QUANTIFYING CLUSTER TEMPERATURE SUBSTRUCTURE

1 Science Justification

1.1 Cluster Cosmology and the Problem of Scatter

X-ray observations of galaxy clusters figured prominently in the establishment of a concordance cosmology during the past decade, providing crucial constraints on the global baryon-to-dark-matter ratio, the normalization of the primordial power spectrum, and the evolution of structure formation (see Voit 2005 for a recent review). Now the cluster community is raising its expectations and developing plans to measure the characteristics of dark energy using observations of cluster evolution (e.g. Haiman et al. 2005). This endeavor will require a much more precise understanding of how observable cluster properties scale with underlying halo mass and how those mass-observable relations vary with redshift—but that will not be enough. We will also need to know the *scatter* in the mass-observable relations and how that scatter evolves with redshift (e.g. Lima & Hu 2005). Failure to account for evolution in the scatter could potentially lead to a spurious detection of evolution in the properties of dark energy (see Figure 1).

Scatter in X-ray cluster properties is directly related to substructure in the intracluster medium. If clusters were all structurally identical, then there would be a one-to-one relationship between halo mass and any given observable property. Generally speaking, any deviation from a mean mass-observable relationship can be attributed to some form of substructure, whether it be a spread in halo concentration at a given mass, variations in the incidence of cool cores, differences in the level of AGN feedback, or the presence of a merger event. All of these deviations can be considered forms of substructure that produce scatter in the mass-observable relations one would like to use for cosmological purposes. While it may ultimately be possible to constrain the amount of scatter and its evolution with redshift using self-calibration techniques (Lima & Hu 2005), such constraints would greatly benefit from prior knowledge about the relationship between scatter and substructure.

Traditionally, the most worrisome form of substructure has been merger events. One often sees cluster samples split into "relaxed" and "unrelaxed" subsamples, with the former assumed to be in hydrostatic equilibrium and the latter suspected of being hopelessly disrupted. Cosmological simulations of clusters indicate that the truth is somewhere in between. The cluster population as a whole appears to follow well-defined virial relations with lognormal scatter around the mean, showing that clusters do not cleanly separate into relaxed and unrelaxed systems (Evrard et al. 2007). Even the most relaxed-looking clusters are not quite in hydrostatic equilbrium (Kravtsov et al. 2006). Instead of simply being "relaxed" or "unrelaxed," clusters occupy a continuum of relaxation levels determined by their recent mass-accretion history.

To make further progress in understanding how merger-related substructure leads to scatter in the mass-observable relations, we need to *quantify* the continuum of cluster relaxation. This can be done straightforwardly for simulated clusters, for which we have complete dynamical information, but is not so simple for observed clusters. The way forward is therefore to use the simulations to identify observable features of clusters that closely correlate with how far a cluster is from hydrostatic equilibrium and how much it deviates from mean mass-observable relations.

1.2 Quantifying Substructure in Simulated Clusters

We are currently studying a set of 121 simulated clusters compiled by Borgani et al. (2004) and Dolag et al. (2004) to determine how closely the 2-D surface-brightness structure of clusters correlates with scatter about the mean mass-temperature relation. We have tested several substructure measures taken from the literature, including axial ratio, centroid variation, and power ratio, and have found that the power ratios of Buote & Tsai (1995) correlate best with the temperature offset of a cluster (Ventimiglia et al. 2007). Figure 2 shows that relaxed-looking clusters tend to be hot for their mass and disrupted-looking clusters tend to be cool for their mass.

Some people may find this result counterintuitive, since relaxed-looking clusters in the real universe tend to have cool cores that depress the mean temperature and disrupted-looking clusters could have strong shocks that ought to raise the mean temperature. However, other analyses of smaller samples of simulated clusters have found a similar tendency for disrupted-looking clusters to be cool for their mass (Mathiesen & Evrard 2001; Kravtsov et al. 2006). The primary reason is that merging clusters have not yet thermalized a significant amount of their kinetic energy and therefore are cooler than their more relaxed counterparts, except for a brief period of time when the initial merger shock peaks in strength (Ricker & Sarazin 2001; Poole et al. 2007). A secondary reason is that even the most sophisticated cooling and feedback mechanisms in present-day simulations still do not produce cool cores like those in observed clusters.

Notice also in Figure 2 that there is still a significant amount of scatter about the best fitting mass-temperature relation, even for a fixed amount of surface-brightness substructure. Much of that scatter comes about because surface-brightness substructure is aspect-dependent—the same cluster looks different from different points of view. It is therefore desirable to have complementary measures of substructure that do not depend on one's point of view.

1.3 Temperature Inhomogeneity

One such aspect-independent measure of substructure was uncovered by Mathiesen & Evrard (2001) in their temperature analysis of simulated clusters. Their fits of single-temperature plasma emission models to the spectra of simulated clusters showed that the best-fit temperature is often band-dependent, with the broad-band temperature often 20% cooler than the hard-band temperature. This temperature discrepancy arises because the presence of a relatively small amount of unthermalized cool plasma pulls down the best-fit temperature, and the effect is greater if the fit includes part of the soft X-ray band (Mazzotta et al. 2004; Vikhlinin 2006). Mathiesen & Evrard (2001) also showed that the temperature discrepancy is greatest shortly after a merger and declines as the cluster approaches a relaxed, fully-thermalized state.

Recent work by our group has shown that a band-dependent temperature discrepancy similar to that predicted by Mathiesen & Evrard (2001) is indeed present in *Chandra* spectra of clusters. Cavagnolo et al. (2007) have measured best-fit temperatures in both a broad 0.7-7 keV band ($T_{0.7-7}$) and a hard $2/(1+z)$-7 keV band ($T_{2/(1+z)-7}$), finding that the ratio $T_{2/(1+z)-7}/T_{0.7-7}$ in a sample of 169 archival clusters has a mean value greater than unity and a spread of values extending from unity to > 1.5 (see Figure 3). However, we will need to compare the statistical properties of our observed sample with a similarly large sample of simulated clusters before we can be certain that these band-dependent temperature ratios accurately reflect a cluster's level of relaxation.

2 Proposed Research

Here we propose a theoretical investigation of the band dependence of best-fit cluster temperatures to see whether the hard-band to broad-band temperature ratio is a useful aspect-independent measure of cluster relaxation. We have good reason to expect that the temperature ratio will be a faithful indicator of temperature inhomogeneity because it tends to unity in the limit of a homogeneous plasma and grows larger as the spread of temperatures in the plasma increases. It is also a much cheaper indicator of temperature inhomogeneity than a 2-D temperature map which requires enough photons for a separate temperature measurement in each spatial bin. We therefore anticipate that temperature-ratio statistics can eventually be profitably applied to large cluster samples to assess the degree of scatter in mass-observable relations and to determine how rapidly the scatter evolves with redshift.

The first step will be to measure temperature ratios in a large sample of simulated clusters. We will start with the same sample we have been using to assess surface-brightness substructure, drawn from the simulations of Borgani et al. (2004) and Dolag et al. (2004). These simulations were performed with the GADGET-2 code, including radiative cooling and supernova feedback, and the clusters we will analyze range in temperature from 2 keV to greater than 8 keV. We will create mock *Chandra* event files from these clusters using the X-MAS code (Gardini et al. 2004) and then derive temperature ratios from them using the same pipeline we used to analyze the archival *Chandra* observations. In these mock observations, we will mask out the cluster cores, just as we do in the actual observations.

Once we have temperature ratios in hand we will perform two separate analyses:

- We will investigate how well temperature ratios correlate with actual departures from hydrostatic equilibrium in the simulated clusters and with deviations from mass-observable relations such as $L_X - M$, $T_X - M$, and $Y_X - M$. Our goal will be to determine whether adding temperature ratio as an additional parameter significantly reduces scatter in the mass-observable relations. If the reduction is substantial, our contribution to the community will be theoretical calibration of a new tool for quantifying cluster substructure and correcting for substructure in future cluster surveys.

- We will compare the statistical distribution of temperature ratios in our simulation sample to the distribution observed in *Chandra* archival clusters. That investigation will determine the degree to which simulations reproduce the observed range of temperature inhomogeneity in clusters, testing whether dissipative processes in the simulations accurately reproduce the actual dissipation kinetic energy in real clusters. If the dispersion among simulated clusters is too small, then dissipation and relaxation probably happen too rapidly. If the dispersion is too large, then dissipation and relaxation in the simulations probably happen too slowly. Resolving this issue is important because many current cluster surveys do not account for the effects of temperature inhomogeneity and may systematically underestimate σ_8 because they underestimate cluster mass at a given temperature (Rasia et al. 2005). Temperature ratios offer the community a way to quantify this potential source of systematic bias.

3 Budget Narrative

The budget will pay for one year of graduate-student support, one month of summer salary for the P.I., a conference trip for both the P.I. and the student, plus page charges and supplies. The graduate student, David Ventimiglia, will be doing the bulk of the work on this project, and it will form a large part of his Ph.D. thesis.

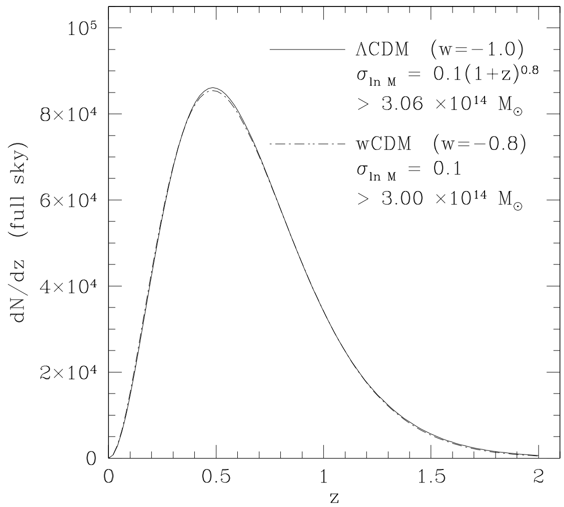

Figure 1: Illustration of degeneracy between cluster-evolution predictions of a model with constant dark energy and evolving scatter in the mass-observable relation (solid line) and a model with evolving dark energy and constant mass-observable scatter (dashed line). The cluster mass threshold is $3 \times 10^{14} M_{\odot}$ with scatter $\sigma_{\ln M}$.

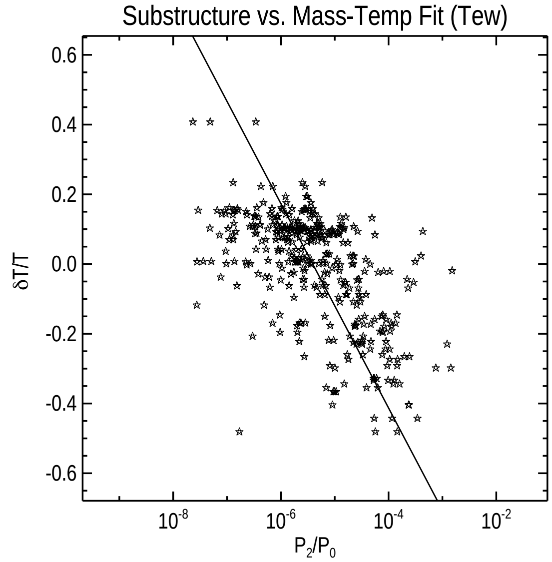

Figure 2: Correlation between the Buote & Tsai (1995) power ratio P_2/P_0 and fractional offset in temperature from the mean mass-temperature relation in a simulated cluster sample (Ventimiglia et al. 2007). Simulated clusters with greater substructure (larger P_2/P_0) are generally cooler for a given mass (smaller $\delta T/T$) because much of their kinetic energy remains unthermalized. Much of the remaining scatter at a given value of $\delta T/T$ arises because surface-brightness substructure is aspect-dependent—the measured value of P_2/P_0 depends on your point of view.

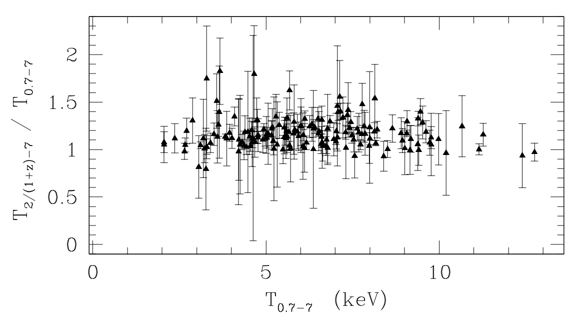

Figure 3: Measured ratio between hard-band temperature $T_{2/(1+z)-7}$ and broad-band temperature $T_{0.7-7}$ in a *Chandra* archival sample of clusters whose cores have been masked (Cavagnolo et al. 2007). Ratios exceeding unity reflect a significant amount of temperature inhomogeneity that can affect the mass-observable relations used for cluster cosmology.

4 References

Borgani, S. et al. 2004, MNRAS, 347, 1078

Buote, D. A. & Tsai, J. C. 1995, ApJ, 452, 522

Cavagnolo, K. et al. 2007, in preparation

Dolag, K. . et al. 2004, ApJ, 606, L97

Evrard, A. E. et al. 2007, astro-ph/0702241

Gardini, A. et al. 2004, MNRAS, 351, 505

Haiman, Z.. et al. 2005, astro-ph/0507013

Kravtsov, A. et al. 2006, ApJ, 650, 128

Lima, M. & Hu, W. 2005, PRD, 72, 043006

Mathiesen, B. F. & Evrard, A. E. 2001, ApJ, 546, 100

Mazzotta, P. et al. 2004, MNRAS, 354, 1

Poole, G. B. et al. 2007, astro-ph/0701586

Rasia, E. et al. 2005, ApJ, 618, L1

Ricker, P. M. & Sarazin C. L. 2001, ApJ, 561, 621

Ventimiglia, D. et al. 2007, in preparation

Vikhlinin, A. 2006, ApJ, 640, 710

Voit, G. M. 2005, Rev. Mod. Phys., 77, 207

5 Previous Chandra Programs

Voit has been P.I. of one *Chandra* theory program (award TM5-6006A) that is now concluding. The object of the program was to compute the spectrum and luminosity of the non-equilibrium soft X-ray line emission from merging cluster systems. A paper is in preparation and will be submitted to ApJ within two months.

Voit has been Co-I on several other Chandra G.O. and archival programs, for which most of the results have already been published or presented at major conferences:

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

  Donahue et al. AAS Seattle poster 2007

  ApJ paper in preparation.

- Cycle 6-AR program "Are Cluster Simulations Realistic"

  Ventimiglia et al. AAS poster, 2007

  Ventimiglia et al. 2007, ApJ paper in preparation

  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"