The dark matter halos of massive, relaxed galaxy clusters observed with Chandra

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ABSTRACT
We use the Chandra X-ray Observatory to study the dark matter halos of massive, dynamically relaxed galaxy clusters, spanning the redshift range $0 < z < 0.7$. The observed dark matter and total mass (dark-plus-luminous matter) profiles can be approximated by the Navarro Frenk & White (hereafter NFW) model for cold dark matter (CDM) halos; for $\sim$ 80 per cent of the clusters, the NFW model provides a statistically acceptable fit. In contrast, the singular isothermal sphere model can, in almost every case, be completely ruled out. We observe a well-defined mass-concentration relation for the clusters with an intrinsic scatter in good agreement with the predictions from simulations. The slope of the mass-concentration relation, $a = -0.45 \pm 0.12$ at 95 per cent confidence, is steeper than the value $a \sim -0.1$ predicted by CDM simulations for lower mass halos. With the slope $a$ included as a free fit parameter, the redshift evolution of the concentration parameter, $b = 0.71 \pm 0.02$ at 95 per cent confidence, is consistent with the same simulations ($b \sim 1$). Fixing $a \sim -0.1$ leads to an apparent evolution that is significantly slower, $b = 0.30 \pm 0.09$, although the goodness of fit in this case is significantly worse. Using a generalized NFW model, we find the inner dark matter density slope, $\alpha$, to be consistent with unity at 95 per cent confidence for the majority of clusters. Combining the results for all clusters for which the generalized NFW model provides a good description of the data, we measure $\alpha = 0.88 \pm 0.29$ at 95 per cent confidence, in agreement with CDM model predictions.

Key words: cosmology: observations – dark matter – X-rays: galaxies: clusters

1 INTRODUCTION

One of the most remarkable results of cold dark matter (CDM) simulations of structure formation is that the density profiles of dark matter halos on all resolvable mass scales, from small satellites to the most massive galaxy clusters, can be approximated by a universal profile, the so-called Navarro-Frenk-White (NFW) profile (Navarro, Frenk & White 1995, 1997)
$$\rho(r) = \frac{\rho_0}{(r/r_s)(1 + r/r_s)^2}. $$ (1)

Here $r_s$ is the characteristic scale radius of the halo and $\rho_0$ is the central density. The model has a central, negative logarithmic density slope, referred to hereafter as the "inner slope"
$$\alpha = -\frac{d \log \rho}{d \log r} \bigg|_{r \to 0} = 1. $$ (2)

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NFW also defined the concentration parameter, $c$, as the ratio of $r_{200}$, the radius within which the matter density is 200 times the critical density, and the scale radius:
$$c = \frac{r_{200}}{r_s}. $$ (3)

They showed that smaller mass halos are more concentrated than the higher mass halos and interpreted this as reflecting the higher formation redshift of the lower mass systems.

Copious numerical work has been devoted to testing these fundamental findings. To explain the mass-concentration relation and its redshift evolution, Bullock et al. (2001) and Eke et al. (2001) introduced simple, but highly successful models for the formation of dark matter halos. In the Bullock et al. (2001) model, for example, only two parameters, $K$, which determines the initial concentration parameter of collapsing halos and $F$, the ratio of the initial collapse mass to the final virial mass of the halo at redshift zero, are required to approximately match the simulation predictions. More recently simple two-parameter power-laws have been used to characterize the
mass-concentration relation \cite{Dolag2004, Shaw2006}. When considering the inner slopes of dark matter halos, a useful generalization of the NFW formula is

\[ \rho(r) = \frac{\rho_0}{(\frac{r}{s})^{\alpha}(1 + \frac{r}{s})^{3-\alpha}} \]  

\[ (4) \]

(e.g., \cite{Hernquist1993, Zhao1996, Jing2000}), where the inner slope \( \alpha \) is a free parameter. From their initial simulations, \cite{Moore1999} found a steeper central slope than NFW, with \( \alpha = 1.5 \). For some years, the question of the precise value for the inner slope remained the topic of much debate. However, a consistent view has now emerged in which real dispersion is expected between the inner slopes for individual halos \cite{Klypin2001, Tasitsiomi2004} and where typical values for the inner slopes of clusters lie in the range \( \alpha \sim 1.1 \pm 0.4 \) \cite{Navarro2004, Diemand2004, 2005}. Recent analytical and numerical work to solve the Jeans equation suggests a value for the inner slope of \( \alpha \approx 0.8 \) \cite{Austin2003, Dehnen2003, Hansen2006}.

In summary, both a tight mass-concentration relation \cite{Shaw2006} and an inner density slope for dark matter halos in the range \( 0.7 < \alpha < 1.5 \) are central predictions of the CDM paradigm for structure formation.

In this paper we use Chandra X-ray Observatory data to study the mass profiles for 34 of the most massive, dynamically relaxed galaxy clusters. Such clusters are among the most promising targets with which to check the central CDM predictions, being both dominated by dark matter \cite{Allen2004} and having a size that allows us to resolve well within the scale radius, even at high redshifts. We employ an analysis method which minimizes the need for priors associated with the use of parameterized models for the X-ray gas density and/or temperature profiles. The restriction to relaxed clusters also minimizes systematic effects associated with, e.g., geometry and possible non-thermal pressure support.

Previous X-ray studies have suggested broad agreement with the theoretically predicted mass-concentration relation \cite{Pointecouteau2005, Zhang2006, Vikhlinin2004, Voigt2006}, at least at low redshifts. Here, we increase the detail of this comparison and, for the first time, measure both the slope of the mass-concentration relation and its evolution. We show that tension may exist between the Chandra data and some simple models based on CDM simulations for lower mass halos.

With regard to the inner density slope, Chandra and XMM-Newton results to date have, in general, suggested good agreement with the CDM predictions \cite{Allen2000, Schmidt2001, Allen2004, Lewis2002, 2003, Buote2004, Arabadjis2002, Arabadjis2004, Andersson2004}. After some initial controversy, there is also an emerging consensus that strong gravitational lensing data support inner dark matter density slopes of about unity in several clusters \cite{Smith2001, Gavazzi2003, Sand2002, Bartelmann2004, Dalal2003, Meneghetti2005, Sand2004}. We extend this work and show that the NFW model provides a good description of the total mass and dark matter profiles for most relaxed clusters, rejecting completely the simple singular isothermal model \( \rho \propto 1/r^2 \). We also obtain a robust result on the inner slope for the ensemble of clusters.

A flat \( \Lambda \) CDM reference cosmology is assumed with Hubble constant \( H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1} \) and matter density \( \Omega_m = 0.3 \). In a few cases cluster masses are quoted with a Hubble constant scale \( h = H_0/100 \text{ km s}^{-1} \text{ Mpc}^{-1} \).

\section{Method}

\subsection{Target selection}

Our target clusters are the most massive, dynamically relaxed clusters known in the redshift range \( 0 < z < 0.7 \). They form a restricted set of the clusters used by Allen et al. \cite{2007}, in preparation) to study the evolution of the X-ray gas mass fraction and constrain cosmological parameters. In detail, we have used only the targets from that study for which the temperature is measured in at least four independent bins, which permits reliable measurements on the inner density slopes. The target clusters all have mass weighted X-ray temperatures measured within the radius \( r_{2500} \), \( kT_{2500} \gtrsim 5 \text{ keV} \) \cite{Allen2007, in preparation}.

The clusters exhibit a high degree of dynamical relaxation in their Chandra images, with sharp central X-ray surface brightness peaks, regular elliptical X-ray isophotes and minimal isophote centroid variations. The clusters show minimal evidence for departures from hydrostatic equilibrium in X-ray pressure maps (Million et al., in preparation). The exceptions to this are RXJ1347.5-1145, and MACS J0744.9+3927, for which clear substructure is observed between position angles of 90-190 degrees and 210-330 degrees, respectively. These regions, associated with obvious substructure, have been excluded from the analysis. The restriction to clusters with the highest possible degree of dynamical relaxation (for which the assumption of hydrostatic equilibrium should be most valid) minimizes systematic scatter and allows the most precise test of the CDM model predictions \cite{Nagai2005}.

\subsection{Observations, data reduction and spectral analysis}

The Chandra observations were carried out using the Advanced CCD Imaging Spectrometer (ACIS) between 1999 August 30 and 2005 June 28. The standard level-1 event lists produced by the Chandra pipeline processing were reprocessed using the CIAO \cite{version 3.2.2} software package, including the latest gain maps and calibration products. Bad pixels were removed and standard grade selections applied. Where possible, the extra information available in VFAINT mode was used to improve the rejection of cosmic ray events. The data were cleaned to remove periods of anomalously high background using the standard energy ranges and time bins recommended by the Chandra X-ray Center. The net exposure times after cleaning are summarized in Table \ref{table:exposure_times}.

\begin{table}
\centering
\begin{tabular}{|c|c|}
\hline
Cluster & Exposure Time (ks) \\
\hline
\end{tabular}
\end{table}

$^1$ \( r_{2500} \) is the radius within which the mean mass density is 2500 times the critical density of the Universe at the redshift of the cluster.

\cite{2006RAS.373.1484S}
Table 1. Summary of the Chandra observations. Columns list the target name, redshift, observation date, detector used, observation mode, net exposure after all cleaning and screening processes, and coordinates from the X-ray centres used in the analysis. Where multiple observations of a single target have been used, these are listed separately. Redshifts for the MACS clusters are from Ebeling et al. 2006, in preparation, and will appear in full in the published article.

| Target        | Redshift | Date        | Detector | Mode     | Exposure (ks) | R.A. (J2000.) | Dec. (J2000.) |
|---------------|----------|-------------|----------|----------|---------------|---------------|---------------|
The data have been analysed using techniques discussed by [Allen et al. (2004)](http://www.astronomy.org) and references therein. In brief, concentric annular spectra were extracted from the cleaned event lists, centred on the coordinates listed in Table 1. Emission associated with X-ray point sources or obvious substructure (Section 2.1) was excluded. The spectra were analysed using XSPEC (version 11.3: Arnaud 1996), the MEKAL plasma emission code (Kaastra & Mewe 1993) incorporating the Fe-L calculations of Liedahl et al (1995) and the photoelectric absorption models of Balucinska-Church & McCammon (1992). We have included standard correction factors to account for time-dependent contamination along the instrument light path. In addition, we have incorporated a small correction to the High Resolution Mirror Assembly model in CIAO 3.2.2, which takes the form of an 'inverse' edge with an energy, E=2.08 keV and optical depth $\tau = -0.1$ (H. Marshall, private communication) and boosted the overall effective area by six per cent, to better match later calibration data (A. Vikhlinin, private communication). Only data in the 0.8–7.0 keV energy range were used in the analysis (the exceptions being the earliest observations of 3C 295, Abell 1835 and Abell 2029 where a wider 0.6 to 7.0 keV band was used).

For the nearer clusters ($z < 0.3$), background spectra were extracted from the blank-field data sets available from the Chandra X-ray Center. These were cleaned in an identical manner to the target observations. In each case, the normalizations of the background files were scaled to match the count rates in the target observations measured in the 9.5–12keV band. Where required, e.g. due to the presence of strong excess soft emission in the field of Abell 2029, a spectral model for any unusual soft background emission was included in the analysis. For the more distant systems (as well as for the first observation of Abell 1835, the ACIS-I observation of Abell 383, and the observations of Abell 2537, RXJ 2129.6−0005 and Zwicky 3146) background spectra were extracted from appropriate, source free regions of the target data sets. (We have confirmed that similar results are obtained using the blank-field background data sets.) In order to minimize systematic uncertainties and due to the specific goals of this work, we have restricted our spectral analysis to radii within which systematic uncertainties in the background subtraction (established by the comparison of different background subtraction methods) are smaller than the statistical uncertainties in the results. All results are drawn from spectral analyses limited to ACIS chips 0,1,2,3 and 7 which have the most accurate calibration, although ACIS chip 5 was also used to study the soft X-ray background in ACIS-S observations. We do not attempt to extend our analyses to larger radii using the data from other chips.

Separate photon-weighted response matrices and effective area files were constructed for each region using calibration files appropriate for the period of observations. The spectra for all annuli for a given cluster were modelled simultaneously in order to determine the deprojected X-ray gas temperature and metallicity profiles, under the assumption of spherical symmetry.

### 2.3 Cluster mass profile measurements

#### 2.3.1 Basics of the mass analysis

Under the assumptions of hydrostatic equilibrium and spherical symmetry, the observed X-ray surface brightness profile and the deprojected X-ray gas temperature profile may together be used to determine the X-ray emitting gas mass and total mass profile of a galaxy cluster. For this analysis, we have used an enhanced version of the Cambridge X-ray deprojection code described by e.g. [White, Jones & Forman (1997)](http://www.astronomy.org). This method is particularly well suited to the present study in that it does not require approximate fitting functions for the X-ray temperature, gas density or surface brightness when measuring the total, gravitating mass. The use of such functions introduces priors into an analysis which can complicate the interpretation of results and, in particular, the estimation of measurement errors.

We have carried out two separate mass analyses: firstly (method 1) an analysis in which the total mass profile (dark plus luminous matter) was modelled using either an NFW or singular isothermal sphere. Detailed results on the X-ray emitting gas profiles were also determined at this stage. Secondly (method 2) an analysis in which the total mass profile was modelled as the sum of three parts: the dark matter halo (fitted with a generalized NFW profile), the X-ray emitting gaseous halo (approximated, for the purposes of this analysis only, with a beta model), and the optically luminous mass of the cD galaxy (approximated with a Jaffe or de Vaucouleurs model).

The normalization, $\rho_0$, of the generalized NFW mass model (eq. 1) is usually written as

$$\rho_0 = \rho_{\text{crit}} \delta_c$$

where

$$\rho_{\text{crit}} = 3H(z)^2/8\pi G$$

is the critical density at the redshift $z$ of the cluster. $G$ is the gravitational constant and the Hubble parameter $H(z)$ in the flat $\Lambda$CDM reference cosmology is defined by

$$H(z)^2 = H_0^2 \left(1 + z\right)^3\Omega_m + 1 - \Omega_m,$$

where $\Omega_m$ is the matter density in units of the critical density.

The amplitude $\delta_c$ depends only on the concentration parameter $c = r_{200}/r_{200}$ is the radius within which the average mass density is 200 times $\rho_{\text{crit}}$. For convenient computation, $\delta_c$ can be written using the Gauss hypergeometric function $\Phi(a,b;c;z)$ (Abramowitz & Stegun 1965)

$$\Phi(y) = \frac{y^{3-\alpha}}{3-\alpha} \Phi(3-\alpha, 3-\alpha; -4-\alpha; -y)$$

as

$$\delta_c = \frac{200}{3} \frac{c^3}{\Phi\left(c^2\frac{4 \Omega_m}{3}ight)}$$

(Wyithe et al. 2001). For the original NFW mass model with

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2 As discussed in the text, priors are required when modelling the dark matter and X-ray and optically luminous matter components separately.
\[ \alpha = 1, \text{ one obtains } \Phi(c) = \ln(1+c) - c/(1+c) \text{ (Navarro et al. 1996).} \]

With mass analysis method 2, the component of the total mass distribution representing the X-ray emitting gas component was described by a beta-model (Cavaliere & Fusco-Femiano 1978)

\[
\rho_{\text{gas}}(r) = \rho_{0,\text{gas}} \left[ 1 + \left( \frac{r}{r_{c,\text{gas}}} \right)^2 \right]^{-\frac{3\beta}{2}},
\]

where \( \rho_{0,\text{gas}} \) is the central gas density, \( r_{c,\text{gas}} \) is the core radius of the gas profile and \( \beta \) is the slope parameter. (We stress that the detailed results on the X-ray emitting gas profiles, used for example in the measurement of cluster gas mass fractions, are determined with method 1 and involve no assumption about the functional form of the gas profile. The use of the beta-model with method 2 simply approximates the contribution of this mass component to the total mass, allowing us to recover the dark matter profiles. Although the beta model does not provide a precise match to the X-ray gas mass distribution in all cases, the systematic uncertainties in the dark matter profiles that result from its use are small, primarily because the X-ray emitting gas contributes only \( \sim 12 \) per cent of the total mass; Allen et al. 2007, in preparation).

All of the target clusters have a single, optically dominant galaxy at their centres. With method 2, we accounted for the mass of stars in the central galaxy using a Jaffe (1983) model (Sand et al. 2002, 2004). This was added to the generalized NFW potential for the dark matter halo and the beta-model for the X-ray emitting gas to obtain the total mass profile. The Jaffe (1983) model is

\[
\rho_J(r) = \rho_{0,J} \left( \frac{r}{r_c} \right)^2 \left( 1 + \frac{r}{r_c} \right)^{-7},
\]

with central density \( \rho_{0,J} \) and core radius \( r_c \). The total mass for the model is finite, \( M_J = 4\pi r_c^3 \rho_{0,J} \). Since including this model into the analysis has only a small effect on the results (Section 4.2), but requires two parameters, we chose to fix these two parameters to sensible values. We adopt \( R_g = 0.76 r_c = 25 \) kpc as a typical effective radius (e.g., Sand et al. 2002, 2005). For the well-studied cD galaxy in MS2137-2353, Sand et al. (2002) measure a total V-band luminosity of \( L_V = 4.16 \times 10^{11} L_\odot \). Using the \( M/L_V \) relation of Fukugita et al. (1998)

\[
M/L_V = 4.0 + 0.38 (t_g - 10 \text{ Gyr}),
\]

where \( t_g \) is the age of the galaxy (we assume a formation redshift \( z_i = 2.0 \)), we estimate the total stellar mass associated with the cD galaxy of \( 1.14 \times 10^{12} M_\odot \). The central galaxy for each cluster in the sample is assumed to have this stellar mass.

We have also carried out a repeat analysis in which the Jaffe (1983) model for the stellar mass associated with the central, dominant galaxies was replaced by a de Vaucouleurs (1948) model. This analytical model is described by the surface mass density

\[
\Sigma(r) = \Sigma_e e^{-7.67(r/R_e)^{1/4}} - 1,
\]

where \( \Sigma_e \) is the surface density at the effective (or half-mass) radius \( R_e \). The 3-dimensional mass profile of the de Vaucouleurs model was calculated by Young (1976) and has a shallower central slope close to unity. However, similar results on the cluster dark matter profiles were obtained in all cases, showing that the precise choice of the galaxy model has a negligible effect on the results.

### Table 2. Regions with residual substructure that were downweighted in the mass analysis. A systematic uncertainty of \( \pm 30 \) per cent has been added in quadrature to all temperature measurements made within radii \( R_{\text{sub}} \).

| Cluster      | \( R_{\text{sub}} \) (kpc) |
|--------------|-----------------------------|
| Abell 1795   | 73.3                        |
| Abell 2029   | 30.0                        |
| Abell 478    | 14.6                        |
| PKS0745-191  | 53.0                        |
| Abell 1413   | 38                          |
| Abell 2204   | 76.8                        |
| Abell 383    | 38.7                        |
| RXJ1504.1-0248 | 79.1                    |
| RXJ2129.6+0005 | 40.4                    |
| Zwicky 3146  | 242                         |
| Abell 2537   | 41.1                        |
| MACSJ2229.8-2756 | 42.0                |
| MACSJ0947.2+7623 | 40.1                |
| MACSJ1931.8-2635 | 41.5                |
| MACSJ1115.8+0129 | 83.4                |
| MACSJ1532.9+3021 | 42.3                |
| MACSJ1621.6+3810 | 43.1                |

\( \chi^2 = \sum \left( \frac{T_{\text{obs}} - T_{\text{model}}}{\sigma_{\text{obs}}} \right)^2 \)

2.3.2 Best-fitting values and confidence limits

Given the observed surface brightness profile and a particular parameterized model for the total mass, the deprojection code is used to predict the temperature profile of the X-ray gas. This model temperature profile is compared with the observed spectral, deprojected temperature profile and the goodness of fit is calculated using the sum over all temperature bins

\[ \chi^2 = \sum \left( \frac{T_{\text{obs}} - T_{\text{model}}}{\sigma_{\text{obs}}} \right)^2, \]

where \( T_{\text{obs}} \) is the observed, spectral deprojected temperature profile and \( T_{\text{model}} \) is the model, rebinned to the same spatial scale using flux weighting.\footnote{In detail, we use the median model temperature profile determined from 100 Monte-Carlo simulations. The outermost pressure, at the limit of the X-ray surface brightness profile, is fixed using an iterative method that ensures a smooth, power law pressure gradient in these regions. The model temperature profiles, for radii spanned by the spectral data, are not sensitive to reasonable choices for the outer pressures.}
For a number of the clusters, the Chandra images indicate small levels of residual substructure in the innermost regions, which probably result from ‘sloshing’ of the X-ray emitting gas within the central potentials (e.g., Markevitch et al. 2001; Ascasibar & Markevitch 2006; Allen et al. 1992) and/or interactions between central radio sources and the surrounding intracluster gas (e.g., Birzan et al. 2004; Dunn & Fabian 2004; Forman et al. 2004; Dunn et al. 2005; Rafferty et al. 2006; Allen et al. 2006). The regions affected by such substructure are listed in Table 2. A systematic uncertainty of ±30 per cent has been added in quadrature to the spectral results from these regions which leads to them having little weight in the mass analysis.

3 RESULTS

3.1 Total mass profiles: NFW versus singular isothermal sphere

Table 3 summarizes the results from the initial mass analysis (method 1) in which the total mass profiles (dark-plus-luminous matter) were modelled using either an NFW (inner slope $\alpha = 1$ fixed) or singular isothermal sphere model ($\rho(r) = A/r^2$, with the normalization $A$ free). We see that for most clusters the NFW model provides a reasonable description of the total mass profiles. For 27 out of 34 clusters, the probability of the $\chi^2$/DOF value based on a $\chi^2$ distribution is 0.05 or better (e.g., Bevington & Robinson 1992) and only for Abell 383 and 1413 does the probability drop below 0.001. In contrast, the singular isothermal sphere model can be firmly rejected for most clusters in the sample.

Combining the results for all clusters, the NFW model gives a total $\chi^2$ of 171.0 for 95 degrees of freedom (DOF) (with Abell 383 and 1413 contributing a total $\chi^2$ of 47.9). The singular isothermal sphere gives $\chi^2 = 3031.1$ for 129 DOF, indicating an extremely low model probability.

3.2 Dark matter profiles: The NFW model and mass-concentration relation

Table 3 summarizes the results from the analysis with method 2, in which the cluster mass distributions were separated into three parts: the dark matter halo (fitted with a generalized NFW profile), the X-ray emitting gaseous halo (approximated with a beta model), and the optically luminous mass of the central dominant galaxy (approximated with a Jaffe or a de Vaucouleurs model). In the first case, we examined models in which the inner slope of the dark matter profile was fixed at $\alpha = 1$ i.e. the standard NFW model.

Our first conclusion is that, as with the analysis of the total mass profiles, the NFW model provides a good overall description of the dark matter profiles in the clusters. For 27 out of 34 clusters, the $\chi^2$/DOF value has a probability of 0.05 or better and only for Abell 383 and 1413 does the model fail significantly. Combining the results for all clusters, the NFW model gives a total $\chi^2$ of 176.1 for 95 degrees of freedom (DOF) (with Abell 383 and 1413 contributing a total $\chi^2$ of 48.0; note that the inclusion of the separate mass components for the X-ray emitting gas and stars introduces no additional free parameters in the fits.) The concentration parameters, $c$ for the dark matter profiles are slightly lower, and the scale radii slightly higher, than for the total matter distributions. However, in general the results are quite similar.

As discussed in Section 1 one of the central predictions from simulations of CDM halos is the mass-concentration relation. In order to allow for the most direct comparison with theory, we have used the values in Tables 3 and 4 to calculate the concentration parameters $c_{\text{vir}}$ and virial masses $M_{\text{vir}}$ measured within the virial radii for the clusters. We adopt the definitions of virial radius and virial mass used by Shaw et al. (2006).

$$M_{\text{vir}} = \frac{4}{3} \pi r_{\text{vir}}^3 \Delta_c(z) \rho_{\text{crit}}(z),$$

where the virial overdensity is given by $\Delta_c = 178\Omega_m(z)^{0.45}$ (Lahav et al. 1991).

Both the virial radii and virial masses are calculated for the total mass model, including all mass components. The concentration parameters are defined by the ratios of these virial radii and the scale radii of the dark matter components, $c_{\text{vir}} = r_{\text{vir}}^{\text{total}}/r_{\text{dark}}^{\text{total}}$. Table 4 lists the results on $c_{\text{vir}}$ and $M_{\text{vir}}$ for the clusters using the standard NFW model ($\alpha = 1$).

Fig. 1 shows the variation of $c_{\text{vir}}$ with $M_{\text{vir}}$ measured from the Chandra data. A tight relation is observed with...
a clear trend for decreasing concentration parameter with increasing mass.

The literature contains a variety of simple analytical forms to describe the expected form of the mass-concentration relation, based on CDM numerical simulations. The simplest of these is a power-law model (Dolag et al. 2004)

\[ c_{\text{vir}}(z) = \frac{c_0}{1 + z} \left( \frac{M_{\text{vir}}}{8 \times 10^{14} h^{-1} M_{\odot}} \right)^{\alpha} . \]  

(16)

Shaw et al. (2006) present one of the largest statistical studies of cluster-sized CDM halos to date. Fitting a \( z = 0.05 \) snapshot of their simulated data with the (Dolag et al. 2004) power-law model, these authors find \( c_0 = 6.47 \pm 0.03 \) and \( \alpha = -0.12 \pm 0.03 \) (68 per cent confidence limits). The dashed line in Fig. 1 shows the model defined by these parameters, overlaid on the Chandra results. The model clearly provides a poor fit to the observations, \( \chi^2 = 125.9 \) for 30 DOF, lying systematically below the data at lower masses and above it in the highest mass range. Note that the two clusters for which the NFW model provides a formally unacceptable description of the Chandra data, Abell 383 and 1413, have been excluded from the fit and are plotted with open square symbols. Note also that the mass-concentration relation of Shaw et al. (2006) is in good agreement with the models of Bullock et al. (2001) (with the parameters from Dolag et al. 2004) and Eke et al. (2001).

One should remember that the Chandra observations reported here are for the most massive, dynamically relaxed clusters known within \( z < 0.7 \). (Our targets represent the most relaxed \( \sim 20 \) per cent of clusters in this mass and redshift range.) We have, therefore, also determined the best-fitting power-law parameters appropriate for the most relaxed 20 per cent of simulated halos with
$M_{\text{vir}} > 2 \times 10^{14} h^{-1} M_\odot$ in the Shaw et al. (2006) study. (In detail, this is done by selecting only those clusters with a substructure fraction, as defined by those authors, $f_s < 0.045$). The resulting power-law fit parameters are $c_0 = 6.8$ and $a = -0.16$. Although giving slightly better agreement with the observations, this model still provides a poor description of the Chandra data with $\chi^2 = 102.9$ for 30 DOF.

Physical motivation for the power-law model and its $(1+z)^{-1}$ redshift dependence is presented by Bullock et al. (2001). In their model they assume that the ratio of the virial mass, $M_{\text{vir}}$, to the volume inside the scale radius, $V_s$, is proportional to the matter density $\rho_m(z_{\text{coll}})$ at the redshift, $z_{\text{coll}}$, when the cluster formed:

$$\rho_m(z_{\text{coll}}) \propto \frac{M_{\text{vir}}}{V_s} \propto \frac{\rho_m \, r_{\text{vir}}^3}{r_s^3} = \frac{\rho_m}{c_{\text{vir}}^3}.$$  

(17)

Since the matter density $\rho_m$ was larger in the past, $\rho_m \propto (1+z)^3$, the typical concentration parameter for a halo of mass $M_{\text{vir}}$ is smaller at higher redshifts, $c_{\text{vir}} \propto (1+z)^{-1}$.

Bullock et al. (2001) associate each redshift with a typical collapsing mass (defined as a fraction $F$ of the final halo mass) through a critical value of the variance $\sigma(z, M)$ of the density fluctuations. Since $\sigma(M)$ for a $\Lambda$CDM model is a power-law for masses $M_{\text{vir}} \lesssim 10^{13} M_\odot/F$, this model yields a power-law for the mass-concentration relation (up to this mass scale) with two free parameters. Bullock et al. (2001) suggest $F = 0.01$ (although $F = 0.001$ is also used in the more recent literature). At the high-mass end,
$M_{\text{vir}} > 10^{13} M_\odot / F$, the model predicts a change in the power-law slope but, unfortunately, also becomes unrealistic as the linear evolution of density fluctuations stalls in the $\Lambda$CDM model, preventing high-mass clusters from forming (Bullock et al. 2001; Kuhlen et al. 2003).

Although the Bullock et al. (2001) model and the power law model of Dolag et al. (2004) are attractive in terms of their simplicity, the limitations of such models for describing the detailed properties of cluster halos should not be overlooked. Firstly, real clusters contain X-ray emitting gas and stars, as well as dark matter. CDM-only simulations do not include cooling and feedback processes which affect the baryonic mass components and modify the overall mass distributions. Secondly, to date, studies of the mass-concentration relation have included very few halos at the largest mass range spanned by the Chandra data; e.g., Shaw et al. (2006) have only a single cluster with $M_{\text{vir}} > 10^{15} h^{-1} M_\odot$. Finally, Zhao et al. (2003) argue that at the highest masses, the Bullock et al. (2001) model may over-predict the evolution of $c_{\text{vir}}$ with redshift.

Motivated by such considerations, we have introduced additional freedom into the power law model of Dolag et al. (2004). As well as having $c_0$ and $a$ as free fit parameters, we also allow the redshift evolution to evolve as $(1 + z)^{-b}$, with $b$ free.

$$c = \frac{c_0}{(1 + z)^b} \left( \frac{M_{\text{vir}}}{8 \times 10^{14} h^{-1} M_\odot} \right)^a. \quad (18)$$

The results from a fit with this model, with $c_0$, $a$ and $b$ all free, are shown by the solid line in Fig. 1. The model provides a significantly improved description of the data with $\chi^2 = 41.5$ for 29 degrees of freedom and best-fitting parameters $c_0 = 7.55 \pm 0.90$, $a = -0.45 \pm 0.12$ and $b = 0.71 \pm 0.52$ (95 per cent confidence limits; similar results are obtained from a Monte Carlo analysis of the $(c_{\text{vir}}|M_{\text{vir}})$ data wherein the results for individual clusters are scattered according to their measurement errors). Although the normalization $c_0$ at $8 \times 10^{14} h^{-1} M_\odot$ and the redshift evolution, $b$, are consistent with the Shaw et al. (2006) simulations and Dolag et al. (2004) model, the mass-concentration relation is noticeably steeper.

Fig. 2 shows the variation of concentration parameter with redshift. At low redshifts, the fit to the Shaw et al. (2006) simulated data with the Dolag et al. (2004) model ($c_0 = 6.47$, $a = -0.12$ and $b = 1$) provides a reasonable match to the data (in agreement with the conclusions drawn by Pointecouteau et al. 2003; Zhang 2004; Vikhlinin et al. 2004; Voigt & Fabian 2006). At higher redshifts, however, the observed $c_{\text{vir}}$ values exceed the Shaw et al. (2006) model predictions. The most striking feature of Fig. 2 is an apparent absence of redshift evolution in the concentration parameter. Indeed, when fixing the slope parameter $a$ to the Shaw et al. (2006) value of $a = -0.12$, a fit with $c_0$ and $b$ free gives a redshift evolution parameter $b = 0.31 \pm 0.49$ (95 per cent confidence limits), consistent with no evolution or even positive evolution of $c_{\text{vir}}$ with $M_{\text{vir}}$. However, note that the $\chi^2$ for this fit is significantly worse ($\chi^2 = 74.7$ for 30 DOF; $\Delta \chi^2 = 33.2$) than for the fit in which the slope, $a$, of the mass-concentration relation is also included as a free parameter (see above). We conclude that any analysis of redshift evolution in the mass-concentration relation should (at least) explore the full parameter space discussed above, with $c_0$, $a$ and $b$ included as free parameters.

Finally, we have estimated the systematic scatter that may be present in the observed mass-concentration relation. This was carried out by modifying the $\chi^2$ estimator to include an additional systematic uncertainty, and increasing the size of this systematic uncertainty until the reduced $\chi^2$ value became equal to unity. Based on the fit with $c_0$, $a$ and $b$ included as free parameters, we estimate an intrinsic systematic scatter in the data of $\Delta \log(c) \sim 0.1$, in good agreement with the predictions from simulations (e.g., Bullock et al. 2001; Wechsler et al. 2002).

In summary, the key results on the mass-concentration relation are 1) the presence of a tight, observed mass-concentration relation for massive, dynamically relaxed clusters. The estimated intrinsic, systematic scatter in this relation is consistent with the predictions from CDM simulations. 2) We observe a slope $a = -0.45 \pm 0.12$ (at 95 per cent confidence) for the mass-concentration relation that is significantly steeper than predicted by CDM simulations for lower mass halos ($a \sim -0.12$. Shaw et al. 2006). 3) The redshift evolution of the observed mass-concentration relation, $b = 0.71 \pm 0.52$ at 95 per cent confidence, is consistent with the value of $b = 1$ in the Bullock et al. (2001) model.

### 3.3 The inner slope of dark matter profiles: generalized NFW models

For the final stage of our analysis, we have included the inner slope of the dark matter profile ($\alpha$, in the generalized
NFW model) as an additional free parameter in the fits with method 2. (Separate components to model the mass contributions from the X-ray emitting gas and the optically luminous matter in the central, dominant galaxies were included in the fits.)

The results on the inner mass profiles are summarized in Table 1. In terms of the goodness of fit, 27 out of 34 clusters give $\chi^2$/DOF values with a probability of 0.05 or better. Of these 27 clusters, 21 have an inner slope consistent with unity at 68 per cent confidence.

In order to obtain a combined result on the inner dark matter profile, we have summed together the results on $\chi^2$ as a function of $\alpha$ for the 27 clusters for which the generalized NFW model provides a reasonable description of the data. The results are shown in Fig. 3 (Note that we have subtracted the overall minimum summed $\chi^2$, of 75.37 for 72 DOF; 127 temperature measurements, 2 free parameters for 27 clusters and one free slope parameter).

| $c_{\text{vir}}$ | $M_{\text{vir}}$ |
|-----------------|-----------------|
| Abell 1795      | 6.16±1.14       |
| Abell 2029      | 8.86±0.50       |
| Abell 478       | 5.15±0.45       |
| PKS0745-191     | 7.75±1.43       |
| Abell 1413      | 6.08±1.96       |
| Abell 2204      | 12.8±2.55       |
| Abell 383       | 5.08±1.03       |
| Abell 963       | 5.79±1.03       |
| RXJ0439.0+0521  | 8.20±1.58       |
| RXJ1504.1-0248  | 7.46±1.41       |
| RXJ1229.6-0005  | 5.23±1.51       |
| Abell 1835      | 4.18±0.65       |
| Abell 611       | 6.48±2.14       |
| Zwicky 3146     | 2.91±3.03       |
| Abell 2537      | 6.15±2.96       |
| MS2137.3-2353   | 8.82±0.75       |
| MACSJ0422.6-2123 | 8.05±1.80    |
| MACSJ1247.6-2521 | 7.82±1.91    |
| MACSJ1229.8-2756 | 9.67±4.87    |
| MACSJ0947.2+7623 | 6.59±2.84    |
| MACSJ1131.8-2635 | 3.59±2.04    |
| MACSJ1115.8+0129 | 2.22±2.30    |
| MACSJ1532.9+3021 | 5.84±1.82    |
| MACSJ1101.7-1523 | 3.73±1.12    |
| MACSJ1720.3+3536 | 5.14±1.66    |
| MACSJ429.6-0253  | 9.36±2.01     |
| MACSJ159.8+0849  | 6.12±1.15     |
| MACSJ329.7-0212  | 5.74±0.55     |
| RXJ347.5-1144   | 5.51±0.90     |
| 3C295           | 9.30±1.31     |
| MACSJ1621.6+3810 | 7.11±3.75    |
| MACSJ1311.0-0311 | 5.35±1.31    |
| MACSJ1423.8+2404 | 9.20±0.83    |
| MACSJ0744.9+3927 | 5.04±1.02    |

Figure 3. The summed $\chi^2$ values as a function of the inner density slope $\alpha$ for the 27 clusters for which the generalized NFW model provides a reasonable fit to the data. The dashed line indicates the 2σ confidence limits. The overall best fit is obtained for $\alpha = 0.88\pm0.26$ (95 per cent confidence limits).

From the summed $\chi^2$ data we obtain a best-fitting inner slope of $\alpha = 0.88\pm0.26$, where the uncertainties are 95 per cent confidence limits. We conclude that our combined result on the inner dark matter density slope is consistent with the range of values predicted by CDM simulations.

4 DISCUSSION

4.1 Previous results on the inner dark matter density slopes

Several of the clusters in the present sample have been the subjects of previous work that has examined the issue of the inner dark matter density slope. MS2137.3-2353 and Abell 963 were studied by Sand et al. (2002, 2004) using a combination of strong gravitational lensing data and optical velocity dispersion measurements for the dominant cluster galaxies. These authors measured surprisingly flat inner slopes for MS2137.3-2353, Abell 963 (which are formally consistent with the findings from the Chandra data presented in Table 3) and four other clusters, and concluded that their results were inconsistent with the standard NFW model ($\alpha = 1.0$) at 99 per cent confidence.

Later work by Bartelmann & Meneghetti (2004) and Dalal & Keeton (2003) cautioned that allowing for deviations from axial symmetry in the strong lensing analysis, using elliptical rather than spherical mass models (as motivated by the data) will modify the constraints on the inner dark matter profiles. These authors concluded that the strong lensing data of Sand et al. (2002, 2004) remain consistent with CDM models, once such effects are taken into account. The X-ray results presented here are also consist-
tent with the standard NFW model ($\alpha = 1.0$) at 95 per cent confidence. It is important to note that X-ray data do not suffer in the same way from uncertainties regarding axial symmetry. For the regular, apparently relaxed clusters in the present sample, the mass models determined from the X-ray data under the assumption of spherical symmetry are unlikely to be affected by asphericity effects by more than a few per cent (Piffaretti et al. 2003; Gavazzi 2005).

Using Chandra data for Abell 2029 (the first ~ 20ks observation only) and parameterized models for the gas density and temperature profiles, Lewis et al. (2003) obtained $\alpha = 1.19 \pm 0.04$ for the inner (total) mass profile. We measure $\alpha = 1.16^{+0.22}_{-0.34}$ for the dark matter at 68 per cent confidence using 94ks of clean data. (For the total mass, a fit with a generalized NFW model gives $\alpha = 1.16^{+0.26}_{-0.22}$). Thus, the present study and Lewis et al. (2003) obtain similar best-fit results, although the statistical uncertainties reported here are significantly larger, despite being based on more data. In part, this highlights the effects that priors, in the form of parameterized models for the gas density and temperature profiles, can have on the analysis. Zappacosta et al. (2006), see also Buote & Lewis (2004) present a detailed study of the nearby, intermediate temperature cluster Abell 2589, for which they also model the dark matter, X-ray emitting gas and stellar mass associated with the cD galaxy separately. They conclude that the standard NFW model with $\alpha = 1$ provides a good description of the dark matter and total mass distributions in the cluster.

Arabadjis & Bautz (2004) studied Chandra data for Abell 1835, Abell 2029, Abell 2204, Zwicky 3146 and MS 2137.3-2353. Fig. 4 of that paper indicates best-fitting values of $\alpha \sim 1.85$ for Abell 2029, $\alpha \sim 1.8$ for Abell 2204, $\alpha \sim 0.9$ for Abell 1835, $\alpha \sim 1.7$ for Zwicky 3146 and $\alpha = 1.6 \pm 0.2$ for MS 2137.3-2353 (with 68 per cent confidence limits of $\sim 10 - 20$ per cent). In general, we find shallower inner dark matter slopes than Arabadjis & Bautz (2004). Our statistical uncertainties are also larger in some cases.

Voigt & Fabian (2006) present results on the inner slopes for 12 clusters, 8 of which are in common with the present study. These authors use a similar non-parametric spectral deprojection technique to measure the deprojected X-ray temperatures in the clusters. Their results on the central slope are in general agreement with those presented here.

### 4.2 On the robustness of the central galaxy model

Sand et al. (2002) present a detailed analysis of the optical properties of the dominant galaxy in MS2137.3-2353 (see also Gavazzi 2003). These authors fit a de Vaucouleurs profile to the galaxy surface brightness, yielding an effective radius $R_e = 5.02 \pm 0.50$ arcsec and a total V-band luminosity $L_V = 4.2 \times 10^{11}$ $L_{\odot}$. Using the redshift-dependent V-band mass-to-light ratio of Fukugita et al. (1998) and assuming a galaxy formation redshift $\sim 2$, we obtain a V-band mass-to-light ratio for the dominant galaxy in MS2137.3-2353 of $M/L_V = 2.75$ and a total stellar mass of $1.14 \times 10^{12}$ $M_{\odot}$. (The stellar mass dominates the total mass within 10 kpc of the center of the cluster. Note that Sand et al. (2002) measure an optical velocity dispersion for the dominant galaxy in MS2137.3-2353 of $\sigma \sim 275$ km/s, from which they infer $M/L_V \sim 3.1$; see also Gavazzi (2003) for a slightly lower $M/L_V$ value). We have adopted these parameters as a template to approximate the mass contribution from stars in the central galaxies of all clusters in the sample, employing either a Jaffe model or de Vaucouleurs model.

In principle, we might expect the results on the inner dark matter density slopes to be sensitive to the choice of parameters used to describe the central stellar mass components. Here, the main systematic uncertainty lies with the assumption that the central stellar mass distribution in MS2137.3-2353 provides a reasonable model for other galaxy clusters in the sample. The assumption of a constant central stellar mass is well motivated; K-band observations of dominant cluster galaxies in X-ray luminous clusters (Brough et al. 2002) show little variation in total stellar mass over the redshift range $0 < z < 1$, with scatter at the level of $20 - 30$ per cent.

To estimate of the effect of departures from a constant central stellar mass on the measured inner dark matter slopes, we have re-analysed the Chandra data for MS2137.3-2353 varying the $M/L_V$ ratio over the range $M/L_V = 0 - 6$ (and thereby changing the central stellar mass by $\sim \pm 100$ per cent). In each case, we have re-determined the constraints on the inner slope $\alpha$. The results are shown in Fig. 4. Note that MS2137.3-2353 is one of the least massive clusters in the sample, and so changes in $\alpha$ with central stellar mass are likely to be larger than for most other clusters in the sample. For $M/L_V = 1.5$, we measure $\alpha = 1.10^{+0.22}_{-0.30}$ at 68 per cent confidence. For $M/L_V = 4$, we measure $\alpha = 0.94^{+0.46}_{-0.24}$. The tendency is for higher $M/L_V$ ratios to give slightly shallower inner dark matter slopes. These results can be compared to the best-fitting result for MS2137.3-2353 with $M/L_V = 2.75$ of $\alpha = 1.00^{+0.25}_{-0.35}$. We conclude that the results on the inner dark matter slope for MS2137.3-2353 are robust against changes in the central stellar mass by $\pm 50$ per cent.

Finally, we note that extending the analysis to model the mass components associated with stars external to central galaxies separately should have a negligible effect on the results. In total, stars contribute only $\sim 2$ per cent of the total cluster mass (e.g., Lin & Mohr 2004, Fukugita et al. 1998).

In conclusion, the results presented here are robust against systematic uncertainties associated with measuring the stellar mass contribution in the clusters.

### 4.3 Residual systematic uncertainties

The clusters studied here are the most massive, dynamically relaxed clusters known and are, therefore, the systems for which the assumption of hydrostatic equilibrium should be most robust. Although, as discussed above, geometric effects and uncertainties associated with separating the dark matter and baryonic matter components are unlikely to impact on the results significantly, some systematic uncertainties remain.

In the first case, it remains possible that small levels of non-thermal pressure support due to e.g. gas motions, cosmic rays or magnetic fields could be present in the X-ray emitting gas and bias the measured masses low. However, the relaxed nature of the clusters argues that large, unaccounted for, bulk and/or turbulent motions are unlikely to be present and that the mass measurements should be re-
covered to better than 10–20 per cent accuracy (Nagai et al. 2007; Rusin et al. 2006). Galaxy clusters are known to contain magnetic fields (e.g., Carilli & Taylor 2002). The issue of magnetic pressure support and its effect on X-ray mass measurements has been studied by Dolag & Schindler (2000) who showed that for relaxed clusters, magnetic pressure support is unlikely to bias mass measurements significantly, even in the central regions. For individual clusters, effects no larger than 10–20 per cent are expected. The similarity of the mass results obtained using method 1, where we measure the total mass and method 2, where we model the dark and baryonic components separately, also argues that any non-thermal pressure component, at the \( \sim 10–15 \) per cent level, distributed in a similar manner to the dark or baryonic matter, is unlikely to have a significant effect on the conclusions. A program to determine the maximum size of non-thermal pressure in the clusters, using a combination of Chandra X-ray data and wide field weak gravitational lensing observations, is underway (Donovan et al., in preparation).

It should also be recognized that although we quote results on the mass-concentration relation appropriate for the virial radii in the clusters, thereby allowing an easy comparison with the predictions from simulations, the X-ray data only extend to about \( r_{2500} \) or approximately a quarter to a third of the virial radius in most clusters. Some systematic uncertainty is associated with extrapolating the allowed range of NFW mass models to these larger radii.

Finally, we reiterate that the simulations used to predict the mass-concentration relation and central dark matter slopes (e.g., Navarro et al. 1995, 1997; Diemand et al. 2004; Shaw et al. 2006) are CDM only. In detail, these predictions may be modified by future numerical work that includes the X-ray emitting gas and stars, and realistic baryonic physics (cooling, star formation, AGN feedback). For the most accurate comparison with the data presented here, such simulations should contain a sufficiently large number of massive, relaxed clusters and be normalized to match the observed X-ray (e.g., temperature profiles, virial relations, X-ray gas mass fraction; Allen et al. 2003, 2004; Vikhlinin et al. 2006) and optical (Croton et al. 2006; Bower et al. 2006) properties.

5 SUMMARY

We have used the Chandra X-ray Observatory to measure the dark matter and total mass profiles for a sample of 34 massive, dynamically relaxed galaxy clusters. Our analysis has employed a non-parametric, spherical deprojection technique that minimizes the need for priors associated with parameterized models for the X-ray gas density and/or temperature profiles. This allows a direct assessment of the goodness of fit to the Chandra data provided by a variety of simple mass models as well as an accurate determination of statistical uncertainties on fit parameters.

We have shown that the NFW model, which is motivated by CDM simulations, provides a good description of the total mass and dark matter distributions in the majority of clusters. In contrast, the singular isothermal sphere model can, in almost every case, be firmly ruled out. Combining the results for all clusters for which the NFW model provides an acceptable description of the dark matter profiles, we obtain a best-fitting result on the inner slope of the dark matter density profile in the clusters, \( \alpha = 0.88^{+0.15}_{-0.11} \) (68 per cent confidence limits).

We observe a well-defined mass-concentration relation for the clusters with an intrinsic scatter in good agreement with the predictions from simulations. The slope of the mass-concentration relation, \( c \propto M_{\text{vir}}^{a/(1 + z)} \) with \( a = -0.45 \pm 0.12 \) at 95 per cent confidence, is significantly steeper than the value of \( a \sim -0.1 \) predicted by CDM simulations for lower mass halos. The redshift evolution, \( b = 0.71 \pm 0.52 \) at 95 per cent confidence, is consistent with the value \( b \sim 1 \) predicted by those simulations.

After this work was preprinted on astro-ph, Buote et al. (2006) preprinted a paper in which they discuss the mass-concentration relation for 39 systems with masses in the range \( 6 \times 10^{12} M_{\odot} \) to \( 2 \times 10^{15} M_{\odot} \). The results for higher mass systems are drawn from the previous studies of Pointecouteau et al. (2005) and Vikhlinin et al. (2006) and are in good overall agreement with the present work.

ACKNOWLEDGMENTS

We thank Laurie Shaw for kindly providing the simulated data from Shaw et al. (2006) and Adam Mantz and Glenn Morris for helpful discussions. We thank our collaborators in the ongoing cluster cosmology work, especially H. Ebeling for his heroic efforts in compiling the MACS sample. We are grateful to the developers of the GNU Octave numerical computation language and the GNU Scientific Library for their ongoing efforts. This work was supported in...
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