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Ph.D. Dissertation Summary

Presented in the dissertation is an analysis of the X-ray emission from the intracluster medium (ICM) in clusters of galaxies observed with the *Chandra* X-ray Observatory. The dynamic state for a sample of clusters is investigated via ICM temperature inhomogeneity, and ICM entropy is used to evaluate the thermodynamics of cluster cores. The key results presented in the dissertation are that ICM temperature inhomogeneity correlates well with the process of cluster relaxation, galaxy clusters have isentropic cores whose distribution is bimodal, and that the processes of active galactic nucleus (AGN) feedback and star formation are highly sensitive to the entropy state of a cluster's core region. Also provided is a descriptive outline for *CORP* – the robust, extensible suite of X-ray data reduction and analysis tools written to complete the dissertation.

ICM Temperature Inhomogeneity

To more accurately weigh galaxy clusters, how secondary dynamical processes (*e.g.* mergers and AGN feedback) alter cluster observables must first be quantified if cluster temperature or luminosity are to serve as accurate mass proxies. It has been demonstrated that spatial cluster substructure correlates well with dynamical state, and that the most relaxed clusters have the smallest deviations from mean mass-observable relations (*e.g.* Ventimiglia et al. 2008). But spatial analysis is at the mercy of perspective. If equally robust aspect-independent measures of dynamical state could be found, then quantifying deviation from mean mass-scaling relations would be improved and the uncertainty of inferred cluster masses could be further reduced. The Cavagnolo dissertation confronts this difficulty via temperature inhomogeneity.

If the hot ICM is nearly isothermal in the projected region of interest, the X-ray temperature inferred from a broadband (0.7-7.0 keV) spectrum should be identical to the X-ray temperature inferred from a hard-band (2.0-7.0 keV) spectrum. However, if unresolved cool lumps of gas are contributing soft X-ray emission, the temperature of a best-fit single-component thermal model will be cooler for the broadband spectrum than for the hard-band spectrum. Using this difference as a diagnostic, the ratio of best-fitting hard-band and broadband temperatures may indicate the presence of cooler gas even when the X-ray spectrum itself may not have sufficient signal-to-noise ratio to resolve multiple temperature components (Mathiesen & Evrard 2001).

Building on the Mathiesen & Evrard (2001) simulation results, the dissertation investigates the band dependence of the inferred X-ray temperature of the ICM for 192 well-observed galaxy clusters selected from the *Chandra* Data Archive. X-ray spectra from core-excised annular regions of fixed fractions of the virial radius, R_{2500} and R_{5000}, are extracted for each cluster in the archival sample. A comparison is made of the X-ray temperatures inferred from single-temperature fits when the energy range of the fit is 0.7-7.0 keV (broad) and when the energy range is 2.0/(1+z)-7.0 keV (hard). On average, the hard-band temperature is found to be significantly higher than the broadband temperature, and the ratio of the temperatures is quantified as $T_{HBR} = T_{2.0-7.0}/T_{0.7-7.0}$, shown in Figure 1. On further exploration, it is found that the temperature ratio T_{HBR} is enhanced preferentially for clusters which are known merging systems. In addition, cool-core clusters tend to have best-fit hard-band temperatures that are in closer agreement with their best-fit broadband temperatures, shown using symbols in Figure 1. Presuming cool cores and mergers are good indicators of dynamical state, the dissertation concludes that T_{HBR} is a useful metric for further assessing the process of cluster relaxation. The work associated with this part of the dissertation is published in Cavagnolo et al. (2008a).

ICM Entropy

ICM temperature and density alone primarily reflect the shape and depth of the cluster dark matter potential, but it is the specific entropy of a gas parcel which governs the density at a given pressure (Voit et al. 2002). In addition, the ICM is convectively stable when, without dramatic perturbation, the lowest entropy gas is near the core and high entropy gas has buoyantly risen to large radii. ICM entropy can also only be changed by addition or subtraction of heat, thus the entropy of the ICM reflects most of the cluster thermal history. Therefore, properties of the ICM can be viewed as a manifestation of the dark matter potential and cluster thermal history - which is encoded in the entropy structure (*e.g.* Voit et al. 2002). ICM Entropy is therefore a useful quantity for studying the effects of feedback on the cluster environment and investigating the breakdown of cluster self-similarity.

The dissertation studies feedback using radial entropy profiles of the ICM for a collection of 239 clusters taken from the *Chandra*Data Archive, presented in Figure 2. It is found that most ICM entropy profiles are well-fit by a model which is a power-law at large radii and approaches a constant entropy value at small radii: $K(r) = K_0 + K_{100}(r/100\ \mathrm{kpc})^{\alpha}$, where K_0 quantifies the typical excess of core entropy above the best fitting power-law found at larger radii and K_{100} is the entropy normalization at 100 kpc. Discussion is presented in relation to theoretical models (*e.g.* Voit & Donahue 2005) explaining why non-zero K_0 values are consistent with the process of energy injection from AGN feedback. Further, it is shown that the K_0 distributions of both the full archival sample and the flux-limited, unbiased primary *HIFLUGCS* sample of Reiprich (2001) are bimodal with a distinct gap centered at $K_0 \approx 40$ keV cm^2 and population peaks at $K_0 \sim 15$ keV cm^2 and $K_0 \sim 150$ keV cm^2 (Figure 3). It is suggested that the bimodal distribution may result from the effects of ICM thermal conduction and cluster-cluster mergers. The results from this work are presented in Cavagnolo et al. (2008b).

Also of interest is how cluster core entropy state is associated with AGN feedback and star formation in the galaxy which resides at the center of a cluster. As an extension of the radial entropy analysis, the dissertation delves into exploring the relationship between some expected by-products of ICM cooling – *e.g.* gaseous instabilities, star formation, and AGN activity – and the K_0 values of clusters. To determine the activity level of feedback in cluster cores, the readily available observables Hα and radio emission are selected as tracers.

Utilizing the results of the archival study of intracluster entropy, the dissertation goes on to show that Hα and radio emission from central cluster galaxies are much more pronounced when the cluster's core gas entropy is $\lesssim 30$ keV cm^2. The prevalence of Hα emission below this threshold indicates that it marks a dichotomy between clusters that can harbor multiphase gas and star formation in their cores and those that cannot. The fact that strong central radio emission also appears below this boundary suggests that feedback from an AGN turns on when the ICM starts to condense, strengthening the case for AGN feedback as the mechanism that limits star formation in the Universe's most luminous galaxies. The results of this work are presented in Cavagnolo et al. (2009). The dissertation results also suggest that the sharp entropy threshold for the formation of thermal instabilities in the ICM and initiation of processes such as star formation and AGN activity arises from thermal conduction. A discussion of this topic is presented in Voit et al. (2008).

References

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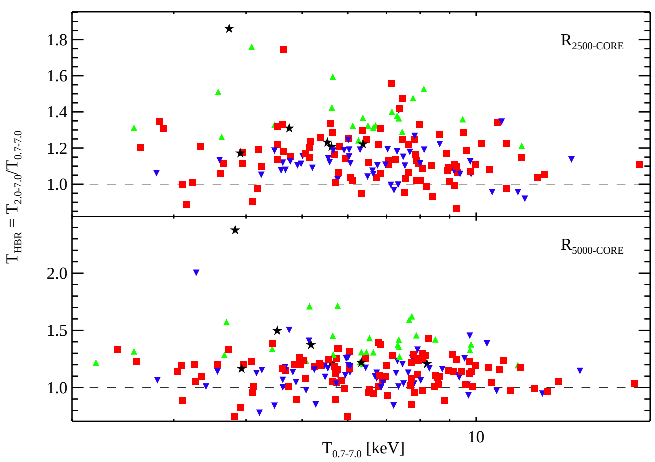

Figure 1: T_{HBR} vs. $T_{0.7-7.0}$. The dashed line is the line of equivalence. Symbols and color coding are based on two criteria: 1) presence of a cool core (CC) and 2) value of T_{HBR}. Black stars are clusters with a CC and T_{HBR} significantly greater than 1.1. Green upright-triangles are NCC clusters with T_{HBR} significantly greater than 1.1. Blue down-facing triangles are CC clusters and red squares are NCC clusters. It is found that most, if not all, of the clusters with $T_{HBR} \gtrsim 1.1$ are merger systems.

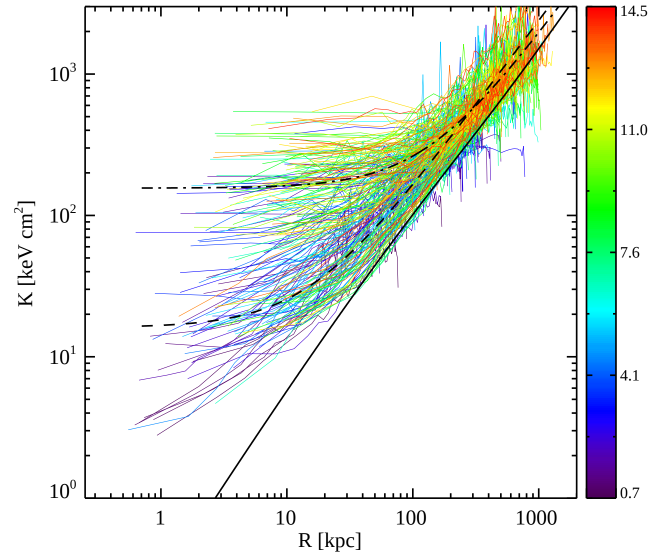

Figure 2: Composite plot of entropy profiles for archival sample. Profiles are color-coded based on average cluster temperature; units of the color bar are keV. The solid line is the pure-cooling model of Voit et al. (2002), the dashed line is the mean profile for clusters with $K_0 \leq 50$ keV cm^2, and the dashed-dotted line is the mean profile for clusters with $K_0 > 50$ keV cm^2.

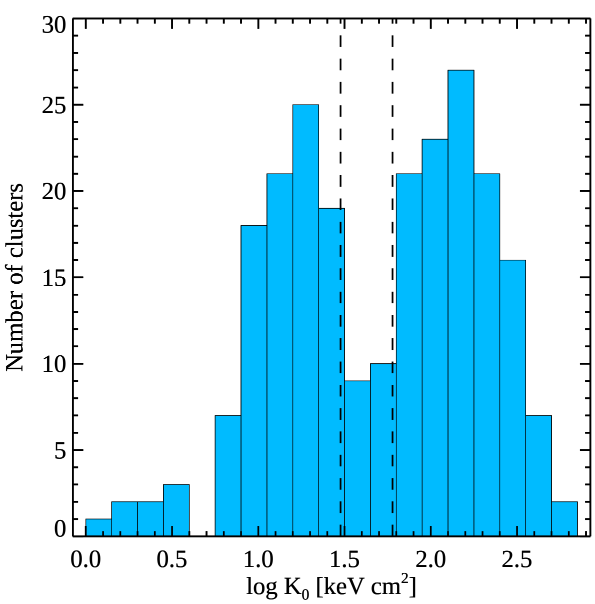

Figure 3: Histogram of best-fit K_0 for all the clusters in the archival study. Bin widths are 0.15 in log space. The distinct bimodality in $K_0$is bracketed by the vertical dashed lines.

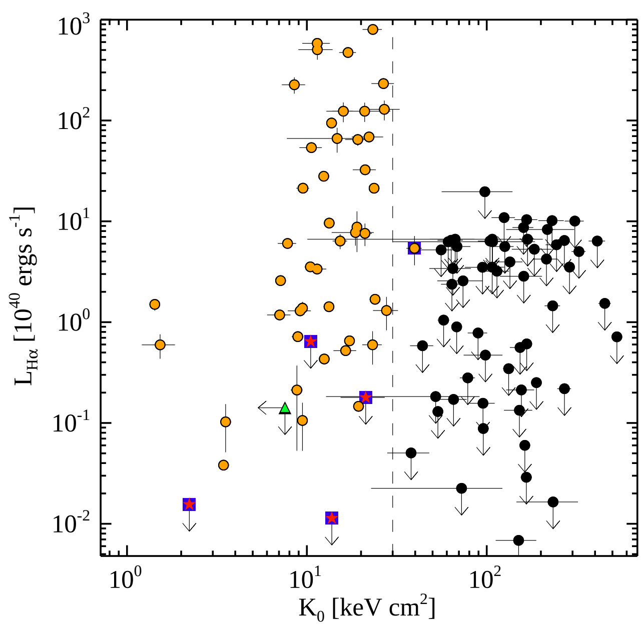

Figure 4: Central entropy vs. Hα luminosity. Orange circles represent Hα detections, black circles are non-detection upper limits, and blue squares with inset red stars or orange circles are peculiar clusters which do not adhere to the observed trend. The vertical dashed line marks $K_0 = 30$ keV cm^2. Note the presence of a sharp Hα detection dichotomy beginning at $K_0 \lesssim 30$ keV cm^2.