FEEDBACK IN CLUSTERS WITH THE MOST POWERFUL AGN OUTBURSTS

1 AGN Feedback in the Cores of Clusters

Chandra images of the cores of galaxy clusters have changed our view of how galaxies form and evolve. In the standard ΛCDM model, galaxies are built hierarchically. Lower mass galaxies form and evolve quickly, building their stars by cooling, infall, and mergers. Massive giant elliptical galaxies are expected to evolve gradually over time, and today they are expected to harbor an abundance of gas and young stars. However, contrary to theoretical expectations, giant ellipticals rarely show evidence for recent star formation [1,2].

Unlike giant ellipticals, central cluster galaxies are burgeoning with star formation at rates of a few to several tens of solar masses per year [12, 22], and they often harbor reservoirs of 10^7 to 10^{10} $M_\odot$ of molecular gas [21]. These properties are observed almost exclusively in galaxies with central X-ray cooling times falling below $\sim 5 \times 10^8$ yr, indicating a causal link between cooling X-ray atmospheres and star formation [19, 20].

X-ray images of the hot atmospheres surrounding these systems show a wealth of structure, including cavities (bubbles), shock fronts, and sound waves [3, 15]. Chandra surveys have shown that periodic AGN outbursts with mechanical energies lying between $\sim 10^{58-62}$ erg [3] and occurring every 10^7 to 10^8 yr are responsible for this structure [27, 29]. Apparently, AGN activity is able to suppress cooling flows, while allowing for enough cooling to fuel the AGN and star formation [3, 28]. The Chandra observations from which this work has emerged have lead to a dramatic and decisive shift in our picture of galaxy formation by identifying AGN feedback as the essential mechanism governing the formation and evolution of massive galaxies and their SMBHs [2, 4, 5]. Understanding how AGN feedback works has become one of the most important problems in all of astrophysics. Chandra has almost singlehandedly laid the foundations for a *quantitative* understanding of the energetics of feedback. Furthering this understanding by studying the most powerful AGN outbursts in clusters is the focus of this proposal.

Summary: We propose moderately deep observations of two clusters selected from the Chandra archive showing evidence for X-ray cavities with energies exceeding 10^{60} erg. Such powerful systems are rare, and thus cannot be efficiently culled from unbiased surveys. Nevertheless, they are vitally important in their own right. It is these systems that place the harshest demands on the central power plant. Thus, they offer real potential for placing meaningful constraints on the two likely mechanisms, accretion power and black hole spin [16, 26]. Furthermore, the most powerful systems are potentially able to drive large-scale outflows of cool, metal-enriched gas, and thus can be studied and compared to the ever growing stable of hydrodynamic jet and feedback models [23, 24, 25]. Such systems are also uniquely suited to investigations of the relationship between the growth of bulges and SMBHs through star formation and accretion. Finally, these systems raise the remarkable possibility that the most powerful outbursts emanate from "ultramassive" black holes whose masses exceed 10^{10} $M_\odot$ [16, 17].

2 SMBH Growth & Evolution of cD Galaxies

The $M_{\rm bulge} - M_{\rm bh}$ (Magorrian) relation [6,7,8] implies that during the bulk of galaxy formation, for every 700 units of mass that went into star formation, roughly one unit was accreted by the nascent galaxy's SMBH. Such a fine degree of tuning suggests that AGN feedback was involved. Understanding how this ratio was imprinted on bulges is central to the question of feedback. The observational difficulties and limitations of studying this complex process in distant galaxies challenges the largest and most sophisticated telescopes. However, the entire cycle of cooling, star formation, and feedback can be probed in great detail in the cores of relatively nearby cooling flow clusters using observations at a variety of wavelengths.

The traditional method used to identify and explore the Magorrian relation [6] involves the measurement of black hole and bulge masses by dynamical techniques. This can be done in only the nearest clusters, such as Perseus and Virgo, but most are out of reach of existing instrumentation. However, it is straightforward to measure the *rates* of bulge and SMBH growth through star formation and cavity power (see details below) in isolated systems and to compare their ratio to the slope of the Magorrian relation. Rafferty et al. [9] found that this ratio shows larger scatter than might be expected assuming central cluster galaxies are growing today in accordance with the slope of the Magorrian relation (see Fig. 1). The bulges and black holes in gas-rich systems, such as Abell 1835 [22], are growing in a manner that is consistent with the Magorrian relation (700:1), while others do not. The most extreme outliers are the most powerful outbursts, i.e., those exceeding 10^{61} erg, such as the Hydra A [14] and MS0735.6+7421 [13, 16] clusters. Assuming they are powered by the accretion of cold gas or hot gas through the Bondi mechanism [9, 10], they are required to channel a remarkably, and perhaps unrealistically, large fraction of this gas onto their SMBHs [9, 16].

In the case of MS0735, with an outburst energy of 10^{62} erg, its nuclear cold gas supply falls far below that required to power its AGN outburst by accretion [16]. In the accretion model, its AGN must be fueled by an inflow of 6×10^8 $M_\odot$ of gas in only 100 Myr. To achieve consistency with Magorrian, it should be accompanied by an enormous starburst. Instead, its nucleus is essentially "red and dead." Its remarkable properties and large departure from the Magorrian slope could be explained if the AGN is instead powered by a rapidly-spinning, 5×10^9 $M_\odot$ black hole, or a $\gg 10^{10}$ $M_\odot$ "ultramassive" black hole accreting by the Bondi mechanism [16]. Circumstantial evidence for the presence of an ultramassive black hole is seen in its unusually large, 3 kpc stellar core radius [16]. The second known system with such extreme properties is Hercules A [14]. Both MS0735 and Hercules A could be easily powered by a Blandford-Znajek-type spin model with a reasonable range of spin parameter and black hole mass, or perhaps by Bondi accretion onto ultramassive holes. Like MS0735, the objects we are proposing to observe, with their potentially high jet powers, are good candidates with which to distinguish between these processes.

3 Goals

1) We will evaluate the partitioning between bulge growth (star formation) and SMBH growth (cavity power) using a combination of X-ray, optical, UV, and IR data.

2) We will compare the available gas supply in the nucleus of the galaxy to the demands on accretion, and evaluate the viability of black hole accretion in comparison to the alternative possibility that they are powered by black hole spin. Accretion is generally *assumed* to be the mechanism driving AGN feedback, but this view is somewhat biased by the properties of distant galaxies and quasars. Central cluster galaxies are quite different. Spin may be more important at late times when galaxies harbor a dwindling supply of cold gas, and yet are able to supply enough energy to offset cooling in their surrounding X-ray halos. Abell 1835, which harbors more than 10^{10} $M_\odot$ of molecular gas, is a prime example of an accretion driven system [22], while MS0735, whose parched nucleus has $< 10^9$ $M_\odot$ of gas cannot be fueled by cold gas alone. A maximally-spinning, 10^9 $M_\odot$ black hole contains $\sim 10^{62}$ erg of energy, enough to stave-off a large cooling flow over the ages of clusters, and to contribute significantly to the excess heat (entropy) in groups and clusters [16]. Thus spin is a potentially important energy source that is just beginning to be explored [26]. Discrimination between accretion and spin can only be made in systems with the most powerful outbursts, as they place the most pressing demands on the fuel supply, black hole mass, and spin rate [16].

3) We will measure the temperature and density of the hot gas well into the nucleus to search for nuclear non-thermal emission that would indicate a state of active accretion. In its absence, the run of temperature and density well into the nucleus will place strong constraints on the viability of the Bondi accretion mechanism. Bondi accretion is energetically feasible in low-power AGN, such as M87 [10]. However, the greater power demands of large AGN outbursts require efficient accretion at levels approaching $\sim 10^{-2}$ of the Eddington rate or larger [9, 10]. X-ray constraints on Bondi accretion have shown it to be energetically infeasible for the most powerful AGN outbursts, unless their black hole masses lie substantially above 10^{10} $M_{\odot}$, or well above their Magorrian values [16]. The existence of such massive black holes has been foreshadowed by large stellar cores found in central cluster galaxies [17, 18], but the largest known were found in MS0735 [16] and in Hercules A. If real, their gravitational spheres of influence, which approach $\sim 0.1-0.3$ arcsec, are within the grasp of HST and some adaptive optics systems. An X-ray measurement of the central temperature and density would provide a useful constraint on the Bondi mechanism.

4) We will determine whether the net cooling rates, after accounting for feedback from the AGN, thermal conduction, and supernova explosions, are are consistent with the observed star formation rates.

5) We will study the jet interaction, and accurately measure the synchrotron radiative efficiency which can be surprisingly low ($\ll 1\%$) in these systems. True jet (mechanical) power can rival the most powerful quasars, while the synchrotron luminosities in these systems often lie among the weaker FR I radio sources [27, 29].

6) We will examine the metallicity structure along and perpendicular to the jet axes to search for evidence of abundance asymmetries that are expected to arise from large-scale AGN outflows seen in hydrodynamical simulations of powerful outbursts [25, 24, 23].

Our long-term goal involves building a sample of several dozen systems using both archival and GO observations spanning a large range in AGN power and star formation rate.

4 Technical Considerations

AGN heating and black hole growth are manifestations of the same process. Both will be measured using what have become standard AGN power indicators including cavity energy, shock strength, and entropy distribution [3]. The clusters will be imaged deeply enough to measure X-ray cooling luminosities and AGN power to a formal precision of about a factor of two. Reaching below this level of precision is prohibitively difficult owing to systematic uncertainties.

AGN power and black hole growth are determined through cavity sizes (volumes) and their surrounding pressures. These measurements yield the work done by the jet as it inflates the cavity. 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 $H = \frac{\gamma pV}{\gamma - 1} = 2.5pV$–$4pV$, giving a systematic uncertainty of roughly a factor of two [9]. Additional uncertainty associated with converting the projected shapes of the cavities into volumes is contributed by underexposed Chandra images. Cavity ages, t, are estimated by their projected locations assuming they travel at buoyant speeds or using the ages of surrounding shock fronts [3]. 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). If the AGN power is due to spin, these measurements will provide an estimate of the combination of spin parameter (rotation rate) and black hole mass that would be required to power the outburst.

The cooling rate will be evaluated in a number of ways, including the use of cooling model fits to the Chandra spectra. The star formation rates are being measured using UV imaging and

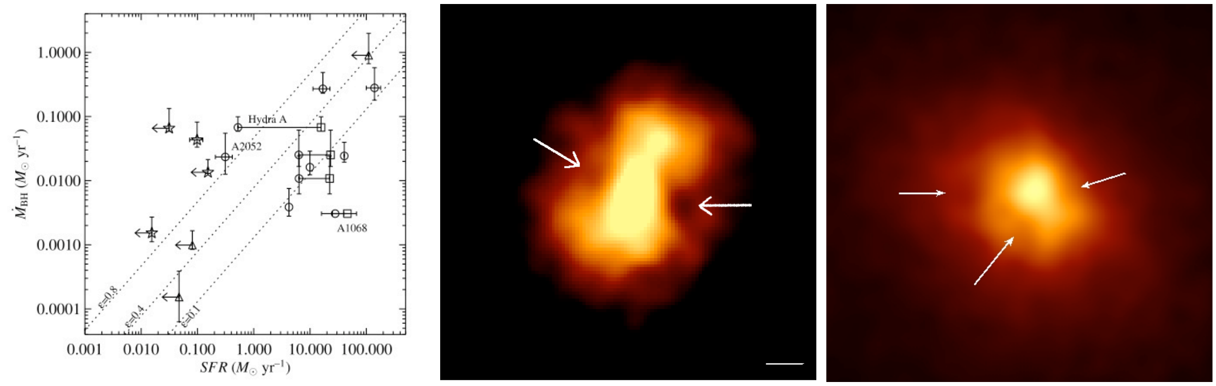

Figure 1:

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** X-ray images of Zw 2701 (27 ksec), and Sersic 159/03 (9.7 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.

far infrared luminosities of from Spitzer. 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 reservoirs of cool gas and/or star formation. Based on underexposed Chandra images, they contain enough evidence of powerful AGN activity to be re-observed. A measurement of AGN power made in this fashion is a noteworthy strength of our 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. We intend to apply for HST images of the central galaxies, as we have successfully done in the past, which will provide a measurement of the core radius and thus indicating whether an unusually large black hole may be present.

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, luminosity) in multiple shells projected on the cavities, cooling regions, and beyond. Moderately deep exposures ($\sim$ 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 hydrodynamic 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 exposures.

5 Targets

We request a total of 120 ksec of observing time to image two clusters listed in descending order of priority.

Zw 2701 at redshift $z = 0.214$ is our prime target. The existing 27 ksec Chandra image of this cluster reveals two cavities (Fig. 2), each $\sim$ 50 kpc in diameter and centered $\sim$ 30 kpc from the cD's nucleus. Their energy content is estimated to be $4pV \sim 1.4 \times 10^{61}$ erg [9], corresponding to a total power of 6×10^{45} ergs^{-1}, but with an uncertainty of factors of $5 - 10$ due to the poor determination of cavity sizes and surrounding pressures. This estimate exceeds the mean cavity power of Cygnus A by four times, placing it among the most powerful AGN outbursts known. These figures imply that its SMBH is growing at a rate of ~ 1 M$_\odot$ yr^{-1}. 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 five 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.

Sersic 159/03 lies at redshift $z = 0.058$. Its existing 9.7 ksec Chandra exposure (after removing flares, see Fig. 3) 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. Assuming the detection of cavities is real, our limit of $4pV = 10^{60}$ erg [9], corresponding to a jet power of 7.8×10^{44} erg s^{-1}, has a systematic uncertainty of factors of several. The cD hosts a bright emission line nebula [11] and a blue color excess [12] consistent with star formation proceeding at a rate of ~ 2 M$_\odot$ yr^{-1}. 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 35,000 net counts from the inner 100 arcsec of the cluster in the existing exposure. Therefore, an additional **40 ksec** of exposure time will yield 3000 counts per annular bin ($0.1 - 7$ keV) in 40 bins well beyond the cD galaxy. Obtaining a deep image of this relatively nearby object will allow us to search for larger, cluster-scale cavities that characterize systems of this power level, such as Hydra A. The observation will provide an accurate cooling profile to compare to the star formation rate, and enough counts to confirm or refute the existence of cavities of $5 - 10$ arcsec in diameter with a surface brightness deficit of $20\% - 40\%$, which is typical of other cavity systems.

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6 History of Chandra Programs (PI only) For McNamara

- Chandra General Observer Project, Cycle 1 (2000-2001): "ACIS Imaging of Cluster Cooling Flows with the Largest Star Formation Rates." The results were published in McNamara et al. 2001, ApJ, 562, L149, Birzan et al. 2004, ApJ, 607, 800, Rafferty et al. 2006.

- 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 have yielded nothing of particular interest because the granted exposure time was half of the requested exposure.

- Chandra General Observer Project, Cycle 3 (2002-2003): "The Fate of Matter in the Moderate Cooling Flow Cluster Abell 1991." The results are reported in Sharma et al. 2004, ApJ, 613, 180.

- Chandra General Observer Project, Cycle 3 (2002-2003): "'A Systematic Study of Cooling Flows and Radio Galaxies Using the Chandra Archive." The results are reported in Birzan et al. 2004

- Chandra General Observer Project, Cycle 4 (2003-2004): "Reduced Cooling and Feedback in Cluster Cooling Flows." Results were reported in McNamara et al. 2005.

- Chandra General Observer Project, Cycle 5 (2004-2005): "A Deep Look at the Radio-ICM Interaction In the Powerful Radio Galaxy Hydra A" Results are reported in Nulsen, P. E. J. et al. 2005, ApJ, 625, L9 and Wise et al. 2007, ApJ, 659, 1153

- 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, Nulsen, P. E. J. et al. 2005, ApJ, 625, L9, McNamara, B. R. et al. 2006, ApJ, 648, 164, Rafferty et al. 2006, ApJ, 652, 216, Rafferty et al. 2008, ApJ, submitted, Birzan et al. 2008, ApJ, submitted.

- Chandra General Observer Project, Cycle 8 (2007-2008): " AGN Feedback and Galaxy Formation in Cluster Cores." A study of Abell 1664 by Kirkpatrick et al. 2009 has been accepted and will appear shortly in the ApJ, and a similar study of RBS797 by Cavagnolo et al. 2009, is underway.

- Chandra Large Project, Cycle 10, "A Deep Image of the Most Powerful Cluster AGN Outburst," (in MS0735.6+7421) is scheduled to be observed in Summer, 2009.