1 Scientific Justification

It is becoming increasingly apparent that feedback from active nuclei (AGN) shapes the development of clusters of galaxies (e.g. McNamara & Nulsen 2007). These are the largest virialized structures in the universe, and most of their baryons are contained in the intracluster medium (ICM), a hot, X-ray emitting gas. The hot gas has 1-3 keV more energy per particle than expected from virial heating in a collapse governed by gravity alone (Wu et al. 2000; Markevitch 1998). The excess is larger than can be accounted for from processes such as starburst-driven winds during the early stages of cluster development.

In another puzzle, recent X-ray observations by Chandra and XMM of "cooling flow" clusters have shown that cooling of the intracluster gas occurs at much lower rates than predicted by simple cooling models (e.g. Peterson et al. 2003). This is true even in clusters with plunging central temperature profiles and central cooling times less than 1 Gyr. Observed cooling rates, based on recent star formation, are only about 10% of the maximal, uncompensated cooling values.

Both of these puzzles may be explained by another recent X-ray discovery. Chandra has found giant cavities in the hot gas surrounding nearly two dozen groups and galaxy clusters (e.g. McNamara et al. 2000; Birzan et al. 2004). The cavities were carved by AGN-driven radio-emitting jets emanating from giant cD galaxies located at their centers. In several clusters, the cavity systems are known to be surrounded by weak but energetic shock fronts (eg., Forman et al. 2007). The energy associated with the cavities and shocks scales in proportion to the X-ray luminosity of the cluster core, and is sufficient to quench cooling in roughly half of the systems studied (Birzan et al. 2004). Simultaneously, the shocks will increase the entropy of the hot gas.

These properties, combined with the existence of very short central cooling times in the hot gas, suggest a feedback cycle of cooling, star formation, and accretion onto the AGN, followed by relativistic jet outbursts that heat the gas and quench cooling. The cycle repeats on a timescale of $10 - 100$ Myr (Birzan et al. 2004; Voit & Donahue 2005).

•Supergiant Cavities and Shocks in Clusters

McNamara et al. (2005) found the most dramatic example of AGN-driven feedback in the galaxy cluster MS0735.6+7421. The shock energy inferred is $\sim 6 \times 10^{61}$ erg, and the age of the shock, based on its size and strength (Mach 1.4), is 1.04×10^8 yr. The strength of the outburst in MS0735 implies that its $\sim 10^9$ $M_\odot$ SMBH must have accreted $\sim 3 \times 10^8$ $M_\odot$ of matter in less than 100 Myr (McNamara et al. 2005). This enormous outburst, the largest yet detected, contains enough energy to quench a cooling flow for several Gyr. In addition it can provide up to $\sim 1/3$ keV per particle of heat to the gaseous atmosphere, a substantial fraction of the $\sim 1 - 3$ keV per particle of excess energy required to "preheat" the cluster. Other energetic outbursts were found in the Hydra A and Hercules A clusters (Nulsen et al 2005ab). These systems show that powerful outbursts in clusters are not uncommon and are likely to be energetically important on large scales.

•Infrared Probes of the ICM Feedback Cycle

Infrared observations are important for studying several phases of the ICM/AGN feedback cycle. During the inflow phase, large amounts of cool intracluster gas are deposited on the brightest cluster galaxy (BCG). Signatures of this material have been detected in the form of nebular line emission (10^4 K), 2 micron molecular hydrogen emission ($\sim 10^3$ K, e.g.

Donahue et al. 2000), neutral hydrogen absorption (10^2 K), millimeter wavelength emission from ~ 30 K molecular gas (Edge et al. 2002), and strong infrared emission at 60 and 100 microns, presumably emitted by cool dust (e.g. Donahue & Voit 2004). In addition, many BCGs are experiencing starbursts with star formation rates $\gtrsim 10$ $M_\odot$ yr^{-1} (e.g. Donahue et al. 2007; Quillen et al. 2007), as judged by optical-UV emission line and continuum indicators. In the most extreme cases, infrared luminosities are comparable to those of the ultraluminous infrared galaxies (ULIRGS).

Owing to the surrounding cool material, some or all parts of a bright AGN may be concealed by dust. The eruption of the radio jets through the dense inner gaseous atmosphere may again induce star formation, and much of this process may likewise be hidden at short wavelengths.

Mid infrared spectroscopy and photometry with Spitzer can provide insights on the feedback cycle not possible in other bands. They will help eliminate the dust extinction effects that we know are present in the deposition region and provide better estimates of star formation rates and gas ionization states. It offers good diagnostics to distinguish between ionization by massive stars and the presence of a luminous AGN. Study of the correlation between bright X-ray filaments and IR emission can test the idea that grains provide an alternative IR cooling channel for the hot gas. Mid-IR spectra provide the best information on the properties of the dust grains in BCGs and hence their origin. Dust found in hot gas may be depleted of small grains by sputtering. Alternatively, dust could be created by intermediate-age, metal-rich stars in the BCGs or be stripped from merging satellite galaxies. Broad-band SEDs from MIPS and IRAC observations allow us to estimate stellar masses, assess the contribution of AGN, and detect excess emission from warm dust.

What powers infrared emission from the cores of such clusters? We know that cooling flows are often very luminous in the infrared. However, the IRAS and ISO spatial resolutions were too coarse to pin down the origin of the emission. If dust acts as a major coolant for the intracluster gas, we expect a distributed mid-IR source. On the other hand, if the emission is powered by a starburst or an AGN, it should trace the more concentrated bright regions in the CDG center.

What are the star formation rates, and how do they compare to the X-ray cooling rates? Star formation in such objects is largely obscured by dust. Infrared radiation longward of $\sim 2\mu$, particularly from the PAH 7.7μ emission emerging from the dusty starbursts will provide independent star formation estimates and help place stronger limits on the amount of gas that is actually cooling and accreting. The star formation rates combined with the molecular gas masses and limits yield a total deposition rate that can be compared to the intracluster cooling rates estimated from XMM-*Newton* and *Chandra*.

What are the physical conditions in the central regions? Using spectral line diagnostics (Voit 1992) we will determine the ionization level and the degree of obscuration and dust content in the central regions. The dust content reflects abundances and the prior physical history of the gas. Mid-IR molecular features are important diagnostics for the character and chemical composition of the grains. The mid-IR neon features discriminate well between photoionization by starlight or that by more energetic sources such as as an AGN or X-ray emission from cooling gas [14]. The [Ne V]/[Ne III] ratio should be small if the emission is dominated by a starburst. In the absence of [Ne V], the [Ne III]/[Ne II] ratio will establish the temperature of the photoionizing stars, which is important to determining the age of the young population and therefore the star formation rate one infers. A better understanding of the massive star population will help us evaluate the effect of supernova explosions on the gas dynamics of the CDG core.

Spitzer observations of these remarkable environments have broad implications. The physics of cooling, accretion, star formation, AGN fueling, and energy feedback forms the bedrock on which most theoretical models for galaxy and supermassive black hole formation are built. The ICM feedback cycle produces one of the few environments in the local universe where such models can be directly tested.

•What have we learned so far?

Broad-brand Spitzer photometry of a sample of 63 Hα-luminous BCGs has shown a wide variety of 3-160 micron spectra, ranging from spectral energy distributions (SEDs) with starburst signatures (70 micron excesses, in particular) to SEDs with a mix of AGN and starburst evidence (Quillen et al. 2007). Starlight provides most of the radiant energy (Donahue et al. 2007; Figure 1). This dominance ($\sim 10^{12} L_{\odot}$) is not surprising since these BCGs are among the most massive galaxies in the universe. The mid-IR excess appears to be typical of that generated by dust heated by the formation of massive stars. However, the temperature of this warm dust may differ from system to system, since we note that the peak of the emission in the more extreme galaxies studied by Egami et al. (2006) occurs at a longer wavelength than the peak for Abell 2597 (Donahue et al. 2007).

IRS spectra for Hα-luminous BCGs have provided further insights. A sample of 8 BCGs was studied by de Messieres et al. (2007 AAS, PI R. O'Connell; Figure 2). They found that some of the spectra of the BCGs are quite unlike those of normal starbursts and AGN. One very interesting result is that most of them lack strong PAH features. What this could mean is that the IR-emitting dust may lack tiny grains. One plausible reason for this lack is X-ray processing of the grains (Voit 1992). Grain sputtering (Draine & Salpeter 1979) by hot electrons can remove the smallest grains. However, a couple of the BCGs in the sample do exhibit PAH features. Another unusual result is the combination of ubiquitous, bright H_2 and low-ionization atomic lines together with flat continua, or even continua that rise to the short wavelengths.

•Perspectives from ICM Entropy in Galaxy Formation Feedback

We plan to analyze all available Spitzer data for BCGs, from IRAC and MIPS photometry to IRS spectroscopy in order to assess the mid-IR properties of the BCG and then compare those properties with the more global properties of the cluster itself (X-ray luminosity, X-ray temperature and temperature profile, and X-ray entropy distribution.) We have been conducting an extensive Chandra archival study of the entropy distribution in the hot ICM of nearby clusters of galaxies (Donahue et al. 2006; Cavagnolo, PhD Thesis). We have now produced temperature and entropy profiles for over 140 clusters of galaxies.

Entropy is an extremely useful thermodynamic observable for studying feedback. With X-ray observations, we can study the distribution of entropy in the ICM by measuring $kT_x/n_e^{2/3}$ as function of position in the cluster. The entropy distribution traces past feedback because high entropy gas retains the imprint of any past feedback event for a very long time. Therefore, instead of organizing our cluster sample by cluster luminosities and temperatures, we study ICM feedback through studying cluster entropy distributions. We can assess both current and past physical processes that have directly to do with feedback to the ICM, including the AGN stabilization of cool cores (Voit & Donahue 2005).

2 Technical Plan

2.1 Sample Selection

Ken Cavagnolo (MSU) has been completing a PhD thesis analyzing over 140 gas entropy profiles in X-ray clusters of galaxies. The data were obtained from the Chandra archive. This work represents the largest uniform measurement of gas entropy distributions in luminous X-ray clusters.

We have cross-correlated this sample of well-studied X-ray clusters with the Spitzer archive. We have identified over 90 cluster centers that have been observed with at least one Spitzer instrument. Figure 3 summarizes our results for the full sample. Of 143 clusters, we found MIPS observations for 77, IRAC observations for 54, and IRS observations for 33. Not all of these observations are yet public, but they will go public sometime in 2008. Each one of these clusters has accurate X-ray properties determined from Chandra data. We note that a wide range of clusters have been observed to date, with a range of cluster X-ray luminosities, temperatures, central entropies, and state of relaxation (or merger). (See figures 3-6).

We will use the standard pipeline projects to create the mosaics we need to achieve our scientific goals. The 70-micron mosaics in our experience occasionally require more work, beyond the standard pipeline choices, to improve the signal to noise. However, the MOPEX GUI has proved to be a very useful tool in our previous Spitzer work, and we plan to make good use of that. We use standard IRAF and IDL tools to measure noise and make photometric estimates. We also use MOPEX to determine PSF-corrected photometry as necessary.

We already have (hard-won) experience in assembling and matching IRS spectra using CUBISM. When possible, compare our results with any existing published results of spectra.

2.2 Statement of Work and Schedule

This work includes data from 33 unique MIPS program IDs (77 clusters), 29 IRAC program IDs (54 clusters) and 19 IRS IDs (33 clusters). No one observing program had the breadth, and no program has what we bring to the table, a complementary uniform analysis of an even larger set of Chandra observations of X-ray clusters. We are requesting partial funding of 3 individuals at two institutions, in order to ensure that we have the time and the expertise available to complete the project.

The plan of work includes:

1. Divide the project into IRS and MIPS+IRAC efforts.

2. For each effort, download and organize all desired and currently available Spitzer data. We will produce a database to manage the catalog and the reduction and analysis state for each BCG.

3. Inspect and assess each dataset for its signal to noise, its specific target area, its suitability for our science goals. (Some of this task can be accomplished prior to download.)

4. Identify systems with complex cores. These would include the cores with merging galaxies, or cluster centers with no obvious BCG at all. These systems are the minority of cluster centers, but will require extra work to manage.

5. Extract broad-band SEDs from IRAC/MIPS photometry and spectra from IRS data, including observational errors.

6. Extract broad-band magnitudes from 2MASS, and, where available, Sloan Digital Sky Survey. SDSS magnitudes for low-redshift BCGs will need to be measured manually, since cataloged measurements are likely to underestimate the total luminosity of the optical system. The 2MASS program has a fairly decent extended source catalog, and only the most nearby BCGs would be affected.

7. Assess total IR luminosities, identify excesses in the mid-IR and the two long-wavelength channels of IRAC (where line emission and PAHs can contribute), and total stellar luminosities.

8. Compare the X-ray properties (particularly central entropy) with the IR properties. One prediction we can test is that clusters in our sample with high central entropies will be much less likely to exhibit luminous 70-micron emission or AGN evidence. A strong prediction, based on the assertion that low-entropy gas feeds both star formation and AGN activity, is that none of the high-central entropy systems will.

9. Write the papers. We expect to write 2 papers based on these results.

The time estimates below include the time required to learn any new reduction, read documentation, and check work.

Tasks 1-4 can be accomplished in about 3 weeks of work. The bulk of the work will be the making the measurements and assessing errors from Spitzer data and assembling those measurements into SEDs (3 months). We plan to split off the IRS work to the University of Virginia, where a student (de Messieres) already has significant experience with that data. The X-ray work is complete, so the comparisons will be straightforward once measurements are in place.

We are requesting $100,000 total. $75,000 will go to MSU to support 5 months of a postdoc and 1 month of summer salary for the PI Megan Donahue. Donahue and the postdoc will lead the MIPS and IRAC analysis, and some of the IRS work. This amount will also include support for 2 domestic trips for the postdoc, computer support (such as an external disk drive, software IDL license renewals - a shared cost), and publications. $25,000 will go to the University of Virginia to support the IRS work of a graduate student, utilizing CUBISM under the direction of Prof. O'Connell.

3 Figures and Tables

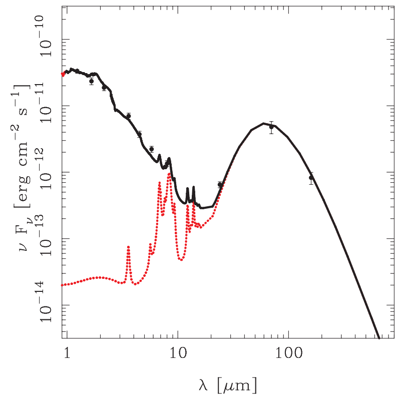

Figure 1: SED for the BCG in Abell 2597 from IRAC and MIPS photometry (Donahue et al. 2007). Note the peak is in the optical; a starburst spectrum is plotted in the red dotted line. The solid line shows the sum of the old stellar population temlate and starburst.

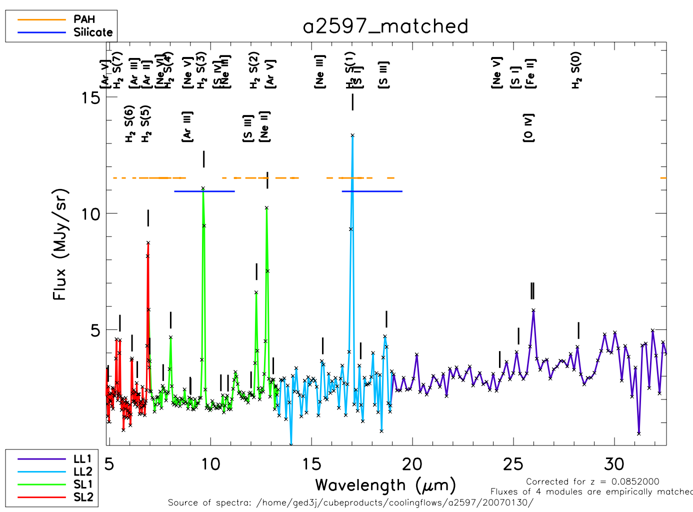

Figure 2: IRS spectrum for the BCG in Abell 2597. Note the prominent H_2 lines and lack of PAH features. All 8 systems studied had very bright H_2 and low ionization lines; PAH features were weak or absent for half of the 8 systems studied (deMessieres et al. 2008).

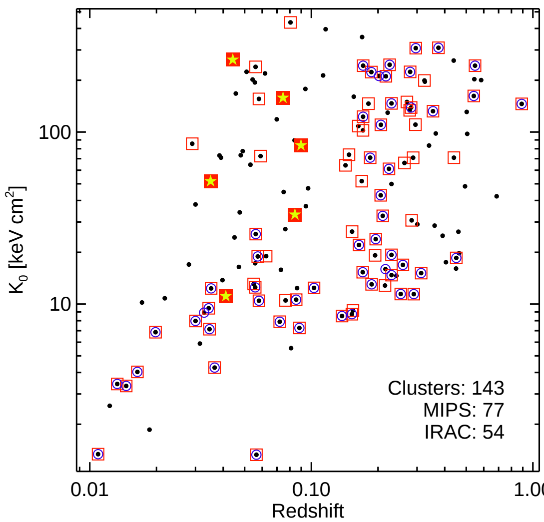

Figure 3: This figure shows the central entropy (in units of keV cm^2) for 143 Chandra clusters. Cluster centers with MIPS observations are plotted with red squares; IRAC observations have blue circles; IRS observations greeen triangles. There is excellent overlap in parameter space between the Spitzer and the Chandra archive samples, except for $z < 0.1$, $K_0 > 10$ keV cm^2 (for which we are also submitting an observing proposal.)

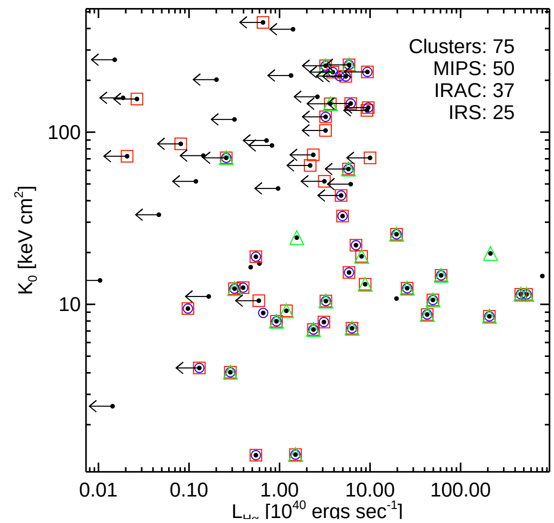

Figure 4: Same code as for Figure 3, but for the 75 clusters for which we also have Hα measurements. Note that there has been excellent Spitzer coverage of these systems.

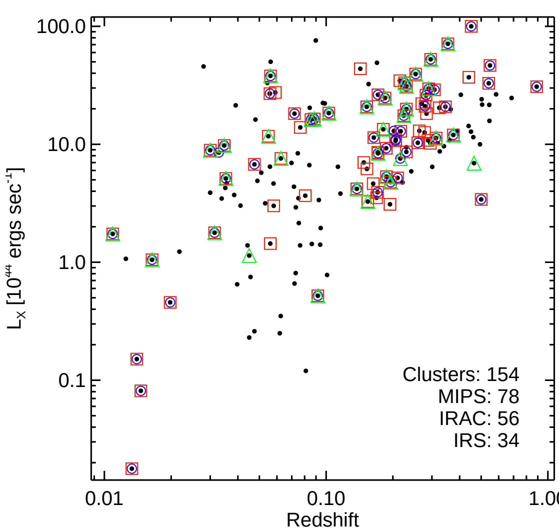

Figure 5: Archived Spitzer observations of cluster centers presented for X-ray luminosity (bolometric) vs. redshift. Coding the same as Figure 3.

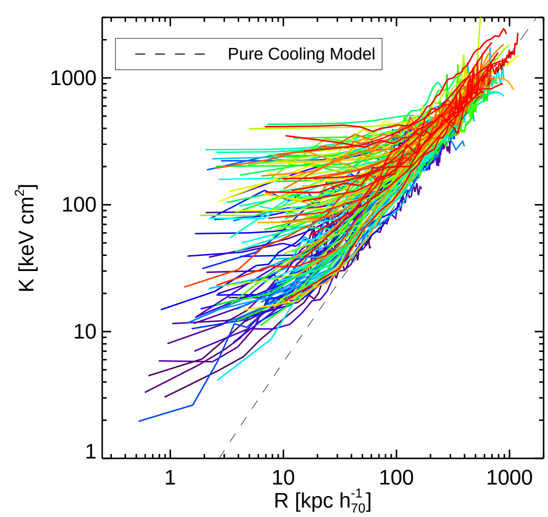

Figure 6: Entropy profiles for 143 clusters of galaxies. (Cavagnolo 2008 PhD Thesis). Note that nearly all of the clusters have similar entropy levels at 200 kpc, but there is a wide range of central entropy, or equivalently, central cooling times. The clusters with low central entropy, or short radiative cooling times also are clusters with cool cores and iron abundance peaks in the core.

4 References

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5 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 Robert O'Connell is a professor in the department of Astronomy at the University of Virginia. He is an expert in UV and spectral diagnostics of stellar populations and emission line systems in elliptical galaxies, merger systems, globular clusters.

PI Relevant publications:

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.

6 Status of Existing Spitzer Programs

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

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

Robert O'Connell in PI on Spitzer program P3384, "Mid-Infrared Spectroscopy of Massive Cluster Cooling Flows," and is a principal Co-I on Spitzer program 20345, "Starbursts and Supercavities in Clusters of Galaxies." The datasets from these programs have been combined. We had considerable difficulty with early reduction of the IRS spectral mapping data but with the advent of CUBISM have obtained excellent extractions for all targets.

Publication: de Messieres, G., O'Connell, R.W., Donahue, M., McNamara, B.R., Nulsen, P.E.J., Voit, M., & Wise, M.W. 2008, "Spitzer Mid-Infrared Spectra of Selected Galaxy Cluster Cooling Flows," BAAS, vol 40.