**POWERFUL AGN: GENERATED BY ACCRETION OR SPIN?**

# 1 AGN Feedback in the Cores of Clusters

Chandra images of the hot atmospheres of galaxies and clusters have revealed a wealth of structure in the form of cavities [15], shock fronts [14], and sound waves [15]. Much of this structure was created by AGN outbursts with energies lying between $\sim 10^{56-62}$ erg [3]. The energy released in these outbursts is enough to compensate for radiative cooling of hot atmospheres and to suppress star formation in ellipticals and brightest cluster galaxies (BCGs) at late times [3, 31]. AGN activity, H$\alpha$ emission [32, 34], star formation [12, 19], and large quantities ($\sim 10^9 - 10^{11}$ M$_\odot$) of molecular gas [33] are all observed preferentially in BCGs centered in hot atmospheres with short central cooling times and low central entropy [28]. These correlations suggest that periodic AGN activity and star formation are both fueled by cooling that is regulated by a finely-tuned feedback loop. In fact, the picture of AGN feedback that has emerged from Chandra and XMM-Newton observations over the past decade may be responsible for shutting down star formation and regulating the growth of supermassive black holes in essentially all massive galaxies at late times [1, 2, 4, 5]. Despite holding great promise as an essential element of galaxy formation, the operational basis for AGN feedback is poorly understood.

How feedback operates and how AGN generate such enormous quantities of energy may be revealed through studies of the most powerful AGN outbursts in clusters. Here we propose to obtain deep observations of the clusters Zw 2701 and Sersic 159/03 to measure their jet powers. Short Chandra observations of these systems have revealed evidence of cavities and other structure with possible jet energies and mean jet powers of $\sim 10^{60-61}$ erg and $\sim 8 \times 10^{44} - 6 \times 10^{45}$ erg s$^{-1}$, respectively. Because of the high energetic performance these systems demand from the central engine, their jet powers are able to levy meaningful limits on the efficiency of accretion onto their SMBHs, and interesting constraints on black hole spin models [16, 26]. Powerful AGN may also drive large-scale outflows of cool, metal-enriched gas that pollute the intracluster medium with metals. Our proposed measurements of jet power are intended to advance our understanding of feedback and the co-evolution of BCGs and SMBHs. Powerful AGN outbursts like these may signal the existence of rapidly spinning black holes with masses exceeding $10^{10}$ M$_\odot$ [16, 17].

# 2 Powering Cluster AGN

A new analysis of the gas content and AGN energetics of BCGs has revealed a puzzling situation in the cores of clusters [35]. If AGN feedback is powered by accretion, we would expect to find a trend between molecular gas mass and jet power. While most systems contain ample supplies of molecular gas to fuel their AGN ($< 10^9\ M_\odot$ to $10^{11}\ M_\odot$), no trend between gas mass and jet power was found (Fig. 1). The gas masses required to fuel the AGN, $M_{acc} \sim E_{cav}/0.1c^2$, lie between $10^6 M_\odot$ and $10^9 M_\odot$ [21]. Their implied specific accretion efficiencies per outburst, defined as $0.1 M_{\rm mol} c^2/E_{\rm jet}$, generally lie between $10^{-2}$ to $10^{-5}$. For comparison, scaling relationships between galaxy mass, luminosity, and central black hole mass [6,7,8] imply that, on average, for every thousand units of matter consumed by star formation, roughly one unit is accreted by the galaxy's SMBH. In other words, SMBHs have an average accretion efficiency of $\sim 10^{-3}$. The absence of a trend between AGN power and gas mass, and the tendency for gas-rich systems to have high star formation rates, suggest that the gas in most systems is consumed primarily, as expected, by star formation and not the SMBH. In fact, Rafferty et al. [9] found that the ratio of star formation rate, measured with UV/IR observations, to the black hole accretion rate, determined by jet (cavity) power, is consistent overall with the slope ($\sim 10^{-3}$) of the scaling relations between black hole mass and bulge mass.

The most energetic systems, those exceeding $10^{61}$ erg, don't follow this trend. MS0735, Hercules A, and Cygnus A, have molecular gas masses $\lesssim 10^9\ M_\odot$ [21, 36], and very low star formation rates. Yet their jet powers are consistent with accretion rates of a few tenths to nearly six solar masses per year. Their specific accretion efficiencies are also unusually high, ranging between $0.5 - 0.03$. For example, if MS0735 is powered by accretion, its enormous $10^{62}$ erg outburst demands a gas inflow of $6 \times 10^8$ $\mathrm{M}_\odot$ in a time span of just 100 Myr. Yet the BGG harbors $< 2 \times 10^9$ $\mathrm{M}_\odot$ of molecular gas, a value that barely exceeds the amount required to power its AGN [16]. Furthermore, if it is to remain consistent with local scaling relations, most of this gas should have been consumed by star formation. Instead its central galaxy is "red and dead." Hercules A [14] and Cygnus A [37] are similar, although not quite so extreme. If they are powered by accretion, these systems have managed to channel most of the gas in their bulges onto their SMBHs, while forming few stars in the past $\sim 10^8$ yr. This scenario is difficult to understand.

There are at least two ways to avoid this problem: First, powerful AGN may be generated primarily by rapidly-spinning, $\sim 10^{10}$ $\mathrm{M}_\odot$ black holes with spin parameters approaching unity. If a significant population of powerful AGN exists in gas-poor hosts, spin must be seriously considered as an alternative powering mechanism. Second, high jet power may be produced by $\gg 10^{10}$ $\mathrm{M}_\odot$ black holes accreting hot gas by the Bondi mechanism [10, 16]. These so-called ultramassive black holes would then be required because the Bondi accretion rate scales with the square of the black hole's mass. High jet powers require high accretion rates. The existence of such large black holes could be confirmed in MS0735 in the near future (HST proposal pending), and others may follow.

# 3 Specific Goals of the Observations

**1)** Using our proposed cavity and shock front measurements, we intend to compare the masses required to power the AGN outbursts to their molecular gas masses. If the ratios are small, as seen in other powerful systems, it would indicate that these systems accrete gas with unusually high efficiency, or that they may be powered by another mechanism, such as Bondi accretion or spin. Our measurement will be sensitive enough to separate these objects from gas-rich systems with much lower jet powers. Gas rich systems evolving normally along the black hole vs. bulge mass scaling relations may be plausibly powered by accretion. We will thus explore the possibility that AGN feedback proceeds in two modes: a spin mode for high jet power systems and an accretion mode for lower power systems (of course, spin may be important in all systems). This modality is best explored by observing powerful AGN that are demanding of the available fuel supply, black hole mass, and spin parameter [16]. **2)** We will evaluate the partitioning between bulge growth (star formation) and SMBH growth (jet power) using a combination of X-ray, optical, UV, and IR data. **3)** We will search for nuclear non-thermal emission that would indicate a state of active accretion. We will place strong constraints on the Bondi accretion mechanism by measuring gas temperatures and densities in the nucleus and extrapolating inward to the Bondi radius. Bondi accretion is energetically feasible only in low-power AGN, such as M87 [10], but would have great difficulty fueling the most powerful AGN [9, 10], unless their black hole masses lie substantially above $10^{10}$ $\mathrm{M}_\odot$ [16]. **4)** After accounting for feedback from the AGN and other heat sources, we will determine whether the net cooling rates are consistent with the observed star formation rates and AGN power. We will study the jet interaction and measure the synchrotron radiative efficiency, which can be surprisingly low ($\ll 1\%$) in these systems [27, 29]. **5)** We will examine the metallicity structure along and perpendicular to the jet axis to search for evidence of abundance asymmetries that are expected to be seen in large-scale AGN outflows [25, 24, 23].

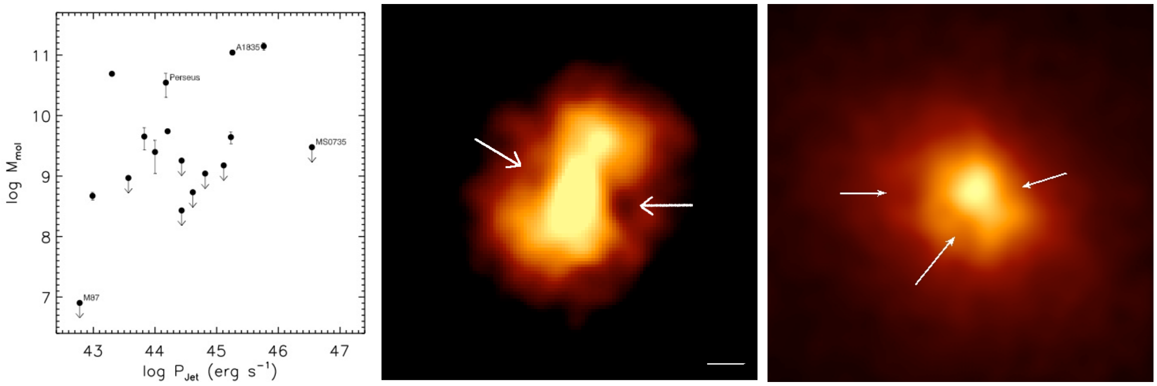


Figure 1:

**Left** No trend is seen between molecular gas mass vs jet power. CO data were taken from papers by Edge and Salome & Combes. **Center** X-ray images of Zw 2701 (27 ksec), and **Right** Sersic 159/03 (9.7 ksec), respectively, showing cavity structure. The bar of emission at their centers may be from gas displaced by the cavities. This feature is common in real and simulated data. The scale bar represents 10 arcsec in both images.

## 4 Technical Considerations

The targets were selected from the most powerful objects in Rafferty et al. [9], which were culled from the archive. To achieve our objectives, we need only to identify and systematically study the most powerful AGN. We do not require more sophisticated sampling. The clusters will be imaged deeply enough to yield 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 jet power will be determined through cavity sizes (volumes) and their surrounding pressures, which yield the work done by the jet as it inflates the cavity. Their enthalpy, $H$ or free energy, depends on the the gas filling them: $\gamma = 4/3$ 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 their projected shapes into volumes will be greatly reduced by deeper imaging. Cavity ages, $t$, will be estimated using their projected locations assuming they travel at buoyant speeds or using the ages of surrounding shock fronts [3]. AGN outburst energy (ignoring spin) then gives a direct and reliable *lower limit* to the mean accretion rate onto the black hole $\simeq 4pV/t\epsilon c^2$, where $\epsilon \simeq 0.1$. These measurements also provide constraints on the spin parameter (rotation rate) and black hole mass required to power the outburst [35]. Cooling rates will be evaluated using cooling model fits to the Chandra spectra. The star formation rates have been measured using UV imaging and far infrared luminosities from Spitzer.

Measuring the temperature and density of the gas surrounding the cavities by a deprojection analysis requires 2000-3000 counts per shell. We require reliable measurements of multiple spectral components (eg., density, temperature, luminosity) in several shells projected on the cavities, cooling regions, and beyond. Moderately deep exposures are needed 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 reliable estimates of the shock energy and Mach number.

## 5 Targets & Exposure Time Justification

We request 150 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 possible cavities (Fig. 1) that may approach $\sim 50$ kpc in diameter. Their energy content is estimated to be $4pV \sim 1.4 \times 10^{61}$ erg [9], corresponding to a total power of $6 \times 10^{45}$ ergs$^{-1}$, but with an uncertainty of factors of $5 - 10$ due to the poor determination of cavity sizes and surrounding pressures. These figures imply that its SMBH is growing at a rate of $\sim 1$ M$_{\odot}$ yr$^{-1}$. 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 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.

The existing image netted only $\sim 12,000$ counts in the inner one arcmin region of the cluster, while the cavities ($r \simeq 7$ arcsec) subtend only 3% of this region, and include only about 150 counts apiece. Roughly 100 counts reside in the cavity and 50 in the rim, which traces the cavity. However the section of the rims at larger radii are indistinguishable from the background. This unfortunately adds a great deal of uncertainty to their size estimate, which factors into the pressure calculation as the cube of the radius. The proposed **100 ksec** ACIS-S3 exposure will boost this figure to $\sim 500$ counts in each cavity region, approximately 1/3 of which will reside in the rims. This will place roughly 80 net counts in the outer half of each cavity rim which will be detectable above the background. The exposure will provide $\sim 3000$ counts per annular bin in 12 bins over and surrounding the cavities for accurate temperature and density (pressure) measurements.

**Sersic 159/03** lies at redshift $z = 0.058$. Its existing 9.7 ksec Chandra exposure (after removing flares, see Fig. 1) already shows a great deal of structure within the BCG. 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 $7.8 \times 10^{44}$ erg s$^{-1}$, has a systematic uncertainty of a few. The BGC hosts a bright emission line nebula [11] and a blue color excess [12] consistent with star formation proceeding at a rate of $\sim 2$ M$_{\odot}$ yr$^{-1}$. The existing exposure netted 35,000 counts from the inner 100 arcsec of the cluster. Using the same logic given for Sersic 159/03, an additional **50 ksec** of exposure time will yield a similar constraint on the cavity sizes and 3000 counts per annular bin ($0.1 - 7$ keV) in 40 bins well beyond the BCG.

Molecular gas masses will be obtained by co-investigator Edge, who will use the IRAM 30m telescope to observe Zw 2701, and the Australian 15m Mopra telescope to observe Sersic 159/03. Both will yield mass detections (above) or limits (below) $\sim 1.5 \times 10^9 M_{\odot}$, which will be interesting in the context of this project.

**References:** 1) Bower et al. 2006, MNRAS, 370, 645 2) Benson et al. 2003, ApJ, 599, 38 3) McNamara & Nulsen 2007, ARAA, 45, 117 4) Sijacki & Springel, 2006, MNRAS, 366, 397 5) Croton et al. 2006, MNRAS, 365, 11 6) Magorrian, J. et al. 1998, AJ, 115, 2285 7) Gebhardt, K. et al. 2000, ApJ, 539, L13 8) Ferrarese, L. & Merritt, D. A. 2000, ApJ, 539, L9 9) Rafferty, D. et al. 2006, ApJ, 652, 216 10) Allen et al,. 2006, MNRAS, 372, 21 11) Jaffe et al. 2005, MNRAS, 360, 748 12) Johnstone et al. 1987, MNRAS, 224, 75 13) McNamara, B.R. et al. 2005, Nature, 433, 45 14) Nulsen, P. E. J. et al. 2005, ApJ, 625, L9 15) Fabian, A.C., et al. 2003, MNRAS, 344, L43 16) McNamara et al. 2009, ApJ, 698, 594 17) Lauer et al. 2007, ApJ, 662, 808 18) Kormendy, J. & Bender, R. 2009, ApJ, L142 19) Rafferty et al. 2008, ApJ, 687, 899 20) Cavagnolo et al. 2008, ApJ, 683, L107 21) Edge, A.C. 2001, MNRAS, 328, 762 22) McNamara et al. 2006, ApJ, 648, 164 23) Heinz et al. 2006, MNRAS, 373, L65 24) Ruszkowski, et al. 2004, ApJ, 611, 158 25) Rasera et al. 2008, ApJ, 689, 825 26) Nemmen, et al. 2007, MNRAS, 377, 1652 27) Bîrzan, L. et al. 2004, ApJ, 607, 800 28) Voit, G. & Donahue, M. 2005, ApJ, 634, 955 29) Dunn & Fabian 2006, MNRAS, 373, 959 31) Peterson & Fabian 2006, PhR, 427, 1 32) Crawford, C. et al. 1999, MNRAS, 306, 857 33) Edge, A.C. 2001, MNRAS, 328, 762 34) Cavagnolo, K. et al. 2008, ApJ, 683, L107 35) McNamara, Rohanizadegan, Nulsen 2010, ApJ, submitted 36) Salome & Combes 2008, A&A, 489, 101 37) Wilson, A et al. 2006, ApJ, 644. L9

# 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, ApJ, 697, 867 has appeared; a study of RBS797 by Cavagnolo et al. 2010, is underway.

- Chandra Large Project, Cycle 10, "A Deep Image of the Most Powerful Cluster AGN Outburst," in MS0735.6+7421 has been observed and its analysis is underway.