WHY ARE SOME BRIGHTEST CLUSTER GALAXIES FORMING STARS?

1 Introduction

The hot T$\sim 10^{7-8}$ K X-ray emitting gas is currently thought to constitute the bulk of the baryonic mass in rich clusters of galaxies. An important aspect of the overall physics of the intracluster medium (ICM) concerns the central regions of clusters ($r \lesssim 10 - 100$ kpc), where the inferred ICM densities and pressures in some cases are sufficiently high that cooling to $T \lesssim 10^4$ K can occur on time scales shorter than the cluster lifetime (e.g., Cowie & Binney 1977; Fabian & Nulsen 1977; Edge *et al.* 1992). These "cooling core" clusters often exhibit intense optical emission-line nebulae associated with the centrally dominant (cD) galaxies at their centers, together with blue continuum excess emission, and the strength of these effects appears to correlate with the cooling rate or central pressure of the X-ray emitting gas (Johnstone, Fabian & Nulsen 1987; McNamara & O'Connell 1992, 1993; Crawford & Fabian 1992, 1993; Allen 1995).

The previous paradigm pictured the ICM as a relatively simple place where gas cooled and slumped in towards the center of the cluster in a cooling flow with mass accretion rates of hundreds of solar masses per year (e.g., Fabian 1994). However, X-ray spectroscopy with XMM-Newton and Chandra has failed to find evidence for gas at temperatures below about one-third of the cluster virial temperature (e.g., Kaastra *et al.* 2001; Tamura *et al.* 2001; Peterson *et al.* 2001,2003). The limits on the luminosity of the intermediate temperature gas imply reductions in the inferred mass accretion rates by factors of 5-10. Recent theoretical models seem to indicate that intracluster conduction, combined with an episodic heat source in the cluster core, such as an AGN or star formation, are candidates for explaining both the X-ray emission from cluster cores and the optical emission-line phenomena associated with the cores with these rapid-cooling spectra (Ruszkowski & Begelman 2002; Voigt *et al.* 2002; Fabian *et al.* 2002; Narayan & Medvedev 2001). One widely considered possibility is that an important source of heat in the ICM is bubbles driven by radio galaxies - e.g., Baum & O'Dea 1991; Tucker & David 1997; Soker, Blanton & Sarazin 2002; Böhringer *et al.* 2002; Dunn, Fabian & Taylor 2005) which halts the cooling of the gas. The ICM now appears to be a very dynamic place where heating and cooling processes vie for dominance and an uneasy equilibrium is maintained. Since these same processes may operate during the process of galaxy formation, the centers of clusters of galaxies provide low redshift laboratories for studying the critical processes involved in galaxy formation and black hole growth. At the present time, the main questions are (1) How much gas is cooling out of the ICM? (2) How much star formation is ongoing? (3) What is the impact of the gas and star formation on the central BCG? (4) What role does feedback from the AGN play?

1.1 Measuring Star Formation with Spitzer

Egami *et al.* (2006) found 3 BCGs with a mid IR excess (MIRE) revealing that IR observations could probe star formation in the centers of clusters. In order to measure the current star formation in BCGs we have undertaken a program of Spitzer observations. We are in process of obtaining observations of a sample of Brightest Cluster Galaxies in 63 clusters selected from the ROSAT all sky survey with high Hα Luminosity (Ebeling *et al.* 1998; Crawford *et al.* 1999). We are obtaining 3.6, 4.5, 5.8, and 8.0 micron images with IRAC and 24 and 70 micron images with MIPS. So far about 70% of the BCGs have been observed in a least one camera. The analysis is still in progress and current results are preliminary.

We find that at least 25% of these high Hα Luminosity BCGs show a MIRE. Since the high $L_{H\alpha}$BCGs are about a third of BCGs in general, this means that at least $\sim$ 10% of the BCG

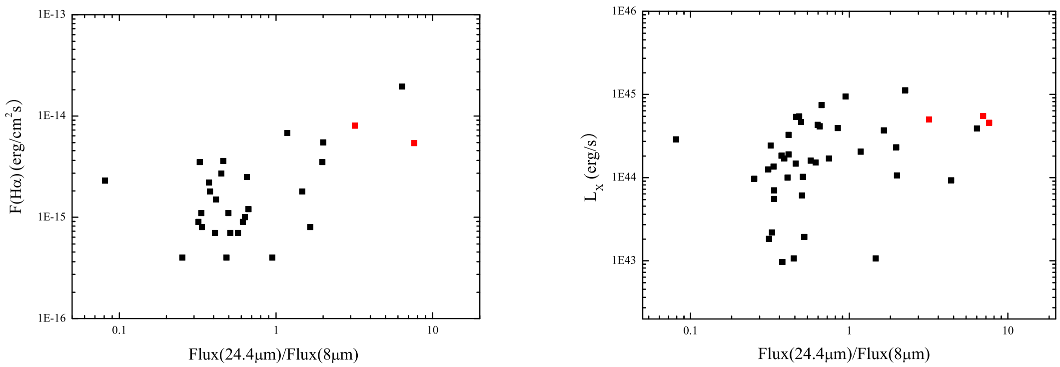

Figure 1: (Left) Hα flux vs. the ratio of the 24 and 8 micron flux densities. (Right) X-ray luminosity vs. the ratio of the 24 and 8 micron flux densities. The objects with a flux density ratio $F24/8 > 1$ are considered to have a strong MIRE. The objects in red possibly contain a significant contribution to the IR from an AGN.

population is currently forming stars. We characterize the MIRE by the ratio of the flux densities at 24 and 8 microns (F24/8). The F24/8 ratio is proportional to the Hα flux (Figure 1a) as expected if both are measures of star formation rate (i.e., the young stars heat the dust and ionize the gas). Assuming that the Infrared luminosity is due to star formation we estimate star formation rates of typically several $M_{\odot}\mathrm{yr}^{-1}$. The MIRE BCGs are found at high X-ray luminosity ($\mathrm{L}_x > 10^{44}$ ergs/s) but most high L_x BCGs do not show a MIRE (Figure 1b). In addition, the F24/8 ratio and the 24 micron luminosity are uncorrelated with the radio power of the BCG (Figure 2). This suggests, surprizingly, that the dynamical effects of the radio AGN are not driving the star formation. It is now clear that a signficant fraction of BCGs is currently forming stars. But we don't understand why or how. Thus, we need to understand the detailed X-ray properties of the BCGS both with and without a MIRE.

2 The Proposal

We propose to use Chandra to study matched samples of nine BCGs at high X-ray luminosity ($\mathrm{L}_x > 10^{44}$ ergs/s) both with and without a MIRE. In this proposal we request observations of 2 of each type (Table 1). One addtional source (A2146 with a MIRE) is proposed by Quillen et al. In the Chandra archive there are 7 BCGs with no MIRE (F24/8 < 0.5), and six BCGs with a strong MIRE (F24/8 > 1) (Table 2). Since the samples are not large, it is important that they are unbiased so that we can trust the results of our comparison of the X-ray properties. The samples defined here will give us the confidence we need to carry out this study. Analysis of the archival data is already underway as part of the PhD thesis of K. Cavagnolo. Figure 3 shows entropy plots for seven of the archival data sets. The current results seem to suggest that low central entropy may be necessary but not sufficient for star formation to occur.

We will reduce and analyze the data in a consistent way. We will determine the surface brightness morphology and derive density and temperature profiles. We will look for systematic differences in the properties of the BCGs with and without a MIRE. Are there differences in the presense or properties of cavities? Perphaps recent AGN activity has been ineffective at heating the gas and preventing star formation? This study should inform our understanding of what physical conditions

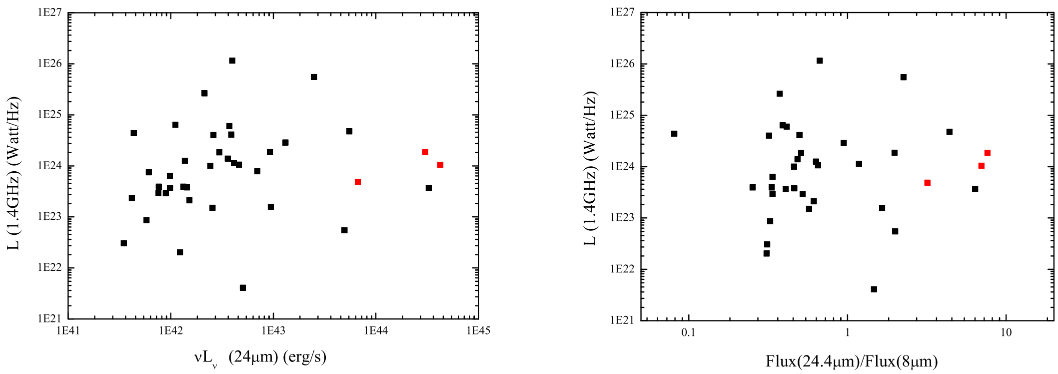

Figure 2: (Left) Radio power vs. the 24 micron luminosity. (Right) Radio power vs. the ratio of the 24 and 8 micron flux densities. The objects with a flux density ratio $F24/8 > 1$ are considered to have a strong MIRE. The objects in red possibly contain a significant contribution to the IR from an AGN.

in the ICM are required for significant ongoing star formation in BCGs at the present epoch.

3 Feasibility

We have chosen to obtain 50,000 counts per cluster. Based on experience with archival clusters studies, such observations are well-suited for deriving the measurements we require: temperature profiles and maps, metallicity and surface brightness profiles, and entropy profiles (we define entropy here to be $K = kT_x n_e^{2/3}$). Bins of 2500 counts allow temperature measurements of $\sim$ 10% at $T_x = 2-3$ keV, which is typical of the cores of cool core clusters. The $1-\sigma$ uncertainty increases to $\pm$1.5 keV at 7 keV, and $\pm$2 keV at 9 keV, so for regions of hotter temperatures, we will bin spectra up to 5,000 counts total. These observations statistically match archival cluster observations, and therefore will allow us to make direct comparison between these clusters and those already observed.

The count rates in Table **??** were derived from unabsorved 0.1-2.4 keV ROSAT fluxes reported in Ebeling et al. (1998), column densities N_H from COLDEN. We used the PIMMS v3.6 tool to derive Cycle 9 ACIS-S count rates between 0.7-8.0 keV. We cut-off the soft end of the spectrum to avoid problems with the contamination issues with the ACIS-S detectors, yet the ACIS-I count rates are about 30% less. Given that these are relatively high surface-brightness extended sources, the higher background of the ACIS-S is not an issue for these measurements.

4 References

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Table 1: Proposed Observations

Source	z	L_x 10^{44} ergs/s	F24/8	N(H) 1E20 cm^{-2}	$F_x 10^{-12}$ ergs/s/cm^{-2}	ACIS-S cps	exp time ks
R1442+22	0.0970	2.7	0.33	2.6	6.6	1.182	42
Z3179	0.1432	4.8	0.32	3.5	5.5	1.053	47
Z348	0.2535	9.8	3.2	3.1	3.6	0.710	70
A646	0.1268	4.5	2.0	4.1	6.3	1.199	42

Table 2: (Col 1) - Source. (Col 2) - Redshift. (Col 3) - X-ray luminosity. (Col 4) - Ratio of flux density at 24 and 8 microns. (Col 5) Galactic column density. (Col 6) 0.1-2.4 KeV unabsorbed ROSAT flux (Ebeling et al 1998, 2000). (Col 7) count rate in ACIS-S. (Col 8) requested exposure time (ks).

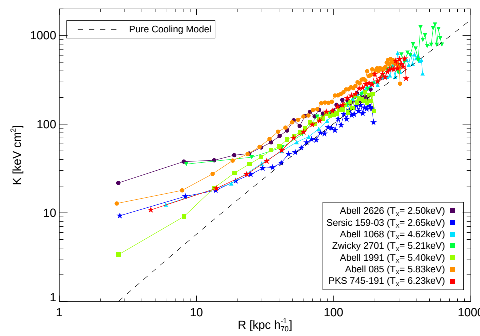

Figure 3: 1-D radial profile of entropy in seven clusters. PKS 0745-191 and A1068 are MIRE clusters and the rest are non-MIRE.

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Table 3: Archival Data

Source	z	L_x 10^{44} ergs/s	F24/8	Instrument	exp time ks
A85	0.0551	10.6	0.46	ACIS-I	40
A1361	0.1167	3.6	0.37	ACIS-S	24
A1991	0.0595	1.4	0.33	ACIS-S	39
A2626	0.0552	2.0	0.41	ACIS-S	25
A4059	0.0475	3.3	0.39	ACIS-S	134
S1101	0.0564	3.7	0.41	ACIS-S	10
Z2701	0.2150	10.7	0.48	ACIS-S	27
A1068	0.1386	7.7	6.4	ACIS-S	27
A1204	0.1706	7.3	1.7	ACIS-I	24
R0821+07	0.1100	2.1	2.0	ACIS-S	10
PKS0745-191	0.1028	22.0	2.2	ACIS-S	58
Z2089	0.2350	11.0	7.0	ACIS-S	9
Z8276	0.0750	4.0	1.2	ACIS-S	8

Table 4: (Col 1) - Source. (Col 2) - Redshift. (Col 3) - X-ray luminosity. (Col 4) - Ratio of flux density at 24 and 8 microns. (Col 5) - Chandra Instrument. (Col 6) - Exposure time (ks).

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5 Previous Chandra Programs

The PI (O'Dea) was also PI of program 04700556 which obtained 30 ks on UGC 408 (obsid 04053). The observations were reduced and analysed as part of the PhD thesis of Avanti Tilak (JHU 2006). A paper is in preparation.

6 PI Curriculum Vitae

Dr. Christopher O'Dea (PhD 1984 Univ. of Massachusetts) is a tenured Associate Professor at the Rochester Institute of Technology. He has worked in the field of clusters of galaxies (esp. AGN in clusters) his whole career.

Selected publications:

1) O'Dea, C., Baum, S., Maloney, P., Tacconi, L., & Sparks, W. 1994, "*Constraints on Molecular Gas in Cooling Flows and Powerful Radio Galaxies*," ApJ, 422, 467 – 479

2) O'Dea, C., Baum, S., & Gallimore, J. 1994 "*Detection of Extended HI Absorption towards PKS 2322–123 in Abell 2597*," ApJ, 436, 669 – 677

3) Balsara, D., Livio, M., & O'Dea, C. 1994, "*Galaxies in Clusters: Gas Stripping and Accretion*," ApJ, 437, 83 – 90 (1994).

4) Sarazin, C., Baum, S., & O'Dea, C. 1995, "*Unusual Radio Structures in the Cooling Flow Cluster 2A0335+096*," ApJ, 451, 125 – 146

5) O'Dea, C., Payne, H., Kocevski, D. 1998 "*An Arecibo Search for Atomic Hydrogen with Broad Lines Widths in Clusters of Galaxies*," AJ, 116, 623 – 633

6) Koekemoer, A. M., O'Dea, C. P., Baum, S. A., Sarazin, C. L., Owen, F. N., & Ledlow, M. J. 1998, "*Constraints on Ultraviolet Absorption in the Intracluster Medium of Abell 1030*," ApJ, 508, 608-620

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14) Laine, S., van der Marel, R. P., Lauer, T. R., Postman, M., O'Dea, C. P., & Owen, F. N. 2003, "*Hubble Space Telescope Imaging of Brightest Cluster Galaxies*", AJ, 125, 478-505

15) O'Dea, C. P., Baum, S. A., Mack, J., Koekemoer, A., Laor, A. 2004 "*HST/STIS Far-UV Observations of the Central Nebulae in the Cooling Core Clusters A1795 and A2597*," ApJ, 612, 131