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ROSAT HRI OBSERVATIONS OF FOUR HIGH-REDSHIFT CLUSTERS OF GALAXIES

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ABSTRACT

ROSAT HRI data for four rich clusters of galaxies at redshifts of ~ 0.5 that contain radio sources are presented. One of the clusters, 53W080, is detected at the 5.2 σ level; 53W076 is marginally detected at the 2.7 σ level; and the other two clusters, 1130+34 and 1245+34, have interestingly low upper bounds on their X-ray luminosities. The X-ray emission is unresolved and could originate from either the hot intracluster medium or the radio source. A comparison of the expected and observed X-ray luminosity of 53W080 suggests that the X-ray emission from this source is produced by the active galactic nucleus (AGN).

Subject headings: galaxies: clusters: general — intergalactic medium — X-rays: galaxies

1. INTRODUCTION

The environments of powerful, classical double, Fanaroff-Riley class II (FR II) radio sources seem to change with redshift. These sources are found in relatively low density environments at low redshift and in both high- and low-density environments at redshifts of ~ 0.5 (Hill & Lilly 1991 [hereafter HL91]; Yates, Miller, & Peacock 1989; Yee & Green 1987). This evolution could be understood in terms of the evolution of the intracluster medium (ICM); FR II sources may be found in distant clusters because the high-pressure ICM that is known to exist in low-redshift clusters may not be in place in more distant clusters. Alternatively, the source environments may evolve because the radio sources themselves evolve. To investigate the relationship between evolution of the environments of FR II radio sources and evolution of the ICM, we obtained *ROSAT* HRI data for four rich (Abell class 0 or greater) clusters of galaxies from HL91 with radio sources at redshifts between 0.35 and 0.55. In particular, we are interested in determining whether the production of X-rays in these high-redshift clusters is associated primarily with discrete sources or with a hot intracluster gas.

The X-ray data analysis and results for the four clusters that were observed with *ROSAT* are presented in § 2; a preliminary version of this analysis is presented by Sokoloski, Daly, & Lilly (1994). The radio and optical properties of the sources are given in § 3. In § 4, we explore the possible origin of the observed X-ray emission by comparing the X-ray luminosities to average values for optically similar low-redshift clusters where the X-ray emission arises from the ICM and to the X-ray emission expected from the central AGN alone based on its radio luminosity. We conclude with a summary of these results in § 5. A related study that includes the four clusters presented here, combined with information available in the published literature, is presented by Wan et al. (1994) and Wan & Daly (1996a, b).

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2. X-RAY DATA ANALYSIS

Three fields containing four high-redshift ($z \simeq 0.5$) clusters were observed with the *ROSAT* HRI camera in 1991 December and 1992 January. The three fields were observed for ~ 8100 s, 6600 s, and 2200 s, respectively, with the observing time for the third field cut short as a result of satellite operational constraints. Two sources, 53W080 and 53W076, are both in the first field. The radio-loud quasar 53W080 is detected at the 5.2 σ level, and the radio galaxy 53W076 is marginally detected at a 2.7 σ level; neither of these sources are resolved. Upper bounds are placed on the X-ray emission of the radio galaxy 1130+34 and the radio galaxy 1245+34; the results for 1245+34 were significantly affected by the short observing time allocated for this field. Values of Hubble's constant of $H_0 = 100\ h$ km s^{-1} Mpc^{-1} and de/acceleration parameter $q_0 = 0$ are assumed throughout.

The results of the X-ray data analysis are summarized in Table 1. The images were processed using the SAO PROS data analysis software within IRAF. Count rates are obtained by extracting source counts from a circular region centered on the source. For the detected sources, the extraction region radii are chosen such that the source counts decrease if the radius is decreased and remained stable if the radius is increased. Thus, for 53W076, counts are extracted from a region $\sim 15''$ in diameter, and for 53W080 from a region with a diameter of 70″, corresponding to radii of $\sim 25\ h^{-1}$ kpc and 150 h^{-1} kpc, respectively. Upper limits for the undetected sources are obtained using radii corresponding to $\sim 150\ h^{-1}$ kpc. The sensitivity of the results to changes in this parameter are small compared to the uncertainties due to photon statistics, which are our dominant source of uncertainty. The region centers for 53W076 and 53W080 are based on the positions found by the source detection algorithm DETECT, as well as the visually identified center of the source photon distribution. For the undetected sources, the extraction regions are centered on the radio source coordinates. For the detected sources, these centers are within $\sim 10''$ of the location of the radio source

TABLE 1

ROSAT HRI DATA ANALYSIS RESULTS

Source (1)	HRI Counts (2)	S/N (3)	f (0.5–2.0 keV) (10^{-14} ergs cm^{-2} s^{-1}) (4)	l (0.5–2.0 keV) ($h^{-2} \times 10^{43}$ ergs s^{-1}) (5)
53W076	8.5 ± 3.2	2.7	2.9 ± 1.1	0.60 ± 0.22
53W080	47.9 ± 9.2	5.2	19.0 ± 3.6	8.2 ± 1.6
1130+34.....	10.3 ± 6.7	1.6	$\lesssim 12.2$	$\lesssim 4.4$
1245+34.....	$\lesssim 19$	n/a	$\lesssim 23$	$\lesssim 5.9$

NOTES.—Col. (2): Source counts were obtained from regions with radii $r \approx 25\ h^{-1}$ kpc and $r \approx 150\ h^{-1}$ kpc for 53W076 and 53W080, respectively, and regions with radii of $r \approx 150\ h^{-1}$ kpc for the 3 σ upper limits on 1130+34 and 1245+34. Col. (3): S/N is the signal-to-noise ratio. Col. (4): X-ray fluxes, calculated using a power-law spectral model; the energy range refer to the observed frame. Col. (5): Source luminosities estimated for an open universe with $q_o = 0$; the energy range refers to the source frame. Limits are 3 σ upper limits.

as listed in the SIMBAD radio catalog. For each source, a background count rate is obtained from a nearby blank-field region and subtracted from the total count rate to give the source counts. Various blank-field region positions and sizes were compared for each source, and the resulting count rates for different background fields are consistent to within our uncertainties. Using the *ROSAT* model background, as described in the *ROSAT* Data Products Guide (Downes et al. 1992), also produces consistent results. A vignetting correction is applied to the data to correct for sources being slightly off-axis; 53W080, however, was the only source that was significantly off-axis, and the correction due to vignetting for this source was $\sim 20\%$.

Fluxes and flux densities at an observed energy of 1.0 keV are computed using all HRI channels and assuming a power-law spectral model $f_{\nu_o} \propto \nu^{-\alpha_x}$ with $\alpha_x = 0.4$; Galactic neutral hydrogen absorbing column densities were obtained from the maps presented by Heiles (1975). The PROS routines qpspec, fit, and xflux were used. A power-law energy distribution with spectral index $\alpha_x = 0.4$ is a good approximation to a thermal bremsstrahlung spectrum, $f_{\nu_o} \propto g(\nu, T)e^{-h\nu/kT}$ [where $g(\nu_o, T)$ is the Gaunt factor], for $0.1 \lesssim h\nu/kT \lesssim 1$; throughout this paper, "ν_o" refers to the observed frequency and "ν" to the emitted frequency. The fluxes and luminosities are only marginally dependent upon the spectral model assumed, since we are in general working with low photon number counts and therefore have large a priori uncertainties due to counting statistics. A steeper energy index $\alpha_x = 1.0$ reduces the calculated fluxes and luminosities by $\sim 10\%$–15%.

Luminosities are calculated by first converting the 1 keV flux density f_{ν_o} for a given source to a luminosity density l_ν at the source frequency $\nu = \nu_o(1 + z)$, and then calculating the integrated luminosity using a power-law spectral model for the luminosity density, $l_\nu \propto \nu^{-\alpha_x}$, with $\alpha_x = 0.4$, where the relation $l_\nu = f_{\nu_o} 4\pi(a_o r)^2(1 + z)$, has been used with the coordinate distance $a_o r$ appropriate for an open universe: ($q_o = 0$), $a_o r = (c/H_o)(1 + z)^{-1}z(1 + z/2)$. The luminosity density is integrated using the simple power-law model described above; the integrated luminosities are listed in column (5) of Table 1, with uncertainties due to photon counting statistics only.

3. RADIO AND OPTICAL DATA

The sources observed are in rich clusters of galaxies (Abell class 0 or greater) at relatively high redshift ($0.35 < z < 0.55$), are known to contain radio sources, and are taken from the sample of HL91. The HL91 sample was compiled in order to study the environments of radio galaxies at high redshift and includes the "1 Jy" B2 sample of Allington-Smith, Lilly, & Longair (1985) and Allington-Smith et al. (1988), from which two of our sources are taken, and the Leiden-Berkeley Deep Survey (LBDS) millijansky sample of Windhorst, Kron, & Koo (1984), from which the other two are taken. A description of the radio and optical properties of the four sources and of the richnesses of their environments follow, with the salient properties summarized in Table 2. The optical properties of the environments of the sources will be used to estimate the expected X-ray luminosity of the ICM assuming no evolution of the relation between optical and X-ray properties, and the radio properties will be used to estimate the X-ray emission from the radio source (see § 4).

TABLE 2

SOURCE INFORMATION

Source (1)	z (2)	Radio Structure (3)	ψ (4)	log $P_{2.0}$ (5)	$N^0_{0.5}$ (6)	R (7)
53W076	0.390	FR I–like	$1''.76 \pm 0''.36$	23.4	11	0
53W080	0.546	Extended but diffuse	10.4 ± 1.2	25.0	$\gtrsim 10$	$\gtrsim 0$
1130+34.....	0.512	FR II	$\approx 78''$	26.2	39	$\gtrsim 2$
1245+34.....	0.409	FR II	$\approx 6''$	25.9	18	1

NOTES.—Col. (4): ψ is the greatest angular extent in arcseconds corresponding to the FWHM, for 53W076 and 53W080 from Kron et al. 1985, and the distance between brightness peaks for 1130+34 and 1245+34 from Allington-Smith 1982. Col. (5): $P_{2.0}$ is the 2.0 GHz power in W Hz^{-1} estimated assuming $H_o = 100$ km s^{-1} Mpc^{-1} and $q_o = 0$ from HL91 for 53W076, 1130+34, and 1245+34, and from Oort & van Langevelde 1987 for 53W080. Col. (6): Number of galaxies within 0.25 h^{-1} Mpc and within 3 mag of the first-ranked member, from HL91, except for the 53W080 value, which is based upon an estimate by Kron et al. 1985. Col. (7): Approximate Abell richness class from HL and Kron et al. 1985.

3.1. *53W076 (66W044)*

53W076 is a relatively faint, red, radio galaxy at a redshift of $z = 0.39$, with an angular extent in the radio of $\sim 2''$. The radio flux density has been measured to be $\sim 1.7 \pm 0.3$ mJy at 1.4 GHz (Kron, Koo, & Windhorst 1985; Oort et al. 1987; Oort & van Langevelde 1987). Kron et al. (1985) give a 3.75 σ upper limit on the 0.6–1.4 GHz (50–21 cm) spectral index of $\alpha_r = 0.89$, where the radio flux density is assumed to have a simple power-law dependence with frequency ($f_\nu \propto \nu^{-\alpha_r}$). Its radio structure is not core dominated, and it does not have significant hot spots (G. J. Hill, 1993, private communication), so it cannot be categorized simply as FR I or FR II; we categorize it as amorphous or FR I–like. Its environment is less rich than those of the other sources we observed, with a richness parameter $N^0_{0.5} = 11$ (number of excess objects within a radius of 0.25 h^{-1} Mpc, assuming $q_o = 0$; see HL91), except possibly for 53W080. Using the correspondence between various richness measures determined by HL91, this value of $N^0_{0.5}$ corresponds to Abell class 0, or N of ~ 40, where N is the number of galaxies not more than 2 mag fainter than the third brightest (G. O. Abell, 1958).

3.2. *53W080 (66W055)*

This source was identified as a blue quasar at a redshift of 0.55 by Oort et al. (1987). Its radio structure is larger than that of 53W076, with an angular extent of $\sim 11''$. This source also has not been classified as either FR I or FR II. The 1.4 GHz radio flux density of this source has been seen to vary by more than 2.5 σ, from $f_{1.4} = 27.6$ mJy (Kron et al. 1985) to 19.5 ± 1.2 mJy (Oort et al. 1987), and hence is likely to be a core-dominated source. Some other recorded flux density values include 18.6 ± 1.1 mJy at 1.5 GHz (Oort et al. 1987) and 25.9 ± 0.9 mJy at 1.4 GHz (Oort & van Langevelde 1987). Kron et al. (1985) list the 0.6 to 1.4 GHz spectral index of this source as $\alpha_r = 0.80$. In the radio, it is brighter than 53W076 but is still an order of magnitude fainter than our other two sources. Kron et al. (1985) classify this cluster as probably of Abell richness class 0 or greater.

3.3. *B2 1130+34*

This bright FR II radio galaxy at $z = 0.512$ has a 2.7 GHz flux density 380 ± 50 mJy (Allington-Smith 1982) that originates entirely from two radio lobes. The spectral index is $\alpha_r = 0.92$ between 0.4 and 1.4 GHz and $\alpha_r = 0.48$ between 1.4 and 2.7 GHz. A conservative upper limit on the radio core flux density of $f_{2.7} = 5$ mJy was estimated from the radio map by taking the lowest contour level (5 mJy beam width^{-1}) times one beam width. In the optical, this source has a low-excitation, weak emission-line spectrum with narrow lines and stellar absorption features (Allington-Smith et al. 1985). The richness parameter $N^0_{0.5}$is 39, which corresponds to a richness greater than Abell class 2 (HL91).

3.4. *B2 1245+34*

The radio galaxy 1245+34 is much smaller in extent than 1130+34 (6″ in angular extent as opposed to 78″) and is classified as an FR II. The 2.7 and 5.0 GHz flux densities are $f_{2.7} = 250 \pm 10$ mJy and $f_{5.0} = 170 \pm 10$ mJy. It also contains no visible radio core, and an upper limit of $f_{5.0} = 5$ mJy was approximated using the same method as above. It has a low-excitation narrow emission-line optical spectrum (Allington-Smith et al. 1988). The richness parameter $N^0_{0.5}$ for this cluster is 18, which corresponds to Abell richness class 1.

4. ORIGIN OF THE X-RAY EMISSION

It is not clear whether the X-ray emission detected is diffuse emission from the ICM of the cluster or is X-ray emission produced by the radio source in the cluster. Further, it is not immediately obvious whether the upper bounds obtained place significant constraints on the X-ray emission from the ICM. In order to assess the significance of the results presented, the X-ray detections and bounds are compared with the expected X-ray luminosities of the ICM of the clusters and of the radio sources, assuming no evolution of the relation between X-ray and other properties with redshift.

Thus, the X-ray luminosities of each of our clusters is compared to a characteristic X-ray luminosity for low-redshift clusters in the same Abell richness class. And, the X-ray luminosity density is used to estimate the radio core luminosity density that would be expected if the X-ray emission is produced by the radio source; the relation obtained by Fabbiano et al. (1984, hereafter FMTLE) for radio galaxies is used. The predicted and observed core radio luminosity densities are compared.

4.1. *X-Ray Emission from Intracluster Gas*

The X-ray luminosity expected from the ICM of each cluster is estimated here based on the optical richness of the cluster and the X-ray luminosity of optically similar, low-redshift clusters.

The low-redshift data sets used for the comparison are the sample of *Einstein* IPC observations analyzed by Abramopoulos & Ku (1983, hereafter AK) and the *Einstein* IPC survey of Jones & Forman (1984, hereafter JF). The first sample includes 53 clusters with redshifts ranging from $z = 0.02$ to $z = 0.31$, with an average value of $z = 0.09$. Richnesses are available for all members of this sample. The second sample contains 46 clusters with redshifts less than $z = 0.08$ (average value $z = 0.05$), 44 of which have richnesses available. Five clusters are common to both samples. Typically, richer clusters have higher X-ray luminosities.

AK calculate cluster X-ray luminosities in the 0.5–4.0 keV energy range by extracting IPC counts from a region with radius 0.75 h^{-1} Mpc, fitting these counts to a hot thermal plasma model with galactic absorption, and then extrapolating to a derived cluster core radius using the King isothermal sphere model. They then correlate these luminosities with several cluster parameters, including two measures of richness. They find a significant correlation between richness (either measure) and X-ray luminosity, with luminosity increasing as richness increases. The first richness measure is N, the number of galaxies within 1.5 h^{-1} Mpc (Abell 1958), and AK find that the dependence of 0.5–4.0 keV X-ray luminosity on N can be expressed as

$$\log L_x = -1.16 + 1.23 \log N \,. \quad (1)$$

The second richness parameter is N_0, the surface density of galaxies within a region of radius 0.25 h^{-1} Mpc (Bahcall 1977), and AK find that

$$\log L_x = -1.86 + 2.28 \log N_0 \,. \quad (2)$$

To use the AK relations, we convert their luminosities to our energy band and cosmology using the model outlined in

TABLE 3

EXPECTED X-RAY LUMINOSITIES BASED ON OPTICAL RICHNESS

Source (1)	l (0.5–2.0 keV) ($h^{-2} \times 10^{43}$ ergs s^{-1}) (2)	R (3)	Predicted l (4)	Average l (AK) (5)	Average l (JF) (6)
53W076	0.60 ± 0.22	0	0.6	1.7 ± 0.6[a]	0.64 ± 0.14
53W080	8.2 ± 1.6	$\gtrsim 0$	0.6	$\gtrsim 1.7 \pm 0.6$	$\gtrsim 0.64 \pm 0.14$
1130+34.....	$\lesssim 4.4$	$\gtrsim 2$	7.9	$\gtrsim 5.5 \pm 1.7$	$\gtrsim 4.5 \pm 1.2$
1245+34.....	$\lesssim 5.9$	1	1.4	2.4 ± 0.5	1.36 ± 0.038

NOTES.—Col. (2): Luminosities were calculated with $H_o = 100\ h$ km s^{-1} Mpc^{-1}, $q_o = 0$, and spectral index $\alpha_x = 0.4$ (see Table 1). Col. (3): R is the approximate Abell richness from Kron et al. 1985 for 53W080 and HL91 for the others. Col. (4): This luminosity, in units of $h^{-2} \times 10^{43}$ ergs s^{-1} is the predicted luminosity for a cluster of given richness based upon the relation between luminosity and richness found by AK for clusters at low redshift. Col. (5): Average luminosity of the clusters in the AK sample with the given richness. Col. (6): Average luminosity of the clusters in the JF sample with the given richness.

[a] This average value is strongly affected by a few high-luminosity sources. The median value and the value predicted by the AK X-ray luminosity–cluster richness relation are close to the JF values. See discussion in the text.

§ 2, i.e., assuming a power law with energy index $\alpha_x = 0.4$. Neither N nor N_0 is directly available for any of the four clusters; values of N are estimated from $N^0_{0.5}$ based on the prescription in HL91, and $N^0_{0.5}$ is used in place of N_0 in equation (2) since the two are very similar. The two relations yield similar results, the average of which is listed in column (4) of Table 3 for each cluster.

JF list cluster X-ray luminosities over the 0.5–3.0 keV energy band and within a radius of 0.25 h^{-1} Mpc from the cluster center. The average X-ray luminosity is computed for each Abell class and is converted to the energy band and cosmology assumed here, as described above. To check for consistency, the luminosities for the five clusters that are common to both samples are compared; these luminosities differ by an average of $\sim 50\%$, with neither of the two groups obtaining consistently higher or lower values, from which it is concluded that the samples are consistent.

Average luminosities for each Abell richness class are estimated for the AK and JF samples and are listed in columns (5) and (6) of Table 3, where they have been modified to the cosmological model and energy band adopted here. The (0.5–2 keV) *ROSAT* luminosities (col. [2]), and the Abell richness class of each source are also listed. Note that 53W080 and 1130+34 only have an approximate lower bounds on the Abell richness class, so their luminosities are expected to be greater than the AK and JF values listed.

There is a small discrepancy between the AK and JF average luminosities for richness classes 0 and 1 (see Table 3). This is probably due to the finite size of each of the richness subsamples. For instance, although the average JF luminosity for richness class 0 (col. [6]) agrees with the predicted AK value (col. [4]), neither of these numbers agrees with the average AK value (col. [5]). This particular discrepancy is due to the fact that the AK sample contained one very high luminosity class 0 source, which strongly affected the average luminosity. The median value for the AK sources in this richness class is ($0.8 \times 10^{43}\ h^{-2}$ ergs s^{-1}), which is much closer to both the JF average value and the predicted AK result; apparently the predicted AK luminosities are not as sensitive to high-luminosity outliers as is the mean value of the luminosity for richness class 0. In general, the predicted AK luminosities are in very good agreement with the average JF numbers.

The average JF values listed in Table 3 are $\sim 30\%$ higher than the median values listed by Burg et al. (1994), where the Burg et al. (1994) numbers for the redshift range from 0.03 to 0.1 have been used after being corrected to the energy band and cosmology assumed here. This is probably because one is a mean and one is a median, but it does give a rough idea of the uncertainty of the values quoted in Table 3 introduced by systematics. The results presented would not be affected by such a 30% change.

A glance at Table 3 suggests that the X-ray emission from three of the four clusters is consistent with the expectation that the X-ray emission is produced by the ICM; the luminosities are not significantly different from those of optically similar low-redshift clusters. The fact that the observed X-ray luminosity of the quasar 53W080 is so much larger than expected from the ICM, coupled with the fact that it is consistent with that expected from the AGN itself based on the radio luminosity density, as described in § 4.2, suggests that the X-ray emission from this source may originate from the AGN rather than from the ICM. This, though, does not preclude the ICM from producing X-rays at the expected level.

4.2. *X-Ray Emission from the AGNs*

Radio-loud AGNs are often X-ray sources. FMTLE establish a relation between the 5.0 GHz radio core luminosity density and 2.0 keV X-ray luminosity density for low-redshift radio galaxies. This relation is used to estimate the radio luminosity density of the cores of the AGNs, assuming that the observed X-ray emission arises from the AGNs. The predicted and observed core flux densities are listed in Table 4.

The correlation between X-ray and radio flux densities used here are derived by FMTLE from a survey of 40 3CR radio galaxies observed with the *Einstein Observatory*. These 40 galaxies are found both in clusters and in the field and span a redshift range from $z \approx 0.001$ to $z \approx 0.3$, with an average value of $z \approx 0.07$. Note that the FMTLE radio–X-ray luminosity relationship for radio galaxies is independent of the radio galaxy environment; FMTLE find no correlation between the AGN X-ray luminosity and a clustering parameter. It is assumed that the relations found by FMTLE do not evolve with redshift.

If the radio spectral index α_r is flat, as would be expected for core radio emission, the numbers in Table 4 can be compared directly. The upper limits in column (3) for 1130+34 and 1245+34 are for core emission, so this assumption is fairly reasonable. The fact that the 53W080

TABLE 4

PREDICTED RADIO FLUX DENSITIES

Source (1)	Predicted f_{ν_o}(core) (mJy) (2)	Measured f_{ν_o} (mJy) (3)
53W076	4 ± 2 (3.6 GHz)	1.76 ± 0.36 (1.5 GHz, total)
53W080	18 ± 6 (3.2 GHz)	19.5–27.6 (1.4 GHz, total)
1130+34.....	$\lesssim 13$ (3.3 GHz)	$\lesssim 5$ (2.7 GHz, core)
1245+34.....	$\lesssim 15$ (3.5 GHz)	$\lesssim 5$ (2.7 GHz, core)

NOTES.—Col. (2): Expected radio core flux density at $\nu_o = 5.0/(1 + z)$ GHz if AGN activity is to account for all of the X-ray emission, from relationship observed by FMTLE between X-ray luminosity density and radio core luminosity density for AGNs. Col. (3): Radio core flux densities estimated from maps in Allington-Smith 1982 or total radio flux densities for sources for which no core flux density was available (from Oort et al. 1987).

radio flux density decreased 30% in less than 3 years indicates that this emission also probably originates in a compact core. If, however, the radio spectrum is actually somewhat steeper, the predicted flux densities, when shifted down to the frequencies where the measured values are available, would be slightly increased. In any case, the X-ray emission from all four clusters is consistent with being produced by AGN emission alone.

5. SUMMARY

ROSAT HRI data for four high-redshift clusters of galaxies known to contain radio sources are presented. The X-ray detections and bounds are compared with the expected X-ray luminosities of the clusters based on their optical richness and assuming no evolution of the relation between optical richness and the X-ray luminosity of the ICM with redshift. The X-ray observations and the relation between the radio and X-ray core luminosities of low-redshift radio galaxies are also used to assess the possibility that the X-ray emission is produced by the AGN. Based on these comparisons, it is likely that the X-rays detected from 53W080 are produced by the AGN. The marginal X-ray detection of 53W076, and the bounds on 1130+34 and 1245+34 are consistent with both ICM and AGN predictions for the origin of the X-ray emission.

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