EXTENDING ACCEPT: A CHANDRA ARCHIVAL STUDY OF THE METALLICITY-ENTROPY RELATIONSHIP IN GALAXY CLUSTERS

1 Scientific Justification

1.1 The ACCEPT Database

We have recently completed a large project to measure the entropy profiles of galaxy clusters in the *Chandra* archive, with the goal of understanding how the properties of the intracluster medium are related to AGN phenomena and star formation in the brightest cluster galaxy (BCG). Entropy, defined here as $K = T_X n_e^{-2/3}$, is the key thermodynamical quantity to measure when assessing the impact of cooling and feedback on intracluster gas because it tracks gains and losses of heat energy more directly than either temperature or density alone (see Voit 2005 for a review). Our analysis of over 200 clusters from the *Chandra* archive has shown that:

- The azimuthally-averaged radial entropy profiles of clusters can almost always be fit using the three-parameter form $K(r) = K_0 + K_{100}(K/100\,\mathrm{kpc})^{\alpha}$, with $\alpha \approx 1.2$ and $K_{100} \approx 150\,\mathrm{keV\,cm^2}$.
- The distribution of core entropy (K_0) appears to be bimodal, with a low-entropy population of clusters having $K_0 < 30\,\mathrm{keV\,cm^2}$, a high-entropy population having $K_0 > 50\,\mathrm{keV\,cm^2}$, and relatively few clusters in between (Cavagnolo et al. 2009, see Figure 1).
- Phenomena associated with AGN feedback and star formation, such as strong radio emission from the BCG, extended emission-line nebulae, and excess blue light, are found only in the low-entropy population of clusters (Cavagnolo et al. 2008, Rafferty et al. 2008, see also Dunn & Fabian 2008).

This dichotomy in cluster properties has been suggested to arise either from the interplay between AGN feedback and conduction (Guo et al. 2008, Voit et al. 2008) or AGN feedback and the terminal velocity of cool infalling material (Soker 2008). Regardless of whether these suggestions are correct, this large dataset is now an important benchmark against which to test theoretical models of cooling and feedback in galaxy clusters.

In order to facilitate theoretical interpretation, the data products resulting from this analysis have been made available to the public via the "Archive of *Chandra* Cluster Entropy Profiles Tables" (*ACCEPT*) database[1]. We have continued to expand the *ACCEPT* database as additional cluster observations have become public. It currently includes 459 ACIS-S/I observations of 352 galaxy clusters with a combined exposure time of 12.5 Msec. After just one month of open public access, the ACCEPT site has already received 476 unique (non-robotic) visitors from 13 countries.

1.2 ICM Metallicity Profiles

Now that we have achieved the original goals of the archival project, we are proposing to extend the *ACCEPT* database to include higher-quality metallicity profiles. The radial distribution of heavy elements in clusters is interesting for two reasons: (1) the heavy-element content of a cluster reflects the integrated amount of supernova activity the cluster has experienced, and (2) heavy elements can serve as a passive tracer of mixing and diffusion in the intracluster medium.

Metals can migrate from their parent star into the ICM through a multitude of pathways: ram-pressure stripping of gas previously bound to a galaxy as it travels through the ICM, tidal stripping of gas via galaxy-galaxy interactions, gas outflow via galactic superwinds, gas ejection from

[1] http://www.pa.msu.edu/astro/MC2/accept/

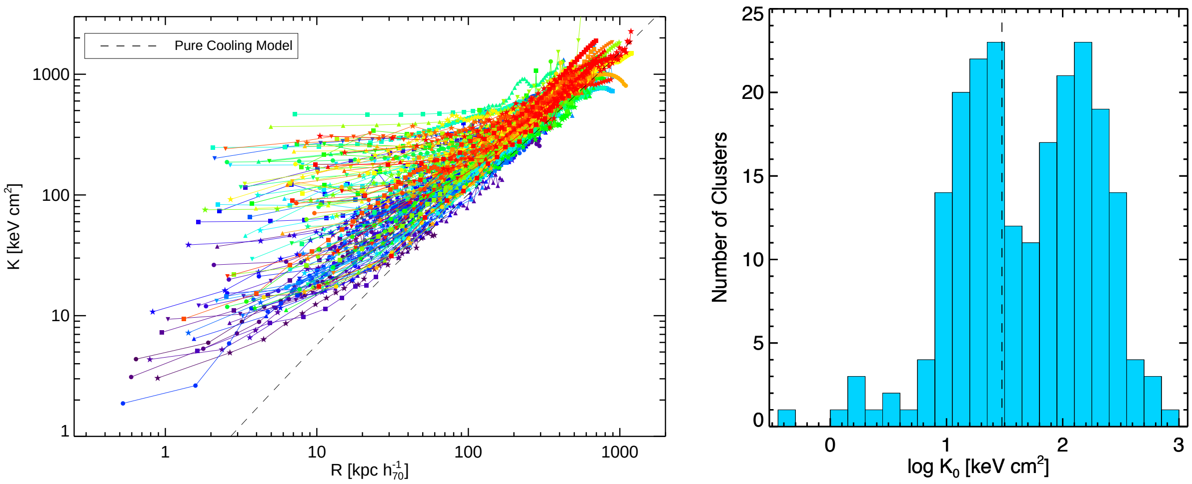

Figure 1: ICM entropy structure in 217 clusters from the ACCEPT database (Cavagnolo et al. 2009). Left panel: Radial ICM entropy profiles. Line colors represent cluster temperature from 2 keV (violet) to 12 keV (red). Most of these entropy profiles can be adequately fit with the function $K(r) = K_0 + K_{100}(r/100\,\mathrm{kpc})^{\alpha}$, with $K_{100} \approx 150\,\mathrm{keV\,cm^2}$ and $\alpha \approx 1.2$. Right panel: Distribution of central entropy. The best-fitting K_0 values have a bimodal distribution with a minimum at $40-50\,\mathrm{keV\,cm^2}$, and the dashed line corresponds to $30\,\mathrm{keV\,cm^2}$.

intergalactic stars, and gas outflows powered by AGN outbursts that uplift enriched gas residing in the cluster core. With current X-ray telescopes, direct observations of small-scale metal-transport processes like ram-pressure stripping or galactic winds are currently limited to mostly nearby objects like Coma or Virgo, and in rare instances spectacular objects like ESO 137-001 (Sun et al. 2007). Once these metals have entered the intracluster medium, they can be redistributed by turbulent diffusion, cosmic-ray driven convection, and entrainment behind AGN-driven outflows and buoyant bubbles (Rafferty et al. 2008, Rasera et al. 2008, Rebusco et al. 2006). In one well-resolved case, we have directly observed the transport of metals by an AGN outflow (Kirkpatrick et al. 2009).

While evidence for each of these metal-transport processes can be gathered from individual high-quality observations, further progress in identifying the primary mode of metal transport will require large-scale comparisons between numerical simulations of metal transport and the aggregate properties of clusters in the *Chandra* archive. The fact that clusters with cool cores, which correspond to our low-entropy population, tend to have strong iron abundance gradients in their cores has long been recognized (e.g., De Grandi & Molendi 2001, Sanderson et al. 2009). However, the reason for this relationship between the entropy gradient and the metallicity gradient is not yet understood. The answer is likely to involve a combination of turbulent mixing and AGN-driven transport that could potentially reveal how AGN outflows have periodically stirred the intracluster medium.

Because the original goal of our project was initially to produce well-resolved entropy profiles for a large number of clusters, our *Chandra* pipeline was optimized to determine high-quality temperature profiles. The sizes of our annular bins were therefore too small for optimal metallicity measurements. Reanalysis of the archival *Chandra* clusters with a binning scheme optimized to measure metallicity will therefore provide an improved set of metallicity profiles to complement the density, temperature, and entropy profiles already in the ACCEPT database, which will enable systematic studies of how the metallicity gradients of clusters depend on their entropy characteristics, surface-brightness morphology, the incidence of AGN feedback, radio power, Hα nebulosity, and BCG star formation.

2 Proposed Analysis

2.1 Data Reduction

We are well positioned to undertake this large archival study thanks to the well-tested, batch-style reduction and analysis pipeline developed for the original version of the *ACCEPT* database. For our proposed extension to this archival study, we will measure global cluster abundances (both with and without the core region) and radial abundance profiles. Where signal-to-noise (SNR) allows, we will also generate 2D abundance maps. We will then model the behavior of the radial abundance profiles by fitting a simple function to each profile to look for trends or correlations among the best-fit abundance parameters and ICM properties such as core entropy, central abundance, the steepness of the abundance gradient beyond the core. Our results can also be compared with results from simulations which include feedback and chemical enrichment (e.g., Fabjan et al. 2008).

This project will allow us to add improved, high-quality abundance profiles for clusters in the *ACCEPT* database. We will decrease the uncertainties of the best-fit spectroscopically determined abundance measurements by increasing the SNR in each spectrum (*i.e.* increasing the number of counts per radial bin, see Figure 2). In addition, we will explore the effect of assuming multi-component models on our results. These complexities include multiple temperature components or variable metal abundances. For spectra with good SNR, we can use the inferred relative abundances of various metal species as a probe of the enrichment rate from various types of supernovae. Based on the size of the *ACCEPT* database and the expected minimum criteria for deriving high-quality abundance profiles (presumably a minimum of 4 radial annuli with 5000 counts per region), we expect to have $\gtrsim 200$ clusters in the archive-limited sample which will cover a broad range of redshifts, luminoisities, and morphologies.

As a bonus, a study this large will also produce interesting comparisons of analysis methodologies and *Chandra* calibrations. We will explore the subtle systematic differences between various spectral models (*e.g.* MeKaL, APEC, GDEM, *etc.*) and how they impact abundance measurements, in addition to quantifying the role of multi-temperature gas in biasing best-fit values. The results in *ACCEPT* were derived using version 3.4.0 of the *Chandra* Calibration Database (CALDB). With a new large study, we will update the analysis to use the new CALDB version 4.1.1, which includes significant changes from v3.4.0. Through comparison of results now in *ACCEPT* with the results of this updated study, we will be able to quantify how the major corrections to the *Chandra* effective area impact existing cluster studies.

2.2 Database Improvements

An important component of our prior archival work was making the results, data, and analysis code available to the entire research community via the *ACCEPT* online database. As with our previous work, all results of the proposed archival study will be added to the *ACCEPT* database so that the observational and theoretical communities will have access to our work and the richness of the *Chandra* archive. The database is currently a blend of ASCII files, binary FITS tables, useful figures/graphics, and has limited interactive functionality. With a new archival study we will convert the existing hybrid database into a proper SQL database. This conversion will allow us to maintain the "flat" look of the site, which provides ease of use, but at the same time allowing us to implement boolean operations directly from the site. This change will circumvent the need for users to download data and manipulate it with their own tools. With an SQL database and overlying PERL and PYTHON tools, custom output files (both ASCII and FITS) and on-the-fly figure generation will also be available through the site. We have budgeted for a moderate hardware investment in local storage and data access through a fiber channel, as well as appropriate software

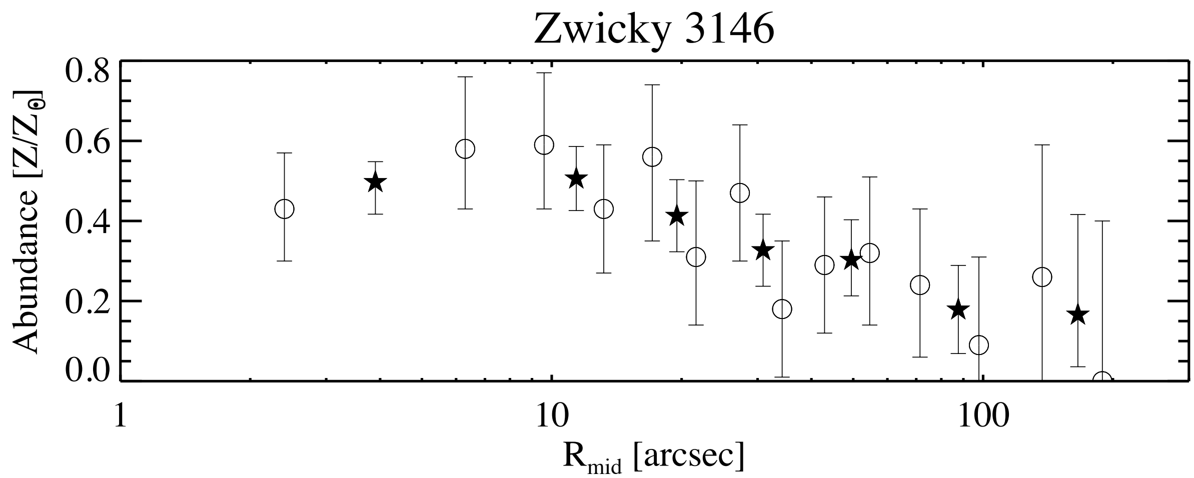

Figure 2: Abundance profiles for the cluster Zwicky 3146 using the original ACCEPT binning (open circles) and optimal binning for metallicity measurement (filled stars). Metallicity-profile uncertainties with the revised binning are reduced by almost a factor of 2 for this cluster, and the improvement will be even greater for cooler clusters.

purchases and upgrades. We are leveraging an existing 3-blade Quad-Core Mac Xserve mini-cluster for this work, purchased with start-up funds of the PI and co-I Donahue. Simple, rapid dissemination of finished work to the largest audience possible benefits both us and the CXC by expanding the scope of our proposed and completed archival work.

3 References

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4 Budget Narrative

The budget of $70,000 will pay for one year of graduate-student stipend and benefits, one month of summer salary for Cavagnolo as a visiting research associate, two weeks of summer salary for PI Voit. Total salary and fringes are $31,800. The budget includes one conference trip for one of the senior investigators and the student ($2,500), plus page charges ($1,800) and supplies ($200). The graduate student, Emily Wang, will be doing the bulk of the work on this project, and it will form a large part of her Ph.D. thesis. A year of graduate tuition (not subject to overhead) is $9,998 for AY 2010-2011. We estimate that about $3,000 will be required to outfit our existing Xserve mini-cluster for shared disk access, fiber channel card, replacement disk drives (the existing internal drives are about 2 years old), and software license renewals and upgrades. The overhead rate at MSU is 52%. No equipment (defined here as items over $5,000) will be purchased.

5 Previous Chandra Programs

Voit is currently P.I. of *Chandra* theory program TM8-9010X aimed at investigating how to measure and quantify temperature substructure in galaxy clusters. A paper partially supported by this grant (Ventimiglia et al. 2008, ApJ, 685, 118) has already been published in ApJ and shows how X-ray surface-brightness substructure is related to deviations from the mean mass-temperature relation in a large sample of simulated clusters. Another paper (Ventimiglia et al. 2009, in preparation) demonstrates that the temperature substructure observed in *Chandra* archival clusters by Cavagnolo et al. (2008, ApJ, 682, 821) is statistically similar to that seen in numerical simulations of galaxy clusters.

Voit is P.I. of *Chandra* theory program TM9-0008X that is performing numerical simulations to investigate how conduction regulates thermal instability in cluster cores. Work on that program has just begun.

Voit was also P.I. of a *Chandra* theory program (TM5-6006A) that has now concluded. This program was to compute the spectrum and luminosity of the non-equilibrium soft X-ray line emission from merging cluster systems. It was motivated by *XMM-Newton* observations of O VII lines that were thought to be coming from galaxy clusters (Kaastra et al. 2003, A&A, 397, 445). We have computed spectral models of non-equilibrium emission and have used them to determine the time-dependent X-ray spectrum of a merging cluster, finding that the line-emission signal is to weak to explain the apparent O VII emission features. However, in the meantime, the motivating observations themselves have been called into question (Bregman & Lloyd-Davies 2006). They are more plausibly explained as arising from solar system charge-exchange emission. Therefore, we have not submitted our theoretical work for publication in a refereed journal.

Development of the ACCEPT database resulted from several Chandra programs on which Co-I Donahue was the principal investigator: Cycle 6-AR program 06800364, Cycle 4-AR program 04800840, and Cycle 4-GO program 04800327.