ABELL 1983: AN EXCEPTIONALLY RARE COOL-CORE CLUSTER WITH HIGH CORE ENTROPY

Introduction

We propose a 35 ksec observation of the peculiar cluster Abell 1983 (A1983; $z = 0.0436$) which has not been targeted with *Chandra*. This cluster has a long core cooling time (~ 3 Gyr) and high ICM core entropy ($K_0 > 30$ keV cm^2) suggesting $> 10^{61}$ erg of energy has been injected into the gas, yet this cluster unambiguously has a cool core, peaked central iron abundance, but no detected Hα or radio emission. A1983 shares characteristics with both the cool core and non-cool core cluster populations, and a detailed study of the cluster core ($r \lesssim 100$ kpc) requires high-resolution data from *Chandra* before a better understanding of this strange cluster's dynamic state can be formed.

The central cooling time of the intracluster medium (ICM) in many clusters of galaxies is $\ll H_0^{-1}$. An expected consequence of short central cooling time was that massive cooling flows, > 100 M$_\odot$ yr^{-1}, should form [1], but these massive flows have instead turned out to be trickles [2,3] with most of the hot ICM never reaching temperatures lower than $\sim T_{\rm virial}/3$. In recent years, this "cooling flow problem" has been the focus of much study as the solutions have broad impact in the areas of galaxy formation, *e.g.* explaining apparent suppression of the high-mass end of the galaxy luminosity function. Researchers are therefore very interested to know what, and how, heating mechanisms act to suppress the formation of a continuous cooling gas phase in cluster cores, and also why the cluster population divides into two types: cool cores (CCs) and non-cool cores (NCCs).

One viable heating source comes in the form of feedback from active galactic nuclei (AGN) [4]. But while several robust models for heating the ICM via AGN feedback now exist, the details of the feedback loop remain unresolved. ICM entropy has proven to be a very useful quantity for understanding the process of AGN heating and its effects on processes such as star formation the suppression of prodigious cooling in CC clusters. ICM temperature, T, and density, ρ, primarily reflect the depth and shape of the dark matter potential well, and taken alone, they do not entirely reveal the thermal history of the ICM. But, in the context of entropy, $K = T\rho^{-2/3}$, one finds a more fundamental property of the ICM which is only altered by heating and cooling. Measuring entropy from X-ray data thereby gives a direct measure of a cluster's thermal history.

One method of parameterizing a cluster's radial ICM entropy profile is by fitting the simple function $K(r) = K_0 + K_{100}(r/100\ \mathrm{kpc})^\alpha$ to the entropy profile and taking the best-fit value of K_0 to be a quantification of the cluster's core entropy. This was the task undertaken in [5] for a *Chandra* archive-limited sample of 240+ galaxy clusters (≈ 13 Msec of data). Shown in Fig. 1 is the log-space distribution of the best-fit K_0 for the *Chandra* archival sample [6][1]). Utilizing the results from that archival study, [7] showed that below a K_0 of ≈ 30 keV cm^2, Hα emission and powerful radio emission ($L_{\rm radio} > 10^{41}$ erg s^{-1}) from the cluster BCG essentially turns-on, a similar result regarding star formation was found by [8]. Clusters in the low-K_0 part of the bimodal population are generally characterized by "relaxed" morphologies, bright compact cores, short central cooling times, strong CCs, line emission from the BCG, and radio-loud AGN. Clusters in the high-K_0 part of the bimodal distribution are generally hot, puffed-up, isothermal clusters with more merger systems than the low-K_0 population.

The characteristic entropy threshold ($K_0 \lesssim 30$ keV cm^2, shown in Fig. 1 by the far-left vertical dashed line) has subsequently yielded insight on the process of when, and possibly how, a multiphase medium can form in cluster cores. [9] hypothesized that the entropy threshold results from the influence of thermal electron conduction. [10] have also shown in their theoretical work that conduction is a possible explanation for the entropy threshold. [9] further propose that the bimodal K_0 distribution results from the effects of conduction whereby cooling in the core of clusters with

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

$K_0 \gtrsim 30$ keV cm^2 is dramatically slowed, and hence those clusters can be slowly removed via mergers and/or very powerful AGN outbursts from the $K_0 = 30 - 60$ keV cm^2 region and moved to higher K_0.

The importance of the galaxy cluster A1983 to this discussion is that it is an extraordinarily rare cluster which has a $K_0 \approx 30 - 60$ keV cm^2 (inferred from $K(r)$ profile shown in [11]) but has a CC and peaked central metal abundance (again using the profiles in [11]). Like all other clusters with K_0 between $30-60$ keV cm^2, *e.g.* the "gap" in the K_0 distribution, the BCG in A1983 is not detected in Hα ($L_{\mathrm{H}\alpha} < 0.2 \times 10^{40}$ erg s^{-1}) and has no associated radio emission ($L_{\mathrm{radio}} < 0.11 \times 10^{40}$ erg s^{-1}). But, unlike any other cluster in the gap, A1983 has a cool core and a highly peaked central ICM metal abundance [11]. It appears on the surface as though A1983 is currently the only example of a cluster which straddles the CC and NCC populations. Is that because the cluster is undergoing a transition from one population to the other? Does this cluster occupy a stage in the ICM entropy life-cycle which is short-lived yet very important if we are to understand the CC-NCC dichotomy?

A1983: An Odd Galaxy Cluster

The discussion presented below utilizes results presented in [11] from the analysis of *XMM-Newton* data, in addition to results from performing our own analysis of the same dataset. Does A1983 actually have a CC? The temperature of the gas within a radius of 50 kpc of the cluster center is $T_X(R < 50 \text{ kpc}) = 1.88 \pm 0.07$ keV, and the global cluster temperature (with the central 70 kpc excised) is measured to be $T_{cluster} \approx 3.2 \pm 0.4$ keV. Defining a CC cluster to have $T_X(R < 50 \text{ kpc})/T_{\mathrm{cluster}} < 1$ at $\geq 2\sigma$, A1983 solidly classifies as having a CC. In addition, the metal abundance profile peaks in the core with a value of $\approx 0.6 \pm 0.08$ $Z_\odot$. From the entropy profile presented in [11], A1983 unambiguously has a K_0 between $30 - 60$ keV cm^2, which lies squarely within the poorly populated gap of the bimodal K_0 population. Of the more than 240 clusters in *ACCEPT*, only 19 have a best-fit K_0 in this same range, and under the CC definition provided above, none of those 19 clusters have a CC and none has a centrally peaked abundance profile.

There is no detected Hα emission from the BCG of A1983 [12], and no detected radio source found in either the NVSS or VLA FIRST. The BCG is however detected as an [O II] $\lambda\lambda 3727, 3869$ emitter and Hδ-Hβ absorber [13]. Additionally, there is a very bright near-UV source detected by *GALEX* ($M_{\mathrm{NUV}} \approx -16$ mag) which is associated with the BCG. So while there is no detection of gas at $T \sim 10^4$ K (as indicated by the lack of Hα), the UV and optical spectral features suggest star formation is present in the BCG (or nascent AGN activity). For a cluster with $K_0 > 30$ keV cm^2, the properties outlined above are very odd and it may be the case that A1983's BCG has a very large corona [see [14] for a discussion of coronae], which acts like a "mini-cooling core." A1983 has one last odd feature: the *XMM-Newton* observation shows the X-ray isophotes to the west of the cluster center are compressed, suggesting the presence of ICM substructure, possibly in the form of a cold front or weak shock.

In some ways, A1983 appears to be a typical non-cool core cluster: a large surface brightness core, no Hα emission from the BCG, no radio emission in the cluster core, and an ICM feature which may be an indicator of recent merger or very energetic AGN feedback activity. But A1983 is an enigma in that it shares traits with cool core clusters: the distance between the location of the BCG and X-ray centroid is $< 5''$, a core temperature < 0.5 T_{virial}, a centrally peaked iron abundance, and the BCG may be forming stars or have a smoldering AGN. A1983 is already a rare object because it has a K_0 which places it in the gap of the bimodal core entropy distribution, but A1983 is the **only** cluster we know of with $K_0 = 30 - 60$ keV cm^2 and a cool core, making A1983 exceptionally rare.

Scientific Questions

A1983 may be an example of a cluster transitioning being from CC to NCC or vice versa.

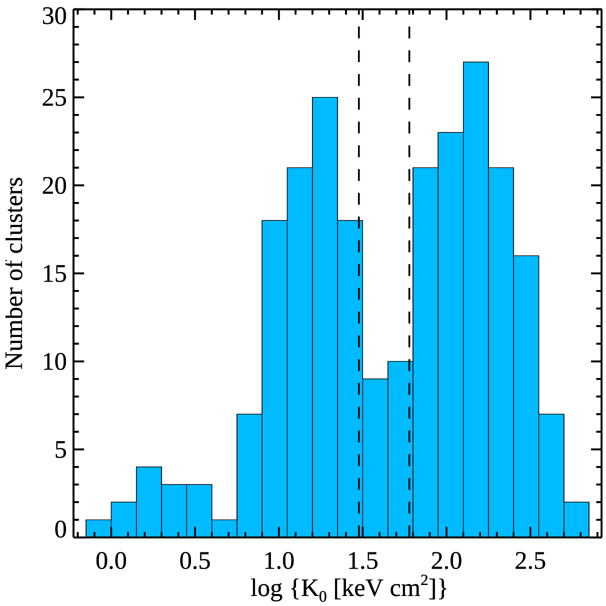

Figure 1: Log-space histogram of best-fit core entropy, K_0, for the current *ACCEPT* database. The dashed vertical lines bound the region $K_0 = 30 - 60$ keV cm^2.

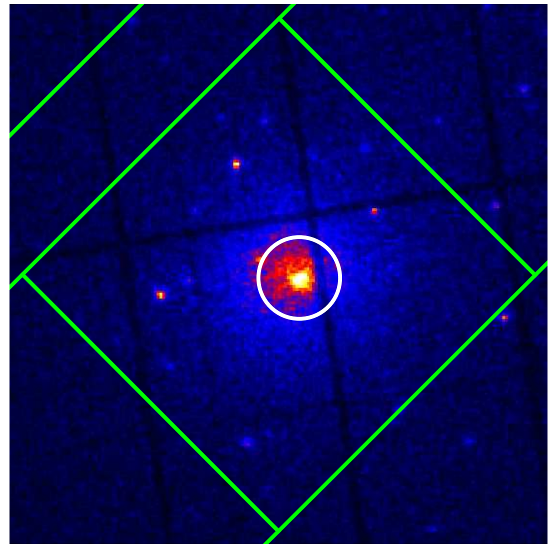

Figure 2: *XMM-Newton* image of A1983. Green square bounds the *Chandra* ACIS-S3 field of view and the white circle has radius 50 kpc.

How this processes proceeds is poorly understood, be it through mergers, very powerful AGN feedback (*e.g.* MS 0735.6+7421), or the prolonged influence of conduction. Studying this system in detail will yield insight into a long-standing question in cluster science: how and why does the cluster population divide nearly evenly between CC and NCC clusters?

The first question we'd like to address is: what is the temperature structure of the cluster core, specifically the inner 50 kpc? Is there multicomponent gas in the core? How is it possible that this high-K_0 cluster has a CC? Is there a distinct transition from hot ICM to cool BCG corona as has been seen in many other high-K_0 clusters? If the BCG corona can be discerned from the ICM, what are the corona's properties (temperature, abundance, density)? Are there bubbles in the ICM? If so, what are the energetics of the outburst which formed them? What do those energetics tell us about the past and future of the cluster and the supermassive black hole at the center of the BCG?

On the matter of the compressed western isophotes, we'd like to know if there is a cold front or shock. The presence of a cold front would serve as an excellent diagnostic of thermal conduction and diffusion in A1983's ICM. If instead there is a shock, this would yield interesting information regarding the energetics of a recent merger event or AGN outburst and if the CC is being disrupted, or possibly destroyed. Moreover, we'd like to know, can thermal conduction prevent gas cooling all the way into the core of the cluster? Is it possible that the CC is presently being heated efficiently by conduction and the core is effectively evaporating?

Improvements on *XMM-Newton* Analysis

We have analyzed the 32 ksec archival *XMM-Newton* observation taken 2002-02-14 by Arnaud. Within an aperture of R_{1000} we measure $\sim$ 15000 source counts for the flare-clean, point source clean events file. We measure a 90% confidence cluster $kT_X = 3.21 \pm 0.4$ keV sans the central 70 kpc (0.65 cts s^{-1}), and 2.22 ± 0.5 keV with the central 70 kpc (0.78 cts s^{-1}). The *XMM-Newton* resolution is insufficient to address the scientific questions we have put forward, to create radial profiles of the core region, and the observation lacks the signal-to-noise for 2D map creation.

Request for *Chandra* Observation

We request a 35 ksec ACIS-S observation of the galaxy cluster A1983 for the purpose of studying the cluster core with a specific focus on analyzing the dynamics and energetics encoded in the ICM. The *XMM-Newton* image of A1983 is shown in Fig. 2 with regions overlaid designating the *Chandra* field of view and the inner 50 kpc. *Chandra*'s high spatial resolution is ideally, and necessarily, suited for observing A1983. We are attempting to resolve features on scales of 5-10 kpc, and at $z = 0.044$, 10 kpc = $11.9''$ or 24 pixels at the resolution of the ACIS detectors. Using the background-subtracted *XMM-Newton* 0.3-6.0 keV count rate for a region extending to $R_{1000} \approx 620''$, an *XMM-Newton* determined global temperature of 2.2 keV, a *Chandra* energy window of 0.5-8.0 keV, for an extended source, and Galactic $N_{\rm H} = 1.79 \times 10^{20}$ cm^{-2}, PIMMS predicts a source count rate of 1.237 cts s^{-1} for the Cycle 12 ACIS-S detector responses. We have selected the ACIS-S detector because the combination of the low cluster temperature range ($kT_{\rm X} = 1.8 - 2.5$ keV) and larger soft energy ($kT_{\rm X} < 2$ keV) effective area of ACIS-S compared with ACIS-I results in an additional 15K counts during a 35 ksec observation.

Under the assumption of no time lost to flares, the requested exposure time is sufficient to yield 9 radial temperature bins containing $\approx$ 5000 counts each. Using the *XMM-Newton* $kT_{\rm X}$ profile as a guide, we simulated spectra in XSPEC using the Cycle 12 responses. Our requested observation enables us to measure temperatures within ± 0.2 keV for $kT_{\rm X} < 4$ keV and ± 0.5 keV for $kT_{\rm X} > 4$ keV. For the inner 50 kpc, the signal-to-noise (SN) will be sufficient to measure temperatures in 2D bins as small as $2.2.''$. The high-SN is vital for measuring properties of a BCG coronae, if one is found, which are typically faint and compact.

To investigate the presence of cold front(s) or shock(s), we will generate high-quality profiles for: temperature, abundance, density, and pressure. If either is found, the cold front(s) will be modeled in detail using the methods outlined in [15], while shock(s) will be modeled using the code of [16]. In addition, we will use profiles of gas mass, gravitating mass, and gas fraction to study the cluster dynamical state. We will then use the difference between the hard-band ($2.0_{\rm rest} - 7.0$ keV) & broad-band (0.7-7.0 keV) temperatures, which has been shown to be a good measure of the dynamical state of the cluster [17], to determine if the cluster has experienced a merger recently. We will also use a hardness ratio profile & map, which are equally good diagnostics of mergers [18], to probe dynamical state. Profiles for entropy, cooling time, effective conductivity, and inferred magnetic suppression factor will be utilized to constrain the physical processes which may be responsible for the cluster thermal state, *e.g.* conduction, shocks, or AGN feedback. Using weighted Voronoi tessellation [19] and contour binning [20] methods we will produce 2D temperature, entropy, density, pressure, and hardness ratio maps which will further illuminate the cluster thermal state and dynamics.

We are encouraged by our extensive experience with similar analyses that A1983, once imaged with *Chandra*, will yield interesting results and information regarding the CC-NCC dichotomy. How this unique, and ostensibly rare, object fits into the framework of cool core evolution may tell us about a very short-lived but very important stage of cluster formation.

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Previous *Chandra* Programs

Chandra General Observer Project, Cycle 10: "The Hyperluminous Infrared Galaxy IRAS 09104+4109: An Extreme Brightest Cluster Galaxy." A detailed study of IRAS 09104+4109 utilizing the 75 ks observation from Cycle 10 is presented in Cavagnolo et al. 2010 which has been submitted to ApJ for publication.

PI Cavagnolo maintains the Archive of Chandra Cluster Entropy Profile Tables (ACCEPT) database and is presently adding 68 new galaxy clusters (128 observations) to the existing 241 clusters currently in the database. As a result of maintaining the database, PI Cavagnolo has analyzed and reduced +684 CXO observations ($>$ 15 Msec of data) and +50,000 spectra.