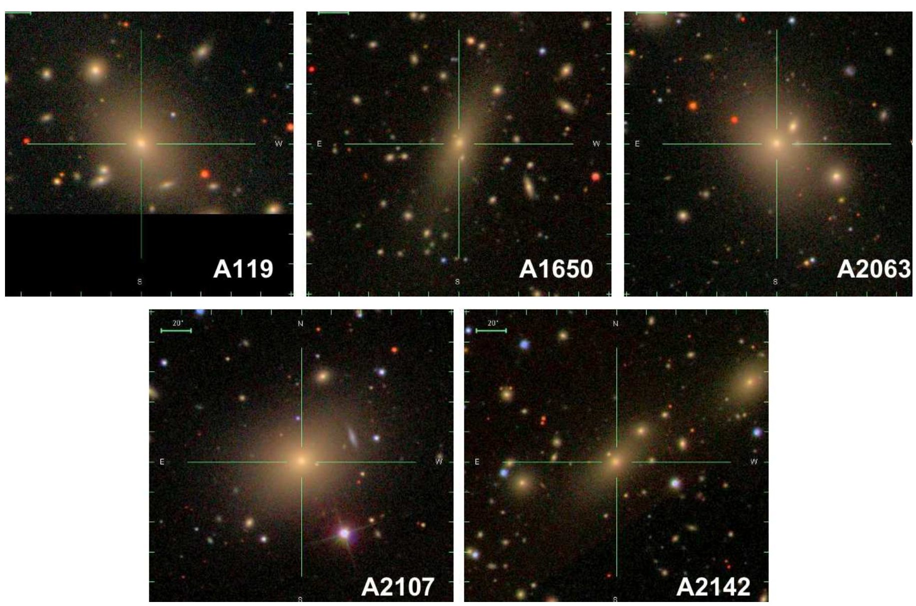

Figure 3: Sloan Digital Sky Survey images of 5 of the 6 BCGs we propose to observe.

5 Observation Summary Table

An observation summary table is provided below, based on the AORs we are submitting with this proposal. The observing time units in the table are in seconds. The on-source exposure time for each IRAC band is identical (3600 seconds); the on-source exposure time for the 24 and 70 micron observations 165.7 seconds and 120 seconds respectively. The estimated fluxes are surface brightness units, in MJy per steradian, corresponding to 10 sigma per pixel detections in 3.5 microns (IRAC) and 70 microns (MIPS).

AOR	Target Name	RA	Dec	AOT	Est. Flux	On-source Times
1	Abell 119	0h56m15.15s	-1d14m59.7s	IRAC Map	0.08	3600.0
2	Abell 401	2h58m56.90s	+13d34m14.5s	IRAC Map	0.08	3600.0
3	Abell 2142	15h58m20.99s	+27d13m59.1s	IRAC Map	0.08	3600.0
4	Abell 2063	15h23m04.87s	+8d38m20.5s	IRAC Map	0.08	3600.0
5	Abell 1650	12h58m41.50s	-1d45m44.3s	IRAC Map	0.08	3600.0
6	Abell 2107	15h39m39.11s	+21d46m57.7s	IRAC Map	0.08	3600.0
7	Abell 119	0h56m15.15s	-1d14m59.7s	MIPS Phot	10	165.7, 125.8
8	Abell 401	2h58m56.90s	+13d34m14.5s	MIPS Phot	10	165.7, 125.8
9	Abell 2142	15h58m20.99s	+27d13m59.1s	MIPS Phot	10	165.7, 125.8
10	Abell 2063	15h23m04.87s	+8d38m20.5s	MIPS Phot	10	165.7, 125.8
11	Abell 1650	12h58m41.50s	-1d45m44.3s	MIPS Phot	10	165.7, 125.8
12	Abell 2107	15h39m39.11s	+21d46m57.7s	MIPS Phot	10	165.7, 125.8

There are 13.35 hrs total in IRAC AORs, 0 hrs total in IRS AORs, and 1.65 hrs total in MIPS AORs, for a total request of 15.0 hours.

6 References

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7 Brief Resume/Bibliography

The PI Megan Donahue is an associate professor in the department of Physics and Astronomy at Michigan State University. She has 25 years of multi-wavelength observing experience from the mid-infrared to the X-rays, including near-IR imaging, optical spectroscopy and imaging, UV spectroscopy. She has also published theory papers in the area of the physical gas and radiation processes in the IGM and ICM. Her current main research interests are the formation and evolution of galaxies and clusters, and in cluster cosmology. She has published 57 refereed journal articles on these topics, and is a co-author of The Cosmic Perspective, one of the most popular astronomy textbook for undergrads on the market.

Co-I G. Mark Voit is an associate professor in the department of Physics and Astronomy at Michigan State University, and his specialty is theoretical astrophysics. His areas of expertise are cosmology, gas and dust processes, clusters of galaxies, AGN. He works extensively with simulations of galaxy and cluster formation to produce observable predictions at the X-ray, optical, and infrared wavelengths. He is also a co-author of the Cosmic Perspective.

Co-I Ken Cavagnolo is an MSU graduate student entering his final year. He has extensive X-ray data analysis experience, including the analysis of 200 Chandra cluster observations. He plans to expand his data analysis skills to include Spitzer with projects proposed for this observing cycle.

Co-I Christopher O'Dea was the PI of a large proposal to observe 63 Hα luminous BCGs. He is a professor of astronomy at the Rochester Institute of Technology and is an expert observer, with experience from the radio to the X-rays, with particular interest in BCGs, gigahertz-peaked radio sources and star formation in cool core clusters.

Relevant publications by the PI:

Quillen, A. et al. 2007, ApJS, accepted. (astro-ph/0711.1118): An infrared survey of the brightest cluster galaxies: Paper I. (Paper II, O'Dea et al. willl be reviewed by the time this proposal is reviewed.)

Donahue, M. et al. 2007, ApJ, accepted (astro-ph/0708.1427): Infrared Emission from the nearby cool core cluster Abell 2597

Donahue, M. et al. 2007, AJ, 134, 14. Star Formation, Radio Sources, Cooling X-ray Gas and Interactions in the Brightest Cluster Galaxy in 2A0335+096.

Sun, M., Donahue, M., Voit G. M. 2007, ApJ, accepted. H-alpha tail, intracluster HII regions, and star formation: ESO-137 in Abell 3667.

Donahue, M. et al. 2006, ApJ, 643, 730. Entropy profiles in the cores of cooling flow clusters of galaxies.

Voit, G. M. & Donahue, M. 2005, ApJ, 634, 955. An observationally motivated framework for AGN heating of cluster cores

Donahue, M. et al. 2005, ApJ, 630, L13. Two clusters of galaxies with radio quiet cooling cores.

8 Status of Existing Spitzer Programs

The PI has not been a PI of a previous Spitzer program.

The co-Is have not been a PI of any previous Spitzer program.

Donahue, M. et al. 2007, ApJ is based on data from a Spitzer GO program, PI W. Sparks.

C. O'Dea is PI of GO-3 program 30659, "A Census of Star Formation in Brightest Cluster Galaxies: Is Star Formation the Ultimate Fate of the Cooling Gas?" A data paper by Quillen et al. has been accepted for publication in ApJ. Suppl. An interpretation paper is close to submission to ApJ.

9 Proprietary Period Modification

There are no modifications to the proprietary period.

10 Justification of Duplicate Observations

There are no duplicate observations.

11 Justification of Targets of Opportunity

There are no ToO observations.

12 Justification of Scheduling Constraints

There are no constraints on this program.