THE HYPERLUMINOUS INFRARED GALAXY IRAS 09104+4109: AN EXTREME BRIGHTEST CLUSTER GALAXY

1 Introduction

In half of all clusters of galaxies, the gas in their cores has a radiative cooling time $< H_0^{-1}$. Thus, one expects layers of cooling, dense, low pressure gas to collapse under the high pressure, hot gas at larger radii initiating a flow of cool gas into the core ([11],[5]). In the cooling flow scenario, one also expects to find a continuum of gas temperatures in cluster cores down to fractions of an eV [12]. However, observations do not find gas at less than $\sim 1/3$ of the ambient cluster temperature and direct evidence, such as gas condensing out of the ICM, for the hypothesized cooling flows has never been found thus creating a "cooling flow problem" [19]. Some mechanism must be acting within cluster cores to retard a continuous cooling gas phase.

The "cooling flow problem" has a viable solution in the form of AGN feedback ([3],[21]), but the details of AGN feedback cycles and instigation are still unresolved [2]. Most models of AGN feedback rely on quenched cooling from heat supplied by kinetic energy generated from a central supermassive black hole (cSMBH) of the brightest cluster galaxy (BCG). Gas is dumped onto the cSMBH, which initiates an AGN feedback cycle, and is followed by ejection of high energy particles which create cavities in the X-ray gas ("bubbles"). The work done by these bubbles on the surrounding ICM, $W_{bubble} = pV$, goes into displacing ICM gas around and into the bubble wake where the gravitational potential energy is then released as enthalpy [4]. Heating of the ICM increases the entropy of the gas, but not necessarily its equilibrium temperature, which is primarily determined by depth of the gravitational potential. This overall heating and cooling cycle is imprinted on the cluster gas entropy, here defined to be $K \equiv kTn_{elec}^{-2/3}$, where T is the gas temperature and n_{elec} is the electron density ([20], [22]). The quantities T and n_{elec} can be measured from X-ray data thereby giving a direct measure of the cluster thermal history via entropy.

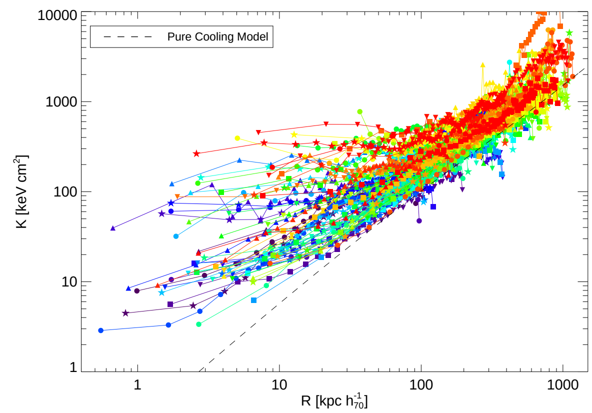

Figure 1: Plotted are the radial entropy profiles for 68 of the 200+ clusters in the PhD sample of Cavagnolo 2008 (in prep.). The curves are color coded purple=coolest to red=hottest. The coolest cluster in the sample is MKW4 at kT=2.06 keV and the hottest cluster is Abell 2163 at kT=12.1 keV.

Figure 1 shows the radial entropy profiles for a portion of the clusters analyzed in the PhD thesis work of Cavagnolo 2008 (in preparation), which is utilizing 200+ *Chandra* archival observations of clusters of galaxies to study their entropy profiles and distributions. The profiles show a marked resemblance irrespective of global cluster temperatures ranging from 2-12 keV. In this work, we have found a strong correlation of increasing central entropy with decreasing radio luminosity, indicating the AGN duty cycle is tied to the ICM entropy distribution.

2 IRAS 09104+4109: An Extreme BCG

At z $<$ 0.5 and $L > 10^{11}L_\odot$ the most common extragalactic objects are infrared galaxies. Among this population are a subset of ultraluminous infrared galaxies (ULIRGs) with $L_{IR} \geq 10^{12}L_\odot$, and an even more rare subset of hyperluminous infrared galaxies (HLIRGs) with $L_{IR} \geq 10^{13}L_\odot$. IRAS 09104+4109 classifies as a HLIRG with a $L_{IR} \approx 10^{13} L_{\odot}$. Most all ULIRGs and HLIRGs are interacting/merging spirals or relics of recent mergers. Unlike fellow HLIRGs, IRAS 09104+4109 is the BCG in the flattened, Abell richness class 2 cluster MACS J0913.7+4056. Even more peculiar is that unlike most all BCGs found in rich clusters, 99% of IRAS 09104+4109's bolometric luminosity comes longward of 1μm and peaks between 5-60μm [16]. This enormous IR luminosity is attributed to an obscured Seyfert type 2 AGN with a large dust torus lying between the broad-line and narrow-line regions ([13], [14]) and not to starbursts, as is the case for many luminous infrared galaxies. The fuel sources for the central AGN may be the optical nebular filaments and companion galaxies within 30kpc of the BCG which are being stripped of their gas and cannibalized [1]. The presence of dust within these filaments and substructures may rule out the hot intracluster medium as their origin ([18],[7]) because of the short sputtering time for dust in hot gas [10]. Of all objects in the IRAS catalog, 09104+4109 hosts the most powerful radio source, a borderline FRII/FRI with $P_{1.4GHz} = 3.2 \times 10^{24}$ W Hz^{-1}. Yet because of the steep radio spectrum and huge IR luminosity, the radio source would be classified as "quiet" at higher frequencies. [14] conclude the radio source has undergone a recent (< 70 kyr) merger event or cataclysmic occurrence which has altered the beaming direction of the central AGN. As a result, the radio lobes are no longer receiving power from the AGN and a new jet axis has been established. In addition, only three other objects in the IRAS catalog are comparable to 09104+4109 in luminosity and they all lie at redshifts which would require very long exposure observations to attain spectroscopic quality signal to noise: IRAS 15307+3252 (z=0.93), IRAS 16347+703 (z=1.334), and IRAS 10214+4724 (z=2.29).

2.1 Bubbles in IRAS 09104+4109

We were surprised to find a probable X-ray cavity $\approx$ 30 kpc NW of the BCG in a cluster at z> 0.4. The highest redshift bubble published to date is in RBS 797 at z=0.350 [17]. The X-ray decrement was mentioned in passing by the PIs of the first *Chandra* observation, §3.1 in [15]. Analysis of the publicly-available, low-resolution radio data from VLA First reveals a suggestive alignment of the NW radio jet and the observed X-ray decrement (Fig. 2). X-ray emission in the opposite direction and on the opposing side of the nuclear region is also suspiciously flat and coincident with the other pole of the radio jet. We suggest the NW decrement is the stem of a larger bubble and the SE plateau results from interaction of the ICM with another large bubble. The detection of dust in the environment surrounding these two features indicates shocking is not playing a major role in heating of the gas. This supports the case for bubbles rather than chance superposition of shocked regions because the rims of bubbles are dense and cold, not dense and hot as would be the case with shocks. Coincidence of the radio jets and two prominent X-ray features is an unlikely chance projection of overdense regions which have no underlying physical connection. If confirmed, these would be the highest redshift bubbles found to date.

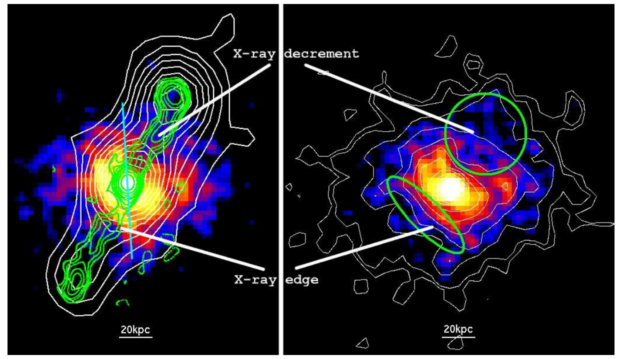

Figure 2: The left panel shows the existing *Chandra* data with low resolution 20 cm VLA First contours (white), high resolution 20 cm VLA contours from [13] (green), and the new AGN outflow axis as determined from the bipolar ionization cone discussed in [14] (light blue line). The right panel shows the same *Chandra* image with X-ray contours and green elliptical regions highlighting X-ray surface brightness decrement and X-ray surface brightness edge.

Bubbles are a way of indirectly studying heating of the ICM by AGN, and in the case of IRAS 09104+4109 we have the chance to see how a rare and peculiar object fits into the now widely used model of quenching cooling in clusters by AGN feedback.

2.2 Scientific Questions

Calling the 100 kpc around IRAS 09104+4109 lively is an understatement. The flurry of activity surrounding the AGN combined with a peculiar amalgam of physical properties makes IRAS 09104+4109 a rare, interesting, and extreme object. One can ask many questions about the large scale structure of this object. In Figure 1, clusters with the lowest central entropy have the most luminous radio sources; the radio source in IRAS 09104+4109 is undergoing a transition from powerful FRII to being mostly radio-quiet/FRI and thus we would expect the radial entropy distribution slope to be relatively flat and bare a resemblance to other radio-quiet clusters, e.g. [8]. But, this object is no where near as relaxed as other radio-quiet clusters and based on the X-ray morphology we would expect the entropy profile to be steeper, resembling other "dynamic" clusters, such as 2A0335+096 or Abell 2029 [9]. So we ask:
1) To which regime does the cluster housing IRAS 01904+4109 more closely belong, radio-quiet or dynamically active? Can we definitively classify this object as being in a short lived and elusive transitional phase of galaxy, cluster, and AGN evolution?
2) Has the change in beaming direction of the radio source created multiple bubbles?
3) What can the energetic properties of these bubbles tell us about the connection between the present phase of AGN feedback and epochs of feedback which may have occurred long prior and have now deposited their energy at large radii thus changing the entropy structure there?
4) Knowing of a recent change in the dynamics of the radio source, can we detect this change by comparing the 2-dimensional entropy and pressure structure at r $<$ 70 kpc of the AGN and r $>$ 70 kpc?
– The duty cycle of AGNs is believed to be $\sim 10^8$ yr, do we find signatures of previous feedback cycles at large radii to constrain the feedback timescale and compare it with other clusters?
Answers to these questions require resolving the extended X-ray emission at radii greater than 70 kpc which we cannot do with the existing *Chandra* observation.

3 Proposed Research

3.1 Why not use existing data?

Using CIAO 3.4.1.1 and CALDB 3.3.0.1, we analyzed the existing ACIS-S3 observation taken 1999-11-03 by Fabian, which was originally used to examine reflected X-ray emission of the AGN [15]. The nominal 9.1 ks exposure shows contamination by two strong flares which reduce the usable exposure time to $\approx$5 ks. However, there is an additional long duration, soft flare which is not associated with the local soft X-ray background which contaminates the remaining exposure time. Only by addition of a cut-off power law to the background during spectral fitting are we able to constrain a temperature for this object, otherwise we find no upper bound on the temperature. This additional background component also introduces an unwanted systematic into the spectral analysis which can create misleading results.

While this observation serves the purpose of analyzing the bright nuclear point source well enough, it is ill-suited for studies of extended emission because the extended emission is poorly resolved for so short a usable exposure time and temperature measures are poorly constrained in radial bins smaller than 70 kpc. Within an aperture of r_{2500} we find, after background subtraction, 8,500 cts. This total is insufficient to create more than two radial temperature bins, and the signal-to-noise is far too low to create 2D temperature, entropy, or pressure maps. We are able to measure a global temperature of $8.06^{+3.25}_{-2.02}$ keV without the central 50 kpc (0.697 cts/s), and $5.45^{+1.31}_{1.05}$ keV with the central 50 kpc (0.888 cts/s), both at 90% confidence. We are unable to resolve any extended emission or spatial features beyond the central $\approx$ 70 kpc.

3.2 Request for new observation

We therefore request a new 50 ks observation of this object for the purpose of resolving gas features and attaining more counts from extended emission at r $>$ 70 kpc, with a specific focus on analyzing X-ray cavities, their association with radio emission and entropy distribution. Chandra's high spatial resolution is perfectly suited for observing IRAS 09104+4109. We are attempting to resolve features on scales of 10kpc and up: at z= 0.442, 10 kpc=1.75$''$ or 3.5 pixels at the resolution of the ACIS detector. The outer edge of the NW radio lobe, which is the maximum outer edge of any bubble we may find, lies at 100 kpc from the nuclear point source and for the SE radio lobe 90 kpc. Using the count rate for the core excised region (since our focus is not AGN properties), a temperature of 8.06 keV, an energy window of 0.7-7.0 keV (which avoids the soft energy effective area and quantum efficiency variations, hard particle background, and small effective area at E $>$ 9 keV) and $N_H = 1.36\times10^{20}$ cm^{-2}, PIMMS predicts a count rate of 0.698 cts/s for Cycle 9 which is consistent with our present analysis.

Under the assumption of no flares, the requested exposure time is sufficient to yield seven radial temperature bins containing $\approx$ 5000 cts each, which will allow us to measure temperatures within +/- 0.3 keV for $kT_{gas} < 4$ keV and +/- 0.7 keV for $kT_{gas} > 4$ keV. These temperature bins combined with surface brightness will then be used to construct a high resolution radial entropy profile to answer the first of our scientific questions, is the cluster containing IRAS 09104+4109 more like radio-quiet clusters or dynamically active clusters? Using the adaptive binning code of [6], we will also construct 2D temperature, entropy, and pressure maps to answer the questions regarding the change in dynamics of the AGN. For the inner 70 kpc the signal-to-noise will be sufficient to measure temperatures in bins as small as 3$''$. We will also use measured densities and temperatures to calculate bubble pressures and consequently the pV work done inflating these bubbles. These energetics calculations can then be used to analyze the AGN feedback mechanism.

We are encouraged by our previous experience with similar analyses that IRAS 09104+4109, once adequately exposed, will yield interesting results. How this unique and extreme object fits into the framework of AGN feedback may tell us about a very short-lived but highly active stage of cluster formation and of the formation of the central galaxy.

References

[1] Armus et al. *Ap&SS*, 266:113–118, 1999.

[2] Babul et al. *MNRAS*, 330:329–343, 2002.

[3] Binney et al. *MNRAS*, 276:663–+, 1995.

[4] Bîrzan et al. *ApJ*, 607:800–809, 2004.

[5] Cowie et al. *ApJ*, 215:723–732, 1977.

[6] Diehl et al. *MNRAS*, 368:497–510, 2006.

[7] Donahue et al. *ApJL*, 414:L17–L20, 1993.

[8] Donahue et al. *ApJL*, 630:L13–L16, 2005.

[9] Donahue et al. *ApJ*, 643:730–750, 2006.

[10] Draine et al. *ApJ*, 231:77–94, 1979.

[11] Fabian et al. *MNRAS*, 180:479–484, 1977.

[12] Ferland et al. *MNRAS*, 266:399–+, 1994.

[13] Hines et al. *ApJ*, 415:82–+, 1993.

[14] Hines et al. *ApJ*, 512:145–156, 1999.

[15] Iwasawa et al. *MNRAS*, 321:L15–L19, 2001.

[16] Kleinmann et al. *ApJ*, 328:161–169, 1988.

[17] Schindler et al. *A&A*, 376:L27–L30, 2001.

[18] Tran et al. *AJ*, 120:562–574, 2000.

[19] Voit et al. *ApJ*, 452:164–+, 1995.

[20] Voit et al. *ApJ*, 576:601–624, 2002.

[21] Voit et al. *ApJ*, 634:955–963, 2005.

[22] Voit. *Reviews of Modern Physics*, 77:207–258, 2005.