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# *CHANDRA* DISCOVERY OF THE INTRACLUSTER MEDIUM AROUND UM 425 AT A REDSHIFT OF 1.47

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## ABSTRACT

We report on the discovery of a candidate cluster of galaxies at redshift $z = 1.47$ based on *Chandra* observations in the field of quasars UM 425A and UM 425B. We detect with high significance diffuse emission due to the intracluster hot gas around the quasar pair. This is the second highest redshift cluster candidate after 3C 294 at $z = 1.786$. The diffuse emission is elliptical in shape with about 17″ extent. If indeed at $z = 1.47$, this corresponds to a physical size of 140 $h_{70}^{-1}$ kpc and 2–10 keV luminosity of $\sim 3 \times 10^{43}$ ergs s$^{-1}$. The cluster is unlikely to be the long-sought gravitational lens invoked to explain the unusual brightness of UM 425A and the close quasar pair. Coexistence of the quasars with the cluster suggests a link of activity to cluster environment. The unusually high luminosity of UM 425A may then be due to a higher accretion rate. We also comment briefly on the X-ray spectra of UM 425A and UM 425B, both of which exhibit broad absorption line optical spectra. The present evidence suggests that the quasars are just a pair and not lensed images of the same quasar.

*Subject headings:* cosmology: observations — galaxies: active — galaxies: clusters: individual (UM 425) — intergalactic medium — X-rays: galaxies: clusters

## 1. INTRODUCTION

It is becoming increasingly clear the we live in a weird universe, filled with about 73% dark energy, 23% dark matter, and only some 4% ordinary matter (Bennett et al. 2003; Spergel et al. 2003). One expectation from this "low-density" cosmological model is that large-scale structures formed early in time. A number of cluster surveys are designed to find high-redshift clusters of galaxies in optical and radio wavelengths (e.g., Shectman et al. 1996; Kurk et al. 2002) to provide independent cosmological constraints. Clusters are identified in X-rays by the diffuse thermal emission from their intracluster gas, which in fact accounts for most of their baryonic mass. A number of X-ray surveys have been very successful in finding clusters, determining their physical properties, and using them as cosmological tools (e.g., Vikhlinin et al. 1998; 2003).

*Chandra*, with its exquisite mirrors (van Speybroeck et al. 1997) and detectors (Garmire et al. 2003), began a new era of cluster research. The subarcsecond point-spread function (PSF) and low background of *Chandra* have allowed detailed studies of low-redshift X-ray–bright clusters (e.g., McNamara et al. 2000; Fabian et al. 2000) and have also led to the discovery of the highest redshift cluster candidate at $z = 1.78$ (Fabian et al. 2001). While the clustering properties of low-redshift clusters are used to determine cosmological parameters (e.g., Bahcall et al. 1999; Collins et al. 2001), just the number density of hot high-redshift clusters can provide constraints to the matter density of the universe (Donahue et al. 1998; Fabian et al. 2001). For example, the existence of a cluster at $z = 1.78$ with temperature greater than 3 keV is inconsistent with an $\Omega_m = 1.0$ universe (Fabian et al. 2001). Finding hot X-ray clusters at high redshifts is therefore quite important.

Here we report the serendipitous discovery of a cluster candidate traced by hot intracluster medium around the quasar pair UM 425A and UM 425B at $z = 1.47$. This quasar pair, separated by 6″.5, was discovered by Meylan & Djorgovski (1989) as a gravitational lens candidate because of the unusually large luminosity of the brighter component and its relatively large redshift. Whether or not the pair represents lensed or binary quasars is a matter of continuing debate. To cause such a wide angle separation, a massive cluster of galaxies along the line of sight would be required, but none was found down to a limiting magnitude of $m_R \sim 24$ mag (Courbin et al. 1995). UM 425A and UM 425B also happen to be broad absorption line quasars (BALQSOs), which supports the lens hypothesis given the relative rarity of these objects. BALQSOs are extremely faint X-ray sources, and in the pre-*Chandra* era X-ray spectroscopy of BALQSOs was practically impossible (Mathur et al. 2000 and references therein). With *Chandra*, many BALQSOs have been detected in X-rays (Green et al. 2001; Gallagher et al. 2002), but spectroscopy has been feasible for only a handful of them. The original objective behind our *Chandra* observation was to study the X-ray spectrum of UM 425A, taking advantage of its unusual brightness. While the main focus of this Letter is the unexpected discovery of the diffuse intracluster medium, we also briefly discuss the BALQSOs. A cosmological model with $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_m = 0.3$, and $\Omega_\Lambda = 0.7$ is used throughout the Letter.

## 2. OBSERVATION AND ANALYSIS

### 2.1. *Chandra Observation*

We observed UM 425 with *Chandra* on 2001 December 13 for an exposure time of 110 ks. The Advanced CCD Imaging Spectrometer (Garmire et al. 2003) was used at the nominal aim point. The data were reduced in the standard manner using *Chandra* interactive analysis software (CIAO, version 2.3; M. Elvis et al. 2003, in preparation) and following the thread for imaging analysis.[1] Figure 2 shows the soft-band (0.3–3 keV) image of the field. The quasars UM 425A and UM 425B are clearly detected with 4675 ± 69 and 20 ± 5 net background-subtracted counts, respectively, in the broad band (0.3–8 keV). In addition, faint extended emission is clearly seen extending west-southwest of UM 425A. Contours of 2, 3, 4, 5, and 6 times the background are overlaid on the image to show the extent and significance of the diffuse emission. Figure 2 shows the adaptively smoothed image of the field in the soft band created using the CIAO tool

[1] See http://asc.harvard.edu/ciao/threads/index.html.

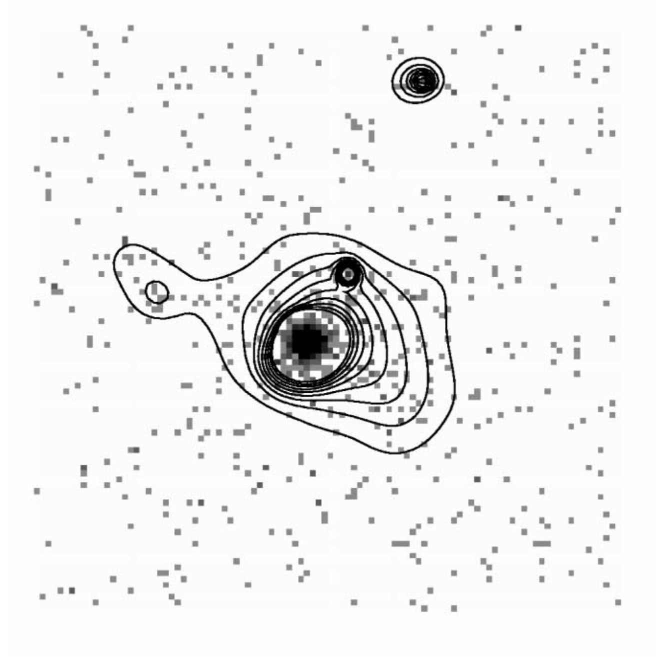

FIG. 1.—Soft-band (0.3–3 keV) image of the UM 425 field overlaid with contours of 2–6 times background level. The contours were generated from the smooth image shown in Fig. 2. In addition to the two point sources UM 425A and UM 425B, the diffuse emission is also evident. The bright source about 25″ north-northwest of UM 425 is a foreground galaxy at $z = 0.1265$ (Meylan & Djorgovski 1989). North is to the top, and east is to the left.

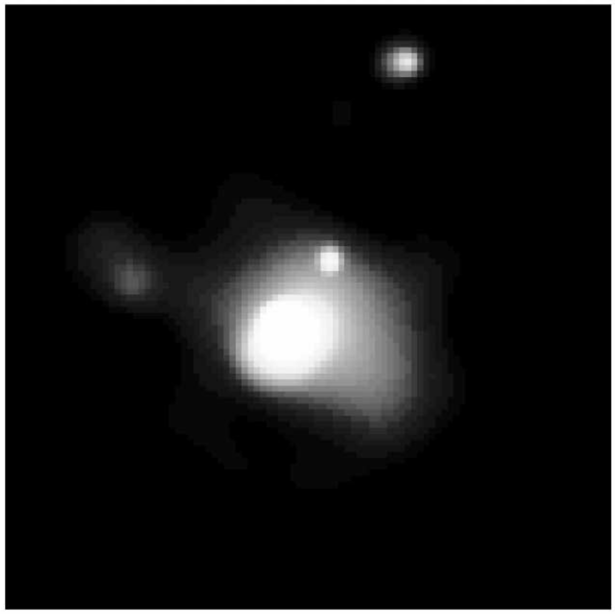

FIG. 2.—Adaptively smoothed exposure-corrected soft-band image of the UM 425 field. In addition to the quasars UM 425A and UM 425B, the diffuse cluster emission is clearly seen in this display.

CSMOOTH and used to generate the contours mentioned above. A Gaussian smoothing function with a threshold of 2 $\sigma$ was applied to the soft-band image and the exposure map, and the smoothed image was then divided by the smoothed exposure map to produce Figure 2. The diffuse emission is clearly seen in this image.

### 2.2. *The Extended Diffuse Emission*

The diffuse emission is somewhat elliptical in shape and extends to about 10″ west-southwest of UM 425A with total extent of about 17″ along the major axis and about 13″ along the minor axis. This corresponds to about 140 kpc by 110 kpc at $z = 1.47$. Because of the presence of the strong point source (UM 425A), it is difficult to determine the exact number of counts from the diffuse emission. To attempt this, we first extracted counts in the energy range 0.3–8.0 keV from a smaller region well outside the area occupied by the point sources. Then we scaled these counts by the area of the entire diffuse emission as shown in Figures 1 and 2. In this way, we estimate 158 ± 18 counts from the diffuse emission and 43 ± 5 counts from a background region of the same size. With 115 ± 19 net counts, the diffuse emission is thus highly significant at the 6 $\sigma$ level.

As another method of estimating the number of counts from the diffuse emission, we extracted all counts from an annular region surrounding UM 425A. The inner 2″ core of the bright point source was excluded, and the extraction region extended out to a radius of 12″, completely covering the apparent extent of the diffuse emission. We then used the ChaRT[2] and MARX[3] tools to simulate the PSF of UM 425A and used the same region described above to extract the counts from the outer wings of the simulated PSF. There were 281 ± 22 counts in the image extraction region, 157 ± 13 in the simulated PSF region of UM 425A, and 20 ± 5 in UM 425 B, resulting in 104 ± 26 net counts from the diffuse emission, consistent with the estimate above.

For spectral analysis, we used the counts from the small extraction region defined above, which is about half the size of the total area of the diffuse emission. With just 57 net counts, the spectral shape cannot be determined accurately. Nevertheless, we performed spectral analysis to obtain a rough estimate of the temperature of the diffuse plasma using the Sherpa spectral fitting package within CIAO. Using a Raymond-Smith thermal plasma model and fixing abundances to 0.1 solar and the foreground absorbing column to the Galactic value ($4.1 \times 10^{20}$ atoms cm$^{-2}$), we find the best-fit temperature to be 2.1 keV at the redshift of the cluster, assumed to be $z = 1.47$. This estimate is highly uncertain; the lower limit on the rest-frame temperature is $kT \gtrsim 0.8$ keV with 90% confidence, and the upper limit is unconstrained. Assuming a rest-frame temperature of $kT = 2.1$ keV, the observed unabsorbed flux is $f_X(0.1\text{–}2.5\ \text{keV}) = 4.6 \times 10^{-15}$ and $f_X(2\text{–}10\ \text{keV}) = 4.6 \times 10^{-16}$ ergs s$^{-1}$ cm$^{-2}$.

### 2.3. *The BALQSOs*

Since BALQSOs are highly absorbed sources, we used absorbed power-law models to fit their X-ray spectra. The presence of excess soft photons, however, often points to partial covering of the source by absorbing material (see Grupe, Mathur, & Elvis 2003 for the detailed procedure of spectral analysis that we follow). For UM 425A, the best-fit spectrum ($\chi^2 = 82.1$ for 112 degrees of freedom) yields the following parameters: $\alpha = 0.93 \pm 0.08$ (where $\alpha$ is the energy index; $f_\nu \propto \nu^{-\alpha}$), column density at the source $N_{\rm H} = (3.1 \pm 0.7) \times 10^{22}$ cm$^{-2}$, and a covering fraction of $f = 0.74 \pm 0.04$. This spectrum and those of other BALQSOs show that strong absorption is the main cause of their X-ray faintness (Grupe et al. 2003; Green et al. 2001; Gallagher et al. 2001).

[2] See http://asc.harvard.edu/chart.
[3] See http://asc.harvard.edu/chart/threads/marx.

UM 425B has too few counts for accurate spectral analysis, but we can test whether the UM 425A spectrum provides an adequate description of the UM 425B data. Keeping all other parameters constant and allowing only flux normalization as a free parameter, the fit is not good. In the bin centered at 1 keV, there are nearly 2 $\sigma$ too few counts compared to the model and systematically too many counts at higher energies. If we allow both the normalization and the absorbing column density to vary, then the resulting absorbing column is $N_{\rm H} = 5 \times 10^{23}$ cm$^{-2}$, over an order of magnitude higher than that in the A component. Alternatively, keeping the $N_{\rm H}$ constant as in component A but allowing the covering fraction to vary leads to $f$ reaching the hard limit $f = 1$. Thus, the spectra of UM 425A and UM 425B are found to be inconsistent with each other.

## 3. DISCUSSION

*Chandra* observations of the UM 425 field have led to the discovery of the hot intracluster medium around the quasar pair. High-$z$ clusters are rare and so are large-separation quasar pairs; chance association of these two uncommon phenomena is unlikely. Even less likely is the chance association of two BALQSOs, which comprise only ∼10% of quasars at $z \lesssim 1.8$ (e.g., Tolea, Krolik, & Tsvetanov 2002). This suggests that the X-ray cluster is at the redshift of the quasars, hosting the pair. Could it be a foreground lens? Aldcroft & Green (2003) have shown that in order to produce the large separation observed in the quasar pair, a lensing cluster at $z = 0.5$ (the redshift at which the lens mass is minimized for a given image separation, corresponding to half the proper distance to the source) would require a minimum temperature of $kT = 1.5$ keV, with luminosity $L_{\rm X}$(0.1–2.4 keV) $\approx 1.5 \times 10^{43}$ ergs s$^{-1}$, resulting in an observed flux of $f_{\rm X}$(0.1–2.5 keV) $\approx 2.3 \times 10^{-14}$ ergs s$^{-1}$ cm$^{-2}$. Given the uncertainty, we cannot rule out a temperature of 1.5 keV of the UM 425 cluster (§ 2.2). However, if the observed cluster has this temperature at $z = 0.5$, the resulting flux is $f_{\rm X}$(0.1–2.4 keV) = $4.2 \times 10^{-15}$ and $f_{\rm X}$(2–10 keV) = $5.6 \times 10^{-16}$ ergs s$^{-1}$ cm$^{-2}$. Thus, the observed X-ray flux is at least a factor of 5 fainter than the minimum flux estimated for the foreground lens. It should be noted that Aldcroft & Green (2003) use an Einstein–de Sitter universe in their analysis; however, even with the cosmology adopted in this Letter, the observed flux is still less than half the minimum flux expected from a lensing cluster. Thus, even if the observed X-ray cluster is at $z \sim 0.5$, it would not be massive enough to cause the observed separation of UM 425A and UM 425B.

The geometry of the system also suggests that the diffuse X-ray emission does not correspond to a foreground lens. Meylan & Djorgovski (1989) point out that if UM 425 is lensed, the lensing cluster should be closer to the fainter of the pair; however, the diffuse emission appears centered around the brighter component, as is clearly seen in Figures 1 and 2. The field of UM 425 has been a target of cluster searches since the quasar pair was thought to be lensed; in addition, there is a small overdensity of galaxies in the field, suggestive of a foreground cluster (Meylan & Djorgovski 1989; Courbin et al. 1995). However, no such cluster is found optically, suggesting that the X-ray cluster reported here is at a much higher redshift. Deep imaging and spectroscopic studies will be required to confirm the redshift of the X-ray cluster, but the present evidence suggests that it is highly likely to be at the redshift of the quasars, hosting the pair. This is exciting, because only one higher redshift cluster is known (Fabian et al. 2001).

Assuming the cluster to be at $z = 1.47$, we find its size to be 140 kpc and luminosity $L_{\rm X}$(0.3–10 keV) = $6.2 \times 10^{43}$ ergs s$^{-1}$ and $L_{\rm X}$(2–10 keV) = $3 \times 10^{43}$ ergs s$^{-1}$ for temperature $kT = 2.1$ keV. These values of temperature and luminosity lie right on the $L_{\rm X}$-$T$ relation for low-redshift groups and clusters (Mulchaey & Zabludoff 1998), which is remarkable given the large uncertainty in the determination of both quantities and possible evolution of the $L_{\rm X}$-$T$ relation with redshift (Vikhlinin et al. 2002). The luminosity is at the lower end of that found for clusters. The observed size of the diffuse emission, however, is small, representative more of a group than a cluster. The faint diffuse emission that we detect must trace the more luminous intracluster gas from the cluster core. Our estimates of temperature and luminosity may then be considered as lower limits. Given the serendipitous nature of this discovery, we cannot determine the space density of such hot high-redshift clusters. The presence of a few such clusters on the sky at redshifts of about 1.5 and higher is consistent with the currently popular cosmological model with $\Omega_m = 0.3$ and $\Omega_\Lambda = 0.7$, but we cannot rule out the $\Omega_m = 1.0$ model based on the poor temperature constraint imposed by just this observation (e.g., Fabian et al. 2001, who find a maximum of 100 collapsed objects with $z > 1.8$ and $kT > 9$ keV).

The association of the X-ray cluster with UM 425A and UM 425B is further evidence that they are a pair of quasars, not lensed images of the same quasar. This interpretation is supported by the different X-ray spectra of the two objects (although, in principle, a time delay coupled with strong variability and/or slightly different sight lines to the nuclear X-ray source can explain the observed difference). We can also explain the unusual brightness of UM 425A without invoking lens magnification. Association of UM 425A and UM 425B with the X-ray cluster, and observations by Martini et al. (2002, who found a high fraction of active galactic nuclei [AGNs] in cluster A2104), suggest that a cluster environment is conducive to the triggering of AGN activity. UM 425A is about 2 mag brighter than other quasars at similar redshifts (Aldcroft & Green 2003). Czerny et al. (1997) argue that most quasars usually radiate at ∼0.01–0.2 of their Eddington luminosity. If UM 425A is radiating near the Eddington limit, its luminosity could easily be an order of magnitude larger than those seen in quasars with similar black hole masses and radiative efficiencies. Such a high accretion rate relative to Eddington may be related to the recent triggering of the quasar (Mathur 2000) and supports the hypothesis that BALQSOs represent an early phase in the quasar life cycle (Canalizo & Stockton 2001; Fabian 1999; Becker et al. 2000). If the fraction of quasars with un-usually high luminosities is small, it may imply that this high accretion phase does not last long. The faint B component was discovered only as a result of its close proximity to UM 425A. Although it is somewhat improbable for both members of a quasar pair to be BALQSOs, it is not prohibitively so. For a given quasar pair, there is a ∼1% chance that both are BALQSOs (assuming a 10% BAL fraction). In the case of UM 425, it could just be a coincidence, or it could be further evidence of a link between cluster environments and the triggering of quasar activity (especially if BALQSOs represent an early stage in quasar evolution).

To summarize, our *Chandra* observations have led to two interesting results: first, the discovery of the second highest redshift cluster candidate, and second, evidence suggesting a connection between the cluster environment and quasar activity and supporting an evolutionary hypothesis to explain the BALQSO phenomenon.

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