1. INTRODUCTION

The Chandra and XMM-Newton observatories have profoundly influenced our knowledge of the gas dynamics in clusters of galaxies. A wide range of phenomena including cold fronts, shocks, and cavities have been studied in a large number of objects over a wide range in redshift due to the unprecedented angular resolution and sensitivity of these two observatories. One of the most unexpected observational results of the Chandra/XMM-Newton era has been the nondetection of large amounts of cooling gas in cluster cores inferred from observations made with the previous generation of observatories. A large fraction of the clusters observed with these two observatories exhibit a disturbed morphology. The role that active galactic nucleus (AGN) outbursts and mergers play in the energy budget and temporal evolution of clusters is still a question of considerable observational and theoretical interest. The study of the most energetic AGN outbursts and mergers is of particular interest as these relatively rare events will have the most dramatic and long-lasting effects on the cluster gas (Birzan et al. 2004).

In this Letter we report the discovery of a ~17 keV cluster associated with the radio galaxy 3C 438. This is the hottest cluster known to date, marginally exceeding the temperature of even the well-studied “Bullet” cluster (Markovich et al. 2002). The high temperature exceeds that of any known relaxed cluster and is almost certainly not indicative of its gravitational mass. The X-ray morphology of the cluster gas is highly disturbed, with an X-ray surface brightness discontinuity that stretches at least 140” (600 kpc) in an arc extending south from the core. Whether this unusually high temperature and complex morphology is the result of a radio outburst or an ongoing major merger is not clear, although we argue that the morphology suggests the latter. The linear size of the radio galaxy 3C 438 is small relative to the surface brightness discontinuity, so the observed features cannot be the result of the current nuclear activity. There are some hints of cavities larger than the lobes of 3C 438 to the east and west of the nucleus, perhaps suggestive of “ghost” cavities created by an earlier epoch of nuclear activity. If these features are the result of a nuclear outburst, the inferred energy to evacuate a single cavity would be 3.4 x 10^63 ergs, at least a factor of a few larger than the outbursts seen in nearby clusters such as Hydra A (Wise et al. 2007) and MS 0735+7421 (McNamara et al. 2005).

This Letter is organized as follows. In § 2 we present the observational details and discuss the cleaning of the data. Our results are presented in § 3. Section 4 contains a discussion of the implications of our results. Section 5 contains a brief summary and conclusion. We assume a cosmology with $H_0 = 71$, $\Omega_M = 0.27$, and $\Omega_{\Lambda} = 0.73$ throughout this Letter (Spergel et al. 2006). The observed redshift ($z = 0.290$; Hewitt & Burbidge 1991) of the host galaxy of 3C 438 corresponds to a luminosity distance of 1481.6 Mpc, and 1” is 4.317 kpc. All uncertainties are at 90% confidence for one parameter of interest unless otherwise stated, and all coordinates are J2000.0. This source lies at relatively low Galactic latitude ($b = −12.98^\circ$); absorption by gas in our Galaxy ($N_H = 2.05 \times 10^{21}$ cm$^{-2}$; Dickey & Lockman 1990) is included in all spectral fits and count rate to flux conversions.

2. DATA ANALYSIS

The radio galaxy 3C 438 was observed for 47.5 ks with the ACIS-S instrument on 2002 January 27 (ObsID 3967). The data were reprocessed to apply the most up-to-date gain and CTI correction, and the event file was filtered to remove events at node boundaries. Standard ASCA grade filtering (i.e., event grades 0, 2, 3, 4, 6) was applied to the data. A light curve was created in the 5–10 keV band after removal of point sources to search for periods of background flaring. Intervals where the background rate was more than 3 $\sigma$ above the mean were removed, leaving ~29.5 ks of good time. X-ray emission from the cluster does not fill the field of view, so a distant region of the S3 chip was used for background for spectral analysis. The composite background files created from multiple observations near the galactic poles would not be appropriate for this observation due to the low galactic latitude and significant absorption. The radio structure of 3C 438 has been studied previously at several frequencies (Hardcastle et al. 1997; Trei-chel et al. 2001). For the current Letter we made a 1.5 GHz radio map with 1.5” resolution from archival VLA data, calibrating and reducing it in the standard manner using AIPS.
3. RESULTS

A Gaussian-smoothed (σ = 6") Chandra/ACIS-S image of 3C 438 in the 0.5–5.0 keV band with 1.5 GHz radio contours (1.5" resolution) overlaid is shown in Figure 1. The most striking feature of Figure 1 is the surface brightness discontinuity in the large-scale gas (white arrows). This discontinuity is an arc that extends more than 140" (600 kpc). This suggests that the cluster is highly disturbed on scales of hundreds of kiloparsecs. There is also a decrement of X-ray counts in a semi-circular region 1' east of the host galaxy of 3C 438. This decrement is suggestive of “ghost” cavities created by the inflation of radio lobes. The radio galaxy 3C 438 lies within the X-ray core but slightly (~4.5", 20 kpc) offset to the northeast from the peak of the X-ray emission. This is more clearly demonstrated in Figure 2, a zoom-in on the nuclear region.

We fitted spectra to eight regions (labeled 1a, 1b, and 2–7) of the cluster gas. The positions of regions 2–7 and the distant background region are shown in Figure 3. Regions 1a and 1b correspond to a circular region (radius 84.5") and an annular region (inner and outer radii of 84.5" and 138.9"), respectively, centered ~19" south-southwest of the nucleus of the radio galaxy. These two regions roughly encompass the X-ray emission inside and outside of the prominent surface brightness discontinuity. Single-temperature APEC models were fitted with the elemental abundances frozen to half the solar value, the column density fixed at the Galactic value, and the redshift frozen at the value measured for the host galaxy of 3C 438. The abundance is poorly constrained if allowed to vary freely, in part because of the high gas temperature. The data were binned to a minimum of 50 counts bin⁻¹. The only free parameters were the temperatures and normalizations. The results of the fits (all statistically acceptable) are summarized in Table 1.

4. INTERPRETATION

The best-fit temperature for the gas within 365 kpc of the nucleus of the cluster (region 1a) is ~17 keV. As can be seen from Table 1, the best-fit temperature on larger spatial scales is consistent with this value, within large errors. There are clearly some cooler subregions contained within 1a, such as the core (region 2) and the gas on the interior of the surface brightness discontinuity (region 3). Even in these cases, however, the cooler gas has a temperature of ~11 keV. The gas

| Region | Temperature (keV) |
|--------|-----------------|
| 1a     | 16.6±2.7        |
| 1b     | 20.7±0.9        |
| 2      | 10.7±1.3        |
| 3      | 10.9±1.4        |
| 4      | >10.0           |
| 5      | 20.6±2.9        |
| 6      | 17.2±3.7        |
| 7      | 26.6±3.9        |

Note.—Regions 1a and 1b are described in the text. Regions 2–7 are shown in Figure 3.

TABLE 1

SUMMARY OF BEST-FIT TEMPERATURES AND 90% UNCERTAINTIES FOR SEVERAL REGIONS OF THE GAS AROUND 3C 438

Fig. 1.—Gaussian-smoothed (σ = 6") Chandra/ACIS-S image of 3C 438 in the 0.5–5.0 keV band with 1.5 GHz radio contours (1.5" resolution) overlaid. All point sources have been removed. The radio galaxy lies well within the cluster core, although offset from the centroid of the X-ray emission. The white arrows denote the position of the surface brightness discontinuity, the green arrow the position of the possible ghost cavity, and the yellow arrows the position of the X-ray filament bounding the northern side of the ghost cavity.

Fig. 2.—Gaussian-smoothed (σ = 3") Chandra/ACIS-S image of 3C 438 in the 0.5–5.0 keV band with 1.5 GHz radio contours (1.5" resolution) overlaid. The X-ray/radio nucleus of 3C 438 lies within the peak of the gas, suggesting motion of the galaxy to the northeast in the larger scale cluster emission.

Fig. 3.—Gaussian-smoothed (σ = 6") Chandra/ACIS-S image of 3C 438 in the 0.5–2.0 keV band with 1.5 GHz radio contours (1.5" resolution) overlaid. Regions 2–7 selected for spectral fitting are overlaid, as well as the local background region. Regions 1a (84.5" radius circle centered ~19" south-southwest of the nucleus of 3C 438) and 1b (an annulus between 84.5" and 138.9" centered at the same point) are not shown.
temperature is beyond that of any known relaxed cluster in the local universe. Assuming a uniform temperature of 17 keV, the unabsorbed bolometric luminosity of the gas within 600 kpc of the host galaxy of 3C 438 is $6 \times 10^{41}$ erg s$^{-1}$. This is therefore one of the hottest, most luminous clusters, rivaling the distant ($z = 0.451$) cluster RX J1347.5−1145 (Allen et al. 2002; Gitti et al. 2004), the hottest, most X-ray–luminous, reasonably relaxed cluster known. This temperature is also comparable to that measured in the highly disturbed “Bullet” cluster ($k_B T \sim 15$ keV, with some regions exceeding 20 keV; Markevitch et al. 2002). Extrapolation of the cluster temperature function derived from clusters with $z < 0.1$ to a gas temperature of 17 keV demonstrates that the space density of such hot clusters is small (Markevitch 1998). There is little or no evolution of the cluster $L_X-T$ relation out to at least $z = 0.5$ (Mushotzky & Scharf 1997, Novicki et al. 2002, among many others). It is therefore unlikely, although not impossible, that the high gas temperature is representative of the gravitational mass of the cluster.

To investigate the gravitational mass of the cluster we consider the surface brightness profile of the cluster. X-ray surface brightness profiles in two 30° wedges north and south of the nucleus (centered on the nucleus) are plotted in Figure 4 (top). The surface brightness discontinuity to the south of the nucleus manifests itself as a sharp change in the slope of the profile at about 95° (410 kpc) from the nucleus. The surface brightness of the gas to the north of the nucleus is relatively smooth, so we fitted a beta-model profile to the data in this wedge between $200 < r < 1500$ (85 kpc $< r < 650$ kpc) to determine the undisturbed density profile. The core radius, $r_c$, is poorly determined in the fits, so we held it constant at 30° (130 kpc). We find a best-fit value of $\beta = 0.52 \pm 0.04$, somewhat flat for a cluster of galaxies, but not unreasonable. The central hydrogen density, $n_H$, is $3.4 \times 10^{-2}$ cm$^{-3}$ for $n_A = 1.2 n_H$, appropriate for a fully ionized plasma with subsolar elemental abundances. We have plotted the gravitational mass of the cluster as a function of distance from the nucleus in Figure 4 (bottom) using the parameters derived from the surface brightness profile assuming hydrostatic equilibrium for two temperatures, 10 and 17 keV. The extrapolations of these two curves to $r_{500}$ (2.6 and 2.0 Mpc for the 17 and 10 keV clusters, respectively) is roughly consistent with the mass profiles derived from the HIFLUGCS sample of 63 clusters with $z < 0.1$ and 1.0 keV $< T < 10$ keV (Finoguenov et al. 2001). The cluster mass at $r_{500}$ is on the order of a few times $10^{15}$ $M_\odot$ in either case. Hydrodynamic simulations of merging clusters show a complex time evolution of the cluster $L_X-T$ relationship (Randall et al. 2002; Rowley et al. 2004), so that determination of mass in this manner may be biased, although the variation of $L_X-T$ during a merger is smaller than our uncertainties on the cluster temperature. In any case, our conclusions below are not sensitive to whether the underlying gravitational mass profile is representative of a $\sim 10$ keV cluster, a $\sim 17$ keV cluster, or an even larger cluster.

The high temperature combined with the highly disturbed morphology suggests that we are witnessing a dramatic event. There are at least three possible scenarios that would explain the high cluster temperature and disturbed morphology. First, an extremely powerful nuclear outburst inflated radio lobes in the gas. Second, this system is a pair of massive clusters of roughly equal mass undergoing a major merger. Third, the observed X-ray surface brightness discontinuity is the result of “sloshing” of the gas due to a minor merger.

If the observed features are the result of a radio outburst, it is clear that the present epoch of nuclear activity cannot be responsible for disturbing the gas on scales of hundreds of kiloparsecs. The radio galaxy 3C 438 is too small (with a projected linear size of only 100 kpc) to be relevant to the observations of the surface brightness discontinuity. It is also too weak: the amount of energy required to evacuate the cavities created by the inflation of the lobes of 3C 438 is only a small fraction of that required to displace the gas to create the surface brightness discontinuity. The bubble enthalpy of the lobes ($4 p V$) is $\sim 2.7 \times 10^{60}$ ergs. Interestingly, the equipartition enthalpy of the lobes is more than an order of magnitude below this, implying a substantial departure from equipartition and/or a significant contribution to pressure from nonradiating particles in the lobes of 3C 438. In this scenario in which the large-scale disturbance in the cluster gas is the result of a nuclear outburst, there must have been an earlier epoch of AGN activity, although there is no evidence of any large-scale, low-frequency radio emission suggestive of aged, steep-spectrum radio plasma. There is what appears to be a “ghost cavity” east of the nucleus (spectrum region 5) 45.6° in diameter and perhaps a budding bubble to the west (spectral region 6), similar to what has been observed in M87 (Forman et al. 2005). The energy required to completely evacuate the eastern cavity ($p V$ work) is $3.4 \times 10^{62}$ ergs assuming that the surface brightness profile of the northern wedge (discussed above) represents the undisturbed gas. The enthalpy of such bubbles is $2.4 \times 10^{63}$ ergs. The energy required to create the discontinuity to the west of region 6 is at least several times this. For comparison, the total thermal energy in the gas to this radius is $\sim 1.5 \times 10^{64}$ ergs.

There are two problems with this outburst scenario. First and most significantly, the energy requirement, a few $\times 10^{63}$ ergs, strongly argues against this hypothesis. This would be the most powerful nuclear outburst known, far exceeding those observed in Hydra A (Wise et al. 2007) and MS 0735+7421 (McNamara et al. 2005). Second, the high temperature of the gas is at best a consequence of mixing, not heating. Finally, simulations by Reines et al. (2005) predict that the outflows from a young active galaxy should be accompanied by a hot X-ray gas, a phenomenon that has not been observed in 3C 438. Each of these three problems argues strongly against the outburst scenario. One possible resolution, however, is that the outburst occurred very recently, and the gas is in a transitional stage between cold and hot. This scenario may be similar to that proposed for the 3C 226 system (Forman et al. 2004).

In any case, the highly disturbed morphology of the cluster is very extraordinary. This is the first time a major merger event has been identified that is not associated with an active galaxy. The high X-ray luminosity of the cluster (Markevitch et al. 2002), the hot gas temperature, the sharp surface brightness discontinuity, and the disturbed morphology all point to some dramatic event in the cluster history. This object is clearly a major merger in progress, one of the most striking that has ever been seen. The question now is whether this high temperature is a characteristic of major mergers or if it is a rare occurrence. It is clear that if we can identify other examples of this phenomenon, we will have found a valuable tool for understanding the evolution of galaxy clusters.
et al. 2005) and would require unrealistically large black hole growth and accretion rate. Assuming 10% efficiency, approximately \(10^{10} M_\odot\) would have to be accreted onto the central SMBH to power an outburst of \(2 \times 10^{46}\) ergs. In addition, the sound crossing time to reach the end of the discontinuity is \(\sim 2 \times 10^7\) yr, so the mass accretion rate would be an unrealistically large \(\sim 100 M_\odot\) yr\(^{-1}\). Second, if the eastern cavity and western bubble are in fact remnants of an earlier epoch of radio activity, they lie at roughly 45\(^\circ\) angles to the direction of the jets of the current outburst. This would imply that the spin axis of the supermassive black hole at the center of the host galaxy of 3C 438 has changed direction within the last 10\(^8\) yr. This is not entirely implausible as the host galaxy may have merged with another galaxy in this period. Optical observations of the host galaxy reveal that there are several nearby companions, although there is no evidence of a recent merger (Madrid et al. 2006). Recent simulations of the viscous dissipation of buoyant bubbles demonstrate that their long-term evolution may have little relation to the initial jet axis (Brüggen et al. 2005).

The other possibility, and the more likely one in our view, is that we are witnessing a major merger between two massive clusters. In this scenario, the X-ray surface brightness discontinuity is a cluster cold front and the high-temperature gas is the hot shocked plasma of the other cluster. One cluster is moving in the plane of the sky. A temperature shock-heated plasma of the other cluster. In this scenario, the X-ray surface brightness discontinuity is the contact discontinuity between two fluids. Such a model has been invoked to explain surface brightness edges observed in Abell 1795 (Markevitch et al. 2001), and there are morphological similarities between Abell 1795 and the cluster gas around 3C 438. The energy required to displace the gas in the gravitational potential of the dark matter to the approximate position of the discontinuity is \(2.3 \times 10^{47}\) ergs (1.4 \(\times 10^{48}\) ergs for a 10 keV cluster). The primary difficulty with the scenario is that the oscillating core is unlikely to have dissipated much energy so that the 17 keV gas temperature represents the quiescent temperature/mass of the cluster. In addition, this can only be considered a “minor” merger that only initiates oscillations of the core gas because of the extremely high temperature/mass of one of the clusters. A merger that dissipates >10\(^{46}\) ergs would be a major event in virtually any other cluster.

5. SUMMARY AND CONCLUSIONS

We report the discovery of a hot (>17 keV), luminous, morphologically disturbed cluster associated with the radio galaxy 3C 438. If this temperature is indicative of the gravitational mass of the cluster, it would be one of the most massive clusters known. It is most likely that the high temperature is the result of a massive merger, although the limited quality of the data prevents a definitive conclusion. Whatever the case, the high temperature and luminosity of the cluster ensures that the origin of the disturbance is one of the most energetic events in the local universe. Deeper Chandra and XMM-Newton observations are required to further elucidate the dynamics and energetics of this system. Smaller uncertainties on the gas temperature beyond the discontinuity would be particularly useful to better constrain the gas dynamics. Lensing measurements of the gravitational mass of the cluster would be useful, but the low galactic latitude, crowded field, and significant optical extinction may make such measurements difficult.

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REFERENCES

Allen, S. W., Schmidt, R. W., & Fabian, A. C. 2002, MNRAS, 335, 256
Birzan, L., Rafferty, D. A., McNamara, B. R., Wise, M. W., & Nulsen, P. E. J. 2004, ApJ, 607, 800
Brüggen, M., Ruszkowski, M., & Hallman, E. 2005, ApJ, 630, 740
Dickey, J. M., & Lockman, F. J. 1990, ARA&A, 28, 215
Finoguenov, A., Reiprich, T. H., & Böhringer, H. 2001, A&A, 368, 749
Forman, W. R., et al. 2005, ApJ, 635, 894
Gitti, M., & Schindler, S. 2004, A&A, 427, L9
Hardcastle, M. J., Alexander, P., Pooley, G. G., & Riley, J. M. 1997, MNRAS, 288, 859
Hewitt, A., & Burbidge, G. 1991, ApJS, 75, 297
Madrid, I., et al. 2006, ApJS, 164, 307
Markevitch, M. 1998, ApJ, 504, 27
Markevitch, M., Gonzalez, A. H., David, L., Vikhlinin, A., Murray, S., Forman, W., Jones, C., & Tucker, W. 2002, ApJ, 567, L27
Markevitch, M., Vikhlinin, A., & Mazotta, P. 2001, ApJ, 562, L153
McNamara, B. R., Nulsen, P. E. J., Wise, M. W., Rafferty, D. A., Carilli, C., Sarazin, C. L., & Blanton, E. L. 2005, Nature, 433, 45
Mushotzky, R., & Scharf, C. A. 1997, ApJ, 482, L13
Novicki, M. C., Sornig, M., & Henry, J. P. 2002, AJ, 124, 2413
Randall, S. W., Sarazin, C. L., & Ricker, P. M. 2002, ApJ, 577, 579
Rowley, D. R., Thomas, P. A., & Kay, S. T. 2004, MNRAS, 352, 508
Spergel, D., et al. 2006, preprint (astro-ph/0603449)
Springel, V., & Farrar, G. 2007, preprint (astro-ph/0703232)
Trechel, K., Rudnick, L., Hardcastle, M. J., & Leahy, J. P. 2001, ApJ, 561, 691
Wise, M. W., McNamara, B. R., Nulsen, P. E. J., Houck, J. C., & David, L. P. 2007, ApJ, 659, 1153