FIRST MEASUREMENT OF A RAPID INCREASE IN THE AGN FRACTION IN HIGH-REDSHIFT CLUSTERS OF GALAXIES

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ABSTRACT

We present the first measurement of the AGN fraction in high-redshift clusters of galaxies (z ~ 0.6) with spectroscopy of one cluster and archival data for three additional clusters. We identify eight active galactic nuclei (AGNs) in these clusters from Chandra data that are sensitive to AGNs with hard X-ray (2–10 keV) luminosity LX,H > 1043 ergs s−1 in host galaxies more luminous than a rest-frame M_μ < −20 mag. This stands in sharp contrast to the one AGN with LX,H > 1043 ergs s−1 that we discovered in our earlier study of eight low-redshift clusters with z = 0.06–0.31 (z ∼ 0.2). Three of the four high-redshift cluster data sets are sensitive to LX,H > 1042 ergs s−1, and we identify seven AGNs above this luminosity limit, compared to two AGNs in eight low-redshift clusters. Based on membership estimates for each cluster, we determine that the AGN fractions at z ~ 0.6 are f_X(LX,H > 1042; M_μ < −20) = 0.028 ± 0.012 and f_X(LX,H > 1043; M_μ < −20) = 0.002 ± 0.002. These values are approximately a factor of 20 greater than the AGN fractions in lower redshift (z ∼ 0.2) clusters of galaxies. The cluster increase also represents substantially faster evolution than observed in the field over this redshift range (a factor of 1.3 and 3.3 for LX,H > 1042 and LX,H > 1043, respectively). The cluster AGN fraction increases more rapidly with redshift than the field, and the increase in cluster AGNs indicates the presence of an AGN Butcher-Oemler effect.

Subject headings: galaxies: active — galaxies: clusters: individual (Cl 0016+1609, Cl 0542−4100, Cl 0848.6+4453, MS 2053−04) — galaxies: evolution

Online material: color figure

1. INTRODUCTION

Measurements of AGNs in low-redshift clusters of galaxies have received substantial recent interest because of their apparent importance for regulating the heating of the intracluster medium (ICM; McNamara et al. 2000; Fabian et al. 2000) and because of the efficiency with which sensitive Chandra observations can identify the relatively rare AGN population in clusters. Martini et al. (2006) showed that 5% of the X-ray–selected AGNs in clusters have (0.5–8 keV) LX > 1041 ergs s−1 in galaxies above M_μ < −20 mag, which is 5 times as many as found via emission-line selection in purely spectroscopic surveys (Dressler et al. 1985). These observations also demonstrated that the excess X-ray point-source surface density observed toward the fields of clusters of galaxies (e.g., Lazzati et al. 1998; Cappi et al. 2001; Sun & Murray 2002) is due to X-ray emission from cluster members and not chance associations.

The high-redshift cluster AGN population has been less studied due to the absence of comparably sensitive Chandra observations of z > 0.5 clusters and also because of the greater difficulty of spectroscopic follow-up. Nevertheless, AGNs are expected to be more common in higher redshift clusters because of the overall increase in the AGN space density at high redshift (e.g., Osmer 2004) and because of the increase in the fraction of star-forming galaxies in clusters at higher redshift (e.g., Postman et al. 2001), which indicates that high-redshift cluster galaxies are richer in cold gas than their lower redshift counterparts. Observations of several high-redshift clusters have also found substantial AGN populations in some clusters (Dressler & Gunn 1983; Johnson et al. 2003, 2006), while surface density studies have found evidence of an increase in the X-ray source surface density at high redshift (Dowsett 2005). Feedback from cluster AGNs could also play a substantial role in shutting down star formation in cluster galaxies, such as illustrated by the significant decrease in blue galaxies found by Butcher & Oemler (1978; the Butcher-Oemler effect).

In this Letter we present the first measurement of the cluster AGN fraction at high redshift (z ∼ 0.58) from analysis of four archival Chandra observations, our spectroscopic observations of one cluster (MS 2053−04), and literature data for three additional clusters (Cl 0016+1619 at z = 0.5466; Cl 0542−4100 at z = 0.630; Cl 0848.6+4453 at z = 0.57). These observations reveal a substantial increase in the cluster AGN fraction at high redshift, and this has many implications for the preheating of the ICM during cluster assembly, the downsizing in the AGN population as a function of environment, and the AGN contribution to X-ray studies of high-redshift clusters for cosmological studies.

2. OBSERVATIONS

We have identified AGNs in MS 2053−04 via spectroscopic observations of X-ray counterparts from archival Chandra observations. MS 2053−04 has been observed twice with Chandra, ObsIDs 551 and 1667, which are a pair of 45 ks ACIS-I observations that partially overlap one another (both include the cluster core). The area of the first of these data sets was imaged with deep BVRI observations using the Tek No. 5 CCD camera at the 2.5 m du Pont telescope at Las Campanas Observatory in 2002 September (the second Chandra data set had not yet been made public). These images were processed, and the galaxies were identified and matched to the X-ray observations, following the procedures described in Martini et al. (2006).

This analysis identified 82 X-ray sources with visible-wavelength counterparts, and these were used to design slit masks for IMACS (Imamori Magellan Areal Camera and Spectrograph; Dressler et al. 2006) on the 6.5 m Walter Baade Telescope of...
the Magellan Project. A total of four multiter slit masks were designed with approximately 180 objects per mask; however, faint sources were assigned to multiple masks, and therefore a total of 617 unique objects were observed. These objects included all X-ray counterparts brighter than $I \leq 23.5$ mag. Additional sources were prioritized by $I$ magnitude to obtain information about the inactive cluster galaxy population. Color- and image-quality constraints were not employed to preselect potential cluster members due to the small expected size of typical cluster members and to the large population of relatively blue or Butcher-Oemler galaxies in this high-redshift cluster.

The four slit masks were observed in 2004 August for 3 hr each, and these data were processed into two-dimensional spectra with the COSMOS package. One-dimensional spectra were extracted with the IRAF APALL package, and redshifts were measured with a modified version of the Sloan Digital Sky Survey pipeline, although each was also inspected by eye. This procedure identified a total of 41 counterparts to X-ray sources, including four at the cluster redshift. To supplement these observations and obtain improved flux measurements, we reprocessed the original Chandra data and added the second ACIS-I pointing. Individual X-ray sources were identified with the CIAO wavdetect algorithm from both the individual observations and a merged version of the observations. This analysis reidentified the four X-ray counterparts at the cluster redshift. We also cross-correlated these X-ray sources with a spectroscopic study by Tran et al. (2005) and identified one additional X-ray source at the cluster redshift. The properties of these five sources are provided in Table 1.

### Table 1

| Name          | Object ID          | $I$       | $V-I$     | log $L_{\text{X},H}$ | $\zeta$ | $R$ (Mpc) | $R/R_{200}$ | Notes                                      |
|---------------|--------------------|-----------|-----------|-----------------------|--------|-----------|------------|-------------------------------------------|
| MS 2053-X1    | CXOU J205647.1−044407 | 21.26    | 0.950     | 0.08                  | 42.80  | 0.600     | 3.57       | 2.35 Not in first X-ray field               |
| MS 2053-X2    | CXOU J205611.7−041155 | 18.96    | 0.020     | 0.08                  | 42.81  | 0.600     | 1.67       | 1.10                                      |
| MS 2053-X3    | CXOU J205621.2−043749 | 19.20    | 0.028     | 0.08                  | 42.43  | 0.584     | 0          | 0 BCG (likely not an AGN)                  |
| MS 2053-X4    | CXOU J205621.2−043552 | 21.35    | 0.017     | 0.08                  | 42.03  | 0.585     | 0.78       | 0.51 $z$ from Tran et al. (2005)             |
| MS 2053-X5    | CXOU J205608.1−043211 | 22.73    | 0.421     | 0.08                  | 42.59  | 0.588     | 2.59       | 1.71                                      |

Note.—AGNs in MS 2053−04 ($z = 0.583$). The columns list, from left to right, our identifier, the full name, the $I$-band magnitude, the $V-I$ color, the log of the hard X-ray luminosity, the redshift, the projected distance from the cluster center in units of megaparsecs, the projected distance relative to $r_{200}$, and notes about the X-ray source.

3. RESULTS

We have identified a total of five X-ray counterparts at the redshift of MS 2053−04, although we only classify the one AGN within $r_{200}$ as a member. The AGN classification is based on the rest-frame, hard X-ray luminosity (2−10 keV) of $L_{\text{X},H} = 10^{42}$ ergs s$^{-1}$ (measured on the merged data sets). Of the remaining four X-ray counterparts, one is associated with the brightest cluster galaxy (BCG). This source is coincident with the peak of the X-ray emission from the ICM, and evidence of an additional AGN component is inconclusive (see also Tran et al. 2005). The three remaining X-ray counterparts lie outside the cluster’s projected $r_{200}$ radius of 1.5 Mpc, which we calculated from the cluster’s velocity dispersion (Carlberg et al. 1997; Treu et al. 2003) of $\sigma = 865$ km s$^{-1}$ (Tran et al. 2005). While they may be bound to the cluster, we adopt the projected radius of $r_{200}$ to compare measurements of the AGN fraction between clusters. Figure 1 presents the visible-wavelength spectra, $R$-band images, and X-ray images of all five of the X-ray sources at the redshift of MS 2053−04.

Calculation of the AGN fraction in MS 2053−04 requires a measurement of the number of cluster members without luminous X-ray counterparts. Following the AGN fraction measurement of Martini et al. (2006), we choose to estimate the number of cluster members above a rest-frame $M_H < -20$ mag, which corresponds to $I = 22.4$ mag for an evolved stellar population at this redshift. As our spectroscopic catalog is not complete for all galaxies to this magnitude limit, we instead use the efficiency of our spectroscopic identification of cluster members, the surface density of resolved, $I \leq 22.4$ mag objects, and the membership data collected by Tran et al. (2005) to estimate the total cluster galaxy population. We calculate this efficiency for the full sample as a function of magnitude and as a function of color, and we conclude that there are approximately 66 galaxies brighter than $M_H < -20$ mag in the cluster.

We searched the Chandra archive and the literature to identify additional clusters at $z \sim 0.6$ with both comparably sensitive observations and spectroscopic observations of the X-ray sources, and we identified three clusters: Cl 0016+1609 ($z = 0.5466$, 61 ks) and Cl 0542−4100 ($z = 0.630$, 51 ks), where the X-ray sources in these fields had been targeted by the ChaMP survey (Kim et al. 2004; Silverman et al. 2005), and Cl 0848.6+4453 ($z = 0.57$, 185 ks), which has been targeted by the SEXTSI survey (Harrison et al. 2003; Eckart et al. 2006). In addition, Cl 0016+1609 has extensive membership data and a measured velocity dispersion of $\sigma = 1234$ km s$^{-1}$ (Dressler & Gunn 1992; Carlberg et al. 1996; Ellingson et al. 1998). From these mem-
We adopt these membership values and the reported completeness of the CNOC survey, we estimate that there are approximately 200 cluster members more luminous than $L_\odot = -20$ mag in Cl 0016+1609. The other two clusters in this sample, Cl 0542−4100 and Cl 0848.5+4453, do not have substantial spectroscopic data outside of the X-ray counterparts. For these clusters, we use the measured X-ray temperatures of 7.9 keV (Xue & Wu 2000) and 3.6 keV (Holden et al. 2001), respectively, to estimate velocity dispersions of $\sigma = 1200$ and 670 km s$^{-1}$. We then use the relationship between velocity dispersion and cluster richness $N_{\text{gals}}$ from the maxBCG survey (Koester et al. 2007) to estimate the number of members brighter than $M^* + 1$, or approximately our galaxy absolute magnitude threshold. From their fitting formula, we estimate that there are 152 members in Cl 0542−4100 and 24 in Cl 0848.5+4453. This relation also predicts 55 members in MS 2053−04 and 172 members in Cl 0016+1609, and these values agree with our previous estimates to within 20%. We adopt these membership values for all four clusters to consistently calculate the AGN fraction; we discuss the uncertainties in this assumption below.

Our observations of MS 2053−04, along with those for Cl 0016+1619 and Cl 0848.5+4453, are approximately deep enough to detect sources to a limiting rest-frame hard X-ray luminosity of $L_{\text{X},H} > 10^{42}$ ergs s$^{-1}$. In these three clusters, we have identified a total of seven AGNs within $r_{500}$ in a total population of 251 galaxies (see Table 2). For comparison, we identified only two AGNs above this limit in a sample of eight low-redshift ($\bar{z} = 0.2$) clusters with a total of 1377 cluster galaxies (Martini et al. 2007). At $\bar{z} = 0.6$, we therefore find that the AGN fraction is $f_{\text{AGN}}(L_{\text{X},H} > 10^{42}; M_g < -20) = 0.028 \pm 0.004$ (seven AGNs divided by 251 cluster galaxies). The quoted uncertainties correspond to 90%, one-sided Poisson confidence limits. The data for the highest redshift cluster in our sample (Cl 0542−4100) are only sensitive to AGNs more luminous than $L_{\text{X},H} > 10^{43}$ ergs s$^{-1}$, and there are a total of eight AGNs within $r_{500}$ above this limit in these four clusters (with an estimated ~400 total cluster members), in striking contrast to the presence of only one comparably luminous AGN in eight low-redshift clusters. For this X-ray luminosity threshold, we estimate that the AGN fraction is $f_{\text{AGN}}(L_{\text{X},H} > 10^{43}; M_g < -20) = 0.020 \pm 0.012$ (Cl 0848.5+4453).

In contrast, at $\bar{z} = 0.2$, the AGN fractions from Martini et al. (2007) are $f_{\text{AGN}}(L_{\text{X},H} > 10^{42}; M_g < -20) = 0.0015 \pm 0.0003$ and $f_{\text{AGN}}(L_{\text{X},H} > 10^{43}; M_g < -20) = 0.0007 \pm 0.0002$ or approximately a factor of 20 lower. Figure 2 plots the cluster AGN fraction for these two luminosity thresholds at low and high redshift and illustrates the significant increase in the cluster AGN fraction at high-redshift compared to the lower redshift sample. For comparison, we also show the relative evolution of the integrated space density of AGNs above these two luminosity thresholds from the parameterization of Ueda et al. (2003). While the overall normalization of the curves is arbitrary, the relative evolution of the $L_{\text{X},H} > 10^{42}$ ergs s$^{-1}$ and $L_{\text{X},H} > 10^{43}$ ergs s$^{-1}$ samples is not. These curves indicate that the cluster AGN fraction increases more rapidly with look-back time than the AGN space density in the field. Specifically, the field AGN space density increases by only a factor of 1.5 from $\bar{z} \approx 0.2$ to $\bar{z} \approx 0.6$ for $L_{\text{X},H} > 10^{42}$ ergs s$^{-1}$ and only a factor of 3.3 for $L_{\text{X},H} > 10^{43}$ ergs s$^{-1}$, compared to the factor of 20 that we observe in clusters. While there is substantial variation between the AGN fractions of individual clusters, if we exclude Cl 0848, the largest contributor to the AGN fraction, and redo the calculation, we still see a factor of 10 increase in the cluster AGN fraction.

While the substantial evolution in the AGN fraction in clusters is due to small numbers of AGNs, it is measured from a large population of inactive cluster galaxies. The measured fractions at low and high redshift are formally inconsistent with the 90%, one-sided confidence intervals. At high redshift, we have more AGNs and, consequently, a more significant measure of the AGN fraction. We therefore use these measurements of the high-redshift AGN fraction, and a binomial probability distribution, to ask what the probability is of detecting two AGNs with $L_{\text{X},H} > 10^{42}$ ergs s$^{-1}$ or
one AGN with \( L_{X,H} > 10^{43} \text{ ergs} \text{ s}^{-1}\) in the low-redshift sample, and we calculate that the probability (for each) is less than 1%. The main systematic error in these calculations is in the number of galaxies brighter than \( M_R < -20 \text{ mag} \) in each cluster. As detailed membership information for MS 2053–04 and CI 0016+1619 agree to within 20% with the richness–velocity dispersion relationship from Koester et al. (2007), systematic errors in membership are insignificant compared to the observed evolution in the AGN fraction. Two additional sources of uncertainty in these estimates are the galaxy luminosity evolution between \( z \sim 0.6 \) and \( z \sim 0.2 \) and the actual sensitivity and completeness of the \textit{Chandra} data sets. First, \( M_R^* \) is approximately 0.4 mag brighter at \( z \sim 0.6 \) than at \( z \sim 0.2 \). Our fixed luminosity threshold extends further below \( M_R^* \) at high redshift, and therefore we have overestimated the cluster membership (relative to \( M^* \)) at high redshift and underestimated the AGN fraction. Second, the \textit{Chandra} observations are not uniformly sensitive to our adopted thresholds of \( L_{X,H} > 10^{42} \text{ ergs} \text{ s}^{-1}\) and \( L_{X,H} > 10^{43} \text{ ergs} \text{ s}^{-1}\); in fact, the 61 ks observation of CI 0016+1609 is shallower than the 90 ks of total integration time available for the center of MS 2053–04. We estimate the size of this effect by calculating the approximate depth of each \textit{Chandra} exposure and integrating the hard X-ray luminosity function of Ueda et al. (2003) from the current depth to \( L_{X,H} > 10^{42} \text{ ergs} \text{ s}^{-1}\). This exercise indicates that we may expect as many as 50% more AGNs if these data were uniformly sensitive to \( L_{X,H} > 10^{42} \text{ ergs} \text{ s}^{-1}\) sources. Two final points are (1) that the spectroscopy of all X-ray sources may not be complete and (2) that it is difficult to unambiguously identify an AGN in the BCG due to the substantial X-ray sources. Two final points are (1) that the spectroscopy of all X-ray sources may not be complete and (2) that it is difficult to unambiguously identify an AGN in the BCG due to the substantial X-ray sources. Two final points are (1) that the spectroscopy of all X-ray sources may not be complete and (2) that it is difficult to unambiguously identify an AGN in the BCG due to the substantial X-ray sources. Two final points are (1) that the spectroscopy of all X-ray sources may not be complete and (2) that it is difficult to unambiguously identify an AGN in the BCG due to the substantial X-ray sources.

Although these estimates correspond to a small fraction of the total cluster galaxy population, they represent a substantial increase over the measured cluster AGN fraction at low redshift. Specifically, in a sample of eight clusters of galaxies with an average redshift of \( z \sim 0.2 \), Martini et al. (2006) measured only one AGN with \( L_{X,H} > 10^{43} \text{ ergs} \text{ s}^{-1}\) and only two AGNs with \( L_{X,H} > 10^{42} \text{ ergs} \text{ s}^{-1}\). From these measurements, we find that the cluster AGN fraction has increased by approximately a factor of 20 for these two hard X-ray luminosity thresholds between \( z \sim 0.2 \) and \( z \sim 0.6 \). This evolution corresponds to a significant increase relative to the measured evolution of the field hard X-ray luminosity function by Ueda et al. (2003) over the same redshift range and points to the existence of an “AGN Butcher-Oemler effect” in clusters of galaxies. The overdensity of AGNs at high redshift could be an additional source of preheating of the ICM during cluster assembly, has important cosmological implications for X-ray studies of high-redshift clusters, and could show how the environment influences the AGN population.

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