A HUBBLE SPACE TELESCOPE LENSING SURVEY OF X-RAY LUMINOUS GALAXY CLUSTERS. I. A383

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Received 2000 August 21; accepted 2001 January 3

ABSTRACT

We present an analysis of the mass distribution in the core of A383 (z = 0.188), one of 12 X-ray luminous galaxy clusters at z = 0.2 selected for a comprehensive and unbiased study of the mass distribution in massive galaxy clusters. Deep optical imaging performed by the Hubble Space Telescope (HST) reveals a wide variety of gravitationally lensed features in the core of A383, including a giant arc, two radial arcs in the halo of the central cluster galaxy, several multiply imaged arcs, and numerous arclets. Based upon the constraints from the various lensed features, we construct a detailed model of the mass distribution in the central regions of the cluster, taking into account both a cluster-scale potential and perturbations from individual cluster galaxies. Keck spectroscopy of one component of the giant arc identifies it as an image of a star-forming galaxy at z = 1.01 and provides an accurate measurement of the mass of the cluster within the projected radius of the giant arc (65 kpc) of (3.5 ± 0.1) × 10^11 M_☉. Using the weak shear measured from our HST observations, we extend our mass model to larger scales and determine a mass of (1.8 ± 0.2) × 10^14 M_☉ within a radius of 250 kpc. On smaller scales we use the radial arcs to probe the shape of the total mass distribution in the cluster core (r < 20 kpc) and find that the density profile is more peaked than a single Navarro, Frenk, & White (NFW) dark matter profile. Our findings imply that the dark matter in A383 may be more steeply peaked than NFW predict and that the cD galaxy measurably perturbs the cluster potential well. The optical and X-ray properties of A383 indicate the presence of a central cooling flow, for which we derive a mass deposition rate of (200 ± 50) M_☉ yr⁻¹. We also use the X-ray emission from A383 to obtain independent estimates of the total mass within project- ed radii of 65 and 250 kpc: (4.0 ± 0.5) × 10^13 and (1.2 ± 0.5) × 10^14 M_☉, which are consistent with the lensing measurements.

Subject headings: cosmology: observations — galaxies: clusters: individual (Abell 383) — galaxies: evolution — gravitational lensing

1. INTRODUCTION

Massive clusters of galaxies represent one extreme of the mass spectrum of collapsed structures at the present day. Their properties are expected to reflect predominantly gravitational processes and therefore provide unique insights into the nature and distribution of the dark matter that drives the formation of structure (e.g., Eke, Cole, & Frenk 1996; Viana & Liddle 1996; Bahcall, Fan, & Cen 1997; Kay & Bower 1999). In particular, accurate measurements of the mass distribution in clusters across a range of scales can be used to test the claim of a universal form for the profiles of dark matter halos (Navarro, Frenk, & White 1997, hereafter NFW97) and hence the nature of dark matter. At large scales the NFW97 profile falls off as ρ ∝ r⁻³, steeper than an isothermal model (ρ ∝ r⁻²). On smaller scales the NFW97 profile breaks to a shallower slope with ρ ∝ r⁻¹, while retaining a central cusp. Analyses of the mass profiles of dwarf galaxies from dynamical studies have used the apparent lack of a central cusp in the density distribution to reject the form of the NFW97 profile and argue instead for the existence of self-interacting dark matter (e.g., Moore et al. 1998). However, on larger scales (e.g., luminous elliptical galaxies and massive clusters of galaxies), the form of the mass profile has yet to be investigated systematically.

The central regions of massive, compact clusters at moderate redshifts (z ≲ 0.5) act as strong gravitational lenses forming multiple images of serendipitously placed back- ground galaxies (e.g., Smail et al. 1996). The properties of the images of these background galaxies (position, relative surface brightness, and parity) can be used to model the distribution of total mass accurately (both baryonic and nonbaryonic) within the cluster core (Kneib et al. 1996, hereafter K96; Smail et al. 1996; Natarajan et al. 1998). Such mass maps provide the most direct and detailed view of the distribution and morphology of dark matter in the centers of galaxy clusters. Strong gravitational lensing by rich clusters is therefore an ideal observational tool with which to test the halo properties predicted by cosmological models.

The first mass maps constructed from lensing observations were produced in the early and mid-1990s (Tyson, Wenk, & Valdes 1990; Mellier, Fort, & Kneib 1993; Fahlman et al. 1994; Kneib et al. 1994; Smail et al. 1995). A significant improvement arrived with the refurbishment of the Hubble Space Telescope (HST), which provided the resolution necessary to identify faint, lensed features in the crowded cores of rich clusters (e.g., K96), thereby allowing more detailed mass models to be constructed.
On small scales, unique constraints can be obtained from radial arcs (rare radially magnified images of background galaxies) that are found in the very centers of a few cluster lenses. Such features are very difficult to detect in ground-based observations, with only a single example known (MS 2137.3 − 23; Fort et al. 1992; Mellier et al. 1993). In contrast to this, HST has uncovered several radial arcs in previously well-studied cluster lenses (e.g., A370, Smail et al. 1996; AC 114, Natarajan et al. 1998) that enabled the first tests of the form of cluster mass profiles on scales of less than ~ 100 kpc (Williams, Navarro, & Bartelmann 1999).

Previous HST studies of rich clusters covered a heterogeneous mix of clusters, either selected because they were previously well studied (e.g., Smail et al. 1997) or because they were known to be strong lenses (e.g., K96; Smail et al. 1996). To study the form of the mass profile in rich clusters in an unbiased fashion, we need HST observations of an objectively selected cluster sample. Ideally, such a sample would be mass selected; however, in the absence of samples compiled from large-scale weak lensing surveys, X-ray–selected cluster samples (Gioia et al. 1990; Ebeling et al. 1998, 2000a; DeGrandi et al. 1999; Ebeling, Edge, & Henry 2000b) are best suited to selecting well-defined samples of massive clusters.

Following this premise, we are conducting a survey of 12 of the most X-ray luminous clusters ($L_X > 8 \times 10^{44}$ erg s$^{-1}$, 0.1–2.4 keV) in a narrow redshift slice at 0.17 $< z < 0.26$, with line-of-sight reddening of $E(B-V) \leq 0.1$ selected from the X-Ray Brightest Abell-type Cluster sample (XBACS; Ebeling et al. 1996). As XBACS is restricted to Abell clusters (Abell, Corwin, & Olowin 1989), it is X-ray flux limited and not strictly X-ray selected. However, a comparison with the X-ray–selected ROSAT Brightest Cluster Sample (BCS; Ebeling et al. 1998, 2000a) shows that 18 of the 19 BCS clusters that satisfy our selection criteria are either Abell or Zwicky clusters. Comparison of the $L_X$ distributions of our sample with the BCS clusters provides additional confirmation that our sample is indistinguishable from an X-ray–selected sample.

In this paper we describe HST observations of the core of one of the first clusters observed in our survey, A383 ($z = 0.188$), which reveal a multitude of strongly lensed features. In combination with color information obtained from ground-based imaging observations in three passbands, the lensed features are used to produce an accurate model of the mass distribution within the central 500 kpc of the cluster. We complement these results with an analysis of the X-ray properties of A383 using archival ROSAT HRI data. In § 2 we describe the observational data, their reduction, and analysis, followed in § 3 by a discussion of the interpretation of these data and the construction of the lens model of the cluster. Finally, in § 4 we summarize the main results of our analysis and present our conclusions. We adopt $H_0 = 50$ km s$^{-1}$ Mpc$^{-1}$ and $q_0 = 0.5$ throughout. At the cluster redshift 1$^\circ$ $\equiv 4.0$ kpc in this cosmology.

2. DATA REDUCTION AND ANALYSIS

2.1. HST Imaging

A383 was observed with the HST WFPC2 camera on 2000 January 25. Three exposures totaling 7.5 ks were taken through the F702W filter. Each exposure was shifted relative to the others by 10 WFC pixels (1″) providing a partial overlap of the chip fields. After pipeline processing, standard IRAF/STSDAS routines were employed to shift and combine the frames to remove both cosmic rays and hot pixels. Corrections for undersampling of the point-spread function (PSF) and geometric distortion of the optics were made using the DITHER package within IRAF (Fruchter & Hook 1997). The final frame (Fig. 1) has a pixel scale of 0′′.05, an effective resolution of 0′′.15, and a 1σ detection limit within the seeing disk of $R_{702} \approx 31$.

To produce a catalog of faint arclets from our data, we first analyzed the HST frame using the SExtractor package (Bertin & Arnouts 1996). All objects with isophotal areas in excess of 30 pixels (0.074 arcsec$^2$) at the $R_{702} = 24.5$ mag arcsec$^{-2}$ isophote (3 σ pixel$^{-1}$) were selected. A steep rollover in the observed differential number counts arising from incompleteness occurs at $R_{702} \sim 25.5$. We estimate the completeness to be ~ 80% (approximately 5 σ) at $R_{702} \sim 25.5$, which we adopt as our magnitude limit, giving a total of 457 sources within a 4.9 arcmin$^2$ area (excluding the PC chip). A total of 17 of these sources are classified as starlike on the basis of their profile shapes and are excluded from our analysis.

The final HST frame (Fig. 1) reveals many previously unknown strongly lensed features, including a giant arc and two radial arcs, making A383 a striking new addition to the catalog of cluster lenses at intermediate redshifts.

2.2. Ground-based Imaging

With the aim of extending our lensing mass map to the turnaround radius of the cluster, we have used the 3.6 m Canada-France-Hawaii Telescope (CFHT) with the CFH12K camera to obtain panoramic images of A383 on the nights of 1999 November 14–16. Total exposure times of 7.2, 6.0, and 3.6 ks, accumulated at six to 10 dither positions, were acquired in the $B$, $R$, and $I$ bands, respectively. Data reduction was performed within IRAF using the MSCRED package including standard bias subtraction and flat-fielding using twilight flats. The dithered exposures were aligned with the Digital Sky Survey frame of the same field to an rms accuracy of 0′′.15. More information on the reduction and analysis of these observations will be presented in a forthcoming paper (O. Czoske et al. 2001, in preparation). Here we use the central regions of the $B$- and $I$-band frames to provide photometry of the lensed features in the cluster core (see Table 1). These two frames have seeing of 0′′.88 and 0′′.71 FWHM, respectively.

In addition to the CFH12K imaging, we have obtained $K$-band images of the core of A383 with the UFTI imager on the 3.8 m United Kingdom Infrared Telescope (UKIRT), Mauna Kea, on 1999 October 14. The final frame was accumulated in 27 dithered subexposures of 90 s duration each to give a total on-source integration time of 2.4 ks, all in photometric conditions. Employing standard procedures, these frames were reduced, combined, and calibrated using observations of UKIRT faint standards bracketing the science exposures. The final frame has seeing of 0′′.42 FWHM with 0′′.09 pixel$^{-1}$ sampling and an effective 5 σ depth of $K = 20.3$.

2.3. Arc Photometry

Arc photometry (Table 1) was performed on the HST frame and aligned, seeing-matched $BR_{702}IK$ frames. We first created a mask frame containing apertures corresponding to each observed arc in the HST frame. We then rebinned the HST mask to the CFH12k pixel scale (0′′.2)
and convolved it with the worst seeing of the ground-based imaging to produce a mask for use with the seeing-matched $BR_{702}IK$ frames. We also checked the seeing-matched frames to confirm that the arc morphology did not vary significantly between passbands. As some of the lensed features are close to bright galaxies, we carefully excluded from the mask apertures any elements of the arcs that are not well resolved against the background of a neighboring cluster elliptical.

The mask frames were then applied to the science frames, and the sky background was estimated by median smoothing over the absent arcs. The sky frames were then subtracted from the science frames and the mask frames applied to the sky-subtracted frames to obtain a set of frames containing solely flux from the arcs. $BR_{702}IK$ photometry was then performed on these frames (Table 1).

Uncertainties in the photometry were estimated by varying the smoothing length used to estimate the sky backgrounds.

2.4. Spectroscopy

On 2000 January 26 we observed the cD galaxy in A383 with the Wide Field Grism Spectrograph on the University of Hawaii 2.2 m telescope. The low-dispersion spectrum obtained in a 1.8 ks exposure in extremely poor seeing (2\'7) shows the full range of emission lines typically found in cD galaxies in cooling flow clusters (e.g., Crawford et al. 1999) and places the cD at a heliocentric redshift of $z = 0.1880 \pm 0.0012$. We also detect a dust lane across the center of the cD galaxy in our $HST$ imaging.

On 2000 January 29 we obtained 28 additional spectra with the LRIS spectrograph (Oke et al. 1995) on the Keck II 10 m telescope in MOS mode, with a total exposure time of
3.6 ks in average seeing of 0\'0.9. Use of the 300/5000 grating centered at 7500 Å provided wide spectral coverage (5000–10,000 Å) at a spectral resolution of 2.55 Å pixel\(^{-1}\). Redshifts were measured independently by three members of our team (O. C., H. E., and J. P. K.) and also using the RVSAO cross-correlation package under IRAF to estimate the errors accurately. Successive 3 σ clipping around the peak of the radial velocity distribution yields a redshift of \(z = 0.1880 \pm 0.0002\) for A383 and a velocity dispersion of \(\sigma = 1150 \pm 120\) km s\(^{-1}\) from 18 galaxy redshifts. Ten other galaxies were found to be background, including B19 at \(z = 0.656\), which lies close to the cluster core (see Fig. 1).

We also obtained a spectrum of the lensed feature B0a, which we show in Figure 2. We identify the strong emission line at 7493 Å as [O\(\text{II}\)] \(\lambda\)3727, which places the galaxy at a redshift of \(z = 1.0103 \pm 0.0001\). This interpretation is confirmed by the identification of Fe \(\Pi\) \(\lambda\)22600 and Mg \(\Pi\) \(\lambda\)2800 absorption features. The properties of this galaxy are discussed further in §3.

2.5. ROSAT/HRI Observation

A383 was observed with the ROSAT HRI in 1995 February for a total integration time of 27.4 ks (ROR 800890). An adaptively smoothed map of the observed X-ray emission is shown in Figure 3. We used a modified version of Steve Snowden’s CAST HRI software to correct for exposure time variations across the field of view and subtract a particle background component.

From the fully processed ROSAT HRI image the total background-corrected HRI count rate from A383 is measured to be \(0.128 \pm 0.005\) counts s\(^{-1}\) within 1.5 Mpc (6.2) of the cluster center, using the mean diffuse background at \(r > 2\) Mpc (82). Assuming a standard plasma emission spectrum, a Galactic hydrogen column density of \(4.1 \times 10^{20}\) cm\(^{-2}\) for this sight line (Dickey & Lockman 1990), a metallicity of 0.3, and an ambient X-ray temperature of \(\sim 7.1\) keV (estimated from the cooling flow–corrected cluster \(L_{X}\)-\(kT\) relation of Allen & Fabian 1998), we derive a total unabsorbed cluster flux of \((6.55 \pm 0.23) \times 10^{-12}\) ergs cm\(^{-2}\) s\(^{-1}\) (0.1–2.4 keV). The corresponding X-ray luminosity is \((9.8 \pm 0.3) \times 10^{44}\) ergs s\(^{-1}\) (0.1–2.4 keV), in agreement with the XBACS value of \((8.0 \pm 2.4) \times 10^{44}\) ergs s\(^{-1}\) in the same energy band (Ebeling et al. 1996).

3. Modeling and Results

In this section we describe the gravitational lens modeling of A383, beginning with a summary of the modeling method. We then discuss the interpretation of the lensed features in this cluster and describe our lens model. The form of the mass profile in the very center of the cluster is then analyzed and compared to theoretical expectations from high-resolution N-body simulations. Finally, we discuss the X-ray properties of A383 and compare the mass distribution determined from the lens model with estimates based on the ROSAT data.

3.1. Lens Modeling Method

We summarize below our lens modeling method. This
FIG. 2.—Spectrum of arc B0a in A383 taken with the LRIS spectrograph on the Keck II 10 m telescope. The arc exhibits a blue continuum, and we identify the strong emission line as [O II] λ3727 and confirm this with several UV absorption features (marked) to give a redshift of \( z = 1.0103 \pm 0.0001 \). The upper spectrum is smoothed to the nominal resolution of the spectrograph and offset vertically for clarity. The shaded regions show areas of the spectrum strongly affected by night-sky lines.

method was described in detail by K96 and references therein.

We use information about observed multiply imaged arcs (position, ellipticity, orientation, redshift) and the mean orientation of singly imaged arclets to constrain an analytical representation of the total projected cluster mass. This analytical representation is based on components associated with likely concentrations of mass (i.e., massive cluster ellipticals). Each component is described by a minimal set of parameters: position, ellipticity, orientation, core radius \( r_{\text{core}} \), cutoff radius \( r_{\text{cut}} \), and central velocity dispersion \( \sigma_0 \). The analytical expression used to describe each component is a smoothly truncated pseudisothermal elliptical mass distribution (K96; Kassiola & Kovner 1993).

The center, ellipticity, and orientation of each mass component are matched to the observed light distribution of the related cluster elliptical. The dynamical parameters \( (r_{\text{core}}, r_{\text{cut}}, \sigma_0) \) of the larger mass components (i.e., a cluster-scale mass and selected bright cluster ellipticals) are kept as free parameters. In order to minimize the number of model parameters, the dynamical parameters of the remaining mass components are scaled with the luminosity of their associated galaxy following K96 and Brainerd, Blandford, & Smail (1996).

Construction of a lens model is an iterative process, as alternative interpretations of the arcs and model parameters are explored. A \( \chi^2 \) estimator quantifies how well each lens model fits the observational data and is defined as the quadratic sum of the differences between the source positions for each set of multiple images (K96; Golse, Kneib, & Soucail...
3.2. Multiply Imaged Features

This section presents the multiple-image assignments used to constrain our lens model. These assignments are based on spectroscopic, morphological, and photometric analysis together with interim lens modeling results.

As a result of the superb resolution of our HST imaging, sufficient detail is resolved in the lensed images of background galaxies to identify five multiple-image systems (B0, B1, B2, B3, and B4) with which to constrain the lens model. Further identification of multiple images is primarily hampered by the faintness of three more candidate systems (B5, B9, and B10). Light from neighboring cluster ellipticals also reduces the amount of detail resolved in some of the multiple images, most notably the radial arcs. In such cases only resolved morphological features (e.g., the break between the two radial arcs as shown in Fig. 5) are used to constrain the model.

The lensed features described in this section are identified in Figure 1, and the multiple images are further illustrated below in Figures 4–6. The photometric and spectroscopic properties of the arcs are summarized in Table 1.

We adopt the notation that, for example, B0 is the background galaxy that gives rise to the multiple images B0a and B0b and similarly B1 denotes the galaxy in the source plane that gives rise to images B1a, B1b, B1c, and B1d in the image plane. We also denote arc substructure by extension of the numeric element of the arc label; for example, B2.1a, B2.1b, B2.1c, B2.1d, and B2.1e are five images of one morphological feature of the background galaxy B2 (Fig. 6 and § 3.2.2).

3.2.1. The Giant and Radial Arcs

We interpret the giant and radial arcs in A383 as the lensed images of three background galaxies, B0, B1, and B4, at $z = 1.01$ (§ 2.3), $z \sim 1.1$, and $z \sim 1.2$, respectively. The images associated with each of these background galaxies are labeled B0a/b, B1a/b/c/d, and B4a/b/c, respectively, in Figures 1, 4, and 5. This interpretation is based on the following evidence:

1. B0a has a spectroscopic redshift of $z = 1.01$ (§ 3.2).
2. The dip in the light profile of the giant arc between B1a and B1b and the symmetry of this image pair suggests that this is a pair of merging images straddling the $z \sim 1$ critical line as it traces a path away from the cluster center toward cluster elliptical 23.
3. The similarity of the optical and optical–infrared colors of B1a, B1b, and B1c (Table 1) and their positions relative to the $z \sim 1$ critical line implies that B1c is a counterimage of B1a/b.
4. B1c is $\sim 0.2$ farther away from the center of the cluster than B0a, suggesting that B1 is at a slightly higher redshift than B0.
5. The radially amplified image (Fig. 5) consists of two segments offset from each other by $\sim 1''$ in the tangential direction. This implies that the radial image consists of two radial arcs, the background galaxy relating to the outer arc lying at a higher redshift than that relating to the inner arc.
6. The tangential offset between B1c and B0a supports the above interpretation of the radial arcs and identifies the inner and outer radial arcs as probable counterimages of B0a and B1a/b/c, respectively.
7. When constrained by B0 and B1, the lens model predicts that the $z \sim 1.2$ critical line bisects the image pair B4a/b and that B4c is the counterimage of this pair. This is supported by the photometry presented in Table 1.

We also estimate the unlensed R-band magnitudes of B0, B1, and B4 to be $M_V \sim -19.3$, $M_V \sim -18.3$, and $M_V \sim -18.5$, respectively (Table 1). Along with its blue optical–infrared color, this suggests that B0 is a low-luminosity star-forming galaxy. The redder colors of B1 and B4 suggest that these galaxies are undergoing lower rates of star formation than B0.

3.2.2. Perturbations by Galaxy Halos

The lensing effect of neighboring cluster galaxy halos on the B2/B3 system (Figs. 1 and 6) demonstrates how galaxy-scale masses measurably perturb the cluster potential. We interpret this complex group of blue arcs as being due to two background galaxies at a redshift of $z \sim 3$. This inter-
interpretation is based on the difference between the $R_{702} - I$ colors of B2c and B3a (Table 1) and the prediction of the lens model that the $z \sim 3$ tangential critical curve lies outside of cluster ellipticals 46 and 23, bisecting each of the image pairs B2a/b, B2d/e, and B3b/c (Fig. 1).

This lens model also predicts the following counterimages of the morphological features of the B2/B3 system (Fig. 6):

1. Six counterimages of B2.1c coincident with B2.1a/b/d/e/f and the center of cluster elliptical 23.
2. Two counterimages each of B2.2c and B2.3c, one each coincident with B2.2e and B2.3e, respectively, and the other one each under the halo of elliptical 23 to the left of B2.1d.
3. Two counterimages of B3a coincident with B3b and B3c.
4. B17 is singly imaged, as it lies outside the $z \sim 3$ caustic.

The predictive power of this interim lens model is clear; however, we restrict the multiple images used in subsequent iterations of the lens model to morphological details that are clearly detected against the halos of neighboring cluster ellipticals (§3.2 and 3.4). For example, B2.1f is not used to constrain subsequent lens models.

Finally, we estimate that in the source plane, B2 and B3 have $M_V \sim -22.0$ and $M_V \sim -22.4$, respectively, both also exhibiting the blue colors typical of star-forming galaxies (Table 1).

3.2.3. Faint Multiple-Image Candidates

B5.—B5 (Fig. 1) is a very faint arc lying in the saddle region between the central galaxy and cluster elliptical 99. We interpret this arc as an image of a background galaxy that is magnified by this saddle and therefore constrain the redshift of the galaxy to be $z \gtrsim 2.4$.

B9 and B10.—This is a pair of extremely faint arcs (Fig. 1) detected only because of the superb resolution and low sky background of the HST observations. Both arcs appear to comprise three images resulting from the magnifying effect of the saddle potential between the cluster center and cluster elliptical 260. We estimate that they lie at a redshift of $z \gtrsim 3$.

3.3. Arclets

We also detect numerous singly imaged arclets in the field of A383 (Fig. 1 and Table 1) and have obtained upper limits on the redshifts of several of them on the basis of being singly imaged.

B16.—This is a complex and unusual arc, the precise nature of which is uncertain. One possibility is that B16 is part of a multiple-image system containing B6; however, photometric analysis (Table 1) does not support this hypothesis. More complete color information will improve our ability to comment on this arc. If B16 is a singly imaged source, it lies at a redshift of $z \lesssim 1.0$.

B6.—We obtain a redshift limit of $z \lesssim 0.9$ for this arclet; however, its blue ($B - R$) and ($R - I$) colors (Table 1) are consistent with it being a star-forming galaxy at $z \sim 1.5 - 2.0$. The latter interpretation supports the possibility that B6 and B16 contain multiply imaged features of a single background galaxy. As noted above, improved photometry of B16 will help to resolve this uncertainty.

B7.—B7 lies at a redshift of $z \lesssim 1.3$, which, on the basis of its ($B - R$) color (Table 1), is consistent with B7 being a moderately star-forming galaxy.

B8.—This arclet has a redshift limit of $z \lesssim 2.0$, while its colors are broadly consistent with this being a star-forming galaxy at $z \sim 1.0 - 1.5$.

B15.—B15 is barely detected above the sky background in the HST frame; however, we detect it at $K = 19.70 \pm 0.05$ in the UKIRT frame, giving $(R_{702} - K) = 5.8 \pm 0.1$. As B15 is singly imaged, we constrain its redshift to be $z \lesssim 3.9$. A full analysis of extreme color objects lying behind our cluster sample is presented in Smith et al. (2001).

3.4. The Lens Model

In this section we present details of our best lens model and the family of models for which $\chi^2 \lessgtr 1$.

Our model of A383 consists of a single lens plane at $z = 0.188$, containing 30 mass components representing the cluster, the cD galaxy, and 28 further individual cluster galaxies. The dynamical parameters ($r_{core}, r_{cut}$ and $\sigma_0$) of four of these masses were optimized in the $\chi^2$ minimization process: the cluster, the cD galaxy (93), and cluster ellipticals 46 and 23. The dynamical parameters of the other 25 cluster ellipticals were scaled with their luminosity.

The model parameters were constrained using both multiple images and the weak shear field estimated from the shapes of the faint galaxies across the whole frame. The multiple images used to constrain the model were B0 (two images), B1 (four images), B2.1 (five images), B2.2 (two images), B2.3 (two images), B3 (three images), and B4 (three images). We computed the best lens model by finding the combination of model parameters that produced the lowest value of $\chi^2$. The fiducial parameters of this model ($\chi^2 = 0.8$)
are presented in Table 2. We also computed the region of parameter space for which \( \chi^2 \leq 1 \) (Table 3) by varying each dynamical parameter of the cluster halo and cD galaxy in turn while allowing the other parameters to find their optimum values. This region of parameter space equates to an uncertainty in image positions of \( \lesssim 0.1' \).

We use the best lens model and the family of \( \chi^2 \leq 1 \) models to calculate the total projected mass within the radius of the giant arc (65 kpc) to be \( (3.5 \pm 0.1) \times 10^{13} M_\odot \). Using the weak shear measurements, we can extend this to larger scales and constrain the projected mass within a 250 kpc radius of the cluster center to be \( (1.8 \pm 0.2) \times 10^{14} M_\odot \).

### 3.5. The Density Profile

The projected surface mass density of the best lens model is plotted as a function of projected distance from the center of the cluster in Figure 7. On scales \( r \gtrsim 10 \) kpc, the density profile is dominated by the cluster-scale mass component, the core radius of which (\( \sim 50 \) kpc) is consistent with previous estimates of core radii from lensing studies (Mellier et al. 1993; Small et al. 1996; Natarajan et al. 1998). The central galaxy mass component causes the density profile to steepen on scales of \( r \lesssim 10 \) kpc, and further substructure is apparent at \( r \sim 90 \) kpc, coincident with the mass components associated with cluster ellipticals 99, 46, and 23. The shape of A383’s profile is, however, only constrained out to \( r \sim 400 \) kpc, this being the extent of the WFPC2 field of view. The mass profile is most accurately measured within \( r \sim 100 \) kpc where information from the multiple images is available.

The slope of A383’s density profile is constrained by the radial arcs, as their radial positions depend on the local gradient of the projected mass. We estimate the slope of the projected density profile (\( \Sigma \propto r^\beta \)) in the region \( r = 10-30 \) kpc to be \( \beta = -0.3 \pm 0.04 \). Deprojecting this result, we calculate the slope of the three-dimensional density profile (\( \rho \propto r^\alpha \)) to be \( \alpha = -1.3 \pm 0.04 \).

Ghigna et al. (2000) have performed the highest resolution numerical simulations of galaxy cluster dark matter halos to date, resolving structure down to \( r \sim 5 \) kpc. They find a deprojected slope of \( \alpha = -1.6 \pm 0.1 \) on scales of \( r = 5-100 \) kpc in a \( \sigma \sim 800 \) km s\(^{-1} \) cluster halo. Our estimate of \( \alpha \sim -1.3 \) for A383 is shallower than the Ghigna et al. (2000) simulations and steeper than a universal NFW profile (\( \alpha = -1 \)).

Recent progress has also been made on the inclusion of gas in numerical simulations (e.g., Pearce et al. 1999). However, the resolution of these simulations precludes analysis of the form of the mass profile on the scales probed by the radial arcs in A383. Higher resolution simulations including gas cooling have been performed by Lewis et al. (2000). However, the mass of the central galaxies in these simulations is unrealistically high, hampering a reliable comparison with our observational results.

Detailed comparison of our lens model with numerical simulations is also limited by the fact that the current lens model does not discriminate between different forms and physical states of matter; it simply uses a collection of mass...
components to describe the distribution of total matter (both baryonic and nonbaryonic). However, we can use the light profile of the cD galaxy (Fig. 7) to infer whether the slope of the density profile at $r = 10–30$ kpc is due solely to the cD galaxy or whether the dark matter halo also plays a role on these scales. Figure 7 shows that the light profile falls off more steeply than the total projected mass density, implying that the steepness of the density profile in this region cannot be caused solely by the cD galaxy. This suggests that the dark matter halo of A383 may indeed be steeper than an NFW97 profile.

We also compare the slope of the three-dimensional density profile at the positions of the two radial arcs. From the lens model we estimate $\alpha = -1.5 \pm 0.04$ and $-1.3 \pm 0.04$ at $r \sim 6.0$ kpc (B0b) and $r \sim 20$ kpc (B1d), respectively. Independent slope estimates are obtained from analytical consideration of the positions of the radial and tangential images of B0 and B1 using $\log (x_\beta/x_\alpha) \sim -1/(\beta - 1) \log (1 + \beta)$, where $x_\alpha$ and $x_\beta$ are the angular positions of the radial and tangential arcs, respectively, and $-1 < \beta < 0$. We calculate $\log (x_\beta/x_\alpha)$ for B0 and B1 to be $-1.04 \pm 0.07$ and $-0.51 \pm 0.03$, respectively, from which we estimate the deprojected density profile slopes to be $\alpha \sim -1.9$ and $\alpha \sim -1.3$ for the inner and outer radial arcs, respectively. The former value is steeper than our lens model as a result of the nonsingular mass profile adopted in the model (§ 3.1). It is, however, consistent with an isothermal peak in the center of the cluster (i.e., on scales of $r \lesssim 10$ kpc) where physical processes are expected to be dominated by the baryonic content of the cD galaxy. The latter value is consistent with our lens model. The upturn in A383’s density profile (Fig. 7) on scales $r \lesssim 10$ kpc implies that the difference between these slopes, specifically the slope at $r \sim 6$ kpc, is due to the mass of the cD galaxy.

Williams et al. (1999) have also used radial arcs to investigate the lensing role of central galaxy halos. Based on numerical simulations of clusters including an $\sim 10^{12} M_\odot$ central galaxy halo, they predict that $\log (x_\beta/x_\alpha)$ should lie in the range $-0.35$ to $-0.65$, for a cluster with the velocity dispersion of A383. The outer radial arc in A383 appears to be consistent with this prediction; however, the inner radial arc falls well outside the predicted range. This discrepancy may be due to simplifying assumptions made by Williams et al. (1999) regarding the nature and complexity of cluster substructure. We also note that, as a result of the (almost) circular symmetry of A383, the radial arcs are not forced to lie at the radial critical line in the image plane, as assumed by these authors. This is another potential source of discrepancy between observations and theoretical predictions.

3.6 X-Ray Properties of A383

The radial X-ray surface brightness profile around the cluster X-ray centroid is shown in Figure 8. We attempt to describe the X-ray emission profile by fitting a standard beta model (Cavaliere & Fusco-Femiano 1978):

$$I(r) = I_0 \left[ 1 + \left( \frac{r}{r_c^{3D}} \right)^{-3 \beta + 0.5} \right]^{-3},$$

convolved with the HRI PSF, to the observed X-ray surface brightness distribution. The free fit parameters are the peak surface brightness ($I_0$), the three-dimensional core radius ($r_c^{3D}$), and the slope parameter $(\beta)$. We note that the use of the beta model implies that the gas is isothermal and in hydrostatic equilibrium. While these assumptions are likely to be violated in most clusters, numerical simulations show that adoption of a beta model introduces, on average, no bias and only a moderate scatter of typically 20% in the cluster mass estimates (Evrard, Metzler, & Navarro 1996).

3.6.1 Mass Deposition Rate

We first describe the non–cooling flow component of the X-ray emission (Fig. 8) with a beta model fitted to the outer regions ($12 \leq r \leq 850$ kpc) of the profile (model A). For this model we find $r_c^{3D} = 23'' \pm 3'$, corresponding to $93 \pm 12$ kpc, and $\beta = 0.65 \pm 0.03$, consistent with the canonical value of $\frac{3}{2}$. The quoted errors include systematic uncertainties that we explored by varying the radial range used for the fit.

Subtracting model A from the observed profile, we find the cooling flow to contribute 13% of the total cluster flux within a radius of 500 kpc, corresponding to a luminosity of $1 \times 10^{44}$ ergs s$^{-1}$ (0.1–2.4 keV). A rough (usually low) estimate of the mass deposition rate ($M$) can be obtained by converting this excess luminosity to the bolometric band (by multiplying by a factor of 3.03 appropriate for the assumed cluster gas temperature of 7.1 keV) and equating it to the luminosity of the cooling flow:

$$L_{\text{cool}} = \frac{5}{2} \frac{M}{\mu m_p} kT$$

(Fabian 1994). We thus derive a lower limit to the mass deposition rate of $M \gtrsim 200 M_\odot$ yr$^{-1}$, a value typical of moderate cooling flow clusters (e.g., Peres et al. 1998).

3.6.2 X-Ray Mass Estimates

We also fit a beta model to the full radial range of the data including the likely cooling flow region (model B). While this model is a poor description of the X-ray emission at large radii (Fig. 8), it provides an acceptable fit to, and an analytic description of, the emission profile at $r \lesssim 100$ kpc. We can therefore use this analytic description to derive the gas density and total binding mass within the core region.

Under the assumption of hydrostatic equilibrium, and using a beta model to describe the radial gas density profile,
the total gravitational model mass within a projected radius $r$ can be obtained from

$$M(< r) = \frac{3\pi \rho c^3}{2G} \left( \frac{r}{c} \right)^3 \left(1 + \frac{r}{r_c} \right)^2$$

(e.g., Soucail et al. 2000).

Using the parameters of model B, we estimate the projected mass within a radius of 65 kpc to be $4.0 \pm 1.3 \times 10^{13} M_\odot$, in good agreement with our lensing mass measurement of $(3.5 \pm 0.1) \times 10^{13} M_\odot$ within the same projected radius (§ 3.2). The equivalent mass estimate within a radius of 250 kpc is more uncertain but is approximately $(1.2 \pm 0.5) \times 10^{14} M_\odot$, again in reasonable agreement with the lensing measurement. We note that the bulk of the uncertainty in the X-ray mass estimates is caused by the adopted error of $\pm 2$ keV in the global gas temperature, $kT$. Forthcoming observations of our full cluster sample with XMM-Newton will allow us to obtain much more accurate X-ray mass measurements on scales of $\sim 10$–1000 kpc.

4. DISCUSSION AND CONCLUSIONS

We have discovered numerous new gravitationally lensed features, including a giant arc and two radial arcs in A383, a massive, X-ray luminous cluster of galaxies at a redshift of $z = 0.188$. This is the first cluster in which two radial arcs have been identified, and these provide a detailed view of the cluster mass distribution on scales of $r \lesssim 50$ kpc.

The morphologies and positions of the arcs have been used, in conjunction with ground-based multicolor photometry, to constrain the mass distribution and compute a precise mass density profile of this cluster within a radius of $\sim 250$ kpc.

Within the core radius ($r \sim 50$ kpc) derived from the lensing analysis, the density profile exhibits a shallower slope ($\alpha \sim -1.3$) than a Moore profile ($\alpha = -1.6$; Moore et al. 1998; Ghigna et al. 2000) and a steeper slope than a single NFW97 profile ($\alpha = -1$). Decisive comparison of our lensing analysis with these theoretical predictions is currently hampered by the fact that our lens model contains the total mass of the cluster (both baryonic and nonbaryonic) whereas the simulations only contain nonbaryonic dark matter. Progress will come with the inclusion of baryons in the highest resolution numerical simulations and separate accounting for baryonic and nonbaryonic mass profiles in lens models.

We have also analyzed the properties of the two radial arcs, interpreting the difference in angular position of these arcs as a signature of the lensing role of the central galaxy. This appears to support the proposal by Williams et al. (1999) that massive central galaxy halos are required to explain the lensing properties of the cores of massive clusters ($\sigma \sim 1000 \text{ km s}^{-1}$). However, only the outer radial arc of A383 falls within the range predicted by Williams et al. (1999) for the angular position ratio of radial and tangential arcs. The inner radial arc lies well outside of their predicted range. This discrepancy is probably caused by simplifying assumptions in the Williams et al. (1999) theoretical models.

The lensing analysis is complemented by an analysis of the cluster’s X-ray properties as obtained from archival ROSAT HRI data. We find strong evidence for a cooling flow in agreement with the optical properties of the cluster and derive a lower limit on the mass deposition rate of 200 $M_\odot \text{ yr}^{-1}$, typical of moderate cooling flow clusters. The X-ray estimates for the total mass within the projected radius of the giant arc are in good agreement with the lensing measurements and are consistent with earlier claims (e.g., Allen 1998) that significant discrepancies between lensing and X-ray mass estimates are caused by substructure in unrelaxed, non–cooling flow systems.

We note that the cluster sample used in our survey is effectively X-ray selected, thus allowing us, for the first time, to measure in detail the mass distribution in massive clusters of galaxies unaffected by optical and projected mass selection biases. The theme of our future program will be to analyze the lensing signal, X-ray emission (as observed with XMM-Newton), and extreme color background galaxies of all 12 clusters in our sample and to trace the form of the mass profile from 50 kpc to 5 Mpc. We will investigate the dispersion in the profiles and the core properties of the clusters and determine how these correlate with the cluster’s dynamical state and the presence of a cooling flow. We shall also attempt to constrain the high end of the cluster mass function and calibrate directly the cluster mass-temperature and mass-luminosity relations at $z \sim 0.2$.

We thank the anonymous referee for constructive criticism that improved the clarity of this paper. We also thank John Blakeslee, Alastair Edge, Geraint Lewis, Ben Moore, Frazer Pearce, and Liluya Williams for stimulating discussions and helpful assistance during the course of writing this paper. Thanks also go to Laurence Jones for helping with the Keck/MOS observations. G. P. S. acknowledges a postgraduate studentship from PPARC. J. P. K. acknowledges support from CNRS. H. E. gratefully acknowledges financial support by NASA grants NAG 5-6336 and NAG 5-8253. O. C. acknowledges support from the European Commission under contract ER-BFM-BI-CT97-2471. I. R. S. acknowledges support from a Royal Society University Research Fellowship. We also acknowledge financial support from the UK-French ALLIANCE collaboration programme 00161XM. UKIRT is operated by the Joint Astronomy Centre on behalf of the Particle Physics and Astronomy Research Council of the United Kingdom. The W. M. Keck Observatory is operated as a scientific partnership among the California Institute of Technology, the University of California, and NASA.

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