Chandra observations of RXJ1347.5-1145: the distribution of mass in the most X-ray luminous galaxy cluster known

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ABSTRACT
We present Chandra observations of RXJ1347.5-1145, the most X-ray luminous cluster of galaxies known. We report the discovery of a region of relatively hot, bright X-ray emission, located approximately 20 arcsec to the southeast of the main X-ray peak, at a position consistent with the region of enhanced Sunyaev-Zeldovich effect reported by Komatsu et al. (2001). We suggest that this region contains shocked gas resulting from a recent subcluster merger event. Excluding the data for the southeast quadrant, the cluster appears relatively relaxed. The X-ray gas temperature rises from \( kT \sim 6 \) keV within the central 25\( h^{-1} \) kpc radius to a mean value of \( \sim 16 \) keV between 0.1 – 0.5\( h^{-1} \) Mpc. The mass profile for the relaxed regions of the cluster, determined under the assumption of hydrostatic equilibrium, can be parameterized by a Navarro, Frenk & White (1997) model with a scale radius \( r_s \sim 0.4\ h^{-1} \) Mpc and a concentration parameter \( c \sim 6 \). The best-fit Chandra mass model is in good agreement with independent measurements from weak gravitational lensing studies. Strong lensing data for the central regions of the cluster can also be explained by the introduction of an additional mass clump centred on the second brightest galaxy. We argue that this galaxy is likely to have been the dominant galaxy of the recently merged subcluster.

Key words: galaxies: clusters: individual: RXJ1347.5-1145 – gravitational lensing – X-rays: galaxies – cooling flows – intergalactic medium

1 INTRODUCTION
The launch of the Chandra Observatory (Weisskopf et al. 2000) in 1999 July has provided the first opportunity for detailed, spatially-resolved X-ray spectroscopy of clusters of galaxies at moderate to high redshifts. The Advanced CCD Imaging Spectrometer (ACIS) on Chandra permits direct, simultaneous measurements of the X-ray gas temperature and density profiles in clusters and, via the hydrostatic assumption, the mass distributions, spanning scales from \( r \sim 10 \) kpc in cluster cores out to \( r \sim 1 \) Mpc at the detection limits.

In this paper, we present the first results from Chandra observations of RXJ1347.5-1145, the most X-ray luminous galaxy cluster known (Schindler et al. 1995). This cluster has been the subject of several previous X-ray, optical and Sunyaev-Zeldovich (SZ) effect studies (e.g. Schindler et al. 1995, 1997; Fischer & Tyson 1997, Allen 1998; Komatsu et al. 1999, 2001; Pointecouteau et al. 1999, 2001). Here, we present the first measurements of the X-ray temperature structure within the cluster and place tight constraints on the total mass distribution. We compare our results with those from strong and weak lensing analyses. A comparison of the Chandra and SZ results, and a determination of the Hubble Constant from the combined data sets, is presented elsewhere (Schmidt & Allen 2002, in preparation).

Except where stated otherwise, the cosmological parameters \( H_0=50 \) km s\(^{-1}\) Mpc\(^{-1}\), \( \Omega = 1 \) and \( \Lambda = 0 \) are assumed. At the redshift of RXJ1347.5-1145 (\( z = 0.451 \)), an angular scale of 1 arcsec corresponds to physical size of 6.81 kpc in this cosmology.

2 OBSERVATIONS
The Chandra observations of RXJ1347.5-1145 were carried out using the ACIS on 2000 March 05 and 2000 April 29. The target was observed in the back-illuminated S3 detector and positioned near the centre of node-1 on CCD 7. The light curves for both observations were of high quality with no strong background flares. The net good exposure times were 8.9 and 10.0 ks, respectively, giving a total good exposure time of 18.9 ks. The focal plane temperature at the time of both observations was 120C.

We have used the CIAO software and the level-2 events files provided by the standard Chandra pipeline processing for our analysis. Only those X-ray events with grade classi-
The raw 0.3 – 7.0 keV Chandra image of RXJ1347.5-1145. The pixel size is 4 detector pixels (1.97 arcsec). (b) Contour plot of the same region, adaptively smoothed using the code of Ebeling et al. (2002) with a threshold value of 3σ. The contours have equal logarithmic spacing.

Komatsu et al. (2001) report the detection of a region of enhanced SZ effect at a position coincident with the X-ray subclump. The enhanced SZ effect is consistent with the higher temperature and density for this region measured from the Chandra data.

No strong X-ray point sources are detected in the Chandra S3 field. (The brightest point source has a flux of $3.1 \times 10^{-14}$ erg cm$^{-2}$ s$^{-1}$ in the 0.5 – 7.0 keV band; Gandhi et al., in preparation.)

3 X-RAY IMAGING

3.1 X-ray morphology

The raw 0.3 – 7.0 keV image of the central 6 × 6 arcmin$^2$ region of the cluster, from the combined 18.9 ks data set, is shown in Fig. 1(a). The pixel size is 1.97 × 1.97 arcsec$^2$, corresponding to 4 × 4 raw detector pixels. Fig. 1(b) shows an adaptively smoothed contour plot of the same data, using the smoothing algorithm of Ebeling, White & Rangarajan (2002). The images reveal a number of notable features. Firstly, we see a sharp central surface brightness peak at a position 13h47m30.63 -11d45m09.3s (J2000.), in good agreement with the optical centroid for the dominant cluster galaxy, 13h47m30.5 -11d45m09s (J2000.; Schindler et al. 2002). The images reveal a number of notable features. Firstly, we see a sharp central surface brightness peak at a position 13h47m30.63 -11d45m09.3s (J2000.), in good agreement with the optical centroid for the dominant cluster galaxy, 13h47m30.5 -11d45m09s (J2000.; Schindler et al. 1995). Secondly, we identify a region of enhanced emission ~ 20 arcsec to the southeast of the X-ray peak (see below). Thirdly, on large scales ($r \sim 80$ arcsec) we detect an extension of the X-ray isophotes to the south.

Fig. 1 shows the data for the central regions of the cluster on a linear 0.492 × 0.492 arcsec$^2$ scale (corresponding to 1 × 1 raw detector pixels). From this figure it appears that the region of enhanced emission to the southeast of the X-ray peak has a roughly circular morphology with a flattened northwest edge. Beyond this edge, at a radius $r \sim 10$ arcsec, the X-ray subclump appears to be separated from the main cluster core by a valley of reduced emission. The spectral analysis in Section 4.2 shows that the X-ray subclump has a hotter temperature than the gas at the same radius in other directions from the X-ray peak and probably contains shocked gas resulting from a recent subcluster merger event.

3.2 Surface brightness profiles

The azimuthally-averaged, 0.3 – 7.0 keV X-ray surface brightness profile for RXJ1347.5-1145 for position angles of 180 – 90 degrees (i.e. excluding the southeast quadrant) and for the disturbed, southeast quadrant are shown in Figs. 3(a,b), respectively. The profiles have been flat-fielded and background subtracted using an on-chip region free from cluster emission. The bin-size is 2 detector pixels (0.984 arcsec).

We see that the data for position angles of 180 – 90 degrees appear regular and, for $r < 500$ kpc, can be approximated ($\chi^2 = 102$ for 72 degrees of freedom) by a $\beta$-model (e.g. Jones & Forman 1984) of the form $S_X(r) = S(0) \left[1 + (r/r_c)^2\right]^{1/2-3\beta}$ with a core radius $r_c = 29.2 \pm 0.7$ kpc and a slope parameter $\beta = 0.535 \pm 0.003$ (1σ errors). Between radii of 0.1 – 1.0 Mpc we find evidence for a steepening of the surface brightness profile with increasing radius: for 0.1 < $r < 1.0$ Mpc the data can be described ($\chi^2 = 131$ for 131 degrees of freedom) by a simple broken power-law model, with a break at a radius of 487$^{+23}_{-16}$ kpc, and slopes in the regions internal and external to the break radius of $-2.25 \pm 0.03$ and $-3.66 \pm 0.18$, respectively. A similar result was obtained for Abell 2390 by Allen, Ettori & Fabian.
 TABLE 1. The results from the analysis of the annular spectra (covering position angles 180 – 90 degrees). Temperatures ($kT$) are in keV and metallicities ($Z$) in solar units. The absorbing column density has been fixed at the nominal Galactic value of $4.85 \times 10^{20}$ atom cm$^{-2}$. The total $\chi^2$ values and number of degrees of freedom (DOF) in the fits are listed in column 4. Error bars are the 1$\sigma$ ($\Delta\chi^2 = 1.0$) confidence limits on a single interesting parameter.

| Radius (kpc) | $kT$ ($\text{keV}$) | $Z$ | $\chi^2$/DOF |
|--------------|-------------------|-----|--------------|
| 0 – 23.5     | $7.04^{+0.79}_{-0.69}$ | $0.48^{+0.17}_{-0.17}$ | 127.6/101 |
| 23.5 – 50.3  | $9.03^{+0.99}_{-0.74}$ | $0.66^{+0.16}_{-0.15}$ | 126.4/130 |
| 50.3 – 97.2  | $11.23^{+1.22}_{-1.02}$ | $0.60^{+0.16}_{-0.15}$ | 190.6/164 |
| 97.2 – 147   | $13.82^{+2.09}_{-1.69}$ | $0.07^{+0.07}_{-0.07}$ | 106.3/119 |
| 147 – 245    | $19.37^{+4.07}_{-2.83}$ | $0.28^{+0.26}_{-0.26}$ | 134.7/134 |
| 245 – 345    | $13.51^{+2.73}_{-2.11}$ | $0.81^{+0.34}_{-0.39}$ | 78.2/89 |
| 345 – 492    | $18.08^{+5.54}_{-4.23}$ | $0.79^{+0.47}_{-0.42}$ | 92.6/85 |
| 492 – 737    | $12.40^{+4.52}_{-2.61}$ | $0.44^{+0.33}_{-0.35}$ | 80.2/81 |
| 0 – 97.2     | $9.32^{+0.57}_{-0.52}$ | $0.55^{+0.09}_{-0.09}$ | 457.9/399 |
| 97.2 – 737   | $15.48^{+1.53}_{-1.16}$ | $0.34^{+0.12}_{-0.12}$ | 502.7/516 |
| 0 – 737      | $12.00^{+0.62}_{-0.59}$ | $0.41^{+0.07}_{-0.07}$ | 987.8/917 |

The data from both Chandra observations were modelled simultaneously using the XSPEC code (version 11.01; Arnaud 1996). We have limited our analysis to the 0.5 – 7.0 keV energy band, over which the calibration of the back-illuminated CCD detectors is currently best understood.

The spectra have been modelled using the MEKAL plasma emission code of Kaast & Mewe (1993; incorporating the Fe L calculations of Liedahl, Osterheld & Goldstein 1995) and the photoelectric absorption models of Balucinska-Church & McCammon (1992). We have fitted each annular spectrum using a simple, single-temperature model with the absorbing column density fixed at the nominal Galactic value ($N_H = 4.85 \times 10^{20}$ atom cm$^{-2}$; Dickey & Lockman 1990). The free parameters in this model were the temperature ($kT$), metallicity ($Z$; measured relative to the solar photospheric values of Anders & Grevesse 1989, with the various elements assumed to be present in their solar ratios) and emission measure. We note that including the absorbing column density as an additional free parameter did not result in significant improvements in the goodness of fit.

4.2 Results

The best-fit parameter values and 1$\sigma$ ($\Delta\chi^2 = 1.0$) confidence limits determined from the fits to the annular spectra (excluding the southeast quadrant) in the 0.5 – 7.0 keV band are summarized in Table 1. The projected temperature each of the annular regions studied, the number of source counts in each 32 x 32 pixel$^2$ sub-region was determined. The individual .rmf and .arf files were then combined using the FTOOLS programs addrmf and addarf (using a script provided by Roderrick Johnstone) to form a counts-weighted spectral response and auxiliary response matrix appropriate for each annulus.
profile determined with this model is shown in Fig. 4. The temperature rises from a mean value of $7.0^{+0.8}_{-0.6}$ keV within $r = 24$ kpc to $kT = 15.8^{+1.6}_{-1.2}$ keV over the $0.1 - 0.5$ Mpc region.

A fit with the same model to the data for the southeast quadrant between radii of 60 – 195 kpc (where the X-ray enhancement is most obvious in the image) gives a best-fit temperature $kT = 18.0^{+2.7}_{-2.3}$ keV. (A similar result, $kT = 18.2^{+3.8}_{-2.9}$ keV, is obtained using a circular region of radius 10 arcsec centred on the enhancement.) In other directions, the mean temperature between radii of 60 – 195 kpc is $kT = 12.7 \pm 1$ keV. The higher temperature and enhanced X-ray surface brightness in the southeast quadrant are consistent with the X-ray gas in that region having undergone shock compression (Section 8).

We find marginal evidence for a metallicity gradient in the cluster, with a mean metallicity for the central 100 kpc radius of $Z = 0.55 \pm 0.09$ solar, as opposed to $Z = 0.34 \pm 0.12$ solar for the 100 – 740 kpc region.

4.3 Spectral deprojection analysis

The results discussed above are based on the analysis of projected spectra. We have also carried out a simple deprojection analysis of the Chandra spectral data using the method described by Allen et al. (2001b).

For this analysis we have used the same annular regions (covering position angles of 180 – 90 degrees) and have assumed that the emission from each spherical shell (the shells are defined by the same inner and outer radii as the annular regions) is isothermal and absorbed by the Galactic column density. The fit to the outermost annulus is used to determine the temperature and emission measure in the outermost spherical shell. The contribution from that shell to each inner annulus is then determined by purely geometric factors (*e.g.* Kriss, Cioffi & Canizares 1983). The fit to the second annulus inward is used to determine the parameters for the second spherical shell, and so forth, working inwards.

The data for all eight annular spectra were fitted simultaneously in order to determine the parameter values and confidence limits. The metallicity was linked to take the same value at all radii. The temperature profile determined with the spectral deprojection method is shown in Fig. 5.
The predicted deprojected temperature profile (grey curve) determined from 100 Monte-Carlo simulations using the best-fitting NFW mass model (with $r_s = 0.40$ Mpc, $c = 5.87$ and $\sigma = 1450 \text{ km s}^{-1}$; Section 5). The predicted profile has been binned to the same spatial resolution as the spectral deprojection results (solid points; Section 4.3), which have been overlaid. The agreement between the deprojected spectral results and the best-fit NFW mass model predictions (reduced $\chi^2 = 0.87$ for $\nu = 6$ degrees of freedom) indicates that the NFW mass model provides a good description of the spatially-resolved Chandra spectra.

4.4 Comparison with previous work

The mean emission-weighted temperature and metallicity for RXJ1347.5-1145 of $kT = 12.2 \pm 0.6$ keV and $Z = 0.42 \pm 0.07$ solar, respectively, measured in the $0.0 - 0.74$ Mpc range over the full 360 degrees, are in good agreement with the values reported by Allen & Fabian (1998; $kT = 12.5^{+0.9}_{-0.8}$ keV, $Z = 0.38^{+0.11}_{-0.10}$ solar) using ASCA data and a similar spectral model. Excluding the data for the southeast quadrant, we obtain only small changes in these results: $kT = 12.0 \pm 0.6$ keV and $Z = 0.41 \pm 0.07$ solar. The Chandra results are also in good agreement with those reported by Schindler et al. (1997) using the same ASCA data and a 3 arcmin radius aperture ($kT = 11.8^{+1.6}_{-1.0}$ keV, $Z = 0.39^{+0.13}_{-0.15}$ solar). The emission-weighted temperature measured with Chandra is slightly cooler than the value of $14.5^{+1.7}_{-1.5}$ keV measured with BeppoSAX by Ettori, Allen & Fabian (2001), as can be expected given the observed temperature profile (Figs. 2, 3) and the different response characteristics of the instruments. (The data for the southeast quadrant are not excluded from the BeppoSAX or ASCA studies.)

The ‘ambient’ emission-weighted temperature measured with Chandra in the $0.1 - 0.5$ Mpc range (i.e. excluding the data for the southeast quadrant, the central, cool region, and the regions at large radii where the temperature may start to decline again) of $kT = 15.8^{+1.2}_{-1.0}$ keV is in good agreement with the value of $15.9^{+0.5}_{-0.6}$ keV estimated from BeppoSAX data by Ettori et al. (2001) using a spectral model which included a constant-pressure cooling flow component. The Chandra result is also consistent with the ambient temperature of $kT = 26^{+8}_{-6}$ keV estimated from ASCA data using a similar constant-pressure cooling flow model (Allen & Fabian 1998), and $kT = 18.6^{+4.1}_{-3.0}$ keV from a re-analysis of the ASCA data by the same authors using the more appropriate ‘isothermal’ cooling flow models of Nulsen (1998). The emission-weighted ambient temperature determined from the Chandra data in the $0.1 - 0.5$ Mpc region is in good agreement with the mean gas mass-weighted temperature of $16.1^{+5.4}_{-2.7}$ keV measured within $r_{2500}$ ($r = 0.72$ Mpc) by Allen, Schmidt & Fabian (2001c). We note that this temperature is also consistent with the predicted value of $kT = 16.8$ keV, using the cooling-flow corrected $kT/L_{bol}$ relation of Allen & Fabian (1998; we assume a bolometric luminosity of $\sim 2.2 \times 10^{46}$ erg s$^{-1}$ as measured by ASCA).

5 MEASUREMENT OF THE CLUSTER MASS PROFILE

5.1 Method

The observed X-ray surface brightness profile (Fig. 3a) and deprojected, spectrally-determined temperature profile (Fig. 5) may together be used to determine the X-ray gas mass and total mass profiles in the cluster. For this analysis, we have used an enhanced version of the image deprojection code described by White, Jones & Forman (1997), and have followed the methods outlined by Allen et al. (2001b) and Schmidt et al. (2001).

A variety of simple parameterizations for the cluster mass distribution were examined to establish which could provide an adequate description of the Chandra data (see below). The best-fit parameter values and confidence limits...
were determined by examining parameter grids and evaluating \( \chi^2 \) for each set of parameters. Spherical symmetry and hydrostatic equilibrium are assumed throughout.

### 5.2 NFW mass models

We find that a good fit (\( \chi^2_{\text{min}} = 5.2 \) for 6 degrees of freedom, hereafter DOF) to the Chandra data for RXJ1347.5-1145 can be obtained using a Navarro, Frenk \\& White (1997, hereafter NFW) model:

\[
\rho(r) = \frac{\rho_{\text{crit}}(z) \delta_c}{(r/r_s)(1 + r/r_s)^2},
\]

where \( \rho(r) \) is the mass density, \( \rho_{\text{crit}}(z) = 3H(z)^2/8\pi G \) is the critical density for closure and

\[
\delta_c = \frac{200}{\ln(1 + c) - c/(1 + c)}.
\]

The best-fit scale radius, \( r_s = 0.40^{+0.24}_{-0.20} \) Mpc and the concentration parameter, \( c = 5.87^{+1.35}_{-0.73} \) (68 per cent confidence limits). The normalization of the mass profile may also be expressed in terms of an effective velocity dispersion, \( \sigma = \sqrt{\delta_m\Omega(z)r_s c} = 1450^{+300}_{-200} \) km s\(^{-1} \) (with \( r_s \) in units of Mpc). The deprojected X-ray gas temperature profile predicted by the best-fitting NFW mass model (given the observed surface brightness profile) is shown overlaid on the observed spectral results in Fig. 6.

![Figure 7](image)

**Figure 7.** The integrated (3-dimensional) mass profile and \( 1\sigma \) errors for RXJ1347.5-1145 determined from the Chandra data using the NFW parameterization (section 5.2). The grey curve shows the X-ray gas mass profile. (The best-fit X-ray gas mass profile and \( 1\sigma \) errors are plotted, although these curves are indistinguishable in the figure.)

\[
\delta_m = \frac{100}{\ln(1 + c_m)}.
\]

For this model we obtain \( \chi^2_{\text{min}} = 8.6 \) (6 DOF), with best-fit values for the scale radius \( r_s = 5.0 \) Mpc (the maximum allowed value in our grid), concentration parameter \( c_m = 0.69 \) and effective velocity dispersion \( \sigma = 2125 \) km s\(^{-1} \) (where \( \sigma = \sqrt{\delta_m \Omega(z) r_s c_m} \)).

Secondly, we examined a simple, non-singular isothermal sphere model:

\[
\rho(r) = \frac{\sigma^2_{\text{iso}}}{2\pi G} \frac{1}{r^2 + r_s^2},
\]

for which we obtain \( \chi^2_{\text{min}} = 4.9 \) (6 DOF) with \( r_s = 45 \pm 10 \) kpc and \( \sigma_{\text{iso}} = 1590 \pm 150 \) km s\(^{-1} \).

We thus find that all of the two-parameter mass models described above provide acceptable descriptions of the Chandra data for RXJ1347.5-1145. We note, however, that a singular isothermal sphere \( \rho(r) \propto r^{-2} \) does not provide an acceptable fit (\( \chi^2_{\text{min}} = 33.1 \) for 7 DOF).

### 5.3 Other parameterized mass models

We have also examined a variety of other parameterized mass models. Firstly, the model of Moore et al. (1998):

\[
\rho(r) = \frac{\rho_{\text{crit}}(z) \delta_{\text{min}}}{(r/r_s)^{1.5} (1 + r/r_s)^{1.5}},
\]

where

\( \delta_{\text{min}} = 60 \ln(1 + c_m) \)

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

\( \rho(r) \) is the mass density, \( \delta_{\text{min}} \) is the minimum allowed value in our grid, \( c_m \) is the concentration parameter, and \( \sigma_{\text{iso}} \) is the effective velocity dispersion.

![Figure 8](image)

**Figure 8.** A contour plot of the chi-squared values obtained for the full range of NFW models studied. The minimum chi-squared value is marked with a cross. Contours have been drawn at intervals of \( \Delta \chi^2 = 2.30, 6.17 \) and \( 11.8 \), corresponding to 68, 95.4 and 99.7 per cent for two interesting parameters. Fig. 6 shows the best-fitting NFW mass profile, which has a virial radius \( r_{200} = c r_s = 2.35^{+0.49}_{-0.33} \) Mpc and an integrated mass within the virial radius, \( M_{200} = 2.29^{+1.74}_{-0.62} \times 10^{15} \) M\(_s\)O. The 1.2-\( \sigma \) errors for RXJ1347.5-1145 determined from the Chandra data are shown in Fig. 6.
Figure 8. A comparison of the projected surface mass density contrast determined from the Chandra X-ray data (Section 5) with the weak lensing results of Fischer & Tyson (1997; solid triangles) and the strong lensing result from Section 6.2 (grey circle). The best-fit NFW X-ray mass model for the relaxed regions of the cluster and 1σ confidence limits (the maximum and minimum values at each radius for all NFW models within the 68 per cent confidence contour shown in Fig. 6) are shown as the dotted and full curves, respectively. The strong lensing point is marked with a grey circle. Note that the strong lensing point should lie above the X-ray results, which exclude the regions of the cluster affected by the second mass clump. We adopt $r_{\text{max}} = 2.72$ Mpc as in Fischer & Tyson (1997).

The agreement between the independent lensing and X-ray mass measurements confirms the validity of the hydrostatic assumption used in the X-ray analysis (having excluded the southeast quadrant) and suggests that the mass profile in the cluster has been robustly determined.

6.2 Strong lensing

Schindler et al. (1995) report the discovery of two bright gravitationally-lensed arcs in RXJ1347.5-1145 using ground based optical imaging. Sahu et al. (1998) present Hubble Space Telescope Imaging Spectrograph (STIS) observations of the cluster which reveal a number of additional strongly-lensed features. The STIS image for RXJ1347.5-1145 is shown in the left panel of Fig. 9. Sahu et al. (1998) also present ground-based spectroscopy of the bright northern arc in the cluster (arc 1) at a radius of 34.9 arcsec (240 kpc) from the dominant cluster galaxy, for which they measure a redshift $z_1 = 0.806$.

Following the methods outlined in Schmidt et al. (2001), we have examined the constraints that the observed strong lensing configuration can place on the mass distribution in the cluster core. We first examined a simple, spherically-symmetric mass model, centred on the dominant cluster galaxy, with the best-fit parameter values determined from the Chandra data for the relaxed regions of the cluster (Sect. 5.2). We find that such a mass model does not provide a sufficient central mass density to explain the strong lensing data.

We next examined refined lensing models in which a second mass component, centered on the second brightest galaxy was introduced, together with appropriate elliptici-
ties for the matter distributions. (The introduction of such a mass clump is well-motivated by the Chandra data for the southeast quadrant of the cluster. The second brightest galaxy is likely to have been the dominant galaxy of the recently-merged subcluster; Section 8). Both mass components have been modelled by elliptical NFW models (see Schmidt et al. 2001 for definitions). The parameters for the main mass component were fixed to the values determined from the Chandra data for the relaxed regions of the cluster in Sect. 5.4, i.e. scale radius $r_s = 0.4$ Mpc, velocity dispersion $\sigma = 1450$ km s$^{-1}$ and concentration parameter $c = 5.87$. The axis ratio and position angle were fixed to the values measured for the dominant galaxy from the STIS data: axis ratio $q = 0.76$ and position angle $\theta = 13.1^\circ$. The centre of the main mass component was fixed to the centre of the dominant galaxy.

The parameters for the second mass component have been determined by requiring that the overall potential is able to produce the northern arc (arc 1) at the measured redshift, $z_1 = 0.806$. For an assumed scale radius $r_{s,\text{clump}} = 0.25$ Mpc, we obtain a best-fitting velocity dispersion $\sigma_{\text{clump}} = 815$ km s$^{-1}$ and a concentration parameter $c_{\text{clump}} = 5.3$. Such parameters are typical for mid-temperature galaxy clusters ($kT \sim 5$ keV, e.g. Allen et al. 2001c). The position, ellipticity and position angle of the second mass component were fixed to the values determined for the second brightest galaxy from the STIS image: $q_{\text{clump}} = 0.79$ and $\theta_{\text{clump}} = 28.1^\circ$.

The redshift measurement for the northern arc constrains the projected mass within the arc radius. It is possible to vary the scale radius for the second mass component and to adjust the concentration parameter accordingly, so long as the projected mass within the arc radius remains constant. The absence of multiple arc images within the cluster core suggests $r_{s,\text{clump}} > 0.1$ Mpc.

Having adjusted the parameters for the second mass component to produce the northern arc, we then examined whether the resulting mass model can explain the other arcs observed by Sahu et al. (1998). Unfortunately, there are no measured redshifts for the other arcs. (Sahu et al. 1998 note a possible lower limit for arc 4 of $z \geq 1$ based on the non-detection of [O\text{II}] in their ground-based spectra, although they caution that the arc may simply be a galaxy without a strong emission-line feature). The details of our model predictions are shown in the right panel of Fig. 9. The results on the predicted arc redshifts and the assumed sizes of the sources are listed in Table 2.

**Table 2.** The redshifts, sizes (in arcsec) and positions (offsets in arcsec with respect to the dominant cluster galaxy in the STIS reference frame) for the sources in the lens model shown in Fig. 9.

| arc | redshift | size (FWHM) | position $\Delta x$ | position $\Delta y$ |
|-----|----------|-------------|----------------------|---------------------|
| 1   | 0.806    | 0.8         | 2.77                 | 10.03               |
| 2   | 0.75     | 0.6         | 5.71                 | 9.44                |
| 3   | 0.97     | 0.6         | 1.00                 | -6.23               |
| 4   | 0.97     | 0.5         | -7.24                | -2.66               |
| 5   | 0.97     | 0.6         | -13.44               | -1.16               |

Figure 9. The (a) observed and (b) predicted gravitational arc geometry in RXJ1347.5-1145. The image in the left panel has been compiled from archival HST STIS data that were originally presented by Sahu et al. (1998). The arrow points to an additional arc-like feature mentioned in the text. The right panel shows the arc geometry predicted by our two-component mass model. The arc numbering has been taken from Sahu et al. (1998). The arcs have been simulated using circular Gaussian surface brightness distributions. The 10%, 30% and 50% brightness contours are plotted. The true source positions are denoted by crosses, with details in Table 2. The central positions for the two mass components are marked with plus signs. Also shown are the critical curves (dash-dotted) and caustic lines (solid; e.g., Schneider, Ehlers & Falco 1992) for a source at a redshift of $z = 0.97$. 

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are cosmology dependent and would be modified slightly if, for example, an accelerating universe with a different Hubble Constant were assumed. For the mass model used here, the predicted redshifts should be accurate to $\sim\pm0.05$, with the exception of arc 4 which is determined more precisely. We have modelled the lensed galaxies using circular Gaussian brightness distributions with the full-width-at-half-maximum (FWHM) values listed in Table 3. The FWHMs for the arcs were adjusted so that their 30 per cent brightness contours provide a good fit to the STIS data. The effects of using different source sizes is illustrated by the different brightness contours in Fig. 1.

Although we include arc 2 in our modelling, we caution that this source appears quite red in the colour image published by Fischer & Tyson (1997) and that it is possible that the source is simply an edge-on spiral galaxy. The predicted redshift for arc 2 is lower than $z_1$, since otherwise the lens model would predict a much stronger distortion. Arcs 3, 4 and 5 are consistent with being at the same redshift. The projected separation of the sources producing arcs 4 and 5 is $43.4\ h_{50}^{-1}\ kpc$. Although arcs 4 and 5 have a similar colour in the data of Fischer & Tyson (1997), it is not possible to explain them as images of the same source using our mass model. In exploring different redshifts for arc 3, we found that for redshifts higher than $z_3 \sim 1$ it is possible to produce a counter image on the other side of the central galaxy. This alerted us to the presence of a blue object (identified from a counter image on the other side of the central galaxy. This

we note that circular NFW models for one or both of the main mass components cannot explain the observed arc shapes and orientations well. In particular, the orientation of arc 4 reflects the orientation of the critical curve (Fig. 9) in its vicinity. A small $\sim5\degree$ difference between the orientation of the observed and predicted arc 4 remains in our best-fit model, which points to a small imprecision of the lensing model.

The grey circle in Fig. 6 shows the azimuthally-averaged, surface mass density contrast at $r = 240 \ kpc$ (centred on the main mass component) for the best-fit strong lensing model. Note that the strong lensing results should lie above the X-ray results at the same radii, since the Chandra analysis excludes the regions of the cluster affected by the second mass subclump. The surface mass density contrast rises sharply between the innermost weak lensing point and the strong lensing result, suggesting that the second mass component is centrally concentrated and does not make a major contribution to the total mass beyond the strong lensing regime.

In conclusion we find that a simple two-component mass model, with ellipticities and orientations for the mass components matching those of the dominant cluster galaxies, provides a reasonable description for the overall arc geometry in RXJ1347.5-1145. Such a model is consistent with the Chandra X-ray and weak lensing results.

7 THE PROPERTIES OF THE CLUSTER GAS

7.1 Electron density and cooling time profiles

The results on the electron density and cooling time as a function of radius, determined from the image deprojection analysis using the best-fit NFW mass model, are shown in Fig. 1. Within the central 500 kpc radius, the electron density profile can be parameterized ($\chi^2 = 43.2$ for 34 degrees of freedom) by a $\beta$-profile with a core radius, $r_c = 27.8 \pm 1.6\ kpc$, $\beta = 0.521 \pm 0.012$ and a central density, $n_e(0) = 2.3 \pm 0.1 \times 10^{-2}\ cm^{-3}$ (1$\sigma$ errors). We measure a central cooling time (i.e. the mean cooling time within the central 1.97 arcsec ($\sim13.4\ kpc$) bin of $t_{cool} = 4.1_{-0.5}^{+0.6} \times 10^8\ yr$ (uncertainties are the 10 and 90 percentile values from 100 Monte Carlo simulations).

7.2 The X-ray gas mass fraction

The X-ray gas-to-total-mass ratio as a function of radius, $f_{gas}(r)$, determined from the Chandra data is shown in Fig. 3. We find that the best-fit $f_{gas}$ value rises rapidly with increasing radius within the central $r \lesssim 40\ kpc$ radius and then remains approximately constant, or rises slowly, out to the limits of the data at $r = 0.74\ Mpc$ where we measure $f_{gas} = 0.14_{-0.027}^{+0.035}$.

Following the usual arguments, which assume that the properties of clusters provide a fair sample of those of the Universe as a whole (e.g. White & Frenk 1991; White et al. 1993; White & Frenk 1993; Evrard 1997; Ettori & Fabian 1999), we may use our results on the X-ray gas mass fraction to estimate the total matter density in the Universe, $\Omega_m$. Assuming that the luminous baryonic mass in galaxies in RXJ1347-1145 is $0.134\ h_{50}^{-2}$ of the X-ray gas mass (e.g. White et al. 1993; Fukugita, Hogan & Peebles 1998) and neglecting other possible sources of baryonic dark matter in the cluster, one can show that $\Omega_m = \Omega_h/1.134f_{gas}$, where $\Omega_h$ is mean baryon density in the Universe. For $\Omega_hh^2 = 0.0820 \pm 0.0072$ (O'Meara et al. 2001) we obtain $\Omega_m = 0.51 \pm 0.12$. For a ΛCDM cosmology with $H_0 = 70\ km\ s^{-1}\ Mpc^{-1}$, our results for RXJ1347.5-1145 would imply $\Omega_m = 0.33 \pm 0.08$.

7.3 Cooling flow models

Under the assumption that the X-ray gas in the core of RXJ1347.5-1145 is in a steady-state cooling flow, we can parameterize the luminosity profile in terms of an equivalent mass deposition rate (e.g. White et al. 1997). The results of this calculation are shown in Fig. 4. We see that the integrated mass deposition rate (MDR) rises with increasing radius within the central 100 kpc, to a maximum value of $\sim1300\ M_{\odot}\ yr^{-1}$.

We have examined the spectrum for the central 100 kpc (radius) region using a model appropriate for a cooling flow with distributed mass deposition. (We use the model of Nulsen 1998 and assume that the integrated MDR within radius $r$, $\dot{M} \propto r$.) The normalization of the cooling-flow component is parameterized in terms of a mass deposition rate, $\dot{M}$. The cooling flow was also allowed to be absorbed by an intrinsic column density, $\Delta N_H$, of cold gas (with solar metallicity) located at the redshift of the cluster. Both $\dot{M}$ and $\Delta N_H$ were free parameters in the fits. Accounting for projection effects, we find that the $0.5 - 7.0\ keV$ spectrum
Figure 10. The results on (a) the electron density and (b) the cooling time, determined from the X-ray image deprojection analysis using the best-fit NFW mass model. Error bars are the $1\sigma$ errors determined from 100 Monte Carlo simulations. A Galactic column density of $4.85 \times 10^{20}$ atom cm$^{-2}$ and a metallicity of 0.4 solar are assumed.

Figure 11. The ratio of the X-ray gas mass to total gravitating mass as a function of radius. The three curves show the best-fit value (dotted curve) and $1\sigma$ confidence limits (solid curves). At $r = 0.74$ Mpc we measure $f_{\text{gas}} = 0.141 \pm 0.035$.

Figure 12. The mass deposition rate (MDR) determined from the image deprojection analysis under the assumption that the central regions of the cluster contain a steady-state, inhomogeneous cooling flow. Error bars are the 10 and 90 percentile values from 100 Monte Carlo simulations. The dotted line shows the best-fitting broken power-law model described in Section 7.3.

for the central 100 kpc radius region is consistent with a cooling flow of $\lesssim 600$ M$_{\odot}$ yr$^{-1}$, intrinsically absorbed by a column density of $1 - 4 \times 10^{20}$ atom cm$^{-2}$, with a mean mass-weighted flow temperature of $\sim 10$ keV.

Fitting the mass deposition profile in Fig. 12 with a broken power-law model, we determine a break radius of $31 \pm 2$ kpc, and slopes internal and external to the break radius of $2.7 \pm 0.3$ and $0.5 \pm 0.1$, respectively ($1\sigma$ errors). Allen et al. (2001a) argue that such breaks may mark the outer edges of the present-day cooling flows in clusters. The predicted MDR for the central $r \sim 20$ kpc radius, where a steady cooling flow with gas cooling to zero degrees might be expected to occur, is $\sim 200$ M$_{\odot}$ yr$^{-1}$. The cooling time of the X-ray gas at the break radius is $\sim 6 \times 10^8$ yr.
As discussed in Section 4.2, the region of enhanced X-ray emission (and enhanced SZ effect; Komatsu et al. 2001) to the southeast of the main X-ray peak is significantly hotter ($kT = 18 \pm 3$ keV) than at the same distance in other directions ($kT = 12 \pm 1$ keV). Following Markevitch et al. (1999), we can model the properties of this region as a one-dimensional shock. In this case, the relative velocity, $v$, of the infalling subcluster and the shock compression factor, $\rho_1/\rho_0$, can be estimated from the pre-shock ($kT_0$) and post-shock ($kT_1$) temperatures. For $kT_0 = 12$ keV and $kT_1 = 18$ keV, we obtain $v = 2250$ km s$^{-1}$ and $\rho_1/\rho_0 = 1.7$. If we instead adopt $kT_0 = 5$ keV, a temperature consistent with the predicted mass of the merging subcluster from the strong lensing analysis discussed in Section 6.2 (using the mass-temperature relation of Allen et al. 2001c), then for $kT_1 = 18$ keV we obtain $v = 4550$ km s$^{-1}$ and $\rho_1/\rho_0 = 3.0$. We note that the roughly spherical appearance of the shocked gas suggests that this material has expanded following the initial shock. Since the material will cool as it expands, it is likely that the initial post-shock temperature exceeded 18 keV and, for $kT_0 = 5$, that the relative collision velocity exceeded 5000 km s$^{-1}$. Such values are broadly consistent with the peak X-ray surface brightness enhancement of a factor $\sim 3$ observed at a radius of $\sim 180$ kpc.

The second brightest galaxy in the cluster lies approximately 18 arcsec to the east and 2 arcsec to the south of the dominant cluster galaxy. This galaxy has an extended, diffuse halo and appears to lie at the centre of a significant sub-concentration of galaxies within the cluster (Fig. 9a). These properties are consistent with it having been the dominant galaxy of the recently merged subcluster. The region of shocked X-ray gas lies approximately 11 arcsec to the south and 6.5 arcsec to the west of the second brightest galaxy. Assuming that the dark matter and galaxies associated with the subcluster have moved on ahead of the shock, it seems plausible that the subcluster travelled in from a PA of $\sim 210$ degrees. This is consistent with the extension of the X-ray emission observed on large scales to the south (Fig. 9b) and the weak lensing mass map presented by Fischer & Tyson (1997). Given the separation of the shocked gas and second brightest galaxy, we estimate that the shock probably occurred a few 10$^7$ years ago. This timescale is consistent with the spatial extent of the shocked gas, assuming that it has expanded at the sound speed, $c_s \sim 1500(T/10^8$K)$^{-1/2}$ km s$^{-1}$. Note also that this timescale is comparable to the time required for the electrons and ions to reach equipartition, so it is possible that the electron and ion populations in the shocked gas have slightly different temperatures.

Despite the evidence for shocked gas in the southeast quadrant, the Chandra data for the rest of the cluster place RXJ1347.5-1145 on the $M_{2500} - kT_{2500}$ and $kT_{2500} - L_{2500}$ relations for relaxed, massive clusters discussed by Allen, Schmidt & Fabian (2001). As discussed in Section 4.4, the shocked gas produces only a small rise in the mean, emission-weighted temperature measured within the central 0.74 Mpc radius. The excess bolometric luminosity of the southeast quadrant between radii of 60-195 kpc (where the shock is most apparent) is $\sim 10^{45}$ erg s$^{-1}$, which corresponds to only $\sim 5$ per cent of the total cluster luminosity (Section 4.4). It therefore appears that the overall temperature and luminosity of the cluster have not been boosted substantially by the merger event. This is supported by the consistent X-ray and weak lensing mass results discussed in Section 6.1.

Ricker & Sarazin (2001) and Ritchie & Thomas (2002) discuss simulations of mergers between clusters with similar central densities and argue that such mergers can lead to significant short-term increases in the overall X-ray temperatures and luminosities of clusters during the periods of closest approach. These effects are most pronounced and long-lived in clusters with relatively low central densities ($n_c < 10^{-3}$ cm$^{-3}$; Ritchie & Thomas 2002). The fact that large boosts in the overall temperature and luminosity are not observed in RXJ1347.5-1145 may be related to the very high central density in the main cluster core ($n_c > 10^{-3}$ cm$^{-3}$; Fig. 10a) and could indicate that the recently-merged subcluster had a relatively low central gas density and interacted only weakly with the main cluster core.

Recently, Cohen & Kneib (2002) have published spectroscopic redshift measurements for 47 cluster members for which they determine a velocity dispersion of $910 \pm 130$ km s$^{-1}$. Inspection of their Fig. 2 suggests that a significant fraction of the galaxies with measured redshifts may have been associated with the recently merged subcluster. This could explain the relatively low velocity dispersion, in comparison to the X-ray and lensing results.

The agreement between the Chandra X-ray and gravitational lensing mass measurements for RXJ1347.5-1145 reinforces the results and conclusions drawn from previous studies of other relaxed lensing clusters e.g. Abell 2390 (Allen et al. 2001b) and Abell 1835 (Schmidt et al. 2001); see also the results for MS1358.4+6245 by Arabadjis et al. (2002). The close agreement of the independent X-ray and lensing masses indicates that the mass measurements are robust and limits the contributions from non-thermal sources of pressure support in the X-ray gas, such as bulk and/or turbulent motions and magnetic fields, in the relaxed regions of the cluster.

9 CONCLUSIONS

The main conclusions from this work may be summarized as follows:

(i) We have reported Chandra observations of RXJ1347.5-1145, the most X-ray luminous cluster of galaxies known. We have identified a region of shocked gas (enhanced X-ray brightness and temperature) to the southeast of the main X-ray peak, at a position consistent with the region of enhanced SZ effect reported by Komatsu et al. (2001). The shocked gas probably results from recent subcluster merger activity. The merger appears not to have boosted the overall luminosity and temperature of the cluster substantially.

(ii) Excluding the data for the southeast quadrant, we have measured the density, temperature and mass profiles for the cluster. The mass profile can be parameterized by an NFW model with a scale radius $r_s = 0.40^{+0.24}_{-0.12}$ Mpc and a concentration parameter, $c = 5.9 \pm 1.4$ (68 per cent confidence limits). The normalization of the mass profile may also be expressed in terms of an effective velocity dispersion, $\sigma = \sqrt{50H(z)r_s c} = 1450^{+300}_{-200}$ km s$^{-1}$.
(iii) The best-fit Chandra mass model for RXJ1347.5-1145 is in good agreement with independent measurements from weak gravitational lensing studies (Fischer & Tyson 1997). The observed strong lensing configuration in the cluster core can also be explained with the introduction of an additional mass clump centred on the second brightest galaxy, which is likely to have been the dominant galaxy of the recently merged subcluster.

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REFERENCES

Allen S.W., 1998, MNRAS, 296, 392
Allen S.W., Fabian A.C., 1998, MNRAS, 297, L57
Allen S.W., Ettori S., Fabian A.C., 2001b, MNRAS, 324, 877
Allen S.W., Schmidt R.W., Fabian A.C., 2001c, MNRAS, 328, L37
Allen S.W., Fabian A.C., Johnstone R.M., Nulsen P.E.J., Arnaud K.A., 2001a, MNRAS, 322, 589
Anders E., Grevesse N., 1989, Geochemica et Cosmochimica Acta 53, 197
Arabadjis J.S., Bautz M.W., Garmire G.P., 2002, ApJ, in press [astro-ph/0109141]
Arnaud, K.A., 1996, in Astronomical Data Analysis Software and Systems V, eds. Jacoby G. and Barnes J., ASP Conf. Series volume 101, p17
Balucinska-Church M., McCammon D., 1992, ApJ, 400, 699
Cohen J.G., Kneib J.-P., 2002, ApJ, submitted [astro-ph/0111294]
Dickey J.M., Lockman F.J., 1990, ARA&A, 28, 215
Ebeling H., Rangarajan F.V.N., White D.A., 2002, MNRAS, submitted
Ettori S., Fabian A.C., 1999, MNRAS, 305, 834
Ettori S., Allen S.W., Fabian A.C., 2001, MNRAS, 322, 187
Evrard A.E., 1997, MNRAS, 292, 289
Fischer P., Tyson J.A., 1997, AJ, 114, 14
Fukugita M., Hogan C.J., Peebles P.J.E., 1998, ApJ, 503, 518
Jones C., Forman W., 1984, ApJ, 276, 38
Kaastra J.S., Mewe R., 1993, Legacy, 3, 16, HEASARC, NASA
Komatsu E., Kitayama T., Suto Y., Hattori M., Matsuo H., Schindler S., Kohji Y., 1999, ApJ, 516, 1
Komatsu E. et al., 2001, PASJ, 53, 57
Kriss G.A., Cioffi D.F., Canizares C.R., 1983, ApJ, 272, 439
Liedhal D.A., Osterheld A.L., Goldstein W.H., 1995, ApJ, 438, L115
Markevitch M., Sarazin C.L., Vikhlinin A., 1999, ApJ, 521, 526
Moore B., Quinn T., Governato F., Stadel J., Lake G., 1999, MNRAS, 310, 1147
Navarro J.F., Frenk C.S., White S.D.M., 1997,ApJ, 490, 493
Nulsen P.E.J., 1998, MNRAS, 297, 1109
O'Meara J.M., Tytler D., Kirkman D., Suzuki N., Prochaska J.X., Lubin D., Wolfe A.M., 2001, ApJ, 552, 718
Pointecouteau E., Giard M., Benoit A., Désert F.X., Aghanim N., Corron N., Lamarrre J.M., Delabrouille J., 1999, ApJL, 519, 115
Pointecouteau E., Giard M., Benoit A., Désert F.X., Bernard J.P., Corron N., Lamarrre J.M., 2001, ApJ, 552, 42
Ricker P.M., Sarazin C.L., 2001, ApJ, 561, 621
Ritchie B.W., Thomas P.A., 2002, MNRAS, 329, 675
Sahu K.C. et al., 1998, ApJL, 492, 125
Schindler S. et al., 1995, A&A, 299L, 9
Schindler S., Hattori M., Neumann D.M., Böhringer H., 1997, A&A, 317, 646
Schmidt R.W., Allen S.W., Fabian A.C., 2001, MNRAS, 327, 1057
Schneider P., Ehlers J., Falco E.E., 1992, Gravitational Lensing, Springer Verlag, Berlin
Weisskopf M.C., Tananbaum H.D., Van Speybroeck L.P., O'Dell S.L., 2000, SPIE 4012, 1 [astro-ph/0004127]
White D.A., Fabian A.C., 1996, MNRAS, 276, 72
White D.A., Jones C., Forman W., 1997, MNRAS, 292, 419
White S.D.M., Frenk C.S., 1991, ApJ, 379, 52
White S.D.M., Efstathiou G., Frenk C.S., 1993, MNRAS, 262, 1023