1 AGN Feedback in Cooling Flows

Many giant cD galaxies resting in the cores of nearby galaxy clusters are experiencing starbursts at rates that rival or exceed those during the peak of galaxy assembly at redshifts beyond $z \sim 2$ (Juneau 2005). The hot gas surrounding them is radiating X-rays so efficiently that it will cool and condense onto the cD, unless the radiated energy is replenished by heating. There is no question that cooling is occurring at some level. These galaxies harbor massive, 10^{9-11} $M_\odot$, reservoirs of molecular gas (Edge 2001), and star formation at rates of $\sim 10 - 180$ $M_\odot$ yr^{-1}. However, the star formation rates lie far below those expected for simple cooling flow models (Crawford et al. 1999), casting doubt on the relationship between cooling gas and star formation.

This doubt has eased with the failure of XMM Newton's grating spectrometer (RGS) to detect soft X-ray emission lines at the levels predicted by simple cooling flow models (Peterson et al. 2003). The RGS and Chandra data are now consistent with gas condensing out of the hot phase at rates that are comparable to the star formation rates. Most of the cooling gas must then be maintained above ~ 2 keV by one or more heating agents (Böhringer et al. 2002).

Of the several possible heating agents, AGN outbursts in the central cD galaxy and/or heat conduction (eg., Kaastra et al. 2004) have emerged as prime candidates. Chandra images of the hot gas have revealed giant cavity systems (bubbles), shocks, and ripples (Fabian et al. 2003) produced by AGN outbursts whose powers often rival or exceed the radiation (cooling) losses (Bîrzan et al. 2004, Rafferty et al. 2006). Even clusters without cavities or other evidence of ongoing AGN activity often have elevated entropy levels from powerful AGN activity that occurred in the recent past (Voit & Donahue 2005). Furthermore, it is difficult to account for the high incidence of (unstable) short cooling times without feedback, which arises naturally from AGN. Therefore, recurrent AGN outbursts are the likely thermostats regulating the cooling of the hot gas in the cores of clusters.

2 The Problem of Galaxy Formation

This situation is rooted in one of the most important outstanding questions of galaxy formation. The cold dark matter (CDM) cosmogony holds that structure forms through the hierarchical growth of dark matter halos (White & Rees 1978). The baryons that settled into halos cooled and condensed at the centers and formed stars and galaxies, a process that should continue in cluster cores today. The problem with this framework is that it fails to correctly predict the luminosity function of galaxies, including the exponential turnover at the bright end, unless feedback from AGN and supernova explosions are considered (Sijacki & Springel 2005, Croton et al. 2005).

Star formation fed by cooling gas is a primary mode of bulge formation in cooling flow systems. The accompanying AGN activity is able to offset the radiation losses in many systems (Bîrzan et al. 2004, Rafferty et al. 2005), and this process inevitably leads to the growth of the central supermassive black hole. Radio sources in clusters have low radiative efficiencies. The AGN power is instead captured in the X-ray cavities and shock fronts, which provide a reliable estimate of the black hole growth rate (McNamara et al. 2005, 2006, Nulsen et al. 2005, Rafferty et al. 2006). Understanding the mutual growth of bulges and black holes, which is a primary goal of this proposal, is one of the most important unanswered questions in galaxy formation.

The slope of the $M_{\rm bulge} - M_{\rm bh}$ (Magorrian) relation in nearby quiescent bulges (Magorrian et al. 1998, Gebhardt et al. 2000, Ferrarese & Merritt 2000) implies that for every thousand units of bulge growth, a few units are accreted by the black hole. This ratio is measurable in accreting cD galaxies in cluster cores. Rafferty et al. (2006) found that the growth of cD galaxies and black holes in a small sample of cooling flows roughly follows the slope of the Magorrian relation (Fig. 1). Although their numbers are small, the scatter in the relationship suggests that bulges and black holes do not grow in finely-tuned lock step, and possibly a variable efficiency of conversion between accreted mass and AGN power. Some of the scatter is surely experimental in nature, and we intend to evaluate this using the targeted observations we propose here.

3 Proposal Goals & Experimental Strategy

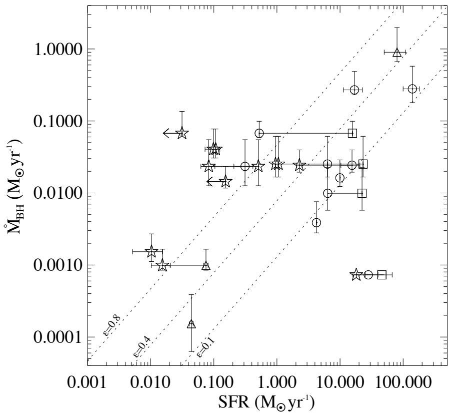
Our goals are: **1)** to explore the relationship between the growth of cD galaxies through star formation and the growth of their supermassive black holes through accretion to determine whether this growth is or is not consistent with the Magorrian relation; **2)** to study the mode of black hole accretion itself; Rafferty et al. (2006) found that depending on assumptions about the central gas density profile and black hole mass, Bondi accretion was effective only in low-power AGN, such as M87, while powerful outbursts are driven by cold accretion at $\sim 10^{-2}$ of the Eddington rate; **3)** to determine whether the net cooling rates, after accounting for feedback from the AGN, thermal conduction, and supernova explosions, are are consistent with the star formation rates; **4)** to study the jet interaction, and to measure the synchrotron radiative efficiency which can be surprisingly low ($\ll 1\%$) in these systems; the jet power can rival the most powerful quasars, while the synchrotron luminosities in these systems often lie among the weaker FR I radio sources (McNamara et al. 2005, 2006); **5)** to search for evidence of mergers (cold fronts) or other structure that may yield insights into other modes of cD growth.

AGN heating and black hole growth are manifestations of the same process, and both will be measured using AGN power indicators such as cavity energy, shock strength, and entropy distribution. The clusters will be imaged to moderate depths that would permit the measurement of X-ray cooling luminosities and AGN power to a formal precision of less than a factor of two, which is roughly the inherent systematic uncertainty of our approach.

AGN power and black hole growth are best determined through cavity sizes (volumes) and their surrounding pressures, yielding the work done by the jet as it inflates the cavities. The enthalpy (free energy) of the cavities depends on the state of the gas filling them, where $\gamma = 4/3$ for a relativistic gas, and $\gamma = 5/3$ for a monatomic ideal gas. Then $E = \frac{\gamma pV}{\gamma-1} = 2.5pV$–$4pV$, giving a systematic uncertainty of roughly a factor of two (Bîrzan et al. 2004). Additional uncertainty is associated with converting the projected shapes of the cavities into volumes, which is worsened by underexposed images. Cavity ages, t, are estimated by their projected locations assuming they travel at buoyant speeds (Bîrzan et al. 2004), or using Mach speeds of surrounding shock fronts (Nulsen et al. 2005). AGN outburst energy then gives a direct and reliable lower limit to the mean accretion rate onto the black hole $\simeq 4pV/t\epsilon c^2$, where $\epsilon \simeq 0.1$ (Fig. 1).

The cooling rate will, of course, be evaluated directly using cooling model fits to the Chandra spectra. The star formation rates are being measured with UV and far infrared luminosities of the starbursts using techniques that are well documented in the literature (McNamara, Wise, & Murray 2004, McNamara et al. 2006, Rafferty et al 2006).

Our approach is new and unique in that cooling flows are among the only systems where an important mode of galaxy and black hole growth can be scrutinized and tested in the same systems. We have chosen clusters whose cDs harbor large reservoirs of molecular gas and/or massive starbursts. They also have strong evidence of AGN-induced structure in the hot gas seen in short Chandra exposures. A measurement of AGN power made in this fashion is a noteworthy strength of this approach. Our method depends on the X-ray analysis alone. AGN (jet) power is measured directly and independently of the radio emission and other radiation processes associated with the black hole and its environment.



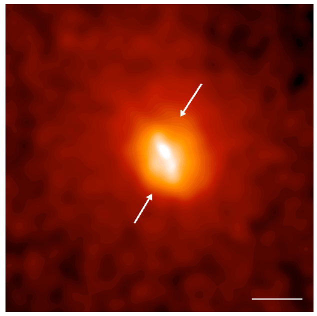
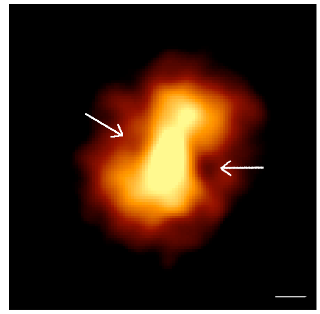
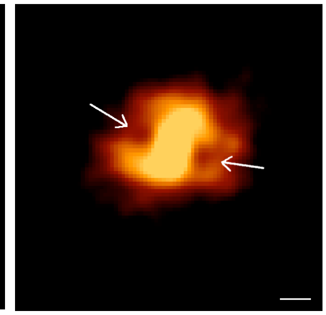




Fig 1 Black hole accretion rate versus star formation rate for the small sample of cDs in cooling flows from Rafferty et al. 2006. The parallel lines represent the slope of the Magorrian relation for hypothetical accretion efficiencies $\epsilon = 0.1, 0.4, 0.8$. **Figs. 2, 3, 4** X-ray images of Abell 1664 (10 ksec), Zw 2701 (27 ksec), RBS 797 (12 ksec), showing possible cavity structure. The bar of emission in the center of each system may be gas that was displaced by the cavities. This is a common signature of a cavity system both in real and simulated data. The scale bars are 20 kpc in length assuming a standard lambda-CDM cosmology.

4 Rationale

We propose to observe three clusters with existing exposures ranging between 10 ksec and 27 ksec whose cD galaxies show cavity-like structure in their X-ray emission. The central gas pressures and apparent sizes of the interaction regions suggest outburst energies exceeding $pV > 10^{59}$ erg, thus they are among the most powerful cluster outbursts implying substantial black hole growth rates. Zw 2701, for example, potentially harbors one of the most powerful eruptions known, with a cavity energy approaching 10^{61} erg, and black hole growth rate approaching 1 $M_\odot$ yr^{-1} (Rafferty et al. 2006). The uncertainties in these measurements are, however, uncomfortably large due primarily to the short Chandra exposures available.

Measuring the pressure, temperature, and other properties of the gas surrounding the cavities requires a deprojection analysis. Depending on the gas temperature, more than 2000-3000 counts per shell are required to yield reliable measurements of multiple spectral components (eg., density, temperature, X-ray cooling luminosity) in multiple shells projected on the cavities, cooling regions, and beyond. Moderately deep exposures (~ 50 ksec) are required to detect and reliably measure low contrast disturbances such as cavities and weak shock fronts surrounding the central radio sources. The depth and location of the brightness jump provides a reliable estimate of the shock energy and Mach number based on a comparison to hydrodynamical models. The moderate duration exposures we propose may reveal the existence of larger scale and more powerful disturbances that can, in principle, be observed in future cycles with longer duration exposures.

5 Targets

We request a total of 160 ksec of observing time to image three clusters. Our targets are listed in descending order of priority.

Abell 1664 at redshift $z = 0.127$ is our prime target based on its existing 10 ksec ACIS-S exposure.

The Chandra image (Fig. 2) already shows a great deal of structure within the cD. The bright central bar of emission could be the characteristic "pinched" morphology of gas along the axis of the cavity system. The locations of possible cavities are indicated, but the exposure is too short to confirm their existence. Therefore, our limit of $pV \sim 10^{59}$ erg has an uncertainty of more than an order of magnitude. Star formation proceeding at a rate of ~ 50 $M_\odot$ yr^{-1} extends over the inner 40 kpc of the cD, making it one of the largest starbursts known in a cD galaxy. In addition, the cD contains 4.4×10^{10} $M_\odot$ of CO (Edge 2001) which is presumably fueling the starburst and possibly the central black hole. Even a restrictive X-ray upper limit on the AGN (cavity/shock) power will provide information about how cooling is proceeding and how the bulge and black holes are growing with respect to each other over time. There are 9400 net counts from the inner 100 arcsec of the cluster in the existing 10 ksec exposure. Therefore, an additional **40 ksec** of exposure time will allow us to obtain at least 3000 counts per annular bin ($0.1 - 7$ keV) in 15 bins covering the cD galaxy. They will provide an accurate cooling profile to compare to the star formation rate, and enough counts to confirm or refute the existence of cavities extending $5 - 10$ arcsec across with a surface brightness deficit of $20\% - 40\%$, which is typical of other cavity systems.

Zw 2701 The existing 27 ksec Chandra image of this $z = 0.214$ cluster reveals two cavities (Fig. 3), each ~ 50 kpc in diameter and centered ~ 30 kpc from the cD's nucleus. Their energy content is estimated to be at least $pV \sim 4 \times 10^{60}$ erg, but with an uncertainty of factors of $5 - 10$ or larger due to the poorly determined cavity sizes and surrounding pressures. This estimate exceeds the mean cavity power of Cygnus A by four times, placing it possibly among the most powerful outbursts known. If confirmed, this is enough energy to quench a cooling flow and to heat the cluster at large. Remarkably, its 1.4 GHz radio luminosity is only $\sim 2 \times 10^{40}$ erg sec^{-1}, which is nearly three orders of magnitude below the estimated cavity power. A new U-band image taken with the MDM 2.4 m telescope on Kitt Peak shows a blue nucleus indicating star formation at a rate of several solar masses per year. An ACIS-S3 exposure will net 450 counts/ksec in the cavity region. The existing image netted only $\sim 12,000$ counts in the inner one arcmin region of the cluster. In order to obtain 3000 counts per annular bin in 12 bins over and surrounding the cavities will require an additional **80 ksec** of exposure time to be added to the existing 27 ksec exposure.

RBS 797 is a $z = 0.345$ cluster with a large cooling flow (~ 880 $M_\odot$ yr^{-1}) and two 20 kpc diameter cavities (Fig. 4) giving a mean AGN power of $pV \sim 3 \times 10^{59}$ erg. Its mean power lies within the measurement errors of the most powerful systems in Bîrzan's (2004) sample. Its cooling luminosity is high, but the measurement uncertainty in the cooling flux and mean cavity power is greater than a factor of 10. Schindler et al. (2001) found strong emission lines in the cD's spectrum, and a new near ultraviolet image taken at MDM shows a massive starburst at its center proceeding at a rate of a few tens of solar masses per year. Gitti et al. (2005) imaged the cD with the VLA at 1.4 GHz and found radio emission filling the cavities in Fig. 4, as well as a new set of 4.8 GHz jets emerging from the nucleus at an oblique angle. The complexity of the radio source and its steep spectrum, suggests stronger AGN activity than the short, 12 ksec snapshot reveals. The existing exposure contains only 5200 net counts in the arcmin region surrounding the cavities. In order to map the cavities and to measure the pressure profile in 10 annular regions located near and surrounding the cavities with 2000 net counts each will require an additional **40 ksec** exposure.

References: 1) Bîrzan, L. et al. 2004, ApJ, 607, 800 2) Crawford, C. et al. 1999, MNRAS, 306, 857 3) Croton, et al. 2005, astro-ph/0508046 4) Edge, A.C. 2001, MNRAS, 328, 762 5) Fabian, A.C., et al. 2003, MNRAS, 344, L43 6) Ferrarese, L. & Merritt, D. A. 2000, ApJ, 539, L9 7) Gebhardt, K. et al. 2000, ApJ, 539, L13 8) Gitti, M. et al. 2005, astro-ph/0510613 9) Juneau et al. 2005, ApJ, 619, L135 10) Kaastra, J. et al. 2004, A& A, 413, 415 11) Nulsen, P. E. J. et al. 2005, ApJ, 628,629 12) Nulsen, P. E. J. et al. 2005, ApJ, 625, L9 13) Rafferty, D. et al. 2006, see astro-ph 14) Schindler, S. et al. 2001, AA, 376, L27 15) Magorrian, J. et al. 1998, AJ, 115, 2285 16) McNamara, B.R. et al. 2005, Nature, 433, 45 17) McNamara, B.R. et al. 2004, ApJ, 601, 173 18) McNamara, B.R. et al. 2006, see astro-ph 19) Sijacki & Springel, 2006, MNRAS, 366, 397 20) Voit, G. & Donahue, M. 2005, ApJ, 634, 955 21) White, S. & Rees, M. 1978, MNRAS, 183, 341

6 History of PI Chandra Programs For McNamara

- Chandra General Observer Project, Cycle 1 (2000-2001): "ACIS Imaging of Cluster Cooling Flows with the Largest Star Formation Rates." The observation of Abell 2597 has been published in: McNamara et al. 2001, ApJ, 562, L149; Birzan et al. 2004, ApJ, 607, 800

- Chandra General Observer Project, Cycle 2 (2001-2002): "Chandra Observations of MS0440.5+0204 & MS0839.9+2938: Cooling Flow Clusters in Formation." A 30 ksec Observation of MS0839.9+2938 was granted, and the data are being analyzed as part of a lager program to study the relationship between star formation and cooling flows.

- Chandra General Observer Project, Cycle 3 (2002-2003): "The Fate of Matter in the Moderate Cooling Flow Cluster Abell 1991." The data were received in December, 2002, and the analysis was reported in Sharma et al. 2004, ApJ, 613, 180.

  Initial results were published in: Birzan et al. 2004, ApJ, 607, 800, McNamara et al. 2004, ApJ, 601, 184, Wise et al. 2004, ApJ, 601, 184, Blanton et al. 2003, ApJ, 585, 227; Blanton et al. 2004, ApJ, 612, 817.

- Chandra General Observer Project, Cycle 4 (2003-2004): "Reduced Cooling and Feedback in Cluster Cooling Flows." We received an image of MS0735.6+7421 whose analysis was published in McNamara, B.R. et al. 2005, Nature, 433, 45

- Chandra General Observer Project, Cycle 5 (2004-2005): "A Deep Look at the Radio-ICM Interaction In the Powerful Radio Galaxy Hydra A," See Nulsen et al. 2005, ApJ, 628,629, and Wise et al. 2006, in preparation.

- Chandra General Observer Project, Cycle 5 (2004-2005): "A Systematic Study of Cooling Flows and Radio Galaxies Using the Chandra Archive II" Initial results published in Birzan et al. 2004, ApJ, 607, 800, McNamara et al. 2004, ApJ, 601, 184, Wise et al. 2004, ApJ, 601, 184; Nulsen et al. 2004, "The Powerful AGN Outburst in Hercules A," Nulsen, P. E. J. et al. 2005, ApJ, 625, L9, a study of Abell 1835, McNamara, B. R. et al. 2006, ApJ, submitted, astro-ph, and see Rafferty et al. 2006, ApJ, submitted, astro-ph for our archival survey of AGN feedback in clusters