The Intracluster Medium in Quasar Host Clusters

The association of quasars with galaxies at similar redshifts allows one to use quasars as markers in locating galaxies and galaxy clusters at moderately high redshifts. This provides one of the most efficient ways to form samples of galaxies and clusters for studies of their evolution. Extensive optical imaging surveys of fields around quasars have yielded a significant number of rich clusters of galaxies associated with radio-loud quasars (RLQs) at $0.2<z<0.8$, providing a large and unique sample of high-redshift galaxy clusters.[1] More rarely, radio-quiet quasars (RQQs) can be found in clusters. We propose to complete our program to obtain high resolution X-ray images of a sample of quasar host clusters at $z<0.7$ to address two major scientific goals. First, the addition of X-ray data to our extensive radio and optical imaging and spectroscopy will enable us to delineate the roles played by the intracluster medium (ICM) in the sustenance and evolution of quasar activity and in determining quasar radio emission and morphology. Second, these data will allow us to compare the X-ray properties of clusters hosting AGN of different radio and optical luminosities with clusters over the same redshift range discovered using other techniques, providing a broad database for the study of galaxy cluster evolution.

It is well established that environment plays a strong role in the triggering and evolution of quasar activity. The quasar population in rich clusters evolves 5–6 times faster than the quasar population in poor environments,[2] such that at $z>0.55$ bright *and* faint RLQs are found in rich clusters, while at $z<0.55$ *only* faint RLQs are found in rich clusters. This evolution may be extrapolated to include very faint AGN activity in radio galaxies in rich clusters.[3] This implies that the physical conditions in quasar host clusters have undergone substantial changes on a dynamical time scale, causing the fading of quasar activity in the cluster centers. Several scenarios may explain this relationship between AGN activity and cluster environment.

One model[4,5] suggests that quasar activity occurs in clusters with a low density ICM ($\lesssim 10^{-4}$ cm^{-3}), where stripping is less effective and more interstellar gas may remain within the host galaxy as fuel. Two lines of evidence suggest this possibility. First, the brightest RLQs in clusters have the classical double-lobed FRII morphology[6] which, at low redshift, is almost always found in poor environments. Second, many of these clusters have blue galaxies in their cores, suggesting that stripping by the ICM has not reached an efficient stage in them. Measuring quasar host clusters' X-ray emission will allow us to compare their ICM densities to those of normal clusters.

An alternative scenario suggests merging as the chief mechanism for triggering and maintaining quasar activity. This model predicts that quasar host clusters are less evolved dynamically and are not virialized.[7] Spectroscopy of quasar host cluster galaxies yields cluster velocity dispersions which are significantly lower than for normal Abell clusters, in support of this model.[8] Quasar host clusters also have very high core galaxy densities, consistent with a high merger rate if the clusters are still dynamically young. X-ray morphology of the clusters may also provide us with information concerning the stage of the dynamical evolution of these clusters. If the clusters are dynamically young and have high merger rates, then we would expect to see mostly irregular X-ray emission,[9] but high core density is normally associated with the regular X-ray morphology of evolved clusters. Thus, quasar host clusters may form a distinct morphological group.

Cooling flows are another mechanism for fueling quasars which predicts the existence of quasars in the centers of rich clusters.[10] X-ray observations directly test this model, since X-ray detections or upper limits provide uncomplicated estimates or upper limits for the electron number density, which determines the cooling time in the clusters and thus the presence or absence of cooling flows. This model also requires that the clusters have regular X-ray morphologies and high core densities, in contrast to merger-induced activity which predicts irregular X-ray morphologies.

The X-ray data available to date[11,12,13] is shown as the solid squares in Fig. 1 (see also Table 1). The three RLQ host clusters observed so far are either normal or underluminous compared to X-ray selected clusters, but two very rare examples of luminous RQQs in rich clusters have cluster X-ray luminosities much greater than expected for their optical richnesses. These two objects, H1821+643 and IRAS 09104+4109, are exceptional in many ways: they are definitely RQQs[14] and yet have the richest quasar host clusters known at any redshift, clusters which are among the most X-ray luminous known. Both objects are IR-luminous, reside in giant elliptical galaxies, have radio morphologies and powers intermediate between FR I and FR II, and are embedded in clusters with smooth X-ray morphologies and cooling flows of $\sim 10^3$ $M_{\odot}$/yr.[12,13]

The admittedly scarce data fit a scenario where RLQs thrive in young clusters with low velocity dispersions *and* ICM densities. When such clusters virialize, the galaxy-galaxy interaction rate declines and the RLQs fade from lack of fuel. (3C 206 resides in an unusual young low-redshift cluster in this scenario.) We suggest that these two luminous RQQs in rich clusters were once RLQs. As their host clusters virialized, their fuel supply dwindled and they began to fade, but the unusual X-ray overluminous clusters developed very strong cooling flows, which replaced galaxy interactions as the quasars' fuel source. Indeed, except for their large optical luminosities, these two objects seem to be just more extreme examples of cooling-flow radio sources.[9,15] Their high optical luminosities may be simply be due to additional fuel from an unusual recent interaction or merger, as hinted by the large IR luminosities, but another possibility is that the high ($\sim 10^3$ $M_{\odot}$/yr) cooling flow mass accretion rates keep the quasars optically luminous but relatively radio quiet. This is consistent with a suggestion by Rawlings[16] that RGs and RLQs cannot exist at high accretion rates onto the central accretion disk because an ion-supported torus[17] is needed to extract spin energy from the central BH and collimate radio jets. However, of the 5 other clusters known which are as luminous and have cooling flows as large as these two RQQ host clusters,[18] none show evidence for optically luminous broad-line AGN. Clearly, more data on RQQ and RLQ host clusters are needed to determine if those we have observed so far are typical.

We have sketched out a simple model which is consistent with the limited data available, but is by no means the only viable model. Still, the model makes the testable prediction that less luminous RLQs should reside in more luminous clusters, and that when RQQs are found in clusters they should have stronger cooling flows than RLQs. We propose to increase our knowledge of quasar host cluster properties and to test these predictions using ROSAT HRI observations of the quasars listed in Table 1. Our sample include 10 well-studied RLQs at $0.2<z<0.7$, located in Abell richness $\gtrsim 0$ environments (measured by the amplitude of the spatial covariance function B_{gq}), with VLA maps, multi-color photometry, high resolution ground-based and HST images, and spectroscopy of many galaxies in each field. Included are the richest RLQ host clusters known at $z<0.6$; a sample of $z>0.6$ targets could feasibly be observed to similar limits with AXAF-I. We also include 7 rare examples of RQQs in rich environments *(italicized)*, for which we will obtain more accurate richnesses and velocity dispersions in support of the X-ray observations. ROSAT or EINSTEIN HRI observations have already been made of 8 of our objects (#7-13, exposure time in parentheses), with 2 detections and 3 upper limits among the 5 observations in hand (Fig. 1). Data on the 5 unobserved fields will extend our knowledge of quasar host cluster X-ray properties to a wider range of redshift, M_{abs}, radio power, and cluster strength, which is essential for testing the different theories outlined earlier. Also, ROSAT data on 3C206 will put much stronger limits on emission from this unique nearby RLQ host cluster than EINSTEIN data alone can.

The second major motivation for obtaining X-ray images of these clusters is to study the evolution of galaxy clusters themselves. X-ray selection based on the presence of gas in deep potential wells, and even optical selection in which clusters are identified based on the visibility of central red galaxies, may systematically select evolved clusters, but clusters chosen by association with quasar activity may not. Optical studies of quasar host clusters show that they differ from low-redshift clusters both dynamically and in the gas content of their member galaxies, and our studies suggest that differences also exist at X-ray wavelengths. Thus, quasar host clusters may be in a distinct, young evolutionary phase, and our sample may prove useful for studying evolutionary signatures in clusters of galaxies. Observations to date show that our sample includes unusual clusters, but more data is needed to understand the full range of quasar host cluster properties.

2. TECHNICAL FEASIBILITY

We have developed data analysis methods to obtain the best upper limits possible when cluster emission is not detected.[11] We bin our data in annuli of a range of widths and subtract off the background and the HRI PSF. By comparing the upper limits in each annular bin to expected cluster emission profiles, we find the bin which sets the strongest upper limit to the cluster luminosity for clusters of various core radii in different cosmologies. When cluster emission is detected, fitting the background, quasar, and cluster to the radial profile yields excellent results.[13] We also utilize aspect correction and deconvolution methods where appropriate. Since quasar host clusters have typical core radii of 125 kpc[19] (30"–16" at z=0.2–0.6), in a 15–30" annulus we should see 26% of the host cluster light. With the typical HRI PSF,[20] in that same annulus we should see only 2% of the quasar light, making it the detection cell typically most sensitive to cluster emission. Table 1 lists the exposure times (in ksec) necessary to detect emission from a cluster with the specified L_X at the given S/N, using a 15-30" detection annulus (15-45" for 3C 206) around the quasar. Quasar fluxes were taken from previous X-ray observations where available, otherwise $L_X=10^{45}$ erg/s was assumed. These limits are sufficient to determine whether the clusters are significantly less X-ray luminous than EMSS clusters of similar richness and redshift (Fig. 1). Exposure times were calculated using the method outlined in ref. 20, assuming $H_o=50$, $q_o=1/2$, T=5 keV for the ICM, 1.1 10^{-6} cts s^{-1} $arcsec^{-2}$ instrumental background, and a power law of energy index $\alpha=2$ for the quasars. HI column densities range from log $N_H=20.0$–20.75.

Table 1. ***ROSAT*** **Quasar Host Cluster Project — Final Sample**

Name	z	B_{gq}	M_{abs}	P_{6cm}	Exp.	Cts[a]	Cts/s[a]	Limiting Cluster L_X
1. 5C 2.10	0.48	1169	-24.0	24.4	**33**	107	8.4E-4	1.5 10^{44} (3σ)
2. 3C 345[b]	0.60	773	-27.2	27.0	**98**	215	5.7E-4	1.5 10^{44} (3σ)
1641+3998[b]	0.60	~500	-24.5	<24	"	187	4.9E-4	1.3 10^{44} (3σ)
3. 3C 206	0.20	683	-25.0	25.1	**73**	143	9.0E-4	0.18 10^{44} (3σ)
4. *2141+040A*[b]	0.41	514	-22.9	<24	**61**	148	6.3E-4	1.0 10^{44} (3σ)
2141+040B[b]	0.46	>300	-25.6	<24	"	140	6.0E-4	1.2 10^{44} (3σ)
5. 4C 57.15	0.44	512	-22.5	25.3	**29**	98	8.8E-4	1.5 10^{44} (3σ)
6. 0405–12	0.57	905	-27.8	26.4	**48**	124	6.7E-4	2.0 10^{44} (3σ)
7. *IRAS09104*	0.44	1210	-26.3	23.8	(8)	—	—	29. 10^{44} detection
8. *1821+643*	0.30	1200	-27.2	24.8	(29)	—	—	23. 10^{44} detection
9. 3C 263	0.66	993	-26.6	26.3	(57)	—	—	3.3 10^{44} (3σ u.l.)
10. 2352–34	0.71	681	-26.7	25.9	(40)	—	—	2.9 10^{44} (3σ u.l.)
11. 3C 215	0.41	1000	-23.3	25.7	(51)	—	—	1.0 10^{44} (3σ)
12. 3C 275.1	0.56	1125	-24.1	26.2	(43)	—	—	2.2 10^{44} (3σ)
13. 3C 281	0.60	792	-25.4	25.9	(53)	—	—	1.8 10^{44} (3σ)
14. *1116+215*	0.18	584	-25.3	23.6	(24)	—	—	—
15. *1309+355*	0.18	554	-24.8	23.6	(9)	—	—	—

[a]Counts are *total* from a cluster at the given L_X; counts/sec are *only* in the detection annulus.
[b]3C345/1641+3998 separation is 8′, and 2141+040AB is 4′, so all targets will be <5′ off-axis.

3. PREVIOUS *ROSAT* OBSERVATIONS

Several groups are studying radio galaxy and BL Lac host cluster emission, and we will compare our data with theirs in future analyses, but little ROSAT data is useful for studying quasar host clusters: long HRI exposures are needed, as the PSPC could not separate cluster and quasar emission at these redshifts. Table 1 includes archival HRI data on 3C275.1 and 3C281 which we will retrieve when it becomes public and analyze with our method, providing a useful crosscheck on techniques used by different groups. Table 1 also includes two PSPC observations of low-z RQQs (#14–15) which we have not yet analyzed; it is likely that ~20ksec HRI exposures of these objects will be requested in future AOs to better separate quasar and cluster emission.

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Figure 1. A plot of the galaxy-cluster center spatial correlation function, B_{gc}, vs. soft X-ray luminosity L_X for a moderate-redshift subsample of EMSS clusters (**open squares**) and our quasar host clusters. **Filled symbols** are data in hand, **dashed lines** are expected upper limits from scheduled or archival ROSAT observations, and **solid lines are expected upper limits for proposed observations.** (The proposed 3C 206 limit is off the bottom of the graph.) The dotted line is the fit to the EMSS data. Upper limits assume H_o=50, q_o=1/2, and r_{core}=125 kpc.