X-ray Point Sources and Radio Galaxies in Clusters: Source of Distributed Heating of the ICM?

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Abstract. In our ongoing multi-wavelength study of cluster AGN, we find ≈75% of the spectroscopically identified cluster X-ray point sources (XPS) with \( L_{0.3-8.0 \text{keV}} > 10^{42} \text{ergs s}^{-1} \) and cluster radio galaxies with \( P_{1.4 \text{GHz}} > 3 \times 10^{23} \text{W Hz}^{-1} \) in 11 moderate redshift clusters \( 0.2 < z < 0.4 \) are located within 500 kpc from the cluster center. In addition, these sources are much more centrally concentrated than luminous cluster red sequence (CRS) galaxies. With the exception of one luminous X-ray source, we find that cluster XPSs are hosted by passive red sequence galaxies, have X-ray colors consistent with an AGN power-law spectrum, and have little intrinsic obscuring columns in the X-ray (in agreement with previous studies). Our cluster radio sources have properties similar to FR1s, but are not detected in X-ray probably because their predicted X-ray emission falls below our sensitivity limits. Based on the observational properties of our XPS population, we suggest that the cluster XPSs are low-luminosity BL Lac objects, and thus are beamed low-power FR 1s. Extrapolating the X-ray luminosity function of BL Lacs and the Radio luminosity function of FR 1s down to fainter radio and X-ray limits, we estimate that a large fraction, perhaps all CRSs with \( L > L^* \) possess relativistic jets which can inject energy into the ICM, potentially solving the uniform heating problem in the central region of clusters.

Keywords: Galaxy clusters, radio galaxies, X-ray AGN

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INTRODUCTION

Observations of galaxy clusters have provided important clues about the formation and evolution of stars, galaxies and AGN in these systems. And based upon the observed correlation between supermassive Black Hole mass and galaxy bulge mass, we expect that there should be numerous AGN in the bright ellipticals in rich clusters as well. Radio-loud AGN have been directly implicated in cluster ICM heating because evacuated “bubbles” in the diffuse X-ray emitting gas have been observed that are spatially coincident with non-thermal radio emission. But what about other non-BCG radio-loud galaxies? Is there a connection between cluster radio galaxies and the X-ray AGN population? What is the spatial distribution of this combined population?

To answer these questions we present a multi-wavelength study of cluster AGN that differs from many previous studies (e.g. \cite{1, 2}) that use X-ray or radio observations, but not both, to detect AGN in only one waveband. Most cluster AGN studies have either employed clusters in a flux-limited survey or simply selected clusters based upon availability. However, since most flux-limited surveys tend to detect the most luminous clusters at higher-\( z \), this selection naturally identifies more evolved structures at earlier
times. This mismatch can result in comparisons which can obscure any true evolution, since more massive clusters are placed at the beginning of the evolutionary sequence and less massive objects at the end. We describe a unique cluster selection method below which avoids the difficulty just described and present a summary of our first results.

SAMPLE SELECTION

Guided by hydrodynamical simulations to track the growth of massive cluster halos \((M > 10^{15} M_\odot)\) from \(z \approx 1\) to the present epoch, we have used the temperature of the ICM as a proxy for cluster mass and have selected eleven \(0.2 < z < 0.4\) clusters that are predicted to evolve into objects like the present-day Coma Cluster (\(kT = 8.2 \pm 0.2\) keV). These 11 clusters are MS 0440.5+0204, Abell 963, RX J0952.8+5153, Abell 2111, MS 1455.0+2232, Abell 1758, MS1008.1-1224, MS2137.3-2353, Abell 1995, MS1358.4+6245, and Abell 370. Our unique method attempts to select clusters of similar mass at a given redshift and thus these clusters on the “Road to Coma” will be used for consistent evolutionary comparisons later. At \(z = 0.3\), the ICM temperature of a Coma Cluster progenitor is predicted to be \(7.0 \pm 2.6\) keV where the temperature spread is due partly to the modest number of realizations of Coma Cluster mass-scale objects in these simulations. The details of the cosmological simulations (similar to [3] and includes preheating of the ICM [4]) will be described in a future publication.

MULTI-WAVELENGTH DATA

We re-analyzed archival *Chandra* observations with adequate exposure times to detect XPSs with \(L_X > 10^{42}\) ergs s\(^{-1}\). XPSs were identified with the CIAO program *wavdetect*. Net XPS counts (0.3-8.0 keV) were estimated within the 95% encircled energy radius and converted to X-ray fluxes by assuming a power-law spectral index of \(\Gamma = 1.7\) \((N_E \propto E^{-\Gamma})\). We have augmented radio survey data (e.g., NVSS, FIRST) with an analysis of new and archival VLA 20cm continuum images to detect radio galaxies with \(P_{1.4GHz} > 3 \times 10^{23}\) W Hz\(^{-1}\) across the entire survey. This limit allows the detection of many lower radio power FR I sources while excluding the lower luminosity radio sources due to star formation (\(P_{1.4GHz} < 10^{22.75}\) W Hz\(^{-1}\), [5]).

Two-color images and/or photometry are publicly available from SDSS, CNOC [6], and/or *ChaMP* [7]. We obtained new optical images (Sloan \(g,r,i\)) of one cluster at Apache Point Observatory (APO). For candidate cluster AGN without published redshift and/or spectra, spectroscopic observations also were obtained for all objects with Sloan \(r < 20.8\) using the APO 3.5m with the Double Imaging Spectrograph (DIS-II), which provides complete spectral coverage from 3700–9000 Å. Spectra for radio galaxies and XPSs are complete to \(M_r < -20.8\) (\(M_r \approx -20.8\)). We define passive galaxy spectra as those showing only stellar absorption lines (e.g., the 4000Å Ca break, Mg I\(b\), Na I), while active galaxy spectra have detectable emission lines (e.g., H\(\alpha\), [O III], etc. with [O III]5007 Å > H\(\beta\)). We do not find any example of a starburst optical spectrum (strong emission lines with [O III]5007 Å \(\approx\) H\(\beta\)) among either the radio galaxies or XPSs.
FIGURE 1. (Left) Composite Color Magnitude Diagram for 11 clusters with 0.2 < z < 0.4: The color difference is the difference between the mean CRS and the observed value. The vertical dashed line marks $M_r^* = -20.8$. The horizontal dashed lines display the typical 3σ spread in CRS colors. Notice that the majority of cluster radio galaxies and XPSs lie on or near the cluster red sequence (CRS), with the exception of sources A and D. (Right): X-ray Luminosity versus Radio Power for cluster radio galaxies and XPSs compared to typical FR 1 galaxies, “core” elliptical galaxies, and Seyfert galaxies.

RESULTS

Within 1 Mpc of the cluster X-ray emission centroid, we find 8 XPSs with $L_{0.3-8.0 keV} > 10^{42}$ ergs s$^{-1}$ and 20 radio galaxies with $P_{1.4 GHz} > 3 \times 10^{23}$ W Hz$^{-1}$, confirmed to be cluster members and have $M_r < -20.8$. Figure 1 (left) displays the composite color magnitude diagram for our 11 clusters. The majority of cluster radio galaxies lie on the CRS, as expected since they are known to reside in passive galaxies [5]. The letter identifiers (A–H) refer to our eight cluster XPSs in decreasing X-ray luminosity order. Two cluster XPSs (sources A and D) are much bluer than the CRS. Source A has an optical spectrum consistent with a Seyfert nucleus (with emission-line luminosity of [OIII] $>>$ Hβ). On the otherhand, Source D is several tenths of a magnitude bluer than the red sequence, but, nonetheless, possesses a passive absorption line spectrum. A composite X-ray spectrum of the 7 XPSs (not including Source A) can be fit with a power-law spectrum with $\Gamma = 1.6 \pm 0.2$ with no evidence for intrinsic absorption and are are hosted by luminous red galaxies with no evidence for typical Seyfert-like emission signatures.

A cumulative radial distribution plot reveals that $\approx 75\%$ of our cluster radio galaxies and XPSs are located within 500 kpc of the cluster center, compared to 40% of the CRS galaxies within the same radius. A two-sided K-S test between the full X-ray + radio population and the CRS galaxy population as a whole are inconsistent with being drawn from the same parent population at $> 99.999\%$ confidence level (K-S D-statistic = 0.36 and probability = $3.3 \times 10^{-6}$). Within 500 kpc 16 radio galaxies and 4 XPSs make up
8±2% of the bright \(L > L^* \approx 265\) CRS galaxies. Our result strongly suggests that the triggering of a radio-loud AGN or an XPS in these cluster galaxies is due to some, as yet undetermined, mechanism related to the ICM density such as in the Bondi accretion model of Allen et al. [8]. Additionally, these non-central cluster AGN sources could provide a naturally distributed source of heating of the ICM.

Figure 1 (right) displays \(L_X\) versus \(P_{1.4GHz}\) for our cluster radio galaxies and XPS, as well as for typical FR 1s [9], “core” ellipticals [10], and Seyfert galaxies [11]. With the exception of three sources our cluster radio galaxies and XPSs rarely overlap with our luminosity limit. Within our survey limits our cluster radio galaxies are consistent with the X-ray/radio luminosities of FR 1s. However, if our cluster XPSs were also FR 1s, we would have detected them in our radio survey. The XPSs appear to have X-ray luminosities and radio power limits consistent with Seyferts, except that the XPSs have no evidence for obscuration in the optical nor in X-rays. However, Source D has an optical color that is \(\sim 0.5\) mag bluer in (g-r) than its associated CRS suggesting a possible power-law AGN excess. We suggest that the properties of our cluster XPSs are very similar to low luminosity BL Lac Objects of the class now called “High-energy-Peak” BL Lacs (or HBLs) (see [12]).

Within 500 kpc we use our detected number of cluster radio galaxies with \(P_{1.4GHz}>3\times10^{23}W\text{ Hz}^{-1}\) and CRS galaxies with \(L>L^*\) to extrapolate the RLF of radio galaxies [13] to \(P_{1.4GHz}>10^{21.5}W\text{ Hz}^{-1}\). We estimate that \(\approx85\%\) of all \(L>L^*\) CRS galaxies are radio-loud. Similarly, using our cluster XPS numbers, we extrapolate the XLF of HBLs [14] to \(L_X>10^{40}\text{ ergs s}^{-1}\) to find that all virtually all \(L>L^*\) CRS galaxies host an XPS. Thus, we conclude that both the XPSs and the radio sources are most readily identified as radio-loud AGN with jets which can transfer heat into the surrounding ICM.

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