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

1. Introduction

The central cooling time of the intracluster medium (ICM) in many clusters of galaxies is $\ll H_0^{-1}$. An expected consequence of this short cooling time is that massive cooling flows, $> 100 \mathrm{M}_\odot \ \mathrm{yr}^{-1}$, should form [**?**], but these ~~torrential~~ flows have instead turned out to be trickles [**?**] with the hot ICM never getting lower than $1/3 T_{\mathrm{virial}}$. In recent years, this "cooling flow problem" has been the focus of much study as the solutions ~~should~~ have broad impact in the areas of galaxy formation, e.g. explaining ~~truncation at~~ the ~~low- and~~ high-mass end~~s~~ of the galaxy luminosity function. The cluster community is converging on agreement regarding what mechanisms act to retard the formation of a continuous cooling gas phase in cluster cores.

The viable heating source comes in the form of feedback from active galactic nuclei (AGN) [**?**]. But while several robust models for heating the ICM via AGN feedback now exist, the details of the feedback loop remain unresolved. Most models of AGN feedback quench cooling by heating the ICM with kinetic or mechanical energy supplied by the central supermassive black hole (~~c~~SMBH) of the brightest cluster galaxy (BCG). Cool gas is channeled onto the ~~c~~SMBH, an AGN feedback cycle is initiated, and the ejection of high energy particles carve out cavities/bubbles in the ICM. The work then done by these bubbles on the surrounding ICM goes into displacing ICM gas around and into the bubble wake where the gravitational potential energy is then released as enthalpy [**?**].

ICM entropy has proven to be a very useful quantity for understanding this process of AGN heating and its effects on ~~ancillary~~ processes such as star formation. 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 put in the context of entropy, $K = T\rho^{-2/3}$, we have a more fundamental property of the ICM which is only affected by heating and cooling. Measuring entropy from X-ray data thereby gives us a direct measure of the cluster thermal history. Recalling that a system is convectively stable only when $dK/dr \geq 0$, we can ~~observationally exploit~~ gravitational potential wells as giant entropy sorting devices. For example, departures from a radial power-law entropy distribution are indicative of past heating and cooling of the ICM.

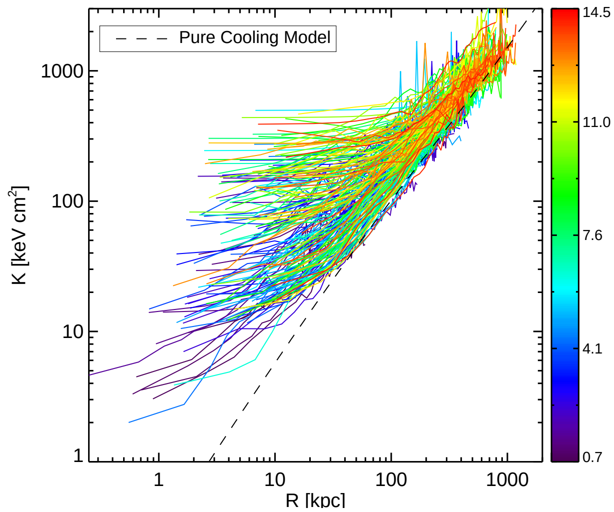

Figure 1: Plot of entropy, $K(r) = Tn_{elec}^{-2/3}$, versus physical radius for the 208 clusters from [**?**]. The observed range of core entropy is consistent with models of AGN feedback. Color coding is for global cluster temperature in keV.

Figure 1 shows the radial entropy profiles for 208 clusters analyzed in the Ph.D. thesis of PI Cavagnolo. These profiles were derived using 272 *Chandra* archival observations with a nominal total exposure time of ~ 9 Msec. The profiles show a marked resemblance irrespective of global cluster temperatures ranging from 1-15 keV. From this extensive entropy project we have found that indicators of feedback, such as radio-loud sources assumed to be AGN related and Hα emission from star formation, are correlated with low (< 30 keV cm^2) core entropy [**?**]. The importance of IRAS 09104+4109 ~~to these results~~ is that we suspect it is an object which doesn't fit neatly into the AGN feedback models, and as such, a detailed study of this peculiar system will be important for further understanding how feedback couples to the processes of star formation, BCG assembly, and heating of the ICM.

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 rare hyperluminous infrared galaxies (HLIRGs) with $L_{IR} \geq 10^{13} L_{\odot}$. IRAS 09104+4109 falls into the category of HLIRG. 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. 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 [**?**] and not to starbursts, as is the case for many luminous infrared galaxies. 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 unreasonably long exposures to attain spectroscopic quality signal to noise: IRAS 15307+3252 ($z = 0.93$), IRAS 16347+703 ($z = 1.33$), and IRAS 10214+4724 ($z = 2.29$).

The fuel for the central AGN in IRAS09104 may be the optical nebular filaments and companion galaxies within 30 kpc of the BCG which are being cannibalized [**?**]. Dust embedded in hot gas has a short sputtering time, thus the presence of dusty, substructure laden filaments likely rules out the hot ICM as the filament origins [**? ?**].

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. [**?**] conclude the radio source has undergone a recent (≈70 kyr) merger or cataclysmic event 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. Adding to the mystery of this object is that the nuclear absorber may have flipped from Compton-thick to -thin in the last decade making IRAS09104 the only "changing-look" AGN ever observed [**?**].

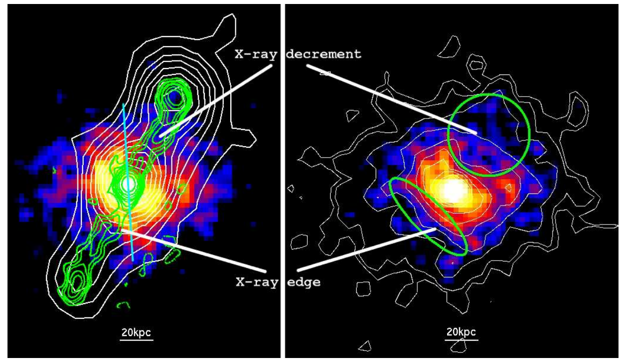

Figure 2: The left panel shows the existing *Chandra* data with low resolution 20 cm *VLA* contours (white), high resolution 20 cm *VLA FIRST* contours (green), and the new AGN outflow axis as determined from the bipolar ionization cone discussed in [**?**] (cyan line). The right panel shows the same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

3. Bubbles in IRAS 09104+410

We were surprised to see what is most likely an X-ray cavity $\approx$ 30 kpc NW of the BCG in a cluster at $z > 0.4$. The X-ray decrement in IRAS09104 was mentioned in passing by the PIs of the first *Chandra* observation (§3.1 of [**?**]). 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 (see 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 highest redshift bubbles observed to date are in RBS 797 at $z = 0.350$, a cluster which was awarded 40 ks of additional time in Cycle 9.

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, peculiar, and low mass object fits into the now widely used model of quenching cooling in clusters by AGN feedback. The detection of dust in the environment surrounding the two X-ray features indicates shocking is not playing a major role in heating of the gas. The presence of dust espouses the case for bubbles, as opposed to a 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 unlikely to be a chance projection of overdense regions which have no underlying physical connection. If confirmed, these would be the highest redshift bubbles found to date.

4. 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 should ask many questions about the large and small scale structure of this object.~~ The radio source in IRAS 09104+4109 is undergoing a transition from a powerful FRII to a mostly radio-quiet/FRI; thus we would expect the radial entropy distribution slope to be relatively flat and resemble other radio-quiet clusters, e.g. Abell 1650. But, IRAS09104 is no where near as relaxed as other radio-quiet clusters and based on the X-ray morphology we expect the entropy profile to be steeper, resembling other "dynamic" clusters, such as A0335+096 or Abell 2029. Thus 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 sets of bubble pairs?
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?
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 and $r > 70$ kpc?
5. Is the power output of the AGN (as measured by bubbles) large enough to quench cooling and shutdown star formation in the BCG?
6. What is the radiative efficiency of the AGN jets?
7. The duty cycle of AGN is believed to be $\sim 10^8$ yrs. Do we find signatures of previous feedback cycles at large radii to constrain the feedback timescale and compare it with other clusters?
8. What is the absorbing Compton thickness of the nuclear source using the Fe Kα line as the primary diagnostic? Does this confirm the "changing-look" nature of the AGN?

Answers to these questions require resolving the extended X-ray emission at radii greater than 70 kpc and having more counts from the core, both of which are not satisfied by the existing *Chandra* and *XMM-Newton* observations.

5. Proposed Research: Why not use existing data?

Using CIAO 3.4 and CALDB 3.4.2, we analyzed the existing ACIS-S3 observation taken 1999-11-03 by Fabian [**?**]. The nominal 9.1 ksec exposure shows contamination by two strong flares which reduce the usable exposure time to ≈ 5 ksec. However, there is an additional long duration soft flare contaminating 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. This additional background component also introduces an unwanted systematic into the spectral analysis which results in larger uncertainty.

While this observation serves the purpose of analyzing the very bright nuclear point source well enough, it is ill-suited for studies of extended emission. Within an aperture of r_{2500} we find 8,500 background-subtracted source counts. 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 ≈ 70 kpc.

6. Request for new observation

We request a new 75 ksec observation of this object for the purpose of resolving ICM features beyond the central 70 kpc, with a specific focus on analyzing X-ray cavities associated with the AGN, threshing out the energetics of the radio-ICM interaction, and deriving the radial entropy distribution. *Chandra*'s high spatial resolution is ideally, and necessarily, suited for observing IRAS 09104+4109. We are attempting to resolve features on scales of 5-10 kpc, and 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 likely the maximum outer edge of any bubble we may find, lies at 100 kpc from the nuclear point source and 90 kpc for the SE lobe. Using the count rate for the core excised region, a temperature of 8.06 keV, an energy window of 0.7-7.0 keV, an extended emission area of $\approx$ 80K arcsec^2, and $N_{HI} = 1.36 \times 10^{20}$ cm^{-2}, PIMMS predicts a count rate of 0.538 cts/s for Cycle 10 which is consistent with our present analysis.

Under the assumption of no flares, the requested exposure time is sufficient to yield eight radial temperature bins containing ≈ 5000 counts each. This will enable us to measure temperatures within ± 0.2 keV for $kT < 4$ keV and ± 0.3 keV for $kT > 4$ keV. These temperature bins combined with surface brightness profiles will then be used to construct high-resolution radial density, pressure, entropy, and mass profiles 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 [?], 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 $1.5''$. We will also use measured densities and temperatures to calculate bubble pressures and consequently the pV work done inflating these bubbles. These energetics calculations will then be used to analyze the AGN feedback mechanism and ICM heating.

We are encouraged by our extensive 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 very important stage of cluster and BCG formation. It will also provide interesting constaints of radiative efficiency, power output, and quenching of cooling in low mass systems, a study of which has not been done to date.

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