CHANDRA OBSERVATIONS OF UNRESOLVED X-RAY SOURCES AROUND TWO CLUSTERS OF GALAXIES

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ABSTRACT

We have searched for unresolved X-ray sources in the vicinity of two rich clusters of galaxies, Abell 1995 (A1995) and MS 0451.6–0305 (MS 0451), using the Chandra X-Ray Observatory. We detected significantly more unresolved sources around A1995 than expected based on the number of X-ray sources to the same flux limit detected in deep Chandra observations of blank fields. Previous studies have also found excess X-ray sources in the vicinity of several nearby clusters of galaxies using ROSAT and recently in more distant (z ≈ 0.5) clusters (RX J0030 and 3C 295) using Chandra. In contrast, we detect only 14 unresolved X-ray sources near MS 0451, which is consistent with the number expected from a cluster-free background. We determine the luminosity functions of the extra sources under the assumption that they are at the distance of their respective clusters. The characteristic luminosity of the extra sources around A1995 must be an order of magnitude fainter than that of the extra sources around RX J0030 and 3C 295. The apparent lack of extra sources around MS 0451 is consistent with its greater distance and the same characteristic luminosity as the A1995 sources. Hardness ratios suggest that, on average, the extra sources in A1995 may have harder spectra than those of RX J0030 and 3C 295. These results indicate that different classes of objects may dominate in different clusters, perhaps depending on the formation history and/or dynamical state of the accompanying cluster.

Subject headings: galaxies: clusters: individual (Abell 1995, MS 0451.6–0305) — X-rays: galaxies: clusters

1 INTRODUCTION

Evidence has accumulated recently that there are more X-ray point sources in the direction of clusters of galaxies than toward cluster-free regions of the sky. Henry & Briel (1991), using ROSAT Position Sensitive Proportional Counter (PSPC) observations, found just about twice as many unresolved sources around Abell 2256 (at z = 0.06; Struble & Rood 1991) as expected from blank-field (no clusters) background observations. The luminosity of these sources, assuming they are at the redshift of the cluster, was found to be about 10^{42} ergs s^{-1} or greater (in 0.5–2 keV). These sources have high X-ray-to–optical flux ratios. Some of the sources in A2256 were identified as cluster member galaxies. Henry & Briel also discuss the possibility that the emission from these sources is due to hot gas in galaxies not removed by ram pressure or evaporation or due to shocks in gas from merging.

Similarly, Lazzati et al. (1998), analyzing ROSAT PSPC images, found an excess number of unresolved X-ray sources in the fields of two nearby clusters: A194 and A1367 (z = 0.018 and 0.022). The spectra of the sources were consistent with thermal bremsstrahlung with T ≤ 2 keV. Lazzati et al. also found evidence for association of some of these sources with cluster member galaxies, implying luminosities between 0.6 and 6.6 × 10^{41} ergs s^{-1} in the 0.5–2 keV band. X-ray emission from hot gas associated with cluster member galaxies had been reported earlier, also based on ROSAT PSPC observations (Grebenyev et al. 1995; Bechtold et al. 1983).

Indirect evidence has also been presented for the existence of an excess population of unresolved X-ray sources associated with Abell clusters. Soltan & Fabricant (1990), using Imaging Proportional Counter data from the Einstein Observatory found excess fluctuations in nearby galaxy clusters, which could be explained by assuming the presence of low-luminosity sources (∼4 × 10^{41} ergs s^{-1}) in clusters with extent less than 1′. They discuss the possibility that the emission from these sources is due to low-luminosity active galactic nuclei (AGNs) or to hot gas in member galaxies. Soltan et al. (1996) found a correlation between the surface brightness of the X-ray background and Abell clusters on scales of a degree, which is much larger than the X-ray emission from the intracluster gas. The characteristic length was found to be about 10 h^{-1} Mpc in radius (where H_o = 100 h km s^{-1} Mpc^{-1}); i.e., extra X-ray emission was found around Abell clusters out to about 15 Mpc (h = 0.65).

Soltan et al. could not explain the extra X-ray emission based on known sources or random fluctuations in their number density. They estimated the required number of excess sources to be about 50% above the expected number of background sources.

Most recently, Cappi et al. (2001), using Chandra Advanced CCD Imaging Spectrometer (ACIS) observations, found twice as many unresolved X-ray sources in the images of two distant clusters of galaxies, 3C 295 (z = 0.46; Dressler & Gunn 1992) and RX J003033.2+261819 (RX J0030; z = 0.5; Vikhlinin et al. 1998), as expected from a cluster-free background to their flux limits (Giacconi et al. 2001; Mushotzky et al. 2000).

Our main goal in this Letter is to present new results on the flux and number distributions of unresolved X-ray sources based on our Chandra ACIS observations of two rich clusters of galaxies: A1995 and MS 0451. We also address briefly the nature of the excess sources.

2 DATA PROCESSING AND ANALYSIS

A1995 is a rich cluster at z = 0.32 with an intracluster gas temperature of T_X = 7.6 keV (Patel et al. 2000). A1995 was observed with the Chandra ACIS in 2000 May and July for 35 and 12 ks. The aim point was on the back-illuminated chip S3 of ACIS-S. The data were taken in full frame mode with a readout time of 3.2 s. We used standard Chandra software tools to clean the data of time intervals with high background and/or bad aspect, remove bad or flickering pixels, and correct
A1995.

Table 1 lists the unresolved X-ray sources detected in A1995.

| X-Ray Source | Counts (0.5–2 keV) | Counts (2–10 keV) | $R^*$ |
|-------------|-------------------|-------------------|------|
| CXOU J45306.70+580313.8 | 585 ± 25 | 179 ± 14 | 18.8 |
| CXOU J45305.82+580309.1 | 342 ± 19 | 79 ± 3 | 19.2 |
| CXOU J45307.10+580205.8 | 306 ± 18 | 74.2 ± 9.2 | 20.8 |
| CXOU J45327.65+580339.5 | 166 ± 14 | 39.7 ± 7.6 | 20.9 |
| CXOU J45305.45+580339.7 | 69.5 ± 8.5 | <10 | 10.2 |
| CXOU J45246.31+580509.7 | 65.4 ± 8.2 | 14.5 ± 4.0 | 20.9 |
| CXOU J45317.46+580300.3 | 56.3 ± 8.2 | 20.9 ± 5.9 | 20.3 |
| CXOU J45233.22+580559.2 | 48.8 ± 7.1 | 17.6 ± 4.4 | 19.5 |
| CXOU J45229.56+580418.2 | 37.5 ± 6.2 | 20.4 ± 4.7 | <22 |
| CXOU J45230.74+580448.5 | 34.5 ± 6.0 | <10 | 16.0 |
| CXOU J45233.56+580456.3 | 28.4 ± 5.4 | 23.0 ± 5.0 | 22.0 |
| CXOU J45324.68+580318.4 | 26.7 ± 5.7 | <10 | <22 |
| CXOU J45316.75+575928.6 | 26.6 ± 6.1 | <10 | <22 |
| CXOU J45248.65+580255.8 | 24.3 ± 5.3 | <10 | 13.2 |
| CXOU J45301.83+580005.7 | 22.1 ± 5.0 | 11.4 ± 4.0 | 22.0 |
| CXOU J45255.19+580056.0 | 20.7 ± 4.7 | <10 | >22 |
| CXOU J45244.00+580203.3 | 20.6 ± 4.7 | 14.2 ± 4.0 | <22 |
| CXOU J45315.41+580448.5 | 20.5 ± 5.6 | <10 | 21.0 |
| CXOU J45253.64+580200.3 | 20.1 ± 4.6 | <10 | >22 |
| CXOU J45319.11+580134.4 | 17.2 ± 4.8 | <10 | >22 |
| CXOU J4520.22+580126.9 | 16.5 ± 4.6 | <10 | >22 |
| CXOU J45315.55+580117.4 | 16.3 ± 4.9 | <10 | >22 |
| CXOU J45242.50+580159.1 | 15.8 ± 4.1 | <10 | <22 |
| CXOU J45322.04+575954.5 | 15.0 ± 4.0 | 7.2 ± 3.0 | 21.1 |
| CXOU J45231.03+580100.9 | 14.5 ± 3.9 | 5.1 ± 2.4 | 21.1 |
| CXOU J45235.73+580656.1 | 12.8 ± 3.7 | <10 | <22 |
| CXOU J45245.50+580519.5 | 12.2 ± 3.6 | <10 | >22 |
| CXOU J45234.49+575904.0 | 11.9 ± 3.6 | 14.2 ± 4.2 | <22 |
| CXOU J45251.93+580464.2 | 10.1 ± 3.3 | 12.3 ± 3.7 | 20.9 |
| CXOU J45222.04+575858.7 | <10 | 25.3 ± 6.4 | >22 |

a R-band magnitude of optical counterparts/limit if not detected.
b GSC2 object (http://www.gsc2.cadc-ccda.hia-iha.nrc-cnrc.gc.ca/gsc2/gsc2).
c IRAS galaxy (F14511+5816).

Table 2 lists the unresolved X-ray sources detected in MS 0451.

| X-Ray Source | Counts (0.5–2 keV) | Counts (2–10 keV) |
|-------------|-------------------|-------------------|
| CXOU J45419.63–30420.5 | 746 ± 28 | 150 ± 13 |
| CXOU J45356.32–25837.7 | 396 ± 20 | 121 ± 11 |
| CXOU J45422.59–30035.2 | 87.9 ± 9.5 | 17.8 ± 4.4 |
| CXOU J45424.75–25849.8 | 69.0 ± 8.5 | 33.1 ± 6.0 |
| CXOU J45426.07–30013.2 | 57.1 ± 7.7 | 12.1 ± 3.7 |
| CXOU J45412.81–30047.7 | 45.2 ± 8.1 | <10 |
| CXOU J45419.20–30521.2 | 28.4 ± 6.0 | <10 |
| CXOU J45408.57–30521.2 | 27.4 ± 6.0 | <10 |
| CXOU J45410.88–30125.2 | 21.4 ± 5.7 | <10 |
| CXOU J45355.65–30409.6 | 19.7 ± 4.9 | <10 |
| CXOU J45406.70–30412.3 | 18.4 ± 4.8 | <10 |
| CXOU J45421.95–25816.2 | 17.2 ± 4.2 | 43.9 ± 6.8 |
| CXOU J45404.19–30403.7 | 12.0 ± 3.9 | <10 |
| CXOU J45421.39–30132.4 | 10.9 ± 3.5 | <10 |
| CXOU J45356.73–30226.1 | <10 | 23.1 ± 5.6 |

3. RESULTS

We detected 29 and 14 unresolved X-ray sources in the fields of A1995 and MS 0451. The sources show no correlation with the spatial distribution of the cluster emission. Source details are given in Tables 1 and 2, and the log N–log S curves are plotted in Figure 1. In Figure 1, we also show the log N–log S curves for the sources near RX J0030 and 3C 295 (Cappi et al. 2001). We quote source densities in terms of number per ACIS chip (8′ × 8′) in order to show the actual numbers of unresolved sources as detected. The expected log N–log S curves from cluster-free background (dashed lines) is taken from Mushotzky et al. (2000), which predicts a slightly higher number density of background sources than Rosati et al. (2002), Campana et al. (2001), and Giacconi et al. (2001) and slightly less than Brandt et al. (2001). We choose the background predicted by Mushotzky

![Figure 1](image-url)
et al. (2000) since it provides the best fit to the high-flux end of our log N–log S curve. We detect sources with fluxes brighter than $6 \times 10^{-16}$ ergs s$^{-1}$ cm$^{-2}$ and $8 \times 10^{-16}$ ergs s$^{-1}$ cm$^{-2}$ in A1995 and MS 0451. We obtained R-band magnitudes for unresolved X-ray sources in A1995 (see details in Patel et al. 2000). The 0.5–2 keV X-ray–to–R-band optical flux ratios of unresolved sources in the field of A1995 (see Table 1) seem to have a similar distribution to those of background sources (Mushotzky et al. 2000).

The log N–log S curve of the unresolved sources in the A1995 field is steeper than that of the background between 1 and $3 \times 10^{-15}$ ergs s$^{-1}$ cm$^{-2}$, which indicates a buildup of extra sources (excess number of sources relative to the background) with fluxes in this interval. There is an indication that for fluxes less than $10^{-15}$ ergs s$^{-1}$ cm$^{-2}$, the slope of the log N–log S curve of A1995 is close to that of the background, suggesting that there are no extra sources with flux below this value. The log N–log S curves of unresolved sources in 3C 295 and RX J0030 show similar signs of a cutoff at low fluxes in the distribution of the excess sources (see Fig. 1). Overall, we find 29 unresolved sources in the A1995 field, as opposed to the expected number for a cluster-free background of about 17.

In the field of our more distant cluster, MS 0451, we find 14 unresolved sources, which is within 1 $\sigma$ from the number expected based on a cluster-free background. Since MS 0451 is at about the same redshift as RX J0030 and 3C 295, our exposure time is longer than those of RX J0030 and 3C 295, and we found no extra sources in the MS 0451 field, we have the simple and potentially important finding that not all clusters have extra unresolved sources associated with them at the flux limits of these Chandra observations.

In this Letter, we estimate the luminosity functions for the extra sources in A1995, RX J0030, and 3C 295 using their log N–log S curves, assuming the excess sources are at the redshifts of their respective clusters. As customary, we used a luminosity function of the form $\Phi(L) \propto (L/L_*)^{-\alpha}$ with a lower cutoff at a characteristic luminosity, $L_*$ (i.e., there are no sources with $L < L_*$). The fits, which are a good description of the log N–log S distribution, are shown as solid lines in Figure 1. We found that the same slope, $\alpha = 3.1$, could describe the unresolved sources in all three clusters. However, the characteristic luminosities were found to be $L_* = 0.5, 4.0, \text{and } 4.8 \times 10^{42}$ ergs s$^{-1}$ in A1995, RX J0030, and 3C 295. The total number of extra sources based on these fits are 10, 12, and 7 (with about $\pm 3$ statistical error) for A1995, RX J0030, and 3C 295. Owing to the cluster emission, our ability to detect faint sources decreases toward the center (about 20 counts per detect cell for A1995). This effect is a fraction of the Poisson fluctuations (it corresponds to missing at most a single additional source), and so we ignore it. We verified, by means of Monte Carlo simulations, that the observations can be drawn from the assumed background distribution plus a distribution based on the derived luminosity functions of the extra cluster sources and that the observations cannot be explained using the same luminosity function for all clusters. Although the uncertainties in the luminosity function parameters are quite high, $\pm 0.5$ in the slope and 30%–40% in the lower cutoff, the characteristic luminosity of unresolved sources associated with A1995 are significantly (about 1 order of magnitude) less than those associated with RX J0030 and 3C 295. Furthermore, when the luminosity function of unresolved sources near A1995 is scaled to the greater distance of MS 0451, the resulting log N–log S is fully consistent with the observed one (see Fig. 1, solid curve associated with MS 0451). On the other hand, it is not consistent with the scaled luminosity function of either RX J0030 or 3C 295 (which are roughly the same distance as MS 0451). We expect the effect of spatial variations in the PSF and effective area, on the completeness function to be small, with an overall effect on the derived luminosity function much less than the errors quoted above.

4. DISCUSSION

The derived luminosity functions enable us to estimate the contribution of the unresolved sources to the overall X-ray emission around clusters of galaxies. The derived surface brightness of unresolved X-ray sources in the $8' \times 8'$ fields near RX J0030 and 3C 295 is comparable to the surface brightness of the X-ray background ($2.6 \times 10^{48}$ ergs s$^{-1}$ cm$^{-2}$ sr$^{-1}$ in the 0.5–2 keV band). This enhancement is about 100 times larger than the central enhancement from large-scale emission ($10^{-4} \text{ ergs s}^{-1} \text{ cm}^{-2} \text{ Mpc}^{-1}$) found by Soltan et al. (1996). The results of Cappi et al. (2001; see their Fig. 4) show that these unresolved sources do not extend beyond the clusters much more than about $4'$, as opposed to the large-scale component of Soltan et al., which extends out to about $30'$ when scaled to the redshifts of RX J0030 and 3C 295 ($\approx 0.5$). Therefore, it is likely that this component contributes only to the compact component found by Soltan et al.

There are a number of possibilities for the nature of these extra sources: cosmic variance, starburst galaxies, a result of gravitational lensing of background objects, or an enhanced number density of AGNs/QSOs. It is unlikely that the extra sources are due to cosmic fluctuations, which are only at the level of about 20%–30%, significantly below the measured factor of 2 (Cappi et al. 2001). It could be possible, however, that the excess of unresolved sources is due to projection effects, with differences arising from whether we are viewing along or perpendicular to a filament of the cosmic web. Starburst galaxies are also unlikely to be the sources Cappi et al. found since their X-ray luminosities are about 10–100 times too faint. However, recent Chandra deep surveys did find some exceptional X-ray bright galaxies at similar redshifts. Gravitational lensing can increase the number of unresolved sources, but only if the log N–log S slope is steep enough ($\geq 0.4$; Croton & Shanks 1999; Mellier 1999). Two opposite effects are competing in determining the number of observed sources: lensing magnifies the flux, but it also reduces the field of view behind the gravitational lens. Lensing would need a significantly higher slope in log N–log S to explain the large number of extra sources in the field. Refregier & Loeb (1997) predict an average reduction of the surface density of faint sources at fluxes less than $10^{-15}$ ergs s$^{-1}$ cm$^{-2}$. Cappi et al. conclude that, as far as spectra and luminosities are concerned, the unresolved sources near RX J0030 and 3C 295 could be AGNs/QSOs associated with the respective clusters.

In Figure 2, we show the hardness ratios (HRs), $(H - S)/(H + S)$, where $S$ and $H$ are X-ray fluxes in the 0.5–2 keV (soft) and in the 2–10 keV (hard) bands, of unresolved sources in the fields of A1995 (squares) and MS 0451 (triangles) as a function of $H + S$ (our results). As a comparison, we also plot the HRs of RX J0300 (asterisks) and 3C 295 (diamonds) from Cappi et al. (2001). Points with one-sided error bars represent sources not detected either in the hard or in the soft band. The average HR of unresolved sources detected in both soft and hard bands near RX J0300 and 3C 295 are $\approx -0.5$, while the average HR of unresolved sources near A1995 is slightly harder, about $-0.25$. These sources near A1995 also have lower fluxes than
sources near the other two clusters, as previously noted (see § 3).

Comparing our Figure 2 to Figure 3 of Rosati et al. (2002), which shows the HRs of sources of different types as a function of their luminosities, we conclude that unresolved sources in RX J0300 and 3C 295 with \( H + S \approx 0.004 \) counts s\(^{-1}\), corresponding to luminosities of about \( 10^{44} \) ergs s\(^{-1}\) at the distance of the clusters, would be compatible to the HRs of type I AGNs (as noted by Cappi et al. 2001). While the faint unresolved sources \( (L_* = 5 \times 10^{44} \) ergs s\(^{-1}\)) in the field of A1995 are concentrated around \( H + S \approx 0.0006 \) counts s\(^{-1}\), HR \( \approx -0.25 \), which falls between normal and starburst galaxies.

Recent results show that the angular correlation function of X-ray–selected AGNs is similar to that of nearby galaxies, suggesting that AGNs sample the mass density in the same way as galaxies sample (Akylas, Georgantopoulos, & Plionis 2000), in contrast to optically selected AGNs, which are found to be more frequent in field galaxies (5%) than in galaxies near clusters (1%; Dressler, Thompson, & Shectman 1985; Osterbrock 1960). Therefore, we would expect more X-ray–selected AGNs in clusters. Since the clustering length of X-ray–selected AGNs and nearby galaxies is the same within errors (\( \approx 7 \) h\(^{-1}\) Mpc; Basilakos 2001; Akylas et al. 2000; Peebles 1993), we would expect the ratio of the total number of galaxies to the number of X-ray–selected AGNs, \( N_{\text{gal}}/N_{\text{AGN}} \), to be \( \approx \langle n_{\text{gal}} \rangle/\langle n_{\text{AGN}} \rangle \) (where \( \langle n_{\text{gal}} \rangle \) and \( \langle n_{\text{AGN}} \rangle \) are the average number densities of galaxies and AGNs in the cluster). However, this effect could account for only about 20% of the excess, much less than a factor of 2, which has been found by Cappi et al. (2001) and in this work.

Our results, that the characteristic luminosities of extra sources are about 1 order of magnitude different in A1995 versus 3C 295 and RX J0030, and that there seems to be a difference between their HRs, argue against cosmic variance and projection effects. They suggest instead that a different class of objects might dominate in different clusters, perhaps depending on the formation history and/or the dynamical state of the cluster.

Perhaps the unresolved sources in A1995 belong to a class of starburst galaxies, a result of enhanced star formation due to interactions between infalling groups of galaxies and the intracluster gas. This enhanced star formation would lead to an excess of blue galaxies around these areas, similar to the Butcher-Oemler effect (Butcher & Oemler 1978). A search for a correlation between galaxy color changes around X-ray sources compared to other areas in the cluster could be used to check this possibility.

At present, the exact nature of these objects is not known. Owing to limited photon statistic, their spectra could not be determined individually; both low-temperature (\( \leq 2 \) keV) thermal bremsstrahlung and power-law spectra can be fitted to their stacked spectra. Revealing the physical properties of these objects would help us to improve our understanding of structure formation, specifically the origin and evolution of the intracluster gas, and the effect of merging. Identification of these sources would also help us to assess the contamination these sources cause in the interpretation of cluster emission as thermal bremsstrahlung from intracluster gas. This contamination would result in an overestimation of the normalization of the X-ray flux from the cluster and would lead to a systematic error in the determination of the Hubble constant using the Sunyaev-Zeldovich effect and thermal bremsstrahlung (see, for example, Molnar, Birkinshaw, & Mushotzky 2002). Follow-up observations of the individual sources are necessary to solve this mystery.

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Fig. 2.—HRs of unresolved X-ray sources as a function of the 0.5–10 keV count rate in the A1995, MS 0451, RX J0300, and 3C 295 fields. The symbols are the same as in Fig. 1.