THE CORES OF REXCESS CLUSTERS

The cores of galaxy clusters hold the answers to four major astronomical questions:

What prevents hot gas in clusters from cooling and condensing? Many galaxy clusters have a central cooling time less than 10 Gyr, and mass accretion rates inferred for these clusters from the classic cooling-flow model once ranged as high as $10^2 - 10^3\, M_\odot$ yr (Fabian 1994). Spectroscopic X-ray observations have now established that the actual cooling and accretion rates in such clusters are much lower than this (Peterson et al. 2001, 2003; Tamura et al. 2001). These clusters tend to have cool cores in which the temperature drops to about half the ambient temperature, but there is little gas at lower temperatures. The cooling process seems to have stopped in its tracks, implying that a compensating heat source resupplies the radiated energy.

Supermassive black holes at the centers of galaxy clusters are an attractive candidate for supplying that heat energy. Clusters suspected of harboring cooling flows are statistically more likely to contain radio radio sources (Burns 1990) that often coincide with cavities in the X-ray emitting plasma, clearly showing that outflows from the nuclei of at least some central cluster galaxies are interacting with the core gas (McNamara et al. 2000, Fabian et al. 2000) through AGN outbursts that introduce $\sim 10^{58} - 10^{61}$ erg into the intracluster medium (Birzan et al. 2004, McNamara et al. 2005). Yet, despite the wealth of circumstantial evidence implicating AGN feedback as the mechanism that halts cooling flows, the details of the supposed feedback loop remain poorly understood.

What truncates the high end of the galaxy luminosity function? Models of galaxy evolution that include only cooling and supernova feedback lead to a galaxy luminosity function with too many extremely luminous galaxies, even when the efficiency of supernova feedback is pushed to absurdly high levels (e.g., Benson et al. 2003). The potential wells of these giant galaxies, many of which would be found at the centers of galaxy clusters, are so deep that supernova feedback fails to prevent rampant cooling and star formation. As a result, the universe's most luminous galaxies are predicted to be blue, in contradiction to their observed redness.

Once again, feedback from supermassive black holes is a promising solution. Recent semianalytical models employing highly schematic treatments of AGN feedback are able to produce populations of giant galaxies with the correct luminosity function and color (e.g., Croton et al. 2006, Bower et al. 2006). However, the treatment of AGN feedback is very primitive and does not explain how the AGN's energy output couples to the surrounding gaseous environment.

What generates the excess entropy in galaxy clusters? Cosmological constraints derived from cluster surveys depend on relations linking cluster mass (M) with observables like X-ray luminosity (L_X) and temperature (T_X). Both L_X and T_X are highly correlated with mass, but are also affected by an excess of entropy in the intracluster medium that becomes progressively more acute as one looks toward lower-mass systems (e.g., Ponman et al. 1999, Pratt et al. 2006). Understanding the origin of excess entropy is therefore of central importance in putting the L_X-M and T_X-M relations on a firmer theoretical foundation and in characterizing how those relations evolve with redshift.

Both analytical models and hydrodynamical simulations suggest that the entropy excess arises from the interplay between cooling and feedback during the formation of a galaxy cluster, and is therefore linked to both the cooling-flow problem and the regulation of galaxy formation (e.g., Voit & Bryan 2001, Borgani et al. 2004). However, numerical simulations that include just radiative cooling and supernova feedback have so far failed to explain the magnitude of the entropy excesses extending to half the virial radius in low-temperature systems and the large dispersion in the L_X-T relation at low temperatures. Another ingredient seems to be needed, and that ingredient may be AGN feedback.

How steep is the central mass profile in galaxy clusters? Models of cosmological structure formation make specific predictions about the mass profiles of galaxy clusters and how the concentration of matter toward the core should depend on halo mass. Early analyses indicated a central density slope $\rho \propto r^{-1}$ (Navarro et al. 1997) or $\rho \propto r^{-1.5}$ (Moore et al. 1998), but later analyses (Diemand et al. 2004, Navarro et al. 2004) concluded that no asymptotic central slope is reached in the numerically resolved region outside 0.5% of the virial radius.

Theoretical considerations have recently challenged this view, suggesting that the central dark matter density slope should indeed be cusped. The central density slope has not yet reached a constant value in any simulation, but the slope of phase-space density, ρ/σ^3, does follow a power law in radius (Taylor & Navarro 2001). Solving the Jeans equation with ρ/σ^3 constrained to be a power law in radius leads to a cusped inner density profile (Hansen 2004), and the most recent analyses show that the central slope should be $\rho \propto r^{-0.8}$ (Austin et al. 2005, Dehnen & McLaughlin 2005, Hansen & Stadel 2006).

X-ray observations of relaxed clusters can be used to test these models under the assumption of hydrostatic equilibrium. *Chandra* is most useful for measuring the slope of the inner mass profile (e.g., Lewis et al. 2003, Voigt & Fabian 2006), while *XMM* is better for establishing the profile's overall shape (e.g., Pointecouteau et al. 2005). Clusters of high central surface brightness are particularly suited for studies of the inner density profile because the gas density and temperature can be more accurately measured at small radii. The best objects are therefore cool-core clusters that appear relaxed, without evidence for recent AGN disruption. If the central density slopes of clusters are observed to have cusps, then the phase space density ρ/σ^3 must be of fundamental importance. This would be a crucial input to theoreticians working to understand the behaviour of self-gravitating systems.

Chandra's Role. *Chandra* is uniquely suited for addressing all four of these major questions. Its high spatial resolution has already revolutionized the study of AGN feedback in cluster cores, enabling systematic explorations of the incidence and energy content of X-ray cavities (e.g. Birzan et al. 2004, Fabian et al. 2003) and high-resolution measurements of temperature, density, and entropy profiles to within 10 kpc of a cluster's core (e.g., Allen et al. 2001, Donahue et al. 2006, etc.). A coherent picture of AGN feedback is beginning to emerge from such studies in which intermittent AGN outbursts impart $\sim 10^{59}$ erg on a $\sim 10^8$ year timescale. Such a mechanism would explain the striking similarity seen among the radial entropy profiles of classic cooling flow clusters (Voit & Donahue 2005, see Figure 1).

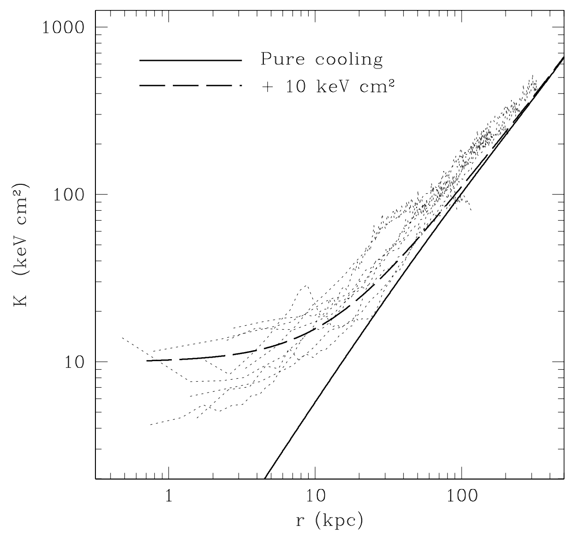

Figure 1: Core entropy profiles of nine classic cooling-flow clusters with $T_X \approx 2.3 - 7.4$ keV. Dotted lines show entropy profiles derived from *Chandra* observations by Donahue et al. (2006). The solid line shows the expected entropy profile for a cluster model in which radiative cooling acts without triggering feedback. The inner plateau at $\sim 10\,\mathrm{keV\,cm^2}$ can be maintained by impulsive AGN outflows of $\sim 10^{45}\,\mathrm{erg\,s^{-1}}$ recurring on a $\sim 10^8$ year timescale.

The next step is to link this emerging picture with cosmological models of cluster formation. Most *Chandra* studies of cluster cores published to date have been "Chandra-archive limited" in that they have concentrated on famous targets of high central surface brightness that were observed early in the *Chandra* mission (but see Bauer et al. 2005). As a result, they shed little light on the incidence of cool cores and AGN outbursts in the cluster population as a whole and are poor samples for exploring a possible duty cycle in the entropy evolution of cluster cores (McCarthy et al. 2004, Donahue et al. 2005). Results from *Chandra* followup of the flux-limited HIFLUGCS cluster sample are showing a substantial diversity of central temperature profiles (Hudson et al. 2007), suggesting that much remains to be learned about the relationship between cluster cores and the global properties of clusters.

The REXCESS Survey. We have designed the Representative XMM-Newton Cluster Structure Survey (REXCESS) specifically to explore how the global scaling relations necessary for cluster cosmology depend on cluster physics (Böhringer et al. 2007). Its clusters were selected from the flux-limited REFLEX survey using a strategy to minimize morphological bias while spanning a wide range in luminosity, mass, and temperature. We separate the REFLEX clusters into luminosity bins and select clusters randomly from each bin so as to ensure that the sample is as close to volume-limited as possible. This selection method makes REXCESS an ideal benchmark for comparisons with cosmological simulations of cluster formation, for understanding cluster physics in the context of structure formation, and for establishing the low-redshift scaling relations that are the foundation of cosmological cluster surveys.

The overall sample comprises 33 clusters at $z < 0.2$ ranging in 0.1-2.4 keV luminosity from $0.4\text{-}26 \times 10^{44}\,\mathrm{erg\,s^{-1}}$ with a minimum temperature ~ 2 keV. It has been completely observed with XMM, with a total of just over 1 Msec devoted to the project, sufficient to obtain roughly 60,000 counts per cluster. The clusters exhibit a wide range of morphologies and about 10% are dynamically young, low surface-brightness clusters not easily detected in flux-limited samples. Temperature profiles have so far been extracted for a subsample of 15 clusters with $T_x = 2.5 - 8.5$ keV (Pratt et al. 2007). Once these profiles are scaled by the average cluster temperature (excluding the central region) and the estimated virial radius, the central regions exhibit the greatest scatter, mostly due to the presence of cool cores (Pratt et al. 2007).

PROPOSED RESEARCH

Here we propose to obtain a complete set of *Chandra* observations for the REXCESS clusters with the highest central surface brightness. Because these clusters have the most centrally concentrated surface-brightness profiles, with peaks unresolved by XMM, they are the most likely REXCESS clusters to reveal new phenomena at higher spatial resolution. Based on previous *Chandra* studies, these are the clusters most likely to have low central entropy, cool cores, and evidence for AGN activity. ***Chandra* observations are essential for linking the detailed properties of cool cores with the larger-scale properties of clusters in the well-studied, carefully-selected REXCESS sample, because *Chandra's* spatial resolution of the central temperature and entropy profiles will be ~ 5 times better than XMM's (e.g., Vikhlinin et al. 2006).**

The minimum surface brightness for this REXCESS subsample is based on the XMM emission measure determined at $0.01R_{500}$ as shown in Figure 2. These profiles have been scaled to account for redshift dimming and the local empirical entropy-temperature relation. Clusters above the adopted threshold of $EM(0.01R_{500}) > 3.0$ clearly have steeper central brightness profiles than the others. Figure 3 shows that *Chandra* clusters above this brightness threshold tend to have cool cores while those below it do not. Eleven of the REXCESS clusters are above the brightness threshold, and only two of them (Abell 1689 and Abell 907) have already been adequately observed with *Chandra*. We are therefore requesting *Chandra* observations of the other nine.

Minimum Entropy and AGN Feedback. The main goals of our *Chandra* observations will be to establish the maximum density and minimum entropy of these cluster cores and to search for X-ray cavities generated by AGN feedback. Only *Chandra* has sufficient spatial resolution to measure the minimum entropy within ~10 kpc of the central black hole, which may be governing the Bondi accretion rate. *Chandra* is also crucial for assessing the fraction of cool-core clusters

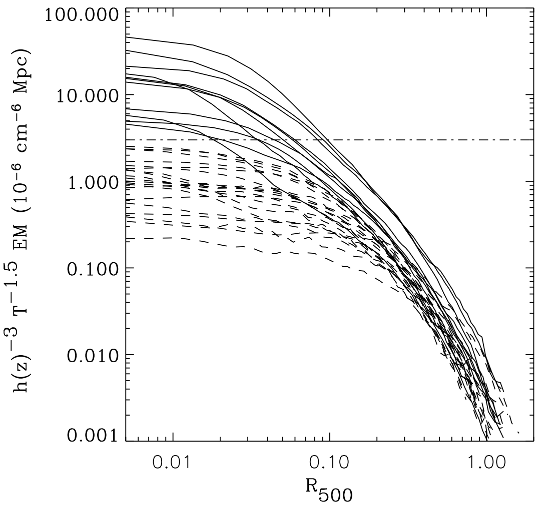

Figure 2: XMM surface brightness (XSB) profiles for 31 of 33 XMM-LP clusters. The remaining two are binary and triplet clusters without bright XSB cores. Eleven clusters lie above the threshold of $EM(0.01R_{500}) > 3.0$. The clusters we propose to observe with Chandra have steep, potentially unresolved T_X and XSB profiles in the central 10", while the others have flat profiles within $\sim$ 50" of the center.

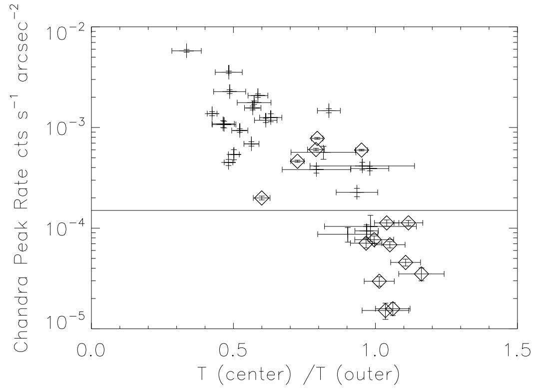

Figure 3: Relation between central surface brightness (in *Chandra* counts) and the central temperature decrement. The small points are from existing *Chandra* observations of cluster cores, and the hollow diamonds are estimates derived from 15 REXCESS clusters (Pratt et al. 2007). The line corresponds to the XMM surface-brightness threshold that we are using to determine the subset for *Chandra* followup.

with and without cavities, because small-scale AGN cavities and other sharp surface-brightness features cannot be seen with XMM's poorer spatial resolution. We will measure the size and local pressure around detected cavities to estimate their energy content, and because REXCESS spans a wide range of T_x and M, we will be able to determine whether the distribution of bubble size, bubble energy, and AGN feedback correlates with global cluster properties. Furthermore, the incidence of bubbles in this representative sample will help establish the duty cycle for bubble production in cool-core clusters. Previous experience with *Chandra* (e.g., Donahue et al. 2006) indicates that 60,000 counts will be sufficient for these tasks, resolving the central density/entropy structure on scales of $\sim 2-5$ arcseconds (corresponding to $\sim 3-10$ kpc at the typical redshifts of the REXCESS clusters) and casting X-ray cavities in this region into sharp relief.

Combining these detailed *Chandra* observations of the centrally-peaked clusters with our XMM observations of the remaining clusters with flatter cores, we will determine the distribution of central entropy and central cooling time among the REXCESS clusters. Models of episodic AGN feedback in clusters predict how the central entropy profile of a cool-core cluster should periodically evolve through time. An unbiased cluster sample like this one ought to contain objects at random stages of such a duty cycle, allowing us to estimate the frequency and duration of AGN outbursts and to compare the distribution of central entropy levels with theoretical predictions. That will provide a crucial check on whether trends seen in earlier, more biased *Chandra* samples apply to the cluster population as a whole. We will also construct a "cool-core function" describing the incidence of cool cores per comoving volume. For each cluster, we will measure the total X-ray luminosity coming from within the region where the cooling time is less than a Hubble time and derive a cumulative distribution function for that quantity.

Cool Cores and Global Properties. Another goal will be to determine how the characteristics of cool cores measured with *Chandra* affect global properties like L_X and T_X and how closely the properties of cool cores correlate with the dynamical state of a cluster. We will measure the degree to which the presence of a cool core shifts the L_X-M and T_X-M relations in this representative sample and then compare those results with cosmological simulations of clusters being done by Stefano Borgani, who is a member of the REXCESS team. We emphasize that the overall REXCESS sample was specifically designed to include all morphological types, so that it can be directly compared with volume-limited samples of simulated clusters.

Central Mass Profiles. Any cool-core clusters that appears undisturbed by AGN will be ideal for measuring the central mass-density profiles of clusters because the assumption of hydrostatic equilibrium will be more secure. For clusters that do show AGN feedback, we still attempt to measure the central mass-density profile by modeling the non-thermal component and deriving temperature and density gradients for the thermal component only.

Supporting Observations. A detailed radio follow-up program for REXCESS is planned, with ATCA observations already awarded for 20 clusters and VLA and GMRT proposals pending. To investigate the expected incidence of cavities detectable in our proposed *Chandra* observations we used the NVSS and SUMSS radio catalogues to constrain the properties of the central radio sources. All of our *Chandra* targets contain a central radio source, unresolved at the resolution of the survey ($\sim$ 45 arcsec), which is consistent with physical sizes similar to nearby cluster centre sources. Based on flux-density measurements from NVSS, and assuming similar physical sizes to nearby cluster-center sources, we find that the internal energies of the central radio sources in our target sample are expected to be between $\sim 5 \times 10^{57}$ and 10^{59} ergs (assuming internal energies $\sim 10-50$ times the minimum energy as typically found for FRI sources: Morganti et al. 1998; Dunn et al. 2005). The expected radio-source internal energies for our sample are therefore in the range of inferred cavity energies reported by Dunn et al. (2005), who found that 70 percent of cool-core clusters have detectable cavities. We therefore expect a similar rate of cavity detection for this sample, with cavity angular sizes expected to be between 4-20 arcsec diameter for the redshift range of our sample.

Table 1: Target and Exposure Description

RXJC	z	F_x 10^{-12}	$N_{\rm H}$ 10^{20}	$\log T$ (K)	ACIS-S ksec	ACIS-I ksec
0605	0.139	9.39	4.3	7.9	34	44*
1044	0.134	9.40	3.9	7.9	34	44*
1141	0.119	5.34	3.3	7.7	64	85
1302	0.084	4.46	1.7	7.5	86	118
0345	0.060	5.76	1.9	7.4	75	103
2014	0.161	14.0	7.4	8.05	22	29*
2149	0.118	6.18	2.3	7.7	53	71
2319	0.098	3.99	1.9	7.6	88	119
0211	0.101	3.22	1.4	7.5	111	152

Exposure Times. Table 1 lists *Chandra* exposure-time estimates based on the unabsorbed 0.1-2.4 keV ROSAT aperture fluxes and $N_{\rm H}$ values from the REFLEX catalog (Böhringer, et al. 2003). The REFLEX apertures $(7-12')$ are larger than ACIS-S $(r < 4')$, so we corrected the expected PIMMS (v3.9b) counts assuming a core radius of 200 kpc and $H_0 = 70$ km/s/Mpc. This correction was $< 5\%$, except for the two closest clusters, where it was 10 and 15% respectively. The ACIS-S exposure times (column 6) are sufficient to obtain 60,000 counts $(0.7-7.0$ keV) within $r < 4'$. The elevated background of the ACIS-S is not significant in the cores of clusters at these brightness levels. We considered ACIS-I (column 7), but the required exposures were $\sim 35\%$ longer. However, to obtain a few profiles extending to larger radii for comparison with XMM, we are requesting ACIS-I data instead of ACIS-S for the three brightest clusters (marked with asterisks), at an additional cost of 27 ksec.

MANAGEMENT PLAN

Our team for this *Chandra* study is the subset of REXCESS investigators who are specifically interested in *Chandra* observations of cool-core clusters. The team has both experienced X-ray observers and theorists who have an established record of publication and of providing derived data products to the HEASARC. Donahue has been PI for multiple Chandra GO and archival projects on clusters of galaxies. She will coordinate the efforts of the X-ray investigators, including providing a central point of access for reduced data and spectra, including backgrounds. She will also acquire K-band data to allow the extraction of dark matter profiles from the cores. Voit will provide extensive theoretical expertise on cool-core clusters, entropy generation in clusters, and feedback from AGN winds. He will coordinate the comparisons with hydrodynamical simulations. Boehringer is PI for the REXCESS Project and is responsible for the interpretation of the data for the full REXCESS Cluster sample. Pratt and Croston are leading the analysis of the XMM profiles. Pratt is experienced in the interpretation of the structure and scaling of clusters. He will compare the results derived here with those from nearby X-ray groups and from a sample of more distant clusters. Croston is an experienced radio and X-ray observer. She will lead the radio follow-up and the study of radio activity in the cluster cores. Ponman and Sanderson will compare X-ray groups with these clusters. Finoguenov will combine the information on the large scale structure from XMM with properties of cluster cores, as resolved by Chandra. Finoguenov has a large program with J.P. Kneib that will observe 100 clusters with Subaru to get weak lensing mass estimates. Most Chandra clusters with $z = 0.1 - 0.3$ and declinations of -70 to +70 degrees will be covered. These data will allow a comparison of the dark matter profile from weak lensing, strong lensing (where visible), and X-ray (hydrostatic equilibrium). Reiprich and Hudson will compare results from this sample with the HIFLUGCS *Chandra* observations. Our team has several independent pipelines for X-ray cluster analyses, which we will use to provide standard products and to assess systematics that stem from choices in data analysis. Pedersen, a 3-time Chandra PI, and Hansen will lead the analysis for deriving the mass profile and compare in detail to model expectations from analytical models and simulations.

REFERENCES

Austin et al. 2005, ApJ, 634, 756.
Allen et al. 2001, MNRAS, 328, L37.
Bauer et al. 2005, MNRAS, 359, 1481.
Benson et al. 2003, ApJ, 599, 38.
Birzan et al. 2004, ApJ, 607, 800.
Böhringer et al. 2007, A&A, in press. (astro-ph/∼April)
Borgani et al. 2004, MNRAS, 348, 1078.
Bower et al. 2006, MNRAS, 370, 645.
Burns 1990, AJ, 99, 14.
Croton et al. 2006, MNRAS, 365, 11.
Dehnen & McLaughlin 2005, MNRAS, 363, 1057.
Donahue et al. 2005, ApJ, 630, L13.
Donahue et al. 2006, ApJ, 643, 730.
Dunn, R. et al. 2005, MNRAS, 364, 1343.
Fabian 1994, ARAA, 32, 277.
Fabian et al. 2000, MNRAS, 318, L65.
Fabian et al. 2003, MNRAS, 344, L43.
Hansen & Stadel 2006, JCAP, 5, 14.
Lewis et al. 2002, ApJ, 573, L13.
McCarthy et al. 2004, ApJ, 613, 811.
McNamara et al. 2000, ApJ, 534, L135.
McNamara et al. 2005, Nature, 433, 45.
Morganti, R. et al. 1988, A&A, 189, 11.
Navarro et al. 1997, ApJ, 490, 493.
Peterson et al. 2001, A&A, 365, L104.
Peterson et al. 2003, ApJ, 590, 207.
Pointecouteau 2005, A&A, 435, 1.
Ponman et al. 1999, Nature, 397, 135.
Pratt et al. 2006, A&A, 446, 429.
Pratt et al. 2007, A&A, 461, 71.
Tamura et al. 2001, A&A, 365, L87.
Vikhlinin, A. et al. 2005, ApJ, 628, 655.
Voigt & Fabian 2006, MNRAS, 368, 518.
Voit & Bryan 2001, 551, 139.
Voit & Donahue 2005, 634, 955.

Previous Chandra Programs for PI Donahue

Cycle 6-GO 06800721 "Deep Observations of Abell 1650"

Donahue et al. AAS Seattle poster 2007; paper in preparation.

Cycle 6-AR program "Are Cluster Simulations Realistic"

Ventimiglia et al. AAS poster, 2007; paper in prep.; Donahue et al. 2007 AAS poster 2007.

Cavagnolo, K. 2008 PhD Thesis, in prep.

Cycle 4- AR program

Donahue, M. et al. 2006, ApJ, 643, 730.

Voit, G. M., Donahue, M. 2005 ApJ, 637, L81. "An Observationally Motivated Framework for AGN Heating of Cluster Cores"

Cavagnolo, K. 2008 PhD Thesis, in prep.

Cycle 4-GO program 04800327

Donahue, M. et al. 2005, ApJ, 630, L13. "Two Clusters of Galaxies with Radio Quiet Cores

Cycle 2 GO Program 02800376

Donahue, M., Daly, R. A., Horner, D. J. 2003, ApJ, 584, 643. "Constraints on the Cluster Environments and Hot Spot Magnetic Field Strengths of the Radio Source 3C280 and 3C254."

Cycle 1-GO program 01800448

Borys, C. et al. 2004, MNRAS, 352, 759. "The nature of a gravitationally lensed submillimetre arc in MS0541.6-0305: two interacting galaxies at $z \sim 2.9$?"

Donahue, M. et al. 2003, ApJ, 598, 190. "The Mass, Baryonic Fraction, and X-ray Temperature of the Luminous, High Redshift Cluster of Galaxies MS0451.6-0305."

Molnar, S. M, Hughes, J. P., Donahue, M., Joy, M. 2002, ApJ, 573, L91. "Chandra Observations of Unresolved X-ray Sources Around Two Clusters of Galaxies."