The isolated elliptical NGC 4555 observed with Chandra

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Accepted 2004 July 23. Received 2004 July 9; in original form 2004 January 5

ABSTRACT
We present analysis of a Chandra observation of the elliptical galaxy NGC 4555. The galaxy lies in a very low density environment, either isolated from all galaxies of similar mass or on the outskirts of a group. Despite this, NGC 4555 has a large gaseous halo, extending to ~60 kpc. We find the mean gas temperature to be ~0.95 keV and the Fe abundance to be ~0.5 Z⊙. We model the surface brightness, temperature and abundance distribution of the halo and use these results to estimate parameters such as the entropy and cooling time of the gas, and the total gravitational mass of the galaxy. In contrast to recent results showing that moderate luminosity ellipticals contain relatively small quantities of dark matter, our results show that NGC 4555 has a massive dark halo and large mass-to-light ratio (56.8$^{+34.2}_{-13.5}$ M⊙/L⊙ at 50 kpc, 42.7$^{+14.6}_{-12.2}$ at 5r_e, 1σ errors). We discuss this disparity and consider possible mechanisms by which galaxies might reduce their dark matter content.

Key words: galaxies: elliptical and lenticular, cD – galaxies: individual: NGC 4555 – X-rays: galaxies.

1 INTRODUCTION

The majority of galaxies are found in groups and clusters (Tully 1987), and this is particularly true of elliptical galaxies. The morphology–density and morphology–radius relations show that elliptical galaxies are most common in the cores of clusters and groups (Melnick & Sargent 1977; Dressler 1980). In a hierarchical model of structure formation, this can be explained as a product of the processes which form ellipticals. The merger hypothesis (Toomre & Toomre 1972) suggests that the product of the merger of two spiral galaxies will be an elliptical galaxy. If this is the case, then galaxy groups are the most likely location of elliptical formation, as these systems have high galaxy densities but relatively low velocity dispersions. The merger of groups to form larger galaxy clusters naturally leads to a large population of elliptical galaxies in the most massive systems.

Given this model of elliptical galaxy formation, it is perhaps unsurprising that the best known elliptical galaxies are found in galaxy groups and clusters. Most clusters and many groups are dominated by a giant elliptical (or cD) galaxy which lies at the bottom of the cluster potential well. X-ray observations have shown these objects to be surrounded by haloes of highly luminous gas (Forman, Jones & Tucker 1985; Trinchieri, Fabbiano & Canizares 1986). The clusters and groups often have their own haloes of hot X-ray emitting gas (Kellogg, Baldwin & Koch 1975), and models of galaxies in the cores of such systems suggest that the galaxy halo is probably enhanced by inflow of gas from the surrounding intracluster medium (Mathews & Brighenti 2003). Owing to their high X-ray luminosities, these galaxies are the most easily observed in X-rays, and most detailed analyses of elliptical galaxies focus on them (e.g. Sakelliou et al. 2002; Jones et al. 2002; Buote et al. 2003).

However, the location of these galaxies in a dense environment, surrounded by a reservoir of high-temperature gas means that their intrinsic properties must always be in doubt. In particular, the question of whether elliptical galaxies produce the observed haloes of X-ray emitting gas through stellar mass loss or accretion from their surroundings is very difficult to answer. It would be greatly simplified if galaxies with little or no surrounding intracluster medium (ICM) could be observed. The importance of this issue has recently increased, owing to reports that some ellipticals may contain very little dark matter or may lack dark matter haloes entirely (Romanowsky et al. 2003). This could provide an explanation for the long known issue of the large degree of scatter in the L_X : L_B relation for elliptical galaxies – galaxies with dark matter haloes have sufficient mass to prevent the escape of hot gas and/or accrete more, while those which lack dark matter do not. It is therefore important to observe ellipticals which do not lie at the heart of a large group or cluster potential well to answer the question of whether ordinary elliptical galaxies can possess significant quantities of hot gas, without the aid of a surrounding deep potential well.

As part of a sample of isolated elliptical galaxies, we have used Chandra to observe NGC 4555, a fairly luminous elliptical galaxy (log L_B/L_B⊙ = 10.78) at a distance of ~90 Mpc. We find that this elliptical, which we show is not the dominant galaxy of any group or cluster, has a sizeable X-ray halo. The hot gas in this halo...
can be used to characterize the dark matter halo surrounding the galaxy. Throughout the paper we assume $H_0 = 75 \, \text{km s}^{-1} \, \text{Mpc}^{-1}$ and normalize optical $B$-band luminosities to the $B$-band luminosity of the sun, $L_{\odot} = 5.2 \times 10^{32} \, \text{erg s}^{-1}$. Abundances are measured relative to the ratios of Grevesse & Sauval (1998), which differ from the older abundance ratios of Anders & Grevesse (1989) in that the solar abundance of Fe is a factor of ~1.4 lower. Details of the location and scale of NGC 4555 are given in Table 1.

In Section 2 we give details of the observation and our data reduction techniques, and Section 3 contains the results of our analysis. Section 4 consists of a discussion of these results, with particular reference to the issue of dark matter in early-type galaxies, and Section 5 summarizes our results and conclusions.

## 2 OBSERVATION AND DATA REDUCTION

NGC 4445 was observed with the ACIS instrument during Chandra Cycle 3, Obs ID 2884. A detailed summary of the Chandra mission and instrumentation can be found in (Weisskopf et al. 2002). The S3 chip was placed at the focus of the telescope in order to take advantage of the enhanced sensitivity of the back illuminated CCDs at low energies. The instrument operated in faint mode, and observed the target for just over 30 ks. The raw data was reprocessed using CIAO v. 3.0.1 and bad pixels and events with ASCA grades 1, 5 and 7 were removed. The data were corrected to the appropriate gain map, and a correction was made to account for the time dependence of the gain using the technique described by Vikhlinin. A background light curve was produced. Some minor background flares were identified and removed, with all periods where the count rate deviated from the mean by more than $3\sigma$ being excluded. The effective exposure of the observation after cleaning was 23.3 ks.

Background images and spectra were generated using the blank sky data described by Markevitch. The data were cleaned to match the background, and appropriate responses were created using the CIAO TASKS MKWARF and MKRMF. As the ACIS instruments are affected by absorption by material accumulated on the optical blocking filter, we applied a correction to the responses. When fitting spectra we generally held the absorption fixed at the measured galactic value of $1.36 \times 10^{20} \, \text{cm}^{-2}$. Point sources were identified using the CIAO WAVDETECT tool with a signal threshold of 10–6. We chose to use only the S3 chip for our analysis, as the galaxy emission should be entirely contained on S3. This choice of signal threshold means that the detection algorithm should identify $<1$ false source in the field of view. Once identified, point sources were removed from the data, using regions of twice the radius given by the detection routine.

## 3 RESULTS

We initially prepared adaptively smoothed images of the galaxy, using the CIAO task CSMOOTH. The data were smoothed to show features with a signal-to-noise ratio of 3 to 5. A scaled background image was smoothed and removed from the data and correction for the variations in exposure across the chip were made. Fig. 1 shows the result of the smoothing with optical contours from the Digitized Sky Survey (DSS) overlaid. From this image, it is clear that the X-ray emission extends well beyond the stellar body of the galaxy, perhaps as far as 60 kpc in some directions.

### 3.1 Two-dimensional surface brightness modelling

To model the X-ray surface brightness distribution of NGC 4555 we prepared source and background images in a 0.3–3.0 keV band, with point sources removed. The energy band was chosen to focus on soft emission and improve the signal-to-noise ratio of the source. Images were binned to a pixel size of 1 arcsec. An appropriate exposure map was also generated, and we used the CIAO SHERPA package to perform the fitting. As the source image has many pixels containing few counts (or none), we use the Cash statistic (Cash 1979) when fitting.

This statistic only provides a relative measure of the goodness of fit, so that while it allows us to improve fits and find the best solution for a particular model, it does not provide an absolute measure of the fit quality. We therefore judge whether fits are satisfactory (or otherwise) by inspection of azimuthally averaged radial profiles and residual images. However, the fits are two-dimensional, and so we can determine parameters such as the ellipticity of the halo.

We performed fits using a beta model, de Vaucouleurs model and combinations of the two with a central point source. When combining the de Vaucouleurs and beta models, the de Vaucouleurs model core radius, axis ratio and position angle (p.a.) were all fixed at the optically determined values ($r_c = 16.11$ arcsec, p.a. = $35^\circ$, axis ratio = 1.26), so that the de Vaucouleurs component would model a discrete source contribution distributed in the same way as the stellar population. We found that the beta model provided an adequate fit to the data and inspection of the residual images and azimuthally averaged radial profiles did not suggest that more complex models improved the fit. We therefore adopt our best beta model fit to

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Table 2. Parameters and 1σ errors of our best-fitting beta model. Position (Pos.) angle is measured anti-clockwise from the north-east.

<table>
<thead>
<tr>
<th>$\epsilon_{\text{core}}$ (arcsec)</th>
<th>$\beta_{\text{fit}}$</th>
<th>Pos. angle (°)</th>
<th>Axis ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.64$^{+0.15}_{-0.14}$</td>
<td>0.577 ± 0.009</td>
<td>26.77$^{+2.43}_{-2.57}$</td>
<td>1.12$^{+0.06}_{-0.05}$</td>
</tr>
</tbody>
</table>

Figure 2. Azimuthally averaged surface brightness profile of NGC 4555, showing our best-fitting beta model. The background level is marked by the dotted line, the model by a solid line and the data by error bars. The profile was azimuthally averaged using elliptical bins with axis ratio and position angle as in the fit. The radius shown is therefore effectively the minor axis radius. Note that 1 arcsec = 0.437 kpc.

Figure 3. Integrated spectrum with best-fitting APEC+APEC+bremsstrahlung model. Lower panel shows residuals to the fit plotted in terms of contributions to $\chi^2$.

describe the surface brightness distribution. The fitted parameters and given in Table 2. Fig. 2 shows an azimuthally averaged radial profile with the fitted model.

3.2 Spectral modelling

As an initial step we chose to fit the integrated spectrum of the entire galaxy halo. The spectrum was extracted from a circular region centred on the peak of the emission, with radius 150 arcsec (~65 kpc). After removal of regions corresponding to point sources were removed, source and background spectra were extracted, appropriate responses created and corrected, and the source spectrum grouped to 20 counts per bin. The spectra were fitted using xspec v. 11.1.0, ignoring energies lower than 0.4 and greater than 8.0 keV. The spectrum was fitted fairly successfully with a model consisting of a 7-keV bremsstrahlung component, and a hot plasma component, modelled using either the MEKAL (Liedahl, Osterheld & Goldstein 1995; Kaastra & Mewe 1993) or APEC (Smith et al. 2001) codes. The bremsstrahlung component was intended to model emission from unresolved point sources. Both bremsstrahlung and power-law models have been successfully used in this role in previous studies (Irwin, Sarazin & Bregman 2000; Irwin, Athey & Bregman 2003). The results of these fits are given in Table 3.

Although the abundances are rather poorly constrained, freeing Fe and particularly Si greatly improves the fits. A MEKAL+bremsstrahlung model with all metals in solar ratios has a reduced $\chi^2$ of 1.196 for 164 degrees of freedom (d.o.f.), a significantly poorer fit. Assuming the abundances given by the APEC fit, we estimate the masses of Fe and Si in the central ~65 kpc of the halo to be $M_{\text{Fe}} = 1.49 \times 10^5 M_\odot$ and $M_{\text{Si}} = 1.83 \times 10^5 M_\odot$, respectively. This gives an Fe-mass-to-light ratio of $2.4 \times 10^{-6} M_\odot/L_{B,\odot}$, considerably lower than the values found for galaxy clusters (Finoguenov, David & Ponman 2000), or even the values suggested for small galaxy groups (4.5 $\times 10^{-4}$, Renzini et al. 1993). It seems reasonable to expect that this relatively small quantity of Fe could be produced by the stellar population of the galaxy without external enrichment.

We also attempted to fit the spectrum with more complex models, including a two-temperature plasma with bremsstrahlung or power law, cooling flow models and multitemperature models. An example spectrum is shown in Fig. 3. None of these produced a statistically significant improvement in the fit. However, inspection of the spectrum showed that the use of a two-temperature plasma model produced a slightly better fit to the high-energy side of the 1-keV Fe peak, and we therefore record this fit in Table 3. Fitting a single temperature model to spectra from gas with multiple

Table 3. Parameters for our best fits to the integrated spectrum. Temperature and abundance are given in terms of 90 per cent error bounds. Flux is calculated for the 0.4–8.0 keV band, is unabsorbed, and is given in units of erg s$^{-1}$ cm$^{-2}$. Gas luminosity is calculated from flux assuming a distance of 90.33 Mpc, and is given in units of erg s$^{-1}$ kpc$^{-2}$. The fits were performed with $N_H$ fixed at the galactic value (1.36 $\times 10^{20}$ cm$^{-2}$) and included a 7-keV bremsstrahlung model. $f_{\text{bremss}}$ gives the fraction of the total flux originating from this component. $Z_{\text{avg}}$ gives the abundance of all other metals apart from Fe and Si.

<table>
<thead>
<tr>
<th>Model</th>
<th>$kT$</th>
<th>$kT_2$</th>
<th>$Z_{\text{avg}}$</th>
<th>Si</th>
<th>Fe</th>
<th>$\chi^2$</th>
<th>d.o.f.</th>
<th>Flux</th>
<th>$L_{X,\text{gas}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>MEKAL</td>
<td>0.91 ± 0.04</td>
<td>-</td>
<td>0.18 ± 0.50</td>
<td>0.52 ± 0.26</td>
<td>0.41 ± 0.20</td>
<td>1.093</td>
<td>162</td>
<td>4.86 $\times 10^{-13}$</td>
<td>4.75 $\times 10^{-13}$</td>
</tr>
<tr>
<td>APEC</td>
<td>0.95 ± 0.04</td>
<td>-</td>
<td>0.24 ± 0.49</td>
<td>0.58 ± 0.31</td>
<td>0.50 ± 0.24</td>
<td>1.056</td>
<td>162</td>
<td>4.54 $\times 10^{-13}$</td>
<td>4.64 $\times 10^{-13}$</td>
</tr>
<tr>
<td>APEC+APEC</td>
<td>0.82 ± 0.04</td>
<td>-</td>
<td>1.36 ± 0.34</td>
<td>0.52 ± 0.39</td>
<td>1.06 ± 0.69</td>
<td>1.040</td>
<td>-</td>
<td>0.186</td>
<td>0.147</td>
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<td></td>
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<td></td>
<td></td>
<td></td>
<td>0.126</td>
</tr>
<tr>
<td>$f_{\text{bremss}}$</td>
<td>0.186</td>
<td>-</td>
<td>0.147</td>
<td>-</td>
<td></td>
<td>0.126</td>
<td>-</td>
<td>4.75 $\times 10^{-11}$</td>
<td>4.64 $\times 10^{-11}$</td>
</tr>
<tr>
<td>$L_{X,\text{gas}}$</td>
<td>-</td>
<td></td>
<td>4.43 $\times 10^{-11}$</td>
<td>-</td>
<td></td>
<td>4.43 $\times 10^{-11}$</td>
<td>-</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
temperature components around 1 keV is known to produce residuals on both sides of the Fe peak (Buote & Fabian 1998; Buote 2000), so this apparent improvement in fit probably indicates that NGC 4555 has a multitemperature halo. It is notable that the measured abundances for this fit are considerably higher than those found for the single temperature plasma fits, again agreeing with previous studies comparing single- and two-temperature fits of multitemperature gas. However, the abundances are rather poorly constrained. To examine whether the large errors in the bins above 3 keV might be responsible for this lack of precision, we rebinned the spectrum above 3 keV to have at least 20 counts per bin after background subtraction. Unfortunately this does not improve the situation; the errors on temperature and abundance are even larger, and the fit has a reduced $\chi^2$ of 1.103 (for 85 d.o.f.), not a significant improvement on our previous fits.

We have sufficient detected counts from the galaxy to allow us to split the halo into four bins and fit spectra from these individually. We use elliptical annuli with axis ratio and position angle taken from the best-fitting surface brightness model. The angular sizes of the bins are 0–20, 20–45, 45–90 and 90–150 arcsec, with distances measured on the semi-minor axis. The spectra and associated responses and background spectra were prepared as described above and fitted individually. These spectra were not of the quality required to fit individual metal lines, so we used MEKAL models with bremsstrahlung components added if necessary. Fig. 4 shows the fitted temperature and abundance in each bin. In each bin we hold the hydrogen column fixed at the galactic value. Only the central bin was improved by the addition of a bremsstrahlung component, which contributes $\sim 16$ per cent of the emission in this bin. A bremsstrahlung contribution is not ruled out in the other bins, but provides no significant improvement in the fit. We also note that inclusion of such a component does not significantly affect the fitted temperature of the MEKAL component. Fit quality in the central bin is good, reduced $\chi^2 = 0.87$ for 29 d.o.f. Fit quality in the outer bins is considerably poorer, with reduced $\chi^2 \sim 1.3$ in bins 2 and 3 and 1.13 in the outermost bin. We tried numerous models including MEKAL and APEC plasmas, power-law and bremsstrahlung components, and multitemperature components such as CEMEKL and MKCFLOW. None produced any significant improvement over a single temperature plasma, and we therefore use the parameters determined by these models as the best fit. We also tested our background subtraction, using a local background extracted from a source-free region of the S3 chip. Bins 1 and 2 showed no significant change in fit statistic or model parameters when using the local background. The best-fitting models for bins 3 and 4 had larger errors on temperature and abundance but were consistent with the fits performed using the blank-sky background data. Fit statistics for these bins were also slightly altered, presumably owing to the poorer statistics of the local background data, which is the likely cause of the larger error regions. We conclude from this that our use of the blank-sky background data is justified and gives accurate results.

Fig. 4 shows that temperature rises from the outer parts toward the core, but turns over and falls in the core. This suggests that radiative cooling in the dense core of the galaxy halo is effective, and has significantly reduced the mean temperature of the gas. The abundance in each bin is more poorly defined, but appears to show a general decrease with increasing radius. This is consistent with enrichment of the galaxy halo by metals lost from the stellar population through stellar winds and supernovae.

### 3.3 Mass, entropy and cooling time

Given the surface brightness and temperature modelling of the halo of NGC 4555, it is possible to estimate three-dimensional properties such as mass, entropy and cooling time. The density profile of the gas can be estimated from the measured profiles and then normalized to reproduce the X-ray luminosity of the galaxy, determined from our best-fitting APEC model. Given the density profile we can use the well-known equation for hydrostatic equilibrium

$$M_{\text{hal}}(< r) = \frac{kT r}{\mu m_p G} \left( \frac{d \ln n_{\text{gas}}}{d \ln r} + \frac{d \ln T}{d \ln r} \right),$$

(1)

to calculate the total mass within a given radius. From density and total mass, we can calculate parameters such as gas fraction, cooling time and entropy where entropy is defined to be

$$S = \frac{T}{n_e^2}.$$

(2)

We estimate the errors on the derived values using a Monte Carlo technique. The known errors on the temperature and surface brightness models, and on other factors such as the total luminosity, are used to randomly vary the input parameters. We then generate 10 000 realizations of the derived parameters profiles, and use these to calculate the 1σ error on each parameter at any given radius.

The only issue which arises in these calculations is the question of how well we can model the temperature profile, which declines sharply in the galaxy core. The central bin has no effect on the value of the parameters at larger radii and increases the complexity of the required model, and we therefore choose to exclude the central temperature bin, and model the temperature profile as if there were no central cooling. The remaining three bins can be well described with a quadratic, which is shown as a dotted line in Fig. 4. Based on this model of the temperature we calculate the parameters shown in Fig. 5.

To calculate the mass-to-light ratio, we use the $H$ band near infrared surface brightness profile of Gavazzi et al. (2000). This profile is made up of a bulge component described by a de Vaucouleurs profile, with $r_e = 4.01$ arcsec, and an exponential
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Figure 5. Projected temperature and deprojected gas density, gravitational mass, gas mass, gas fraction, entropy, cooling time and mass-to-light ratio for NGC 4555. The inner boundary of the plots is 5 kpc, the radius within which we know our temperature model to be inaccurate. Solid lines show values derived from the best-fitting temperature and surface brightness models, grey regions show 1σ errors.

disc with \(r_e = 17.42\) arcsec. We assume that these measurements hold for the \(B\)-band optical light, and normalize the profile to the \(B\)-band luminosity, with a bulge-to-disc ratio of 0.33. We note that the mass-to-light ratio at the inner limit of the plot is \(\sim 9\), a little higher than the value of 5–8 generally assumed for the mass-to-light ratio of the stars alone.

The outer limit of the plots is determined by the radius to which we can measure the temperature, and the inner limit by the radius of the innermost temperature bin. The inner limit is chosen to exclude the 5-kpc radius region in which we know our temperature model to be wrong. We also note that both the temperature and surface brightness model profiles were determined using the semi-minor axis as the radius descriptor. The profiles shown in Fig. 5 should therefore be considered to show properties which are azimuthally averaged around ellipses whose position and ellipticity are determined by the best-fitting surface brightness model, with the radial scale indicating the semi-minor axis.

3.4 Point sources

As described in Section 2, we used the CIAO WAVDETECT tool to identify point sources in the field of view. Several sources are found to lie within the extended emission surrounding NGC 4555, but only two lie within optical extent of the galaxy, defined by the \(D_{25}\) ellipse. Of these, one is coincident with the galaxy core. Surface brightness fitting of the galaxy X-ray halo (see Section 3.1) does not show strong evidence for a central point source, and we conclude that the identification from WAVDETECT actually corresponds only to the peak of the galaxy halo, not to a separate source.

The remaining source lies \(\sim 15\) arcsec north-east of the galaxy centre, and does not correspond to any feature visible in the DSS optical or 2-Micron All Sky Survey (2MASS) infrared images. There are no objects listed at its position in NASA Extragalactic Data base (NED). We extracted a count rate for the source, in the full Chandra band and in a 0.5–2.0 keV band. Background subtraction was carried out using a region immediately surrounding the source, and should therefore account for contamination by the galaxy halo. Based on the background subtracted count rate we estimated the flux and luminosity of the source assuming a bremsstrahlung model with \(kT = 5\) keV, and a power-law model with \(\Gamma = 1.96\), typical of high-luminosity point sources in other galaxies (Irwin et al. 2003). The results are given in Table 4.

If this source is in fact part of the NGC 4555 system and is actually a single object rather than an unresolved cluster of sources, then it is extremely luminous, \(\log L_X \sim 39.43\) erg s\(^{-1}\). We can estimate the probability of finding a background source with the
measured flux within the $D_{25}$ ellipse based on the sources found in the Chandra deep field south (Tozzi et al. 2001). The $D_{25}$ ellipse has an area of $\sim 3.62 \times 10^{-4}$ deg$^2$, which means that we would expect to find $\sim 0.02$ sources with the observed (or greater) flux in that area. Assuming that the background distribution of sources is the same as the Chandra deep field, this suggests that the source is probably part of NGC 4555, and must therefore be classed either as an ultraluminous X-ray source, or considered to be an unresolved cluster of sources.

4 DISCUSSION

4.1 Environment

NGC 4555 was selected as part of a sample of isolated ellipticals, extracted from the Lyon–Meudon Extragalactic Data Archive\(^3\) (LEDA). Sample galaxies were selected using the following criteria.

(i) Morphological type $T \leq -3$, i.e. early-type galaxies.
(ii) Virgocentric flow corrected velocity $v \leq 9000$ km s\(^{-1}\).
(iii) Apparent $B$-band magnitude $B_r \leq 14.0$.
(iv) Galaxy not listed as a member of a Lyon Galaxy Group (Garcia 1993).

The restrictions on apparent magnitude and recession velocity were imposed to minimize the effect of incompleteness in the catalogue. The LEDA catalogue is known to be 90 per cent complete at $B_r = 14.5$ (Amendola et al. 1997), so our sample should be close to 100 per cent statistically complete. The selection process produced 330 galaxies which could be considered as potential candidates. These were compared to the rest of the catalogue and accepted as being isolated if they had no neighbours which were:

(i) within 700 km s\(^{-1}\) in recession velocity;
(ii) within 0.67 Mpc in the plane of the sky; and
(iii) less than 2 mag fainter in $B_r$.

The criteria were imposed to ensure that the galaxies did not lie in groups or clusters, and to ensure that any neighbouring galaxies were too small to have had any significant effect on their evolution or properties.

To check the results of this process, all candidate galaxies were compared to the NED and the DSS. A NED search of the area within 0.67 Mpc of each candidate identifies galaxies not listed in LEDA. We also examine DSS images of this region for galaxies of similar brightness to the target which are not listed in either catalogue. The process produced 40 candidate isolated elliptical galaxies, of which NGC 4555 is one.

Although NGC 4555 meets the criteria described above, it does have a number of galaxies relatively close to it. We have therefore examined the surrounding galaxy population in order to determine whether NGC 4555 is on the outskirts of a group or cluster. Fig. 6 shows a DSS image of the region surrounding NGC 4555, which is marked in the centre of the image. The scale is shown by the two large circles, which have radii of 0.67 and 1 Mpc. All galaxies listed in NED within 1 Mpc which have measured recession velocities are marked on the plot. Crosses indicate galaxies $>700$ km s\(^{-1}\) away from NGC 4555, circles those within this velocity range. All galaxies marked by circles have apparent magnitudes at least 2 mag fainter than NGC 4555, with the exception of IC 3585, a nearby S0 galaxy which NED shows to be $\sim 600$ kpc and 687 km s\(^{-1}\) from NGC 4555. It is only $\sim 1.5$ mag fainter than our target, and so would appear to violate our isolation criteria. However, the velocities available from NED have not necessarily been corrected in the same way, so the LEDA velocities should provide the more accurate measure of relative distance. Using the LEDA Virgocentric flow corrected velocities, the difference between the two galaxies is 758 km s\(^{-1}\), putting IC 3585 just outside our chosen velocity limit.

Fig. 7 shows histograms of the local velocity field within 1 Mpc of NGC 4555. In the upper panel we show galaxies found in NED, which were required only to have a measured redshift. In the lower panel we show galaxies found in LEDA, which were required to have a measured redshift and apparent magnitude. We have marked galaxies whose magnitudes indicate that they have a $B$-band luminosity in excess of $10^{10}$ erg s\(^{-1}\). The remaining galaxies have $2 \times 10^9 < L_B < 10^{10}$ erg s\(^{-1}\). NGC 4555 is represented in each plot by the shaded region at lowest recession velocity.

Although the plots do suggest some sort of extended structure, it is clear that the galaxies in this region do not form a relaxed group. Similarly, it is clear that NGC 4555 is separated from the other

\(^3\)http://leda.univ-lyon1.fr

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4.2 Comparison with other systems

As mentioned in Section 1, recent studies of the velocity dispersion profiles of some ‘ordinary’ ellipticals have shown them to have lower mass-to-light ratios than were expected (Romanowsky et al. 2003). This suggests that the dark matter content of these galaxies is minimal, at least within the radius to which the measurements extend (\(\sim 5r_e\)). The profiles are incompatible with the dark matter profiles predicted by simulations of structure formation in a cold dark matter dominated universe, leading to the conclusion that either the haloes take the predicted form but have much lower masses than expected (the results are consistent with zero dark mass), or that the dark matter halo takes a very different form, perhaps with most of the mass at larger radii. Four elliptical galaxies, NGC 821, 3379, 4494 and 4697, have been shown to have this unexpected lack of dark matter. Of these, three are in small groups and are the brightest elliptical in each system. NGC 821 is a rather more isolated system, not part of any known group or cluster. All of the galaxies are relatively X-ray faint, undetected (or only marginally detected, in the case of NGC 4697) by ROSAT, and two have been shown to possess relatively small amounts of X-ray emitting gas (Irwin et al. 2000; O’Sullivan & Ponman 2004). This lack of a sizeable X-ray halo could be a consequence of the lack of dark matter in these galaxies, as the stellar mass alone would be insufficient to retain a large gaseous halo.

For comparison with NGC 4555, we use the mass-to-light ratios at \(5r_e\) for NGC 4494, 3379 and 821, quoted by Romanowsky et al. (2003). An overall mass-to-light ratio for NGC 4697 of \(M/L = 11M_\odot/L_\odot\) was found by Méndez et al. (2001), but this is for a radius of \(\sim 3r_e\). For NGC 4555 itself we have three different measurements of \(r_e\), one overall value, which assumes a de Vaucouleurs profile, and the effective radii of bulge and disc components from Gavazzi et al. (2000), who decompose the surface brightness profile of the galaxy into two components. Their result is rather confusing, as their profiles assign only 33 per cent of the \(H\)-band light of the galaxy to the bulge component, which would suggest that NGC 4555 is a misclassified S0. However, NGC 4555 is classified as an elliptical in both NED and LEDA, and in fact Gavazzi et al. list its morphological type as elliptical. We therefore believe that the overall effective radius probably gives the best indication of the scale of the galaxy, but quote mass-to-light ratios at three radii. The ratios are listed in Table 5. Using the overall effective radius, it is clear that NGC 4555 has a considerably larger mass-to-light ratio than the three other ellipticals. The Gavazzi et al. disc component effective radius produces a similar result, and only if the bulge component is used do we find comparable figures. We assume that this is a poor measure of the true scale of the NGC 4555, and that the galaxy has a larger mass-to-light ratio than the three Romanowsky et al. ellipticals.
It is also possible to compare our results with other X-ray mass estimates from the literature. A number of early-type galaxies have mass estimates available, but the requirement for high-quality data means that the majority of these galaxies are highly luminous and reside in the cores of groups and clusters. Techniques similar to ours have been used to produce mass profiles of galaxies such as NGC 507 (Paolillo et al. 2003), NGC 1399 and 1404 (Paolillo et al. 2002), NGC 2563, 4325 and 2300 (Mushotzky et al. 2003), NGC 4472, 4636 and 5044 (Mathews & Brighenti 2003, and references therein).

However, these are all group or cluster dominant galaxies, with the exception of NGC 4472, which dominates a subclump in the Virgo cluster, and NGC 1404, which has a truncated halo, probably caused by interaction with Fornax cluster gas. Using an alternate technique, Loewenstein & White (1999) determined constraints on mass and mass-to-light ratio for a sample of ∼30 galaxies for which global temperature measurements are available, but more detailed density and temperature profiles are not. The authors find that the relation between X-ray temperature and optical velocity dispersion determined from the sample of Davis & White (1996) implies a fairly constant mass-to-light ratio within 6r_e of ∼23 h_75^2 M_⊙/L_⊙. Once again, however, the sample of galaxies used is heavily weighted toward those elliptical which dominate groups and clusters – 20 of the 30 galaxies listed by Davis & White are group or cluster dominant ellipticals, and a further three should probably be excluded – M32, a dwarf elliptical interacting with M31, NGC 4406, undergoing strong interaction with the Virgo ICM, and NGC 4472 which is mentioned above. It is also worth noting that of the remaining seven galaxies, six are located in either the Virgo or Fornax clusters, and could have had their dark matter haloes altered by interactions with their environment.

A third technique for determining the presence of dark matter from X-ray observations has been demonstrated in a series of papers studying NGC 1332, NGC 3923 and NGC 720 (Buote & Canizares 1994, 1996, 1997, 1998; Buote et al. 2002). These galaxies have non-spherical stellar and X-ray distributions, and the authors employ geometric arguments to show the need for a dark matter component to explain their ellipticity and the relative position angles of the gas and stars. They are able to model the dark halo and produce strong constraints on the total mass and mass-to-light ratio, under the assumptions of hydrostatic equilibrium and that rotation has a minimal influence on the potential. These models suggest that NGC 720 has a mass-to-light ratio of ∼23 h_75^2 M_⊙/L_⊙. Once again, however, the sample of galaxies used is heavily weighted toward those elliptical which dominate groups and clusters – 20 of the 30 galaxies listed by Davis & White are group or cluster dominant ellipticals, and a further three should probably be excluded – M32, a dwarf elliptical interacting with M31, NGC 4406, undergoing strong interaction with the Virgo ICM, and NGC 4472 which is mentioned above. It is also worth noting that of the remaining seven galaxies, six are located in either the Virgo or Fornax clusters, and could have had their dark matter haloes altered by interactions with their environment.

Another class of elliptical galaxies which should be compared with NGC 4555 are the fossil groups. These are systems in which all the major galaxies of a group collapse at an early epoch, merging to form a single giant elliptical embedded in a group scale dark matter and X-ray halo (Ponman & Bertram 1993). As these systems appear as a single elliptical with no neighbouring galaxies of similar size, our optical selection criteria would likely identify them as candidate isolated ellipticals. Fossil groups can be identified by four main features (Jones et al. 2003). These are: (1) they have an X-ray luminosity typical for a galaxy group L_X > 10^{45} erg s^{-1}; (2) their X-ray halo is highly extended; (3) the dominant elliptical is at least 2 mag brighter than the other group galaxies; and (4) the dominant elliptical is surrounded by a halo of faint galaxies, the unmerged members of the galaxy group. Criteria 3 and 4 can be refined in that a luminosity function of the galaxies in the fossil group will have only one galaxy with optical luminosity greater than L_s, the luminosity of this galaxy will be significantly higher than would be expected from the luminosity functions of other groups, but the tail of dwarf galaxies will be relatively similar to that of other galaxy groups (see in particular fig. 7, Jones, Ponman & Forbes 2000). NGC 4555 fails the first of these criteria in that its X-ray luminosity is only ∼4.4–4.7 × 10^{44} erg s^{-1} (model dependent). The extension of the halo of NGC 4555 is also smaller than any known fossil group. The one possible exception is NGC 6482, a fossil group observed with Chandra, whose halo extends off the ACIS-S detector and so is as yet poorly characterized as regards extent (Khoshroshahi, Jones & Ponman 2004). The optical luminosity and isolation of NGC 4555 has been dealt with in Section 4.1, and from this the galaxy appears to be isolated enough to meet condition 3 for fossil group status. Testing condition 4 is more difficult, as we do not have redshifts to be isolated enough to meet condition 3 for fossil group status. Criteria 3 and 4 can be refined in that a luminosity function of the galaxies in the fossil group will have only one galaxy with optical luminosity greater than L_s, the luminosity of this galaxy will be significantly higher than would be expected from the luminosity functions of other groups, but the tail of dwarf galaxies will be relatively similar to that of other galaxy groups (see in particular fig. 7, Jones, Ponman & Forbes 2000). NGC 4555 fails the first of these criteria in that its X-ray luminosity is only ∼4.4–4.7 × 10^{44} erg s^{-1} (model dependent). The extension of the halo of NGC 4555 is also smaller than any known fossil group. The one possible exception is NGC 6482, a fossil group observed with Chandra, whose halo extends off the ACIS-S detector and so is as yet poorly characterized as regards extent (Khoshroshahi, Jones & Ponman 2004). The optical luminosity and isolation of NGC 4555 has been dealt with in Section 4.1, and from this the galaxy appears to be isolated enough to meet condition 3 for fossil group status. Testing condition 4 is more difficult, as we do not have redshifts for the faint galaxies around NGC 4555. However, we extracted the positions of all galaxies without redshift listed in NED within 0.44r_e of NGC 4555 (equivalent to 0.7 Mpc at the distance assumed, 90.33 Mpc) and plotted a radial profile of surface number density of galaxies around our isolated elliptical. If NGC 4555 were a fossil group we might expect to see higher number densities around it, caused by the surrounding halo of fainter group members. We note that the galaxies listed have magnitudes as faint as 19.5 mag, and we are therefore likely to be missing some of the faintest galaxies which have not been identified and listed in NED. However, we find no evidence of an overdensity of faint galaxies around NGC 4555 and it seems unlikely that the inclusion of a small number of fainter objects could change this result. This combination of environmental and X-ray properties argues strongly against NGC 4555 being a fossil group.
tell us a great deal about ellipticals at the centres of larger structures, but we cannot know what the influence of their environment is. There are a small number of objects in the Loewenstein & White (1999) study which might be individually useful, but unfortunately the technique used applies to the full sample of galaxies and does not provide mass-to-light ratios for each elliptical. We therefore conclude that while we can compare our results for NGC 4555 to these X-ray mass estimates, we must do so cautiously, considering that we may be comparing systems of quite different scale and content.

Two conclusions might be drawn from these comparisons. Firstly, as we have already demonstrated, NGC 4555 is not in the core of a virialized group, and is therefore not surrounded by a group or cluster scale dark matter potential. Its observed properties therefore confirm that elliptical galaxies can possess dark matter haloes of their own, regardless of their environment. The mass of dark matter seems to be comparable to that found for ellipticals in Hc cores of groups and clusters. It is to be expected that at larger radii, group and cluster dominant ellipticals would have considerably higher mass-to-light ratios than NGC 4555, and it would be interesting to extend our mass profile further to investigate this. The low dark matter content found in the three ellipticals studied by Romanowsky et al. show that while ellipticals can possess dark haloes, not all of them do. This raises an important question; what determines whether elliptical galaxies have dark matter haloes?

One possibility is that all elliptical galaxies are formed with dark matter haloes, but some later lose them through interactions with other galaxies. Close interactions between galaxies can cause tidal stripping of the dark matter halo (Mathews & Brighenti 1997) as well as gas and stars. Simulations of interactions among multiple galaxies in a compact group suggest that a large amount of the dark matter may in fact be dispersed, forming a common halo but not bound to any particular galaxy (Barnes 1989). The simulations also show that the dominant galaxy of the group retains a sizeable dark matter halo, but it is possible that there are circumstances in which this would not be the case. NGC 4494, 3379 and 4697, all of which are the most luminous and presumably most massive elliptical in their groups, might have lost their dark matter in this way.

NGC 821 is more difficult to explain as a product of tidal stripping. The galaxy is relatively isolated, but it is not a member of any group or cluster, and in fact meets the isolation criteria described in Section 4.1. As it has no massive neighbours and does not appear to be part of a larger structure, there is little chance that it has suffered tidal stripping. Another method of removing its dark matter halo, or forming such a galaxy without a halo, therefore appears to be required.

Whereas we can compare the mass and mass-to-light ratio of NGC 4555 with the galaxies studied by Romanowsky et al., comparison of the gas mass and gas fraction with other systems is hampered by the lack of detailed studies of bright ellipticals outside the cores of groups and clusters. As mentioned previously, almost all elliptical galaxies for which mass and gas mass profiles have been calculated are the dominant galaxies of larger structures. Their properties are likely to be affected by the surrounding potential, and models of galaxies embedded in a dense intragroup medium show that the galaxy can accrete gas from its environment (Brighenti & Mathews 1999), thereby changing its gas fraction. An alternative is to compare NGC 4555 to a sample of poor groups. These have gas temperatures similar to that we observe in NGC 4555, and sufficient numbers have been studied to make samples reliable. We use the 0.3–1.3 keV sample of Sanderson et al. (2003) which contains two elliptical galaxies but is dominated by poor groups.

For an accurate comparison, it is necessary to compare properties at a common radius, relative to the overall size of the system. This is usually done using $R_{200}$ (where $R_{200}$ is a good approximation of the virial radius). Unfortunately we do not have a measured value of $R_{200}$ for NGC 4555 and we cannot calculate one based on our three-dimensional models, as the temperature model is not accurate beyond the outer radius we have used. Based on the Sanderson et al. groups, a typical $R_{200}$ for a system of this temperature might be $\sim 500$ kpc. If we adopt this value, we see that while the 0.3–1.3 keV poor groups have gas fractions of $\sim 1$ per cent at 0.1 $\times$ $R_{200}$, NGC 4555 has a gas fraction a factor of $\sim 5$ lower. This result is of course dependent on the value of $R_{200}$ chosen. The Sanderson et al. systems have values of $R_{200}$ ranging from $\sim 200–800$ kpc, but even if we assume a larger $R_{200}$ (and therefore measure gas fraction at a larger radius) we still find that NGC 4555 has a gas fraction considerably lower than that of poor groups.

5 SUMMARY AND CONCLUSIONS

We have used Chandra to observe the relatively isolated early-type galaxy NGC 4555. An examination of its environment suggests that the galaxy is not a member of a virialized group, though it may be part of a loose association or filament of galaxies. It is unlikely that the galaxy is in the core of a larger, group-scale dark matter potential, as is the case with many of the early-type galaxies whose X-ray properties have been studied in more detail. Despite the lack of a surrounding group potential, we find that the galaxy possesses an extended gaseous halo with a temperature of $kT \sim 0.95$ keV and Fe abundance $\sim 0.5 Z_{\odot}$.

We measure the surface brightness distribution of the gaseous halo and find that it is reasonably well described by a single beta model, supporting the spectral results which suggest that emission from gas dominates over emission from point sources. We also measure the temperature and abundance profiles and find evidence for a central cooling region, though confirmation of this would require fitting a multitemperature model which at present we have insufficient counts to do. Assuming the gaseous halo to be in hydrostatic equilibrium, we use these measurements to estimate the gas mass, entropy, cooling time, total gravitating mass and mass-to-light ratio of the system. We find a mass-to-light ratio of $4.2^{+0.6}_{-0.2} M_{\odot} / L_{\odot}$ at $5 R_e$ demonstrating that dark matter makes up an important part of the galaxy mass budget.

A recent optical study of the dark matter content of three ellipticals by Romanowsky et al. (2003) shows a quite different result. All three galaxies have very low dark matter content, and two are consistent with having no dark matter at all, at least out to 5 $R_e$. At least one of these galaxies (NGC 4494) is X-ray faint, and two of them are members of galaxy groups. We suggest that the X-ray luminosity of early-type galaxies, which is dependent on the size of X-ray halo which they can maintain, may be an indicator of their possession, or lack of, a dark matter halo. This raises the question of how galaxies could lose (or gain) an extensive dark matter halo, and how we might distinguish between different processes which could affect such haloes. This is clearly a question which deserves further consideration, and it seems likely that both improved models and further observations of early-type galaxies will be required before it can be answered.

ACKNOWLEDGMENTS

We are grateful to S. Helsdon for the use of his three-dimensional gas properties software and J. Kempner for the use of his Chandra...
reduction software. We are also indebted to D. Forbes for his help in the early stages of the project, and to an anonymous referee for their efforts to improve the paper. This research has made use of NED and DSS. This research was supported in part by NASA Grant Nos NAG5-10071 and GO2-3186X.

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