DEEP XMM-NEWTON AND CHANDRA OBSERVATIONS OF CL J1226.9+3332: A DETAILED X-RAY MASS ANALYSIS OF A z = 0.89 GALAXY CLUSTER

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ABSTRACT

Deep XMM-Newton and Chandra observations of Cl J1226.9+3332 at z = 0.89 have enabled the most detailed X-ray mass analysis of any such high-redshift galaxy cluster. The XMM-Newton temperature profile of the system shows no sign of central cooling, with a hot core and a radially declining profile. A temperature map shows asymmetry with a hot region that appears to be associated with a subclump of galaxies at the cluster redshift but is not visible in the X-ray surface brightness. This is likely to be the result of a merger event in the cluster but does not appear to significantly affect the overall temperature profile. The XMM-Newton temperature profile and combined Chandra and XMM-Newton emissivity profile allowed precise measurements of the global properties of Cl J1226.9+3332. Within an overdensity radius of 500 times the critical density at z = 0.89 (R500), we find kT = 10.4 ± 0.6 keV, Z = 0.16 ± 0.05 Z⊙ and M = 5.2 ± 0.8 × 1014 M⊙. We obtain profiles of the metallicity, entropy, cooling time, and gas fraction and find a high concentration parameter for the total density profile of the system. The global properties are compared with the local L-T and M-T relations, and we are able to make the first observational test of the predicted evolution of the Y_{X-M}^{z=0} relation. We find that departures from these scaling relations are most likely caused by an underestimate of the total mass by ~30% in the X-ray hydrostatic mass analysis due to the apparent recent or ongoing merger activity.

Subject headings: cosmology: observations — galaxies: clusters: general — galaxies: clusters: individual (Cl J1226.9+3332) — galaxies: high-redshift — intergalactic medium — X-rays: galaxies

Online material: color figures

1. INTRODUCTION

Clusters of galaxies are an important tool for testing and improving cosmological models. High-redshift clusters, in particular, provide the strongest constraints. Measurements of the total and baryonic mass functions and baryon fractions of distant clusters have been used to measure cosmological parameters (e.g., Vikhlinin et al. 2003; Henry 2004; Allen et al. 2004). Even with the precise measurements of cosmological parameters provided by cosmic microwave background and supernova observations (e.g., Spergel et al. 2003; Tonry et al. 2003), clusters play an important role by providing independent constraints with different parameter degeneracies (Allen et al. 2004). Large samples of distant clusters will be detected by ongoing and planned surveys using X-ray (e.g., Romer et al. 2001), optical (e.g., Gladders & Yee 2005), Sunyaev-Zel’dovich effect (SZ; e.g., Ruhl et al. 2004), and weak-lensing (e.g., Hamana 2004) techniques. Such samples will be able to place strong constraints on the dark energy density and equation of state, but the most powerful constraints require mass estimates for many clusters (Majumdar & Mohr 2003).

The most reliable X-ray mass estimates require radial temperature and density profiles of the intracluster gas to allow the solution of the equation of hydrostatic equilibrium. However, the low X-ray fluxes of typical high-redshift clusters make the observing time needed to meet these requirements prohibitive. Sufficiently deep observations for clusters at z > 0.5 are very rare (e.g., Jeltema et al. 2001; Arnaud et al. 2002; Donahue et al. 2003; Maughan et al. 2004b); for most clusters at high redshifts, masses must be estimated from observed global properties such as X-ray luminosity and temperature. The scaling relations between cluster properties at high redshifts are then of key importance, and their uncertainty is a dominant contributor to the error budget of derived cosmological parameters (Henry 2004). Furthermore, studies of the evolution of the cluster scaling relations can be used to probe cluster formation and the history of non-gravitational heating (e.g., Ettori et al. 2003; Maughan et al. 2006b).

At z = 0.89, galaxy cluster Cl J1226.9+3332 is the hottest, most luminous known at z > 0.6. The only comparable system is MS 1054.5–0321 at z = 0.83, an actively merging system that is somewhat cooler and less luminous than Cl J1226.9+3332 (Jee et al. 2005). Unlike that very disturbed system, Cl J1226.9+3332 has a relaxed morphology, making it a promising candidate for a

1 Chandra Fellow.

2 Comparisons here are made with all clusters listed in the BAX database (http://bax.ast.obs-mip.fr), a compilation of published X-ray properties of galaxy clusters.
reliable hydrostatic mass estimate. ClJ1226.9+3332 was detected in the Wide Angle ROSAT Pointed Survey (WARPS; Scharf et al. 1997; Ebeling et al. 2001), and an analysis of a 15 ks AO1 XMM-Newton observation confirmed its temperature at 11.5 keV with a bolometric luminosity of $5 \times 10^{45}$ ergs s$^{-1}$ and a relaxed morphology (Maughan et al. 2004a). An early, short Chandra observation of ClJ1226.9+3332 was presented by Cagnoni et al. (2001), who also pointed out that the VLA FIRST catalog shows a faint pointlike radio source at the cluster center, consistent with a low-luminosity radio-loud active galactic nucleus (AGN). ClJ1226.9+3332 has also been detected in the SZE (Joy et al. 2001), and the properties of the member galaxies have been investigated (Ellis & Jones 2004; Ellis et al. 2006).

In this paper we present new XMM-Newton and Chandra observations of Cl J1226.9+3332. In the following sections we describe the data reduction and background subtraction techniques and present the results of the imaging and spectral analysis. The radial profiles of the cluster properties such as mass, temperature, and entropy are then investigated and the global properties of the system are compared with those of other clusters. In the Appendix we present a novel method for defining contour levels in smoothed X-ray images. Numerical subscripts are used on cluster properties to indicate the overdensity with respect to the critical density at the radius at which (or within which) the property was measured. The critical density at the cluster’s redshift is used in this definition. We assume a flat ACDM cosmology with $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$ and $\Omega_M = 0.3$ throughout, and uncertainties are quoted at the 68% level. At the cluster’s redshift, 1" corresponds to 7.8 kpc.

2. DATA REDUCTION

The XMM-Newton data (ObsID 0200340101) were reduced and analyzed with the Science Analysis Software (SAS) version 6.5 and the most recent calibration products available as of 2006 June 1. A light curve of the field of view was produced in the 10–15 keV band for each of the three EPIC cameras. The light curves were filtered to reject periods of high background, and approximately 16 ks of data were rejected. The cleaned light curves exhibited stable mean count rates, and the clean exposure times were 68 and 75 ks for the pn and MOS detectors, respectively. A local background region and the Read & Ponman (2003) blank-sky background data sets were used for background estimates where appropriate, as discussed below.

The Chandra data consisted of two ACIS-I observations (ObsID 3180 and 5014), which were reduced and analyzed consistently. The level 1 event files were reprocessed with the latest calibration (as of 2005 November), applying the charge transfer inefficiency and time-dependent gain corrections. Background flare filtering was performed with 1c_clean in the 0.3–12 keV band excluding the target CCD and all sources detected by the pipeline processing. The good time remaining for each observation was 25 ks. The period D blank-sky background files (Markevitch 2001) were appropriate for both observations, and these were reprojected onto the sky coordinates of each observation. Both observations were taken in VFAINT telemetry mode, so the additional VFAINT cleaning procedure was applied to the source and background data sets.3

3. BACKGROUND CONSIDERATIONS

In periods free of background flaring, the background is dominated by X-rays at low energies ($\lesssim 2$ keV) and particles at high energies ($\gtrsim 2$ keV). The X-ray component includes a significant contribution from Galactic emission, which varies with position on the sky. The blank-sky background data sets are compiled from multiple pointings with different Galactic X-ray fluxes and so may not agree well with the soft X-ray background in the source data set. However, the blank-sky data sets enable background estimates to be made at the same detector position as the source, eliminating instrumental effects, and furthermore, many extended sources fill the field of view of Chandra or XMM-Newton, prohibiting the measurement of the background in the source data set. Due to its high redshift, Cl J1226.9+3332 occupies a small area on the detectors, leaving large source-free regions in which the background emission can be measured. This local background was compared with the blank-sky files to determine the optimal choice of background for imaging and spectral analyses.

Images were created in the 0.7–2 keV band for each detector, along with exposure maps to correct for chip gaps, bad pixels, and telescope vignetting. The three XMM-Newton pn and MOS images and the two Chandra ACIS-I images were combined to give separate XMM-Newton and Chandra images, and these were exposure corrected. Background images and exposure maps were created in the same way from the blank-sky data sets for each detector. Sources in these images were then detected with the wavelet detection algorithm of Vikhlinin et al. (1998). The detected point and extended sources were then excluded from the analysis of Cl J1226.9+3332. Due to the possible difference in the soft Galactic X-ray flux between the source and background data sets, the blank-sky images were normalized to match the flux in the source-free regions in the target images. For both the XMM-Newton and Chandra images, radial profiles of the source and background images and their exposure maps were created and used to determine the detection radius ($r_d$) of the cluster emission. Emission within $r_d$ was then excluded and the background images were normalized to the remaining emission. The detection radius was recomputed and the process was repeated until $r_d$ converged. This procedure provides a reliable measurement of both the cluster extent and the normalization of the blank-sky images in the imaging band.

Figure 1 shows the source and background profiles for the XMM-Newton and Chandra images. The good agreement of the

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3 The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.

4 Available at http://hea-www.harvard.edu/~maxim/acxf/acsbg/.

5 See http://asc.harvard.edu/ciao/threads/aciscleanvf.
source and background profiles at $r > 300''$ indicates that the source exclusion and background normalization were successful. Note that the increasing background with radius (most noticeable in the XMM-Newton data) is due to the fact that the particle background component is not vignetted, so the exposure correction incorrectly boosts this background component. In this imaging analysis, the effect is the same in the source and background images and cancels out. However, this effect is a cause for concern if an off-axis region is used to extract a local background spectrum. These normalized blank-sky background images were thus used for all of the imaging analysis for all data sets, while the background subtraction for the spectral analysis is discussed in more detail below. The consistency of the XMM-Newton and Chandra surface brightness profiles of Cl J1226.9+3332 is demonstrated in § 6.1.

A prime motivation in defining $r_d$ was to fully exclude any significant cluster emission to enable measurement of the background in the target observations. To this end $r_d$ was conservatively defined as the radius beyond which no further radial bins had a detection of $>0.5$ $\sigma$ above the background. The detection radius for XMM-Newton was 210$''$ and for Chandra was 126$''$. For each detector, spectra were extracted from the target data sets after excluding all sources and the cluster emission out to $r_d$, to give a local background spectrum. Blank-sky background spectra were extracted for each detector with the same spatial regions excluded, and the local and blank-sky background spectra are plotted in Figure 2.

The Chandra blank-sky background spectra were normalized to match the 9.5–12 keV count rates in the target data sets. At these high energies, the background is dominated by particle events. The left panel of Figure 2 shows the background spectra for the Chandra ObsID 3180 observation (ObsID 5014 is consistent). The good agreement between the spectra above 1.5 keV indicates that relative contributions of the particle and X-ray background components are the same in the target and blank-sky data sets. The excess in the local background at the soft end is due to Galactic X-ray emission. These soft residuals are accounted for in our spectral analysis of the Chandra data by including a model for this soft thermal component (see § 5). We conclude that the blank-sky background files provide a reliable background measurement for the Chandra data sets.

The XMM-Newton blank-sky background spectra were normalized by the ratio of the count rates of events detected outside the field of view of the XMM-Newton telescopes. These events are due solely to the particle background. It is clear in the middle and right panels of Figure 2 that the flux in the particle-induced fluorescent lines agrees well in the target and blank-sky spectra, but the flux elsewhere is significantly lower in the local background spectra. This suggests that the relative contribution of the particle background component is significantly greater in the target data set. A similar effect has been found in other XMM-Newton observations (Maughan et al. 2006a; Khosroshahi et al. 2006), and we emphasize the importance of comparing the blank-sky and local background spectra whenever possible. A possible resolution to this discrepancy would be to normalize the spectra by the count rate in the 2–7 keV band, but this would lead to an underestimate of the flux in the fluorescent lines. Furthermore, the slopes of the spectra are different due to the differing particle background contributions. We thus conclude that the blank-sky data sets cannot be used for the spectral analysis of this XMM-Newton observation. Instead, we define a local background annulus region between 250$''$ $< r < 500''$

This local background region lies farther off-axis than the cluster emission, so the vignetting of the background photons must be considered. Vignetting effects were corrected by using the SAS evigweight task. This assigns a weight to every event based on the ratio of the effective area at its detected position and energy to the effective area on-axis at the same energy. This procedure cannot distinguish between vigneted X-rays and nonvignetted particle events, leading to the incorrect boosting of the particle background. Figure 1 demonstrates that this is already a significant effect by $r \sim 400''$.

For a given source region, this effect can be removed with the aid of the XMM-Newton closed filter background data sets, which consist of purely instrumental and particle events. A “boosted-particle” spectrum was created for each camera by running evigweight on the closed filter background and extracting a spectrum from the local background region. This replicates the treatment of the particle events in the source data set. These boosted-particle spectra were then normalized to the 10–14 keV count rate in the local background spectra and subtracted from them, creating a vignetting-corrected “X-ray only” background spectrum. A similar boosted-particle spectrum was then extracted from the source region in the closed filter data, normalized by the same factor and added onto the “X-ray only” background spectrum (after scaling by area). The resultant background spectrum then consisted of an X-ray background that was correctly weighted for the vignetting at the background region and a particle component that was incorrectly weighted in exactly the same way as the particles in the source spectrum. The net effect is that the particle and X-ray backgrounds are both subtracted correctly. This has a significant effect on the temperatures measured at large radii where the background dominates, and this method was followed for all XMM-Newton spectral analysis.

4. CLUSTER MORPHOLOGY

The exposure-corrected Chandra and XMM-Newton images of Cl J1226.9+3332 were smoothed to the 3 $\sigma$ level using the adaptive smoothing algorithm of Ebeling et al. (2006). The pre-smoothed Chandra image was full resolution (0.5$''$ pixel$^{-1}$),
while the XMM-Newton image was binned to 1.1" pixel$^{-1}$ in order to improve smoothing efficiency while still oversampling the point-spread function (PSF). Contours were then derived from the smoothed images at flux levels defined so that the emission in the region between two adjacent contour levels was detected at $>3\sigma$ above the emission in the next lowest band. This contouring algorithm is described in detail in the Appendix and allows the significance of features in contour plots to be determined easily by eye.

Figure 3 shows a wide-field view of Cl J1226.9+3332 with XMM-Newton contours overlaid on a Keck II $I$-band image. The image is dominated by the bright, circular Cl J1226.9+3332 in the western half, but the foreground cluster Cl J1227.3+3333 is visible in the eastern half of the image. Cl J1227.3+3333 appears unrelaxed and consists of several subclumps of galaxies at a similar spectroscopic redshift ($z = 0.766$). All of the sources seen in the contours are consistent with point sources except for the northern peak of Cl J1227.3+3333 and Cl J1226.9+3332. Figure 4 shows the Chandra contours of Cl J1226.9+3332 on the same optical image. These contours demonstrate the regular, relaxed appearance of the emission in Cl J1226.9+3332.

5. SPECTRAL ANALYSIS

5.1. Methodology

Before discussing the different spectral analyses performed, we give an overview of the spectral extraction and fitting methods used for the XMM-Newton and Chandra data. In all cases, responses were generated for the spectral extraction regions, weighted by the distribution of counts in the region. Cluster spectra were modeled in XSPEC with a single-temperature, APEC (Smith et al. 2001) plasma model, and with the exception of the MOS data as noted below, the absorbing column was fixed at the Galactic value inferred from 21 cm observations (Dickey & Lockman 1990). During fitting, the APEC normalization, metal abundance, and temperature were the only free parameters. When data from multiple detectors were fitted simultaneously, the temperature and metal abundances of the models were tied, but the normalizations were not.

For the XMM-Newton data, only the best-calibrated events (FLAG = 0) were selected, and the modified local background spectra discussed in § 3 were used for each detector. The MOS and pn spectra were fitted in the 0.4–7 keV energy bands, avoiding the bright fluorescent lines above 7 keV in the pn and minimizing any remaining problems with the particle background subtraction.

For the Chandra data, the background spectra were taken from the blank-sky data sets. A spectrum of the soft residuals due to Galactic X-ray emission differences between the target and blank-sky data sets was produced for each data set by subtracting a blank-sky background spectrum from a local background spectrum extracted in the same region. This was fitted with a 0.18 keV, unabsorbed APEC model of zero redshift (Vikhlinin et al. 2005). This model was included as an additional background component in all spectral fits, with the normalization scaled by the difference in extraction area. The cluster spectrum was fitted by an absorbed APEC model in the range 0.6–9 keV and the best-fitting temperature was found. The model was refitted with the soft Galactic component normalization set to $\pm 1\sigma$ and again with the overall blank-sky background renormalized by $\pm 2\sigma$, and the resulting systematic temperature uncertainties were added in quadrature to the statistical uncertainties.

5.2. Cross Calibration

In order to test the spectral calibration of the different detectors before combining their data, a single spectrum was extracted from $r < 50''$ for each detector. Selecting only the central cluster region in this way maximized the signal-to-noise ratio of the spectra, reducing the uncertainties due to the background subtraction. No point sources were detected within this region by either Chandra or XMM-Newton. To further simplify the comparison, the metal abundances were fixed at $0.3 \ Z_\odot$. The spectra were fitted separately and simultaneously in different combinations, and example spectra are plotted in Figure 5.

The results of the spectral fitting are summarized in Figure 6. The filled symbols show that the temperatures measured with EPIC MOS were significantly higher than the pn measurements; the 90% confidence intervals do not overlap. The absorbing column was then allowed to vary, and the agreement in $kT$ was improved dramatically. The best-fitting pn absorbing column did not vary significantly from the Galactic value ($1.38 \times 10^{20}\ cm^{-2}$), and the pn temperature was unchanged. In the case of the combined MOS spectra, however, the best-fitting absorption was significantly higher than the Galactic value at $(4.1 \pm 1.0) \times 10^{20}\ cm^{-2}$ (90% errors) and the temperature was significantly reduced. The
absorbing columns found when fitting the MOS data independently of each other were also consistent with this value. All of these spectral fits were statistically acceptable, whether the absorbing column was fixed or varying.

The open symbols in Figure 6 show the temperatures measured when the absorbing column was fixed at \(4 \times 10^{20} \text{ cm}^{-2}\) for the MOS data; all EPIC measurements agree well. The statistical precision of the ACIS measurements, meanwhile, cannot exclude any of the XMM-Newton measurements. The fact that the MOS fits require an absorbing column significantly higher than Galactic suggests that there is an outstanding calibration problem at low energies for those detectors and that the pn temperature should be more reliable. We note that assuming Galactic absorption, but fitting the MOS spectra in the 1–7 keV band, gave a temperature of 11.6 ± 0.9 (68% confidence), which is consistent with the values obtained when fitting the pn alone and the combined detectors with elevated MOS absorption. This gave further confidence in our approach of increasing the MOS absorption. Thus, all further spectral fits were performed for all EPIC detectors combined in the 0.4–7 keV band with the absorbing column frozen at the Galactic value for the pn and at \(4 \times 10^{20} \text{ cm}^{-2}\) for the MOS data (lower lines). The variation in the best-fitting temperature caused by setting the MOS absorbing column to its 90% limits was taken as an indication of the additional systematic uncertainty due to this problem. This uncertainty was added in quadrature to the statistical errors on all subsequent temperature measurements, resulting in an increase of \(\approx 50\%\).

5.3. Spectral Profiles

The XMM-Newton observation of Cl J1226.9+3332 is sufficiently deep to provide radial profiles of its spectral properties. Spectra were extracted from annuli centered on the X-ray centroid (with point sources excluded) and were fitted as before (including our boosted-particle background correction method). The resulting projected temperature profile is plotted in Figure 7. The data from the three EPIC cameras were fitted simultaneously for these results, with the temperatures tied, the pn absorbing column frozen at the Galactic value, and the MOS absorbing column at \(4 \times 10^{20} \text{ cm}^{-2}\).

To model the temperature profile of Cl J1226.9+3332, we follow the method of Vikhlinin et al. (2006, hereafter V06) of...
projecting a model of the three-dimensional (3D) temperature distribution along the line of sight and fitting that to the observed projected temperature profile. In doing this, we use the algorithm of Vikhlinin (2006) to predict the observed temperature for the combination of temperatures and emissivities of gas along the line of sight in each bin. The emissivities were determined from our analysis of the gas density profile (§ 6.1), and the metal abundance of the gas was set at 0.3 $Z_{\odot}$ at all radii (varying the metal abundance had negligible effect on this analysis, which is reasonable, as the emission is continuum dominated at these high temperatures). The temperature profile model of V06 was used to model the 3D temperature distribution:

$$kT(r) = kT_0 \left( \frac{r}{r_{\text{cool}}} \right)^{a_{\text{cool}}} + \frac{kT_{\text{min}}}{kT_0} \left( \frac{r}{r_{\text{cool}}} \right)^{b_{\text{cool}}} + \frac{(r/r_{\text{min}})^a}{\left[ 1 + (r/r_{\min})^b \right]^{c/h}}. \quad (1)$$

Here $kT_0$ is a normalization, and $r_{\text{cool}}$ and $a_{\text{cool}}$ parameterize the scale radius and slope of a central cool region within which the temperature decreases to $kT_{\text{min}}$. The third term in equation (1) is a broken power law describing the transition to a declining temperature profile at large radii. This model was simplified slightly to reduce the number of free parameters by fixing $a = 0$ and $b = c/0.45$, in line with the average profile found by V06 in a sample of relaxed nearby clusters. The best-fitting 3D model had $kT_0 = 22.0$ keV, $r_{\text{cool}} = 47.4$ kpc, $a_{\text{cool}} = 0.0$, $kT_{\text{min}} = 2.7$ keV, $r_{\text{min}} = 329$ kpc, and $c = 0.72$, and the model and its projection are plotted in Figure 7. This model has as many degrees of freedom as data points in the profile and has degeneracies between parameters, so the uncertainties on all dependent quantities were computed by a Monte Carlo method. Caution should thus be used in placing a physical interpretation on the individual best-fitting parameters; the model is intended to provide a physically motivated analytical description of the observed temperature profile. A simpler model

$$kT(r) = kT_0 (1 + r/r_0)^{-\alpha} \quad (2)$$

was also fitted to the data, giving $kT_0 = 13.3$ keV, $r_0 = 1.0$ Mpc, and $\alpha = 1.1$. While the V06 model was used for all results quoted subsequently, this simpler model gave consistent results and uncertainties throughout.

This method of modeling the temperature profile does not take the effect of the XMM-Newton PSF into account. As the surface brightness profile of Cl J1226.9+3332 is not sharply peaked and the temperature profile bins are all $\gtrsim 15''$ (the approximate FWHM of the PSF), the mixing effect of the PSF on the temperature profile is not expected to be large. This was verified by fitting the spectra from all radial bins simultaneously with absorbed APEC models, using the xspecf model in XSPEC to model the redistribution of photons by the XMM-Newton PSF. The resulting PSF-corrected temperature profile was consistent with the original profile, with the noise fluctuations amplified and large uncertainties. The original uncorrected temperature profile was used for all further analysis.

The projected metal abundance profile of Cl J1226.9+3332 is plotted in Figure 8. The statistical uncertainties on the metal abundance measurements are large due to the high ionization state of the plasma. The data suggest a radially decreasing abundance profile but are also consistent with a flat abundance profile.

5.4. Temperature Map

The two-dimensional projected temperature distribution in ClJ1226.9+3332 was investigated by constructing a temperature map following the methods described in Maughan et al. (2006a; see also O’Sullivan et al. 2005). In brief, spectra were extracted from many overlapping circular regions in the cluster, the radii of which were chosen to contain at least 1000 net photons. The best-fitting temperature for the spectrum from each region was assigned to the pixel in the temperature map corresponding to the center of that region. The result is a smooth image of the projected temperatures, in which nearby pixels are not independent. The spectra were fitted as before, but the metal abundance was fixed at 0.3 $Z_{\odot}$.

The resulting projected temperature map is shown in Figure 9. The temperature structure shows asymmetry that is not apparent in the surface brightness distribution. There is significantly hotter emission to the west and southwest of the cluster core than in the surrounding gas at the same radius. Figure 10 shows contours of the X-ray temperature overlaid on the optical image. The region of hotter emission appears associated with an overdensity of galaxies (confirmed cluster members) to the southwest of the core, suggesting that a merger event may be responsible for the temperature asymmetry.

A new temperature profile was produced, with the sector containing these hotter regions excluded, and the temperatures obtained were not significantly different from those measured with the sector included. This indicates that this hot region does not significantly bias our temperature profile measurement. However, if it is related to merger activity in the cluster, this will undermine the assumption of hydrostatic equilibrium used in the following mass analysis of Cl J1226.9+3332.

6. MASS ANALYSIS

6.1. Gas Density Profile

The X-ray emissivity of the intracluster medium depends strongly on the gas density and only weakly on its temperature. This means that the observed projected emissivity profile can be used to accurately measure the gas density profile. For each annular bin in the surface brightness profile, the observed net count rate was corrected for area lost to chip gaps, bad pixels, and excluded regions and converted to an integrated emission measure. For each bin, the conversion factor was calculated assuming an absorbed MEKAL (Kaastra & Mewe 1993) plasma model folded through an ARF generated for that region and an on-axis RMF. The absorption of the spectral model was set at the Galactic value, and the metal abundance was set at 0.3. The temperature of the
spectral model in each bin was given by the best-fitting 3D temperature model. We note that the dependence of the conversion from count rate to emission measure on the assumed temperature is weak; this analysis was repeated assuming that the cluster was isothermal for the purpose of deriving the emission measures, and the results were not significantly changed.

Projected emission measure profiles were derived from the ACIS and pn data (0.7–2 keV energy band) in this way and are plotted in Figure 11. The radial bins were set to a minimum width of 15″ for the pn profile, to minimize the effect of the XMM-Newton PSF, and the profiles agree very well. The MOS data were omitted here for simplicity, as the pn data alone were sufficient to extend the profile beyond the range of the temperature profile, which is the limiting factor in the mass analysis.

To model the emissivity profile, we used the modified $\beta$-profile used by V06 to describe the emission measure profile of the gas in nearby relaxed clusters:

$$n_p n_e = n_0^2 \left( \frac{r}{r_c} \right)^{-\alpha} \left( \frac{1 + r^2/r_c^2}{1 + r^2/r_c^2} \right)^{3\beta-\alpha/2} \left( 1 + r/r_c \right)^{-1/\gamma}. \quad (3)$$

![Projected temperature map of Cl J1226.9+3332 with Chandra contours of X-ray surface brightness overlaid.](image1.png)

**Fig. 9.** Left: Projected temperature map of Cl J1226.9+3332 with Chandra contours of X-ray surface brightness overlaid. Right: The top panels show the 1 σ lower (top left) and upper (top right) limits on the temperature values. The bottom panels show the radii used for spectral extraction and the reduced $\chi^2$ of the spectral fits.

![Contours of the projected X-ray temperature overlaid on the optical image of Cl J1226.9+3332.](image2.png)

**Fig. 10.** Contours of the projected X-ray temperature overlaid on the optical image of Cl J1226.9+3332. Contours are set at 6, 9, 12, and 15 keV.

![Projected emission measure profile of Cl J1226.9+3332 as measured with Chandra and XMM-Newton plotted along with the best-fitting model.](image3.png)

**Fig. 11.** Projected emission measure profile of Cl J1226.9+3332 as measured with Chandra and XMM-Newton plotted along with the best-fitting model. The XMM-Newton data within the central 500 kpc were excluded to minimize PSF effects. The dotted line marks the radius of $R_{500}$. 
This model can describe a steep core component and any steepening of the data beyond the standard $\beta$-profile at large radii. An additive core component has been removed from the V06 model here as it was not required by the data. This emission measure model was then projected along the line of sight and fitted to the observed projected emission measure profile. The model was fitted to the Chandra and XMM-Newton pn data simultaneously, with the pn data within 500 kpc excluded to minimize PSF effects. The best-fitting model is plotted in Figure 11. The gas density is then related to the emission measure by $E = 8\pi n^2 \int R \, dr$, assuming a cosmic plasma with helium abundances given by Anders & Grevesse (1989). For comparison with other work, the profile was also fitted with a standard $\beta$-model, and the best-fitting parameters were $r_c = 105 \pm 5$ kpc and $\beta = 0.64 \pm 0.01$.

6.2. Mass Profiles

The 3D models of the gas density and temperature distributions enable the total gravitating mass of Cl J1226.9+3332 to be derived under the assumptions of spherical symmetry and hydrostatic equilibrium. Figure 12 shows the total and gas mass profiles of Cl J1226.9+3332, with the shaded regions indicating the $1 \sigma$ uncertainties. The error analysis was performed by producing 1000 randomizations of the observed temperature and emission measure profiles based on their measurement uncertainties. The full analysis was repeated for each randomization, and the $\pm 34$ percentiles of the distribution about the value determined from the nonrandomized data gave the $\pm 1 \sigma$ uncertainties on each parameter.

The enclosed gas mass fraction ($f_{\text{gas}}$) profile of Cl J1226.9+3332 was also computed, and the resulting profile is plotted in Figure 13. The profile increases out to $R_{500}$, which is consistent with the profiles measured by V06 for local clusters. The value of $f_{\text{gas}}$ we find for Cl J1226.9+3332 at $R_{2500}$ ($0.10 \pm 0.01$) is consistent with that measured by Allen et al. (2004) from Chandra data alone.

7. ENTROPY AND COOLING TIME PROFILES

The entropy ($K$) of the intracluster gas can give useful insight into its energetics (e.g., Ponman et al. 1999; Voit & Donahue 2005). The entropy profile of Cl J1226.9+3332 was derived from the 3D temperature and gas density models according to the definition $K = kTn_e^{-2/3}$ and is plotted in Figure 14. In order to model this entropy profile, we started with the baseline entropy profile due to gravitational effects alone, derived from numerical simulations by Voit et al. (2005): $K(r) = 1.32K_{200}(r/R_{200})^{1/3}$. $K_{200}$ was estimated following the method suggested by Voit et al. (2005), with

$$K_{200} = 362kT_{200}E(z)^{-4/3},$$

where $E(z)$ gives the redshift variation of the Hubble parameter and $kT_{200}$ was estimated from the mass within $R_{200}$ via $kT_{200} = GM_{200}m_p/2R_{200}$. For Cl J1226.9+3332 $kT_{200}$ was found to be 6.6 keV by extrapolating the mass profile model to $R_{200}$, and hence $K_{200} = 1226$ keV cm$^{-2}$. The baseline entropy profile is plotted in Figure 14 and is clearly not a good description of the data. The data suggest a large entropy excess above the gravitational baseline in the central regions of Cl J1226.9+3332. To
model this, a constant entropy level ($K_0$) was added to the baseline model to give

$$K(r) = K_0 + 1.32K_{200}(r/R_{200})^{1.1}. \quad (5)$$

This model was fitted to the entropy values measured at the midpoints of the six temperature bins of Cl J1226.9+3332. The best-fitting model had $K_0 = 132 \pm 24$ keV cm$^2$ and is plotted in Figure 14. The model is a good description of the data ($\chi^2/\nu = 1.7/5$) and a significant improvement on the baseline model alone. Donahue et al. (2006) used a similar model to fit entropy profiles in nearby cooling flow clusters, and the central entropy level $K_0$ is significantly higher in Cl J1226.9+3332 than the values of $\sim 10$ keV cm$^2$ found by Donahue et al. (2006). The entropy profile of Cl J1226.9+3332 is also significantly different from those measured for a sample of nearby relaxed clusters by Pratt et al. (2006), who found good agreement with the Voit et al. (2005) baseline profile with no additional constant entropy level. These differences are consistent with the high central temperature and lack of cool core in Cl J1226.9+3332 and are likely a result of the suspected merger activity in the system.

The 3D gas density and temperature profiles enable the cooling time profile of Cl J1226.9+3332 to be computed, using the relation

$$t_{cool} = 8.5 \times 10^{10} \, \frac{\eta_{p}}{(10^{-18} \, \text{cm}^{-3})} \left(\frac{T}{10^7 \, \text{K}}\right). \quad (6)$$

(Sarazin 1986). The resulting profile is plotted in Figure 15, along with the Hubble time at $z = 0.89$, and shows that the gas in the central regions of Cl J1226.9+3332 would take $\sim 6$ Gyr to radiate its thermal energy away. This, combined with the possibility of a recent merger event (implied by the asymmetry in the temperature map and galaxy distribution), makes the absence of cool gas in the core of this system unsurprising. As pointed out by Cagnoni et al. (2001), there is a faint pointlike radio source at the center of Cl J1226.9+3332, consistent with a low-luminosity radio-loud AGN. This is also a candidate for energy input into the cluster core at some point in the past.

8. DISCUSSION

8.1. Comparison with Theoretical Density Profiles

The deep XMM-Newton observation of Cl J1226.9+3332 has enabled a uniquely detailed mass analysis of a $z = 0.89$ galaxy cluster. This allows comparison with theoretical density profiles for the first time at such high redshift. A profile was constructed using the densities calculated at the midpoint of each temperature profile bin, with uncertainties derived from the Monte Carlo realizations. These data points were fitted by a Navarro et al. (1996, 1997) NFW profile:

$$\rho(r) = \frac{\delta_c}{(r/r_s)(1 + r/r_s)^2}, \quad (7)$$

where the normalization $\delta_c$ can be expressed in terms of the halo concentration $c_\Delta$ and the overdensity factor of interest $\Delta$:

$$\delta_c = \frac{\Delta}{3 \ln(1 + c) - c/(1 + c)}. \quad (8)$$

The scale radius $r_s$ is then related to the overdensity radius $R_\Delta$ by the concentration $c_\Delta = R_\Delta/r_s$. This model has been used successfully to describe the density profiles of both simulated and observed clusters of a range of masses.

The model was fitted to the density profile of Cl J1226.9+3332 using $\Delta = 500$, and the best-fitting parameters were $c_{500} = 5.3^{+1.0}_{-1.3}$ and $r_s = 0.18 \pm 0.04$ Mpc ($\chi^2/\nu = 4.2/4$). Using $\Delta = 200$ scales the concentration to $c_{200} = 7.9^{+1.7}_{-1.4}$. The data and best-fitting model are plotted in Figure 16. The measured concentration of Cl J1226.9+3332 is significantly higher than that found for local clusters of a similar mass by V06 (from Chandra data) or Pointecouteau et al. (2005) based on XMM-Newton data. Furthermore, simulations predict that $c_\Delta$ should decrease with increasing redshift (for a fixed mass; e.g., Wechsler et al. 2002; Bullock et al. 2001). Wechsler et al. (2002) also found that concentration increases with the time between the epoch at which a cluster is observed ($z_{\text{obs}}$) and at that time it formed ($z_{\text{form}}$): $c_\Delta \propto (1 + z_{\text{obs}})/(1 + z_{\text{form}})$. With $z_{\text{form}} \sim 2.6$, the concentration of Cl J1226.9+3332 would be in line with these predictions. However, given the suspected merger activity in Cl J1226.9+3332, $z_{\text{obs}} \approx z_{\text{form}}$ seems more likely, with the high concentration resulting from the merger activity.

8.2. The Global Properties of Cl J1226.9+3332 and the Scaling Relations

To enable comparisons with other works, we compute the global properties of Cl J1226.9+3332 within different radii. These
are summarized in Table 1. The temperatures and metal abundances were obtained from single-temperature fits to the spectra extracted within each radius using the combined XMM-Newton data. These represent some of the most precise such measurements for a high-redshift system. The metal abundance is slightly lower than the values of $Z = 0.3 Z_{\odot}$ observed in local clusters (e.g., Fukazawa et al. 1998) but is consistent with the declining abundance with redshift predicted by Ettori (2005) based on modeled supernova rates.

We computed the bolometric luminosity of the cluster by scaling the value measured within $R_{500}$ out to 1.43 Mpc (for consistency with Markevitch 1998) and out to infinity using the measured surface brightness profile. We find $L_X(r < 1.43 \text{ Mpc}) = 4.57 \pm 0.11 \text{ ergs s}^{-1}$ and $L_X(r < \infty) = 5.12 \pm 0.12 \text{ ergs s}^{-1}$, including uncertainties on the temperature and metal abundance in those on the luminosity. These luminosities are consistent with those found by Maughan et al. (2006b) based on a shorter XMM-Newton observation of Cl J1226.9+3332.

The measured properties of Cl J1226.9+3332 were then compared with the local luminosity-temperature ($L-T$) relation of Markevitch (1998):

$$L_X(r < 1.43 \text{ Mpc}) = 6.35 E(z) \left( \frac{kT}{6 \text{ keV}} \right)^{2.64} \text{ [erg s}^{-1}] \quad (9)$$

Here we have converted the $L-T$ relation to our cosmology and included the predicted self-similar evolution. The properties of Cl J1226.9+3332 were found to agree very well with the predictions of this relation. Cl J1226.9+3332 was then compared to the local mass-temperature ($M-T$) relation derived by V06,

$$\frac{M_{500}}{10^{14} M_{\odot}} = 2.93 E(z)^{-1} \left( \frac{kT_{500}}{5 \text{ keV}} \right)^{1.61} \quad (10)$$

The $M-T$ relation is again converted to our cosmology with the predicted self-similar evolution. The V06 data and $M-T$ relation are plotted in Figure 17 along with the data point for Cl J1226.9+3332, which falls significantly below the V06 $M-T$ relation.

Finally, Kravtsov et al. (2006) recently proposed a new mass proxy for clusters, $Y_X$, obtained by multiplying the gas mass and temperature measured within $R_{500}$ together. This quantity was found to scale with mass with smaller scatter than other X-ray observables, and simulations showed that the scatter is less than 8% even for unrelaxed clusters and that the scaling relation evolves self-similarly. The high-quality X-ray data for Cl J1226.9+3332 enable us to test these predictions observationally for the first time at high redshift. In Figure 18 we reproduce the $Y_X-M_{500}$ plot from Kravtsov et al. (2006) including the V06 data points. Following Kravtsov et al. (2006), we parameterize the $Y_X-M_{500}$ relation as

$$E(z)^{2/5} \frac{M_{500}}{10^{14} M_{\odot}} = 1.58 \left( \frac{Y_X}{4 \times 10^{13} M_{\odot} \text{ keV}} \right)^{3/5} \quad (11)$$

Here the normalization found from the simulations of Kravtsov et al. (2006) has been reduced by 15% (in line with the recommendation in that work), to better agree with the observed V06 cluster data. Cl J1226.9+3332 has a mass that is slightly low compared to the local clusters (although it is within the scatter at the 1σ level). This could be due to stronger than expected evolution in the $Y_X-M_{500}$ relation, with $E(z)^{-4/5}$ resulting in good agreement. A more likely explanation, however, is that the offset from the relation is caused by errors in one or both parameters. The simulations of Kravtsov et al. (2006) show that the scatter in $Y_X-M_{500}$ is very small, even for merging clusters. Taking the measured $Y_X$ of Cl J1226.9+3332 as an indicator of the true total mass then implies that the X-ray analysis underestimates the true mass by
Numerical simulations have shown that merging clusters tend to have lower temperatures for a given mass than relaxed systems, as the increase in thermal energy of the gas does not match the increase in mass due to the merger (Mathiesen & Evrard 2001; Kravtsov et al. 2006). Furthermore, nonthermal pressure support from gas turbulence enhanced by a merger would also lead to mass underestimates when hydrostatic equilibrium was assumed (e.g., Nagai et al. 2007). Thus, the suspected merger event in Cl J1226.9+3332 could be responsible for an underestimate of the total mass using X-ray methods. The good agreement of Cl J1226.9+3332 with the $L-T$ relation is not inconsistent with this explanation, as mergers have been found to boost the luminosity and temperature of clusters approximately simultaneously, moving them along the $L-T$ relation (Randall et al. 2002; Röyle et al. 2004).

8.3. The Effect of Systematic Temperature Errors

As discussed in § 5.2, an artificially high absorbing column was required when fitting the MOS spectra to produce agreement with the pn data. It appears likely that the pn data are the more reliable in this case, as the best-fitting pn absorbing column is close to the Galactic value while the MOS is significantly higher. However, the full analysis was also repeated with the MOS column fixed at the Galactic value, resulting in systematically higher temperatures in the combined EPIC fits. Vikhlinin et al. (2005) also found cluster temperatures measured with Chandra that were systematically higher by ~10% than those measured by XMM-Newton. It is thus instructive to evaluate the effect that systematic increase to the individual temperatures would have on the inferred properties of Cl J1226.9+3332.

Reassuringly, the total mass, gas mass, overdensity radii, and luminosity of Cl J1226.9+3332 did not change significantly when the Galactic column was used for the MOS data. These quantities are all robust to residual uncertainties in the EPIC calibration. The only significant change was in the temperatures, with the global temperature increasing to 11.8 keV, with a corresponding increase in $Y_{X}$. The agreements with the $L-T$, $M-T$, and $Y_{X}-M_{500}$ relations were thus all worsened by the higher $kT$. The derived mass did increase slightly in this test, but it remained within our uncertainties because we included a large systematic contribution in our error budget and because the shape of the temperature profile did not change significantly in this experiment, even though its normalization did. An isothermal mass estimate would have been much more sensitive to the increase in $kT$.

9. SUMMARY AND CONCLUSIONS

High-quality XMM-Newton and Chandra data of Cl J1226.9+3332 have enabled the most precise X-ray mass analysis of any such high-redshift system. The temperature profile of the system showed no sign of central cooling, with a hot core and a radially declining profile. The cooling time of the gas only drops marginally below the Hubble time in the center of the cluster. A temperature map showed asymmetry in the temperature distribution with a hot region that is apparently associated with a subclump of galaxies but is not visible in the X-ray surface brightness. This is likely to be the result of a merger event in the cluster but does not appear to significantly affect the overall temperature profile.

The entropy profile in Cl J1226.9+3332 was not well described by the gravitational baseline profile of Voit et al. (2005) and required an additional constant entropy level. The $f_{\text{gas}}$ profile increases with radii out to $R_{500}$ and is consistent with the profiles observed in local clusters. The global properties of Cl J1226.9+3332 were compared with the local scaling relations and found to be consistent with the $L-T$ relation, but to fall below the $M-T$ and $Y_{X}-M_{500}$ relations. As $Y_{X}$ is insensitive to mergers, this implies that the total mass is underestimated by ~30% in the X-ray analysis, probably due to departures of the gas from hydrostatic and virial equilibrium. The high NFW concentration parameter found for Cl J1226.9+3332 is likely also due to the merger activity. Given the high luminosity of Cl J1226.9+3332, it is likely to be one of the only distant clusters for which such rich X-ray data are obtained with the current generation of satellites.

Finally, we note that prior to this study, Cl J1226.9+3332 was considered to be a rare example of a massive, relaxed high-redshift cluster. Even in our deep XMM-Newton data, the cluster appears to be relaxed in surface brightness, but the temperature structure revealed by the spectral mapping belies this appearance. Temperature structure has been observed in lower redshift systems that have relaxed appearances (e.g., Andersson & Madejski 2004; Pratt et al. 2005), but spectral maps at $z > 0.5$ are extremely rare (the only other examples being Jeltema et al. 2001; Maughan et al. 2006a). Given the increasing fraction of clusters with substructure at high redshifts (Jeltema et al. 2005) and the likely 30% mass underestimate we find for Cl J1226.9+3332, we emphasize the importance of using mass estimators that are insensitive to (or calibrated for) merger effects when deriving cluster masses for cosmological studies.

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APPENDIX
A SIGNIFICANCE CONTOURING METHOD

Here we describe the procedure used to define contour levels based on the significance of the emission enclosed between them. For this method to succeed, the image used to define the contour regions needs to be sufficiently smoothed that smooth contiguous regions can be defined even where the number of counts is low. An adaptive smoothing algorithm is most suited for this purpose as it uses a large smoothing kernel in regions of low signal-to-noise ratio but maintains high spatial resolution where the signal-to-noise ratio is high. Two adaptive smoothing algorithms were tested: asmooth (Ebeling et al. 2006, on which the CIAO task assmooth is based), and the XMM-Newton Science Analysis Software (SAS) smoothing tool (this tool is also called assmooth, but for clarity we refer to it herein as assmooth). Note, however, that the CIAO assmooth is inferior to the Ebeling et al. (2006) assmooth algorithm. This is addressed by Ebeling et al. (2006), and some shortcomings of assmooth are pointed out by Diehl & Statler (2006).
We found that for this particular purpose, the `asMOOTH` was more suitable than `xmmsmooth` as `xmmsmooth` created artifacts around point sources and pixelation in the cluster cores (even with a high smoothing significance threshold) that were incompatible with our contouring algorithm. We note that both `asMOOTH` and `xmmsmooth` are less sensitive to regions of depressed emission than regions of excess emission.

To set the lowest contour level, the flux was measured in the background image for that cluster (after it had been normalized to match the local background level) in a circle of radius 6'' at the cluster center. The lowest contour level was then set at a flux of 3 $\sigma$ above this background level. The flux interval between this level ($f_0$) and the peak of the cluster flux was divided into 500 logarithmically spaced intervals ($f_i$, $i = 1$ to 500). The next contour level was set at $f_1$, and spatial regions bounded by the contours at $f_0$ and $f_1$ were defined on a smoothed image of the X-ray emission. For each distinct region, the significance of the emission contained in that region above the background was measured using the counts in the original unsmoothed source and background images. Regions that contained emission detected at $>3 \sigma$ significance were kept, and the others were rejected.

The process was then repeated with an upper flux limit of $f_2$. Where regions had passed the previous step, new “child” regions were defined bounded by the contours at $f_1$ to $f_2$ and were by definition fully enclosed by the passing parent region from the previous step. Where regions failed the previous step, new regions bounded by contour levels $f_0$ and $f_2$ were defined. This process was then repeated for all of the flux levels $f_i$, with the significance of the emission enclosed by each region measured with respect to its local background. The local background for all child regions was measured in their respective parent region. For the lowest level regions bounded by contours at $f_0$ and $f_1$, the blank-sky background image was used to measure the background level.

An image of some of the regions used to define the contour levels in the `Chandra` image of Cl J1226.9+3332 is shown in Figure 19 for illustration. Region 1 is bounded by contour levels at $f_0$ and $f_1$ and contains emission detected at $>3 \sigma$ above the emission in region 1 in the background image. Region 2 uses the emission in region 1 as the background level above which to measure its significance. Regions 3 and 4 use region 2 as a background, but their significance is measured independently. Note that this contouring scheme means that contour levels cannot be interpreted in the same way as in standard contour plots; separate contours that are the same number of contours above the background are unlikely to correspond to the same flux level in the smoothed image.

In applying this method to a large number of `Chandra` observations of clusters (B. J. Maughan et al. 2007, in preparation), it was found that an artificial “banding” could result. This is a repeated sequence of two tightly grouped contours followed by two widely spaced contours. The reason for this is that the statistical uncertainties on the blank-sky background counts in a region are generally very small, so a narrow contour band is sufficient for a 3 $\sigma$ detection. When that narrow band is used for a background for its child region, the uncertainties on the background level are relatively large due to the small number of counts, so a wide contour band is required for a 3 $\sigma$ detection. The next band is then narrow because of the relatively small background uncertainties in the wide parent region, and the process repeats. In order to prevent this, an additional criterion was imposed to regulate the process. In order for a region to pass, it was required that the contained emission be detected at $>3 \sigma$ and that the statistical uncertainty on the enclosed flux be smaller than some threshold. A threshold of 5% was used for the majority of the clusters, but a higher (lower) threshold was required for the faintest (brightest) clusters. This regulation prevents the banding problem and means that, particularly in the brightest clusters, the significance of some regions is somewhat larger than the 3 $\sigma$ threshold.

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