

The mass and dynamical state of Abell 2218

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ABSTRACT

Abell 2218 is one of a handful of clusters in which X-ray and lensing analyses of the cluster mass are in strong disagreement. It is also a system for which X-ray data and radio measurements of the Sunyaev–Zel’dovich decrement have been combined in an attempt to constrain the Hubble constant. However, in the absence of reliable information on the temperature structure of the intracluster gas, most analyses have been carried out under the assumption of isothermality. We combine X-ray data from the *ROSAT* PSPC and the *ASCA* GIS instruments, enabling us to fit non-isothermal models, and investigate the impact that this has on the X-ray derived mass and the predicted Sunyaev–Zel’dovich effect.

We find that a strongly non-isothermal model for the intracluster gas, which implies a central cusp in the cluster mass distribution, is consistent with the available X-ray data and compatible with the lensing results. At $r < 1$ arcmin, there is strong evidence to suggest that the cluster departs from a simple relaxed model. We analyse the dynamics of the galaxies and find that the central galaxy velocity dispersion is too high to allow a physical solution for the galaxy orbits. The quality of the radio and X-ray data does not at present allow very restrictive constraints to be placed on H_0 . It is apparent that earlier analyses have underestimated the uncertainties involved. However, values greater than $50 \text{ km s}^{-1} \text{ Mpc}^{-1}$ are preferred when lensing constraints are taken into account.

Key words: galaxies: clusters: individual: A2218 – cosmic microwave background – dark matter – distance scale – gravitational lensing – X-rays: galaxies.

1 INTRODUCTION

The masses of galaxy clusters can be determined in three main ways: using the velocity dispersion of the galaxies, the pressure gradient in the hot intracluster gas derived from X-ray imaging and spectroscopy, and by analysing the lensing of background galaxies by the cluster potential. Each of these approaches involves assumptions and is vulnerable to various systematic errors. It is therefore useful to compare the results of the different techniques. The X-ray and lensing approaches are generally considered the most reliable. Results from them have now been compared for a number of clusters (Fort & Mellier 1994). The agreement is often reasonable, but there are a few spectacular exceptions, of which Abell 2218 (hereafter A2218) is the most well-studied example.

A2218 is an optically compact (core radius ≈ 1 arcmin; Dressler 1978) cluster of galaxies, located at a redshift of 0.171 (Kristian, Sandage & Westphal 1978), and classified as richness class 4 (Abell, Corwin Jr & Olowin 1989). The cluster appears well relaxed, with the majority of the galaxies centred around the sole cD galaxy. However, detailed photometric studies (Pello–Descayre et al. 1988; Pello et al. 1992) suggest the existence of a second,

smaller galaxy concentration, displaced from the cD by 67 arcsec. Spectroscopic study (Le Borgne, Pello & Sanahuja 1992) performed on the central region (< 4 arcmin) of A2218 has provided redshift information for 66 of the objects within the core, and has shown that the average velocity dispersion is 1370 km s^{-1} .

A succession of X-ray telescopes have allowed the properties of the hot gas within A2218 to be established. With the *Einstein* IPC and HRI (Perrenod & Henry 1981) and *ROSAT* PSPC (Siddiqui 1995), the emission was found to be smooth (on scales ~ 1 arcmin), azimuthally symmetric and centred on the cD galaxy. Fitting a polar profile of the surface brightness with a King model gave a core radius of 58_{-16}^{+16} arcsec and a β -value of 0.63 (Boynton et al. 1982). Integrated spectral analyses with *Ginga* gave a gas temperature of $6.72_{-0.4}^{+0.5}$ keV and metallicity of $0.2_{-0.2}^{+0.2} Z_{\odot}$ (McHardy et al. 1990). By virtue of *Ginga*’s bandwidth, this determination is commonly accepted as the most accurate estimate of the mean gas temperature. Most recently, deep observations with the *ROSAT* HRI (Markevitch 1997) have shown the presence of significant X-ray substructure within the cluster core, suggesting that the cluster may have undergone a recent merger event. This may account for the absence of any signs of a cooling flow in the cluster (Arnaud, private communication; White 1996).

Several previous comparisons (Miralda-Escude & Babul 1995;

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Kneib et al. 1995, 1996; Natarajan & Kneib 1996) between strong lensing and X-ray analyses have found a factor of 2 discrepancy in the gravitating masses predicted by the two methods. Suggested explanations have centred upon the assumption of hydrostatic equilibrium for the cluster gas, the possibility that magnetic fields may provide significant pressure support to the gas and the presence of substructure within the cluster.

The Sunyaev–Zel’dovich decrement associated with A2218 has been extensively studied (Jones et al. 1993; Birkinshaw & Hughes 1994; Saunders 1996). These results have been used, in conjunction with X-ray data, to constrain the Hubble constant (Silk & White 1978; McHardy et al. 1990; Birkinshaw & Hughes 1994). These analyses have been made in the absence of reliable information about temperature variations in the intracluster gas and have therefore been forced to make simplifying assumptions, such as that of isothermality (McHardy et al. 1990; Birkinshaw & Hughes 1994; Kneib et al. 1995). This assumption is without a strong theoretical foundation and conflicts with the results of most cosmological simulations (Navarro, Frenk & White 1995, 1996; Tormen, Bouchet & White 1996), which show temperature declining with radius, and mass distributions which have a central cusp. The question then arises as to whether simplifying assumptions have significantly biased the conclusions of previous X-ray analyses. For example, is the apparent discrepancy between the X-ray and lensing masses unavoidable or does it arise simply from the use of inappropriate assumptions in the X-ray analysis?

Motivated by the desire to avoid such restrictive assumptions, we have carried out an X-ray analysis which combines the capabilities of *ROSAT* and *ASCA*. The limited spectral bandwidth and resolution of the *ROSAT* PSPC is compensated for by the superior spectral properties of *ASCA*. Conversely, the poor spatial performance of *ASCA* is complemented by the higher spatial resolution of *ROSAT*. This approach has never before been applied to A2218.

The central aim of this paper is to improve our understanding of A2218 by comparing the results of our X-ray analysis with lensing, Sunyaev–Zel’dovich and galaxy velocity studies. It also serves as a case study on the possible dangers of assuming an isothermal gas, when one has no information to the contrary. Throughout the paper we assume an Einstein–de Sitter cosmology with $\Omega = 1$, $q_0 = 0.5$ and $H_0 = 50 \text{ km s}^{-1} \text{ Mpc}^{-1}$, except where otherwise stated.

2 X-RAY ANALYSIS

The objective of the analysis is to use spatially and spectrally resolved X-ray data to constrain models of the distribution of gas properties in the cluster. For an in-depth discussion of the procedures covered in this section, see Cannon (1997).

2.1 Spectral-image modelling

We work with X-ray spectral images, which constitute blurred records of the spectral properties of the cluster projected along the line of sight. Since information about the disposition of material perpendicular to the plane of the sky is not available, it is necessary to make some assumptions about the geometry of the source. We assume that the cluster is spherically symmetric. In practice, A2218 is slightly elliptical, with an axis ratio of 0.8 (Siddiqui 1995). However, this modest ellipticity should not introduce any serious errors into our derived masses (Fabricant, Rybicki & Gorenstein 1984).

It is important to allow for the spatial and spectral blurring introduced by the telescope, as described by the instrument point

spread function (psf) and energy response matrix. We adopt a forward fitting approach (Eyles et al. 1991; Watt et al. 1992), in which the properties of the gas are parametrized as analytical functions of cluster radius. The emission from each spherical shell in the cluster is computed using a Raymond & Smith (1977, hereafter RS), hot plasma code. After correcting for cluster redshift, the spectral emissivity profiles are folded through the instrument spectral response, projected along the line-of-sight, rebinned into an xy grid and blurred with the psf. This produces a predicted spectral image which can be directly compared to the observed data, using a maximum-likelihood statistic. Iteratively adjusting the model parameters results in a ‘best-fitting’ to the data.

Using analytical forms for the radial distribution of gas properties has the advantage of regularizing the solution (i.e. suppressing instabilities in the deprojection and deblurring processes), however one runs the risk that the solution may be dictated by the mathematical function imposed. This can lead to overconfidence in derived results, as acceptable alternatives which might fit the data are ruled out by the limitations of the available models. The commonly employed restriction of isothermality is an extreme example of this. We attempt to avoid this problem by using a range of radial functions. This is particularly important for the temperature, and we use not only a number of parametric forms for $T_{\text{gas}}(r)$, but also an alternative approach in which $T_{\text{gas}}(r)$ is determined indirectly, by fitting a model for the mass distribution, as discussed below. The gas density profile is much more readily determined by the X-ray data, so we have fitted only two radial forms.

Assuming that the intracluster gas is in hydrostatic equilibrium in the potential well of the cluster, the total gravitating mass within radius r , from the centre of the cluster, is related to the gas temperature and density by

$$M_{\text{grav}}(r) = -\frac{kT_{\text{gas}}(r)}{G\mu m_p} \left[\frac{d \ln \rho_{\text{gas}}(r)}{d \ln r} + \frac{d \ln T_{\text{gas}}(r)}{d \ln r} \right] r, \quad (1)$$

where $\rho_{\text{gas}}(r)$ is the gas density, $T_{\text{gas}}(r)$ the gas temperature, μ the mean molecular weight and m_p the proton mass.

2.1.1 Gas density

The gas density is well constrained by the X-ray surface brightness, since the PSPC is largely insensitive to variations in temperature for $T > 3 \text{ keV}$. Surface brightness profiles are generally well fitted by core-index type models (King 1962, 1972):

$$\rho_{\text{gas}}(r) = \rho_{\text{gas},0} [1 + (r/r_c)^2]^{-\alpha_p} \quad (2)$$

where $\rho_{\text{gas},0}$ is the central gas density normalization (a.m.u. cm^{-3}), r_c the core radius (arcmin) and α_p the density index (unitless). The main deviations from this form occur at small radii, where cooling flows give rise to surface brightness cusps in many clusters, though not in A2218.

Recent N -body studies (Navarro et al. 1995, 1996; Tormen et al. 1996) have achieved good fits to dark matter (DM) and gas profiles in simulated clusters with an alternative description. The profiles are found to steepen progressively, from $\rho_{\text{gas}}(r) \propto r^{-1}$ in the core, to r^{-3} near the virial radius, following the form

$$\rho_{\text{gas}}(r) = \rho_{\text{gas},0} [x(1+x)^2]^{-1}, \quad (3)$$

where $x = r/r_s$, r_s being the scale radius (arcmin). Both of the above analytical forms have been fitted to the X-ray data for A2218.

2.1.2 Gas temperature

The gas temperature distribution is less well determined, since this requires a combination of spatial and spectral resolution which has not generally been available in the past. We consider a variety of simple models: a linear temperature ramp (LTF),

$$T_{\text{gas}}(r) = T_{\text{gas},0} - \beta r, \quad (4)$$

where $T_{\text{gas},0}$ is the gas temperature (keV) at the cluster centre, β the temperature gradient (keV arcmin⁻¹) and r the radius (arcmin); a King-type temperature description (KTF),

$$T_{\text{gas}}(r) = T_{\text{gas},0} [1 + (r/r_T)^2]^{-\beta}, \quad (5)$$

where r_T is the temperature core radius (arcmin) and β the temperature index (unitless); and a polytropic temperature description (TTF),

$$T_{\text{gas}}(r) = T_{\text{gas},0} [1 + (r/r_c)^2]^{\alpha_p(1-\gamma)}, \quad (6)$$

where r_c is the gas density core radius (arcmin) and γ , the polytropic index (unitless), is fitted as a free parameter varying between isothermality ($\gamma = 1$) and adiabaticity ($\gamma = 5/3$).

2.1.3 Gravitating mass

An alternative to fitting $\rho_{\text{gas}}(r)$ and $T_{\text{gas}}(r)$ is to fit $\rho_{\text{gas}}(r)$ and $M_{\text{grav}}(r)$. The corresponding temperature profile can then be inferred, via equation 1. We use several alternative forms, motivated by the distribution of galaxies in clusters (Rood et al. 1972), and by the results of N -body simulations. These include: a core-index description (DMF),

$$\rho_{\text{DM}}(r) = \rho_{\text{DM},0} [1 + (r/r_c)^2]^{-\alpha_{\text{DM}}}, \quad (7)$$

where $\rho_{\text{DM},0}$ is the central dark matter density normalization (a.m.u. cm⁻³), r_c the core radius (arcmin) and α_{DM} the density index (unitless); a model based upon the simulations of Navarro et al. (1995) (DNF),

$$\rho_{\text{DM}}(r) = \rho_{\text{DM},0} [x(1+x)^2]^{-1} \quad (8)$$

where $x = r/r_s$ and r_s is the scale radius (arcmin); and a Hernquist profile (DHF),

$$\rho_{\text{DM}}(r) = \rho_{\text{DM},0} / [2\pi b(1+b)^3] \quad (9)$$

where $b = r/r_s$ and r_s is the scale radius (arcmin).

2.1.4 Fitting the models

Determination of the best-fitting parameters for a cluster model proceeds in the way commonly employed for spectral fitting. The fit statistic employed is maximum likelihood, rather than chi-squared, since the data are generally strongly Poissonian. The fit and its local slope are determined at some initial position in the parameter space. This information is used to predict an improved set of model parameters and the fit statistic is re-determined. The process is iteratively repeated until the statistic slope falls below a pre-determined value. One limitation of this method, however, is that the fitting tends to follow the local gradient in the statistic, until it encounters a minimum. Thus the fit can become trapped in a ‘valley’, which it regards as the best-fitting result, even though a more suitable combination of parameters may occur elsewhere. To avoid this, we randomly perturb models during analysis and force them to re-fit (to check if the same minimum is produced).

Confidence regions can be derived for each best-fitting parameter, by offsetting the parameter of interest from its best fit value

(both above and below the best fit), and re-optimizing the other parameters. The resulting increase in the fit statistic, from its optimum value, is used to determine what offset would need to be applied in order to create a user-defined change in the statistic. This defines the required confidence interval. We use the form of the maximum likelihood statistic introduced by Cash (1979), such that changes in the statistic have the same significance as changes in chi-squared. Hence, for each parameter, an increase in the Cash statistic of 1 corresponds to a 68 per cent confidence interval, and an increase of 2.71 to 90 per cent confidence. The above process is repeated for each model parameter for which an error estimate is required.

Errors in physical quantities which are functions of radius (such as mass or temperature) are generally affected by several model parameters. We derive error envelopes for such quantities by taking the outer envelope of all of the curves generated by perturbing each free parameter to its upper and lower error bounds. Because these envelopes are derived using every parameter combination, each offset to its error bounds, the result is a *conservative* estimate of the statistical uncertainty.

Once the total gravitating mass distribution has been determined (using equation 1, if the mass has not been modelled directly), the various mass components in the cluster can be separated. The gas mass profile is calculated from the fitted parameters. The galaxy mass profile can be constructed from the observed luminosity profile for the cluster, assuming a constant mass-to-light ratio. Subtraction of these components from the total mass profile then yields the dark matter profile.

2.2 ROSAT PSPC reduction

The aim of the *ROSAT* analysis is to obtain well-constrained gas density parameters, which can then be utilized in the *ASCA* analysis.

The raw data, obtained on 1991 May 25, were reduced using the Starlink ASTERIX X-ray analysis package. Periods of high background were removed from the data, reducing the effective exposure time to 42 ks but making the background subtraction substantially more reliable.

Subtraction of the X-ray background was accomplished by selecting data from an annulus (27–33 arcmin), ignoring pixels covered by the detector support structure or containing point source emission. This background sample was then extrapolated to cover the whole field, using the PSPC energy-dependent vignetting function. Since the X-ray surface brightness profile for A2218 can be traced to a maximum radius of 12 arcmin, the chosen background annulus is free of source emission. In the following analysis, the data are restricted to lie within 9 arcmin to avoid possible systematic effects from uncertainties in the background subtraction at large radius.

The exposure-corrected, background-subtracted PSPC data were summed to provide an integrated cluster spectrum and split into concentric annuli, centred on the cluster core, within which spectra were extracted. Fitting these spectra gives an indication of the depth of the cluster potential well and the radial structure of the cluster gas density and temperature parameters (see Fig. 1). However, any gradients present in these distributions will tend to be underestimated, as a result of the smoothing effects of the instrument psf and projection along the line-of-sight. Using annuli of width greater than the instrument psf minimizes the former effect.

In order to create a spectral image data set, allowing a full spatial and spectral analysis, the data were formed into images of channel

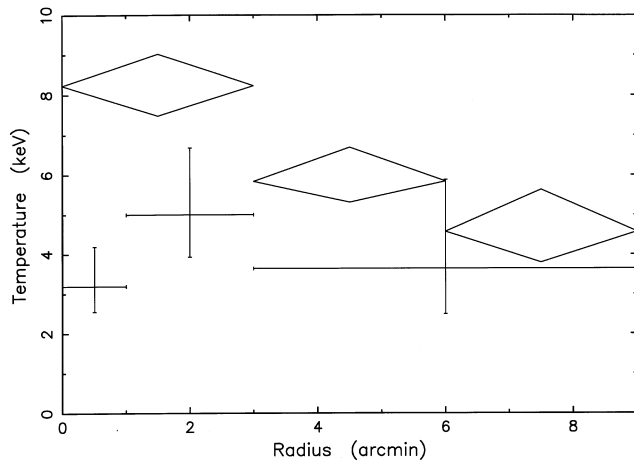


Figure 1. Gas temperatures derived in projected annuli. The barred crosses are taken from *ROSAT* PSPC analysis and the diamonds from *ASCA* GIS analysis. The results suggest a temperature decline with radius, with weak evidence (from the PSPC) for central cooling.

width 10, over the channel range 11–230 (approximately 0.2–2.3 keV). This results in a data cube, from which specific regions can be selected and analysed.

Within the cluster emission there is one bright source contaminating the data, located at a radius of 11.1 arcmin from the cluster centre. In the PSPC analysis, the point source can be eliminated by ignoring the data collected in that region. However, this is not possible with *ASCA*, since the extended psf ensures that it is not discernable as a discrete source. To determine whether the source significantly affects our analysis, we model it using the PSPC data. The cluster emission is first fitted with the point source pixels removed. This model of the cluster emission is then subtracted from the original data, leaving behind just the point source, which is fitted with a power-law spectral model.

The fitted index, 1.25, indicates the softness of the source – the majority of the flux is emitted below 0.5 keV. This is consistent with identification of the source as SAO17151, a bright star with a soft spectrum (Markevitch 1997). If the PSPC-determined model for the point source is subtracted from the *ASCA* data, the cluster fits are modified to the extent that a 1.5 per cent difference in the total gravitating mass at 2 Mpc results. This effect is negligible compared to other errors, so no attempt has been made to remove the source from the *ASCA* data.

2.3 *ASCA* GIS reduction

The *ASCA* analysis aims to constrain the gas temperature and metallicity profiles, using the PSPC-derived gas density profile. A2218 was observed by the *ASCA* X-ray telescope on 1993 April 30. In this paper we use only data from the two gas imaging spectrometers (GIS2 and GIS3), since these have a wider field of view (~ 50 arcmin diameter) and greater high-energy detector efficiency (up to 10 keV) than the CCD detectors (SIS0 and SIS1). An additional reason is that an accurate model for the large, asymmetrical and energy-dependent psf is available for the GIS detectors, constructed from Cyg X-1 observations. These restrict analysis to a maximum radius of 18 arcmin and an energy-range of 1.5–11 keV (Takahashi et al. 1994), which is not a significant limitation in the case of A2218.

Standard procedures for *ASCA* analysis, followed in this paper, are given by Day et al. (1995). The recommended screening criteria

are applied to the raw data, removing data taken during times of high background flux. Subtraction of the X-ray background is complicated by the telescope psf. This has the effect of ensuring that no region of the detector is free from source flux. Hence, we extract an ‘average’ background data set from the publicly distributed set of blank-sky pointings (Day et al. 1995). These data sets suffer from mild point-source contamination, as sources are not completely averaged out, but are currently the best available solution.

The results of a naive annular spectral analysis of the *ASCA* data are shown in Fig. 1. However, it is important to bear in mind the limitations of this approach. Cross-talk between annuli is significant (Takahashi et al. 1994), and the energy-dependent spreading of flux results in a distorted temperature profile, such that analysis of a simulated isothermal cluster would give a temperature which rises with radius. In practice, the temperature appears to *decline* with radius, indicating that a real gradient is present.

For 3D analysis, spectral-image data sets with contiguous energy bands of width 50 raw channels are created. Since the cluster centre is offset from the detector centre, data beyond a radius of 9 arcmin are not fitted (the offset added to the radial extent of the source is similar to the maximum radius where psf calibrations apply). This restriction minimizes the effects of poor calibration and high background near the detector edge. As both GIS instruments behave similarly, the data sets are fitted simultaneously. The Cash statistic has been used to identify best-fitting models, but similar results – for best-fitting parameters and for comparison between the quality of fit of different models – are obtained using the χ^2 statistic.

3 RESULTS

We first compare the results of our analysis with published studies, to investigate whether the fitted models are consistent with earlier work on A2218.

Integrated spectral analyses of clusters produce ‘mean’ quantities which are representative of the entire object. Assuming isothermality, McHardy et al. (1990) derived a gas temperature of $6.72^{+0.5}_{-0.4}$ keV together with an iron abundance of $0.2^{+0.2}_{-0.2} Z_{\odot}$ (using an RS emission code, where all other heavy element abundances were fixed at $0.5 Z_{\odot}$). This is in agreement with an earlier, much less well-constrained examination (Perrenod & Henry 1981). More recently, Mushotzky & Loewenstein (1997) have derived $T = 7.2$ keV and $Z = 0.18 \pm 0.07 Z_{\odot}$, from an integrated *ASCA* spectrum.

Fitting an RS model to our *ROSAT* data results in a gas temperature of $4.7^{+1.1}_{-0.9}$ keV and a hydrogen absorption column of $2.6^{+0.2}_{-0.1} \times 10^{20} \text{ cm}^{-2}$ (with metallicity fixed at the *Ginga* value). This absorption agrees with the Stark level of $2.58^{+0.18}_{-0.18} \times 10^{20} \text{ cm}^{-2}$ (Stark et al. 1992). The temperature is lower than the *Ginga* result of McHardy et al. (1990), but the energy range of the PSPC is not very suitable for determining the temperature of such hot gas. It has been found previously (Markevitch & Vikhlinin 1997) that PSPC results tend to be biased low for high-temperature clusters. Fitting an integrated spectrum simultaneously to the GIS2 and GIS3 data gives a gas temperature of $6.73^{+0.46}_{-0.44}$ keV and a metallicity of $0.20^{+0.08}_{-0.08} Z_{\odot}$ (with the hydrogen column fixed at the PSPC value), in good agreement with the *Ginga* and Mushotzky & Loewenstein (1997) results.

The ability to extract and analyse spectra from independent regions of the cluster represents a significant advance over analysis of the integrated emission. Fig. 1 shows the derived annular temperature profiles from both *ROSAT* and simultaneous GIS2/

GIS3 analysis. The PSPC results are consistent with Siddiqui (1995), with a possible temperature drop visible in the central bin. However, the evidence for central cooling is statistically rather weak, and the derived central cooling time of $\sim 1.5 \times 10^{10}$ yr is comparable with the Hubble time, so a strong steady-state cooling flow appears to be ruled out.

If the hydrogen column is fitted, using the PSPC data, it is found to be consistent with the Stark value (Stark et al. 1992) throughout the cluster, apart from a slight rise in the centre. This may be a result of matter deposited by an earlier, disrupted cooling flow (as noted by Siddiqui 1995). The ASCA analysis suggests that the metallicity may be slightly lower than the integrated value in the cluster centre, with a shallow radial rise. However, all points are consistent with the McHardy et al. (1990) value of $0.2 Z_{\odot}$.

Analysis using spectral-image data sets allows extraction of the 3D gas density and temperature distributions within A2218. In the subsequent cluster analysis, both ‘temperature models’ [fitting for $\rho_{\text{gas}}(r)$ and $T_{\text{gas}}(r)$] and ‘mass models’ [fitting for $\rho_{\text{gas}}(r)$ and $M_{\text{tot}}(r)$] are used. Parameters representing the metallicity and cluster position are also fitted.

The best constrained parameters derived from PSPC analysis pertain to the shape of the gas density distribution. Comparable analyses have been carried out using *Einstein* (Perrenod & Henry 1981; Boynton et al. 1982; Birkinshaw & Hughes 1994), and *ROSAT* (Siddiqui 1995) data. These studies agree that when a King profile is assumed, A2218 is well modelled with a core radius, r_c , of ~ 1 arcmin and an index, α_p , of ~ 1 (equivalent to a β -value of 0.67). Higher resolution analysis, using the *ROSAT* HRI, has been performed by Squires et al. (1996) and Markevitch (1997). These studies detect the presence of smaller-scale structure, with three surface brightness peaks visible within the central arcmin, none of which coincides with the central cD galaxy. This structure cannot be resolved with either the PSPC or GIS detectors, and indicates that the core of A2218 departs from a fully relaxed state.

Since *ASCA* is poor at constraining the gas density distribution for such a compact source, the PSPC fit values for core radius and index are carried over into the *ASCA* spectral-image analysis. To obtain the appropriate density parameters, a linear temperature ramp model is fitted to the entire PSPC data within a radius of 9 arcmin, with the temperature parameters fixed at those derived from an initial fit to the GIS data. This model is then re-fitted to the GIS data, complete to a radius of 9 arcmin, with the gas density core radius and index fixed, allowing a fit of the temperature parameters. In an iterative process, this model is alternately fitted to the PSPC and GIS data sets until no further change is observed in the parameter values. With consistency achieved, the ‘standard’ gas distribution for A2218 is determined to be $r_c = 0.91^{+0.03}_{-0.03}$ arcmin, $\alpha_p = 0.96^{+0.02}_{-0.01}$, in good agreement with the comparable results discussed above. If an NFW profile is assumed, the required scale radius, r_s , is $10.27^{+0.21}_{-0.20}$ arcmin. However, the NFW parametrization is neither preferred nor disallowed by the PSPC data, so we only use a King parametrization for the gas density distribution in the following analysis.

3.1 All cluster data

Fixing the gas density shape parameters at these King values, a range of models were fitted to the *ASCA* spectral-image data. On the basis of their Cash statistic, a set of models best fitting the observed cluster data within a radius of 9 arcmin is selected (Table 1 lists the main parameters for each model) as representative of A2218. As can be seen from the table, the isothermal model is a significantly

Table 1. Temperature and statistic parameters for a variety of fitted 3D models are shown. Note that the MMMC is not a best-fitting model in the same sense as the others, as is described in the text. For all models, the gas density core radius, r_c , and index, α_p , are fixed at the values determined from the *ROSAT* data. Explanations for the model acronyms are given in the text.

Model Form	Central T_{gas} (keV)	T_{gas} Gradient (various)	Relative Cash Statistic
LTF	9.64	0.63	−636.08
LTF (ISO)	7.90	zero	−626.85
TTF	19.01	1.20	−634.53
KTF	8.98	3.18	−635.96
DNF	15.59	n/a	−636.12
DMF	9.24	n/a	−635.20
DHF (MMM)	20.42	n/a	−635.33
MMMC	16.44	n/a	−632.50

poorer fit to the data. It is included for comparison with the other models. All of the temperature profiles obtained for this set (apart

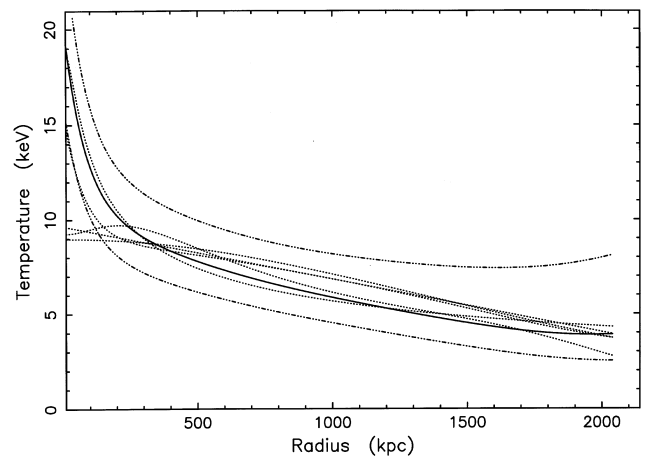


Figure 2. Fitted 3D temperature profiles for the cluster gas. The MMM (solid) is plotted together with its 90 per cent error envelope (dash-3dot) and the remaining best-fitting models (dotted). All of the profiles feature gas temperatures which decrease by a factor of ~ 2 or more within the region of analysis, and are consistent beyond the cluster core.

from that for the isothermal model) are plotted in Fig. 2. Beyond the central arcmin (~ 230 kpc) the profiles are in good agreement and quite non-isothermal. The typical 90 per cent confidence envelope for an individual model (remember that these are conservative envelopes) generally encompasses the spread of these best-fitting profiles (a single error envelope is included to illustrate this point). Within the central region, which lies within a single *ASCA* psf, a greater spread in temperature is allowed by the data. However, despite this divergence in temperature at small radius, all of the best-fitting models, bar the isothermal model, have similar Cash statistics (see Table 1).

The abundance of heavy elements has been assumed, in all of the above models, to be constant over the cluster. However, the spectral capabilities of *ASCA* allow us to test this assumption. Allowing a linear metallicity gradient with the best-fitting linear temperature ramp model gives a slope of $2.8^{+4.5}_{-6.5} \times 10^{-2} Z_{\odot} \text{ arcmin}^{-1}$, a value consistent with uniform metallicity. The effect of this best-fitting slope upon other model parameters is negligible, hence freezing the metallicity gradient at zero does not bias our analysis.

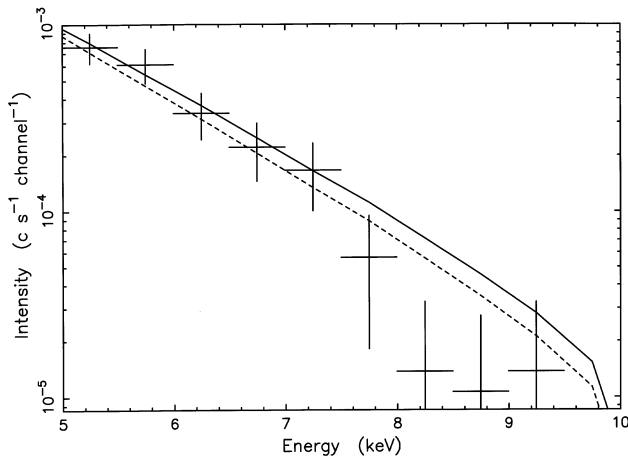


Figure 3. The GIS3 spectrum from the central 1 arcmin (crosses) is compared to the prediction from the MMM model (solid) and the isothermal model (dashed). The MMM model provides more flux at high energy, because of the centrally increasing temperature, but the difference is very small. Both models are consistent with the observed data.

3.2 Central cluster data

We now examine the claim that lensing analyses require a larger cluster mass than is consistent with the X-ray data. The model which provides the greatest gravitating mass at the critical radius (~ 85 kpc) is therefore selected for examination. This model, the DHF best fit, using a Hernquist description for the DM distribution and a King description for the gas density profile (see Table 1), implies a high central gas temperature. In the following comparisons, we refer to this model as the ‘maximum-mass model’ (MMM).

The MMM temperature profile features a factor of 2 rise within the central 1 arcmin. This raises two questions: does such a steep temperature gradient raise physical problems (would it be convectively unstable?), and is it consistent with the X-ray spectral data observed within the central region? We will return to the first question in Section 5.

To address the latter question, GIS3 spectra integrated within $r = 1$ arcmin, where the MMM temperature rises steeply, are compared with the predictions of the MMM and isothermal models in Fig. 3. For clarity, only the energy range of 5–10 keV is displayed, since this is where the impact of very hot gas will be most apparent. Although the MMM provides a reasonable fit to the spectral imaging data *as a whole*, it does not follow that the data in the central regions need be consistent with the high model temperature. In practice, for both instruments (while the GIS2 spectra are not shown in Fig. 3, they behave similarly to the GIS3 spectra) the MMM is a good match to the data. The isothermal model is, however, also consistent with the restricted data set. The conclusion from this is that while the data do not rule out a central temperature rise, they do not require one either. The reason for this is that within the *ASCA* bandpass, plasmas with temperatures of 8 and 18 keV do not have substantially different spectral signatures and are thus difficult to differentiate (this is analogous to the difficulty that the PSPC has in dealing with clusters hotter than 2–3 keV). This problem is compounded by the limited spatial resolution of *ASCA*.

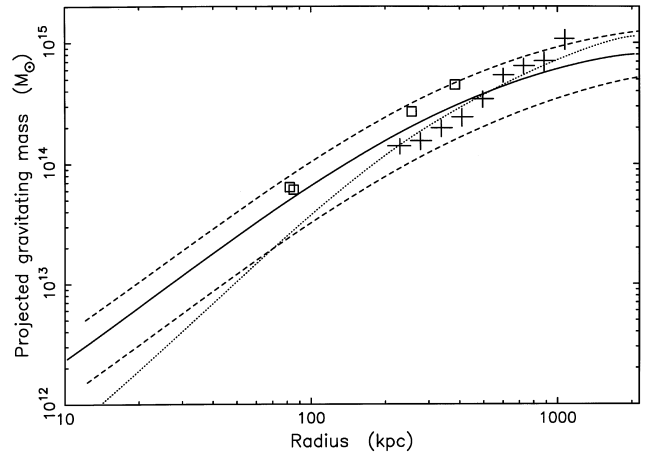


Figure 4. Projected gravitating mass profiles for the MMM (solid line) and isothermal (dotted line) are plotted. Also shown is the 90 per cent error envelope for the MMM (dashed lines). Overlaid are strong lensing points from Kneib et al. (1995) and Loeb & Mao (1994) (boxes), together with the weak lensing points of Squires et al. (1996) (crosses).

4 COMPARISON OF X-RAY AND LENSING MASSES

Deep optical observations of A2218 reveal a number of major arcs and a wealth of minor arclets. These features are the result of gravitational lensing, an effect which is independent of the physical state of the cluster gas. Instead, uncertainty lies in the characteristics of the background galaxies and the possibility of matter subclumps along the line-of-sight.

Using the models fitted to A2218, we can derive projected gravitating mass profiles, suitable for comparison with the results of lensing analysis. This involves assuming a maximum outer radius for the cluster mass distribution. In the following analysis we take this to be the maximum radius of the data used in cluster fitting, which is 9 arcmin (~ 2 Mpc). The choice of projection radius has a minor impact upon the derived projected mass profiles (compared to other uncertainties) so long as the chosen radius is sufficiently large, ≥ 2 Mpc. For example, the difference in projected mass within 2 Mpc, between models with maximum radii of 2.0 and 3.0 Mpc, is 9 per cent.

Since lensing analysis measures the matter distribution on both small (strong lensing occurs where the surface mass density is high) and large (weak lensing is theoretically observable to the edge of the cluster) scales, comparison with X-ray results is extremely informative. In Fig. 4 the X-ray derived projected mass profiles for the MMM and isothermal model are plotted, together with the lensing results of Kneib et al. (1995), Loeb & Mao (1994) and Squires et al. (1996).

4.1 Strong lensing

Strong lensing analysis has been performed, using spectroscopically observed arcs, by a variety of groups (Loeb & Mao 1994; Kneib et al. 1995, 1996; Saraniti, Petrosian & Lynds 1996; Natarajan & Kneib 1996). These analyses provide the gravitating mass within the critical radius associated with the formation of giant arcs, which in A2218 is 22.1 arcsec (~ 85 kpc).

The two strong lensing points, plotted in Fig. 4 at this radius, are consistent with a projected mass of $\sim 6 \times 10^{13} M_{\odot}$, despite their use of different mass distributions (Kneib et al. 1995 assume a bipolar

Table 2. Projected gravitating masses from strong lensing and X-ray analysis are compared at the radii used by Kneib et al. (1995). At the critical radius, the isothermal mass is a factor of 2 too low, although the discrepancy reduces greatly at larger radii.

Source/Mass	85 kpc ($\times 10^{13} M_{\odot}$)	256 kpc ($\times 10^{14} M_{\odot}$)	383 kpc ($\times 10^{14} M_{\odot}$)
Kneib 1995	6.1	2.7	4.5
Loeb & Mao 1994	6.4	–	–
MMM	$5.3^{+1.2}_{-4.1}$	$2.0^{+0.5}_{-1.6}$	$3.0^{+0.7}_{-2.4}$
Isothermal	$2.8^{+0.2}_{-0.2}$	$1.6^{+0.2}_{-0.1}$	$2.8^{+0.1}_{-0.1}$

mass model while Loeb & Mao 1994 use an isothermal sphere distribution). The corresponding projected mass for the MMM is $5.3^{+1.2}_{-4.1} \times 10^{13} M_{\odot}$. The uncertainty associated with this mass is large enough to include the lensing derived value, so, within the calculated errors, the X-ray and strong lensing analyses are consistent, when the MMM is used. The corresponding mass from the isothermal model is $2.8^{+0.2}_{-0.2} \times 10^{13} M_{\odot}$ (see Fig. 4), in agreement with the factor of 2 discrepancy reported by previous analyses (Loeb & Mao 1994; Miralda-escude & Babul 1995; Kneib et al. 1995).

The bipolar mass model of Kneib et al. (1995) was used by these authors to extract a further two masses (see Fig. 4), at the radius of the second mass clump (256 kpc) and at the maximum radius where giant arc constraints can be applied (383 kpc). The projected, enclosed gravitating mass at these radii for both the MMM and the isothermal model are given in Table 2. No error estimates are given by Kneib et al. (1995) for the lensing masses. However, it can be seen that both of these outer lensing points lie just outside the statistical error envelope of the MMM, unlike the mass derived at the critical radius. This is a result of the MMM profile flattening at large radius. Note, however, that both of the outer predicted masses depend upon the bimodal model of Kneib et al. (1995), whereas the inner point can be derived in a model-independent fashion.

The Kneib et al. (1995) bimodal mass model has received additional support from detailed optical observations by Ebbels et al. (1996). In this analysis, the redshift of one of the faint arcs was determined for the first time and found to be in good agreement with the value predicted by Kneib et al. (1995).

The conclusion which can be drawn from this X-ray/strong lensing comparison is that it is *not* clear that the results from the two approaches are inconsistent. We have shown that when a model such as the MMM is used, which includes a central mass cusp, the predicted masses at the critical radius agree within the X-ray statistical error envelope (see Table 2). If the gas is assumed to be isothermal, the previously noted discrepancies can be reproduced (see Fig. 4).

4.2 Weak lensing

A statistical analysis of the weakly lensed arclets has been carried out by Squires et al. (1996), allowing the slope of the surface mass density to be mapped within a radius of ~ 1 Mpc. Fig. 4 shows that, within errors, the magnitudes of the weak lensing points are consistent with the MMM. However, the trend indicated by these points is for a steeper profile, providing more gravitating mass at large radii than is predicted by the MMM.

A significant difficulty with the weak lensing analysis, noted by Squires et al. (1996), is the procedure used for normalization. This is done by defining a reference annulus at large radius, within which the cluster mass contribution is assumed to be negligible. Since the

annulus used by Squires et al. (1996) has an inner radius of 800 kpc, while the X-ray surface brightness profile can be traced to $r > 2$ Mpc, some shear signal from the cluster must actually be present within the reference annulus. Hence the recovered normalization is an underestimate, such that the weak lensing mass profile can only be regarded as a lower bound to the projected mass. The impact of this is examined further in Section 6. The correction for this effect has been estimated by Squires et al. (1996) to be a factor of ~ 1.2 – 1.6 in projected mass.

If the weak lensing points are adjusted to take account of this factor, this has two important implications for the MMM comparison. First, the normalization of all data points increases, bringing the inner points into better agreement with the MMM profile while the outer points move further from consistency. Secondly, because this adjustment is a DC effect for the reconstructed projected surface mass density (of the cluster), it does not act equally on the radially integrated points. Hence, when the normalization is raised, the slope of the weak lensing mass profile in Fig. 4 *increases*, bringing it into greater conflict with the MMM profile. Thus the flatter slope of the MMM cannot be made consistent with the weak lensing points by shifting the reference annulus to larger radii.

Even when the normalization adjustment is applied, this is insufficient to ensure full consistency with the outer strong lensing points of Kneib et al. (1995), which (see Table 2) lie above the values of 1.5 and $2.5 \times 10^{14} M_{\odot}$ predicted at the same radii by weak lensing. There is, however, a well-understood effect whereby the weak lensing signal is suppressed at small radii because of contamination by cluster galaxies, reducing the derived weak lensing mass (Kaiser & Squires 1993; Squires et al. 1996). Correcting for this would bring the inner weak lensing points into greater consistency with both the strong lensing and X-ray results.

Overall, then, this comparison indicates that at large radii (> 250 kpc), the weak lensing and X-ray analyses are reasonably consistent, though the weak lensing results tend to give more mass at large radii. Further work (observations of increased numbers of arclets over a wider field) is required to reduce the uncertainty in the weak lensing analysis and to move the reference annulus to larger radii, where the cluster mass contribution is lower.

5 GAS ENTROPY

In Fig. 5 the derived gas entropy profiles for the best-fitting cluster models are plotted. These indicate that beyond a radius of ~ 120 kpc the entropy increases with radius, as is expected for gas which is convectively stable. However, within this radius three of the best-fitting models (including the MMM) exhibit a slight inward rise in entropy, making the gas convectively unstable. For the MMM, the predicted increase in entropy which occurs between a radius of 120 kpc and the cluster centre is ~ 30 per cent. The reason for this behaviour is that the temperature increases rapidly at small radii while the gas density is forced to flatten (as a result of the use of a King model description). However, it is precisely this temperature increase that allows the model to achieve consistency with the gravitational mass derived from strong lensing.

As noted in Section 3, the NFW gas parametrization is neither preferred nor disallowed by the PSPC data. However, if the King gas density parametrization used for the MMM is replaced by the NFW parametrization, the central entropy drops by ~ 75 per cent (see Fig. 5). This difference is large enough to ensure that entropy rises continuously at all radii, removing the problem of convective instability.

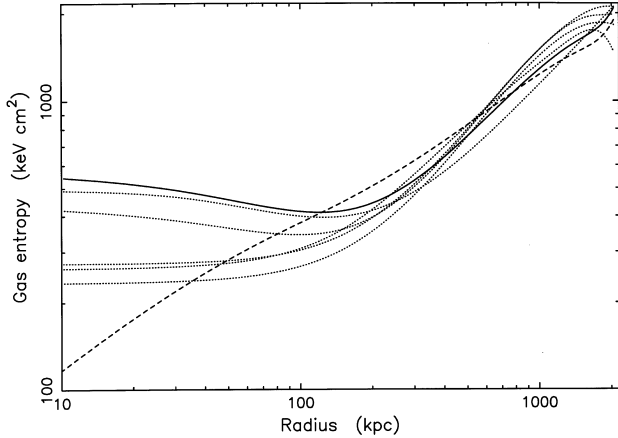


Figure 5. Derived entropy profiles for the cluster gas. The MMM is plotted for both a King (solid) and an NFW (dashed) gas density distribution. The remaining best-fitting models (dotted) are plotted using the King parametrization. It can be seen that all of the models are consistent with a gas which is convectively stable, except within ~ 120 kpc, where the high central gas temperatures of certain models (such as the MMM, see Table 1) lead to an increase in entropy. Where the NFW gas density form is used, the derived entropy increases at all radii.

6 CENTRAL GALAXY MASS

An alternative method for bringing the strong lensing and X-ray analyses into agreement has been examined by Makino (1996). In this study, a massive central galaxy was embedded within the cluster to increase the predicted core mass without violating observational X-ray constraints. As the cD galaxy envelope can be traced to at least 25 arcsec (96 kpc), which encompasses the critical radius, this is potentially an important consideration.

Makino (1996) tested this hypothesis by, first, constructing a total mass distribution which included both cluster and cD components. These were parametrized by a King mass model (equation 7 with $\alpha_{\text{DM}} = 3/2$) and an isothermal sphere mass model ($\alpha_{\text{DM}} = 1$), respectively. Secondly, the gas temperature distribution was constrained to be isothermal at large radius (beyond the cD galaxy) and to rise or fall linearly with r at small radius. By assuming the gas to be in hydrostatic equilibrium, the gas density distribution corresponding to different temperature models was extracted and compared to the observed *Einstein* surface-brightness data.

Constraining the temperature to be isothermal at $r > 31$ arcsec, at the McHardy et al. (1990) derived value, Makino (1996) found that models consistent with both the X-ray surface brightness and with enough central mass to account for the strongly lensed arcs had two notable features. First, a cD component was required to ensure that the critical surface mass density was attained by the model. Secondly, the gas temperature rose sharply within 31 arcsec, reaching a central value of ~ 11 keV. Models which did not include a cD mass contribution, or which assumed the gas to be isothermal at all radii, were unable to provide sufficient mass at small radii to account for the lensing data, whilst remaining consistent with the *Einstein* data.

The projected gravitating mass within 1.5 Mpc, from the model favoured by Makino (1996), of $1.3 \times 10^{15} M_{\odot}$ is in reasonable agreement with the MMM value of $9.0^{+1.4}_{-5.3} \times 10^{14} M_{\odot}$. This consistency is also found at smaller radii, $r = 100$ kpc, where Makino (1996) obtains a mass of $5.2 \times 10^{13} M_{\odot}$ compared to $6.6^{+1.5}_{-5.1} \times 10^{13} M_{\odot}$ for the MMM. It should be noted that the MMM employs a mass profile with a central mass cusp

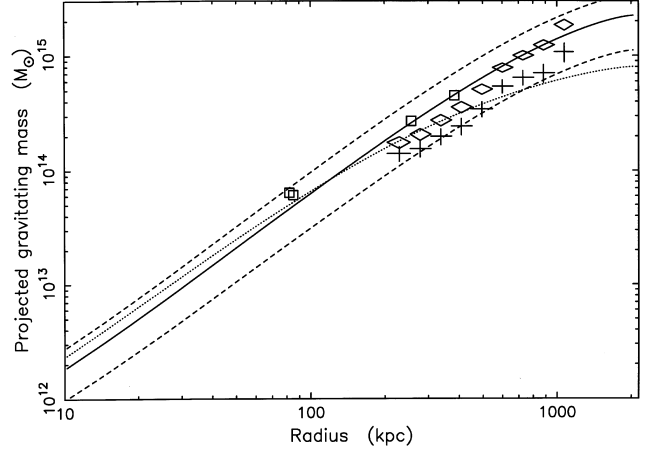


Figure 6. The projected gravitating mass profile for the MMM (dotted line) is compared with that of the MMMC (solid line). Also shown is the 90 per cent error envelope for the MMMC (dashed lines). Overlaid are the strong lensing points from Kneib et al. (1995) and Loeb & Mao (1994) (boxes), together with the weak lensing points of Squires et al. (1996) (crosses). Also shown are the weak lensing points after correction for cluster mass (as predicted by the MMMC) within the lensing reference annulus (diamonds). It can be seen that the MMMC provides a good match to both the strong and weak lensing points (especially after re-normalization of the latter).

($\rho_{\text{DM}} \propto r^{-1}$) but does not include any discrete component corresponding to the central galaxy. We now explore the effect of adding this central component to our model.

Adding a central galaxy of radius 100 kpc and adjustable mass normalisation to the MMM, we find that the statistical quality of the fit deteriorates. The largest additional mass allowed, at the 95 per cent level, is $1.7 \times 10^{12} M_{\odot}$ (within 100 kpc). From here on this model is referred to as the MMMC, since it represents the MMM plus a central galaxy mass. Note however that the MMM, which contains no central mass component, is still statistically preferred (see Table 1).

This central mass is substantially less than the Makino (1996) value of $5.2 \times 10^{13} M_{\odot}$ (recall, however, that our cluster profile contains a central cusp, whilst Makino's has a flat core). Compared to the MMM, it provides a mass increase at the critical radius of only ~ 5 per cent. However, whilst the addition of a central mass component has little impact at small radius, it has the rather counter-intuitive effect of providing more mass at large radius. The reason for this is that, in the case of the MMM, the DM distribution has a scale radius of $1.89^{+0.06}_{-1.16}$ arcmin. When a central mass component is added, the DM profile no longer needs to peak so sharply and its scale radius increases to $6.79^{+0.95}_{-1.49}$ arcmin.

Fig. 6 shows the MMM and MMMC mass profiles compared to the strong and weak lensing results. It can be seen that the increased mass of the MMMC at large radius (compared to the MMM) allows it to be consistent, within its 90 per cent statistical confidence envelope, with both the two outer points derived by Kneib et al. (1995) and the weak lensing points of Squires et al. (1996).

We can use our models to estimate the baseline error involved in the weak lensing analysis, as a result of cluster mass residing within the reference annulus employed by Squires et al. (1996). In Fig. 6 the result of using the MMMC to correct the weak lensing results for this mass is also plotted. It can be seen that the points come into better agreement with the MMMC profile, particularly at $r \geq 500$ kpc. At smaller radii, the weak lensing points still lie systematically below the MMMC profile, although this is to be expected (see Section 4.2) as a result of the dilution of the lensing

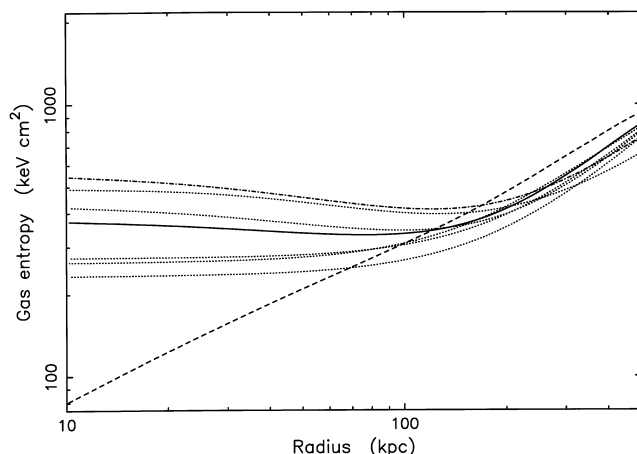


Figure 7. Derived gas entropy profiles for the inner 500 kpc region are plotted. The MMMC (solid line) can be seen to provide a considerably flatter central entropy profile than the MMM model (dash-dot line), where both use a King model for the gas density. If an NFW gas density form is used with the MMMC (dashed line), the derived entropy can be seen to increase at all radii. The remaining best-fitting model profiles (dotted) are included for comparison.

signal by cluster galaxies.

In Fig. 7 the derived gas entropy profile for the MMMC is compared with those from the best-fitting X-ray models within the central 500 kpc region, where the MMM shows a noticeable rise. It can be seen that the MMMC provides a flatter central entropy distribution, such that the gas is less likely to be subject to convective instability.

7 ANALYSIS OF GALAXY MOTIONS

The dynamics of cluster galaxies provide a further way of investigating the mass distribution in clusters. In the case of A2218, galaxy redshifts are available only within a few core radii of the centre. However, this includes the region in which the lensing analysis of Kneib et al. (1995) and the high resolution X-ray observations of Markevitch (1997) suggest that the potential may be seriously disturbed.

Galaxy velocity and position data have been obtained from the NASA Extragalactic Database. This consists largely of the data obtained by Le Borgne, Pello & Sanahuja (1992), who performed an extensive photometric survey of the cluster core. On the basis of the 3σ clipping technique of Yahil & Vidal (1977), 49 of the 53 galaxies with measured redshifts are identified as cluster members. All of these galaxies lie within 3 arcmin of the X-ray centroid of the cluster, which has been adopted as the centre for this optical analysis. The average line-of-sight velocity dispersion, calculated using the 49 cluster galaxies, and corrected (Harrison 1974) to the cluster rest frame, is 1354^{+176}_{-118} km s⁻¹.

This galaxy distribution has been studied using the techniques described by Hobbs & Willmore (1997), using the Jeans equation to relate the spatial and velocity distribution of the galaxies to the gravitating mass profile for the cluster. The aim of such an analysis is to determine the radial behaviour of the anisotropy in the galaxy velocity distribution, since no information about galaxy orbits is otherwise available. Since the radial distributions of galaxy density and velocity are projected along the line of sight, the analysis requires an extrapolation to large radius of the X-ray determined mass profile, the galaxy velocity dispersion profile and the galaxy surface density profile. Extrapolating the galaxy profiles is par-

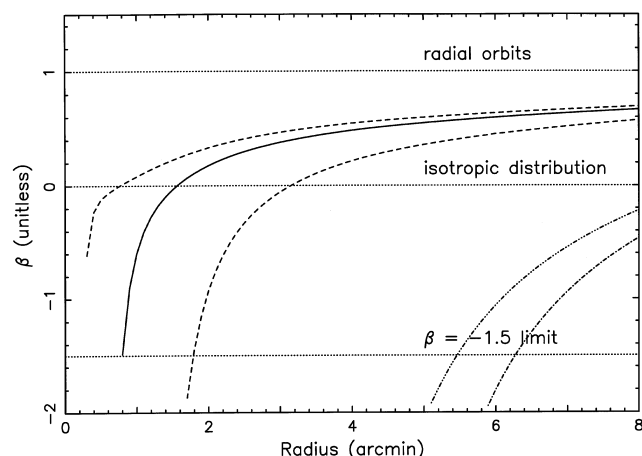


Figure 8. The anisotropy parameter for the two mass models discussed in the text is plotted as a function of radius. The anisotropy derived using the MMMC mass profile is indicated by the solid line, together with its 90 per cent uncertainty envelope (dashed lines). The MMM (dash-dot line) is shown together with its upper error bound (dash-3dot line) only, since the lower bound is unphysical at all radii. The MMMC is acceptable at $r \gtrsim 1$ arcmin, while the MMM is only allowed at radii beyond the observed edge of the optical data. Both models predict predominantly radial orbits at large radius. The $\beta = -1.5$ limit refers to the constraint from simulations (referred to in the text) that anisotropies more negative than -1.5 should not have had time to develop.

ticularly uncertain because data only extend out to ~ 2 arcmin (~ 500 kpc) and include no information (except in projection) regarding the behaviour of these profiles beyond this region.

The anisotropy is studied through β , the anisotropy parameter, which is 1 in the case of purely radial orbits, 0 for an isotropic velocity distribution and increasingly negative as the orbits become predominantly circular, with the limiting case of $-\infty$ for purely circular orbits. It is unlikely, however, that the full range of allowed values of β is covered in any cluster. On the basis of numerical simulations, Yepes & Dominguez-Tenreiro (1992) found that over the lifetime of most clusters, anisotropies corresponding to a β more negative than -1.5 are unlikely to have had time to develop.

For the galaxy surface density profile, a standard modified-Hubble profile $\{\Sigma = \Sigma_0[1 + (r_p/r_c)^2]^{-1}\}$, with a canonical core radius of 250 kpc, has been used. The same parametrization has been adopted by Natarajan & Kneib (1996), who carried out an analysis rather similar to that presented here. The line-of-sight velocity distribution has been fitted by a linear ramp model using a maximum likelihood method. The best fit has a central velocity dispersion of 1478^{+345}_{-321} km s⁻¹, while the gradient, although consistent with zero, is such that the dispersion falls with radius at a rate of -114^{+257}_{-240} km s⁻¹ arcmin⁻¹.

The results of the analysis are shown in Fig. 8, in which the calculated anisotropy parameter profiles for both of the most interesting X-ray mass models (the MMM and MMMC) are shown. Although the shape of the MMMC anisotropy profile is in detail different from those presented by Natarajan & Kneib (1996), the conclusion is the same – there is a divergence in the degree of anisotropy in the core of A2218. This is a result of the high central line-of-sight velocity dispersion being inconsistent with the mass provided by either the MMM or MMMC.

In our anisotropy profiles, the anisotropy plummets to $-\infty$ at a non-zero radius (within the central ~ 1 arcmin in the case of the MMMC model) and within this radius the solution is unphysical, requiring an imaginary velocity dispersion. There are two possible

reasons for this. First, in comparison with other clusters, A2218 has an unusually large central velocity dispersion. Numerical simulations (Schindler & Bohringer 1993) have shown that the velocity dispersion can increase by up to a factor of 2 during a merger event. This occurs during the violent relaxation phase of the merger. At this time, the assumptions underlying any analysis based upon the Jeans equation are invalid. This provides one way in which the unphysical behaviour of the anisotropy parameter can be understood.

Secondly, the unphysical values of β may be indicating that the spherically symmetric model, and assumptions that our solution uses, may be in error. This is supported by several sets of independent evidence which suggest that the cluster core is disturbed, on the scale of ~ 1 arcmin. Kneib et al. (1995) find that the strong lensing data require a bimodal potential, Markevitch (1997) uses high-resolution X-ray data to indicate that the cluster strongly deviates from spherical symmetry in the core and recently Girardi et al. (1997) showed that the combined galaxy spatial and redshift data indicate the presence of two merging galaxy subclumps. Thus, there are good reasons to believe that A2218 has recently undergone a merger event, upsetting the virial equilibrium in the cluster core.

In the case of the MMM model, the solutions are unsatisfactory throughout the region for which galaxy data are available, such that a more widespread upheaval would be required to account for the high velocity dispersion.

8 SUNYAEV-ZEL'DOVICH EFFECT

The Sunyaev-Zel'dovich (SZ) microwave decrement (Sunyaev & Zel'dovich 1972) results from inverse-Compton scattering of cosmic background photons by electrons in the cluster gas. The magnitude of the effect depends upon the integral of the gas pressure along the line of sight and hence has a different dependence on gas density than does the X-ray surface brightness. By combining an analysis of the X-ray emission with the observed SZ effect, it is possible to determine the distance of the cluster, and hence H_0 . Recent measurements (Birkinshaw & Hughes 1994; Jones et al. 1993; Saunders 1996) have been used to place constraints upon the Hubble constant in this manner. Birkinshaw

& Hughes (1994) measure the decrement in a linear strip across the cluster, deriving the 1D profile. Jones et al. (1993) and Saunders (1996) work with 2D images of the decrement, allowing construction of a parametrized model for the observed microwave decrement.

Several different observations of the decrement for A2218 have been combined with X-ray data, assuming an isothermal plasma, to constrain H_0 (Silk & White 1978; McHardy et al. 1990; Birkinshaw & Hughes 1994; Jones 1995). The results obtained vary widely, with the most disparate estimates being 24^{+23}_{-10} km s $^{-1}$ Mpc $^{-1}$ (McHardy et al. 1990) and 65^{+25}_{-25} km s $^{-1}$ Mpc $^{-1}$ (Birkinshaw & Hughes 1994).

In Fig. 9 the predictions of our X-ray analysis are compared with the measurements of Birkinshaw & Hughes (1994) and the allowed envelope of Jones et al. (1993), assuming $H_0 = 50$ km s $^{-1}$ Mpc $^{-1}$. The typical statistical uncertainty for a single model is similar to the scatter between the best-fitting model predictions; both of these are small compared to the SZ error envelope.

At radii greater than 100 kpc, the observed and predicted decrements are in excellent agreement. However, at smaller radii, the decrement observed by Birkinshaw & Hughes (1994) lies significantly below the X-ray model predicted profiles. Limitations inherent to beam-switching single-dish measurements are that they are prone to baseline errors and beam dilution. Thus our analysis is not based upon the Birkinshaw & Hughes (1994) data, but instead makes use of their results only to allow a comparison with earlier studies.

These problems are not shared by the observation of Jones et al. (1993), whose calculated envelope encompasses both the Birkinshaw & Hughes (1994) observations and the majority of the predicted profiles for $H_0 = 50$ km s $^{-1}$ Mpc $^{-1}$, with the MMM being an important exception. This discrepancy occurs because the MMM requires a steep gas temperature gradient at small radii (see Fig. 2), resulting in a high prediction for the central decrement. If the gas is assumed to be isothermal (which is not statistically allowed by our X-ray data) the predicted SZ decrement at large radius is significantly greater than that from the best-fitting ASCA models (see Fig. 9). However, the isothermal model cannot be discriminated against on this basis as it remains consistent with the large SZ error envelope.

If an alternative value of H_0 is assumed, the predicted decrements obtained from the best-fitting X-ray models can be varied to achieve consistency with the SZ observations. The dependency is such that for a given X-ray surface brightness, the predicted SZ decrement varies as $H_0^{-0.5}$. Hence, assuming a higher Hubble constant will lead to a lower X-ray predicted decrement. The 2D SZ observation of Jones et al. (1993) and Jones (1995) is ideal for such a comparison because, first, it avoids the uncertainty inherent in the Birkinshaw & Hughes (1994) analysis and, secondly, upper and lower bounds to the allowed decrement are derived. However, it should be noted that these decrements have been analytically parametrized to allow a fit to the mosaicked SZ image and hence include a degree of model dependence (Jones 1995). With this caveat in mind, it is possible to determine the range of H_0 allowed by the SZ and X-ray results.

Under the requirement that at least one of the ASCA best-fitting models must be consistent with the results of Jones et al. (1993), we find that H_0 can be limited to the very conservative range 37–230 km s $^{-1}$ Mpc $^{-1}$. The lower bound is obtained by determining what value of H_0 is required to make the SZ prediction from the LTF model (which predicts the lowest central decrement of any of the models) equal to the Jones et al. (1993) upper bound. The upper

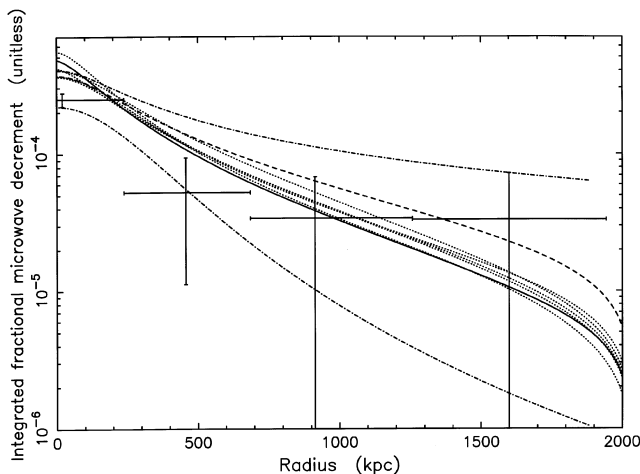


Figure 9. Sunyaev-Zel'dovich decrement profiles predicted from the MMM (solid line) and best-fitting cluster models (dotted lines), together with the decrement which occurs when an isothermal model is used (dashed line). The observed results of Birkinshaw & Hughes (1994) (crosses) and Jones et al. (1993) (dash-dot 1 σ error envelope) are overlaid. A Hubble constant of 50 km s $^{-1}$ Mpc $^{-1}$ is assumed.

bound, which is clearly ruled out by other H_0 determinations, is obtained by determining the value of H_0 which would decrease the SZ prediction from the TTF model (which provides the highest central decrement of any of the models) such that it matches the Jones et al. (1993) lower bound. Using a value of H_0 outside these bounds results in all of the ASCA best-fitting models becoming inconsistent with the SZ observations.

The main conclusion of this analysis is that only weak constraints on the Hubble constant can be obtained, with even the very low McHardy et al. (1990) result being allowed within its errors.

However, this determination neglects an important additional constraint, namely the gravitating masses extracted from lensing analysis. If we consider only the MMM and MMMC, which have been shown to be the preferred models when strong lensing is taken into account, the allowed range of H_0 is more tightly constrained.

The predicted central decrements from the MMM and MMMC (for $H_0 = 50 \text{ km s}^{-1} \text{ Mpc}^{-1}$) are 4.8×10^{-4} and 4.0×10^{-4} respectively. These are compared to the Jones et al. (1993) upper bound of 4.0×10^{-4} . To achieve consistency between these results, H_0 must be $> 62 \text{ km s}^{-1} \text{ Mpc}^{-1}$ for the MMM and $> 50 \text{ km s}^{-1} \text{ Mpc}^{-1}$ for the MMMC. Lower values of the Hubble constant ensure that the predicted decrements do not lie within the Jones et al. (1993) bounds.

If the constraint of isothermality (at the fitted temperature of $7.9_{-0.6}^{+0.7} \text{ keV}$) is applied, the predicted central decrement is 3.7×10^{-4} . When the value of H_0 is allowed to vary, the range allowed by the Jones et al. (1993) bounds is $30\text{--}105 \text{ km s}^{-1} \text{ Mpc}^{-1}$. This is consistent with the value of $H_0 = 38_{-16}^{+18} \text{ km s}^{-1} \text{ Mpc}^{-1}$ derived by Jones (1995).

In summary, the constraints currently available from SZ observations combined with X-ray measurements are too weak to constrain the Hubble constant to greater accuracy than $37\text{--}230 \text{ km s}^{-1} \text{ Mpc}^{-1}$. This range accommodates (within errors) the previously determined values of $24_{-10}^{+23} \text{ km s}^{-1} \text{ Mpc}^{-1}$ (McHardy et al. 1990), $65_{-25}^{+25} \text{ km s}^{-1} \text{ Mpc}^{-1}$ (Birkinshaw & Hughes 1994) and $38_{-16}^{+18} \text{ km s}^{-1} \text{ Mpc}^{-1}$ (Jones 1995). However, when lensing observations are introduced (which favour the MMMC model), the Hubble constant is required to be greater than $50 \text{ km s}^{-1} \text{ Mpc}^{-1}$. This result highlights the importance of using both non-isothermal gas models and an approach which incorporates constraints in addition to those provided by the X-ray and SZ observations alone.

9 DISCUSSION

We have analysed *ROSAT* PSPC and ASCA GIS X-ray data, fitting spherically symmetric emission models to allow the extraction of cluster properties. The use of ASCA data allows the gas temperature structure to be discerned, a significant advance over earlier instruments. The analysis procedure utilizes this information by fitting a variety of parametric forms for gas density and gas temperature or gravitating mass. This avoids restricting the unknown temperature profile to a single form.

Since the analysis presented here removes the constraint of isothermality, it is important to understand the effect that this assumption has. When isothermality is applied to equation 1, it degenerates to:

$$M_{\text{grav}}(r) = -\frac{kT_{\text{gas}}r}{G\mu m_p} \left[\frac{d \ln \rho_{\text{gas}}(r)}{d \ln r} \right] \quad (10)$$

Hence the *shape* of the mass profile is constrained by the gas density profile alone. Since the latter is commonly taken to follow a King model, the gravitating mass distribution is forced to take the

form of an isothermal sphere, with $\rho(r) \propto r$ at large radius and flattening within a region determined by the gas core radius.

The main results are as follows.

(1) Comparison with strong lensing indicates that the previously reported discrepancy is not present when the MMM is used. A consequence of the extra mass required within the critical radius is a high central gas temperature, which may be related to the disturbed nature of the core. So by relaxing the assumption of isothermality and using an appropriate parametrization for the dark matter distribution (one which includes a mass cusp), the observed X-ray and strong lensing data can become consistent.

(2) The suggestion by Makino (1996), that the cD contributes a significant fraction of the cluster mass at small radius has been tested. The maximum central mass which can be added to the MMM, before the Cash statistic shifts beyond the 95 per cent error level, is $1.7 \times 10^{12} M_{\odot}$ (within 100 kpc). Thus the massive galaxy required by Makino (1996) is ruled out, if the underlying DM distribution follows the form of the MMM model. The effect of adding the maximum allowed central galaxy mass is to extend the DM distribution. Because of this, the MMMC is found to be more consistent than the MMM with the outer two data points extracted from the Kneib et al. (1995) strong lensing analysis.

(3) At larger radii, 200–1000 kpc, the projected mass profiles of the MMM and MMMC are consistent with the weak lensing results of (1996). When the slope of the mass profile is considered, the MMMC becomes the favoured model, as the MMM distribution is considerably flatter than the trend of the weak lensing data. It is important to recognize that the weak lensing analysis provides only a lower limit to the actual mass distribution (since cluster mass is known to reside in the weak lensing control annulus). Hence, although the MMMC provides more mass than the weak lensing results currently allow, this discrepancy may be resolved when statistical lensing of the background galaxy population is observed to greater radii (so that a control annulus beyond the edge of the cluster can be used).

(4) The steep central rise in temperature required by the MMM leads to a corresponding increase in entropy. Under these conditions the gas is likely to be convectively unstable within ~ 120 kpc. This is either a reflection of the true physical state of the ICM or a model-dependent effect, related to the parametric forms assumed for the gas density and temperature. Evidence for the former is provided by Markevitch (1997), whose HRI analysis indicates the existence of central substructure, perhaps as a result of merging activity. If this is the case, the gas is likely to have been violently shock-heated, such that the assumption of equilibrium within the cluster core is no longer secure. On the other hand, the problem of convective instability is lessened with the MMMC, because of the lower fitted central temperature. In addition, replacing the King gas density profile with an NFW description can resolve the problem entirely. This is a consequence of allowing the density to rise, rather than flatten, in the cluster core.

(5) Analysis of galaxy orbits provides another probe of the core region of A2218. Using the derived anisotropy of the galaxy velocities, it is possible to extract information about the gravitational potential and possible presence of substructure. Beyond the central 1 arcmin region, the velocity dispersion data are consistent with the MMMC. At smaller radii, a physically reasonable solution for the anisotropy parameter cannot be attained with any of the derived X-ray mass distributions. This suggests that the central velocity dispersion has been raised to its high observed value during the violent relaxation phase of a merger event. Thus, even though

the galaxy data are too poorly sampled spatially to indicate the presence of substructure, the velocity information supports the analyses of Kneib et al. (1995) and Markevitch (1997).

(6) Comparison with 2D Sunyaev–Zel’dovich observations indicates that the Hubble constant is only weakly constrained, to a range of $37\text{--}230\text{ km s}^{-1}\text{ Mpc}^{-1}$. This is a result of the high level of uncertainty which occurs when errors in the SZ and X-ray data are combined. More restrictive constraints on the value of H_0 can be obtained if additional information is used, such as lensing observations. When the MMM and MMC are combined with the SZ data, low values of the Hubble constant are ruled out and we find that $H_0 > 50\text{ km s}^{-1}\text{ Mpc}^{-1}$. This result conflicts with the previously determined value of $24^{+23}_{-10}\text{ km s}^{-1}\text{ Mpc}^{-1}$ (McHardy et al. 1990), but agrees with the later estimate of $65^{+25}_{-25}\text{ km s}^{-1}\text{ Mpc}^{-1}$ (Birkinshaw & Hughes 1994). The differences between these results, and that derived here, are dominated by several factors. The first, and most important, of these is that an unwarranted assumption has been made about the gas temperature in these earlier studies – that it is isothermal. This biases the analysis and also results in overoptimistic error estimates. Secondly, McHardy et al. (1990) and Birkinshaw & Hughes (1994) both use (different) 1D SZ measurements, which are prone to baseline uncertainties. Thirdly, these studies use the less accurate gas density information from *Einstein*, rather than *ROSAT*.

Note, however, that these results are all based upon the commonly made assumption that the X-ray and SZ observations can be made consistent purely by manipulating the value of H_0 . If the cluster gas, at small radius, is not in hydrostatic equilibrium, this methodology may be in error.

10 CONCLUSIONS

Combining the above results, it appears that A2218 consists of two distinct regions. At small radii (≤ 1 arcmin), the X-ray morphology is extremely disturbed (Markevitch 1997) with both the strong lensing (Kneib et al. 1995) and galaxy data (Girardi et al. 1997) indicating the presence of bimodal structure. An X-ray model (the MMC) consistent with the strong lensing data requires the gas temperature to rise steeply within the core, possibly at such a high rate that the gas is convectively unstable. When this model is combined with the observed galaxy data, a physical solution cannot be obtained for galaxy orbits within the core. Taken together, these results suggest that A2218 has recently undergone a merger, shock-heating the gas and disturbing the equilibrium of the components within the cluster. This explains the lack of a cooling flow in the system.

Outside the core, our results show that the data can be consistently interpreted on the basis of a cluster in equilibrium. The gas temperature falls to $< 10\text{ keV}$, consistent with the observed galaxy velocity dispersion, and the gas entropy increases with radius. The MMC provides a mass profile consistent with both the outer two strong lensing points and the weak lensing mass profile (with the proviso that the latter is likely to represent an underestimate of the true mass profile). When the MMC is combined with the galaxy velocity data, a physical solution for the galaxy orbits is recovered. The SZ data, which are sensitive to the gas pressure at large radius, are consistent with the MMC when $H_0 \geq 50\text{ km s}^{-1}\text{ Mpc}^{-1}$.

Thus, while it is premature to regard a model such as the MMC as a complete description of the physical structure of A2218, it does appear to explain all the data available beyond the disturbed core. To probe further, more detailed X-ray and weak lensing observa-

tions are required.

One of the principal conclusions to be drawn from the present analysis is that it is dangerous to assume an isothermal ICM without supporting evidence. This can lead to biased conclusions and underestimated errors.

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REFERENCES

- Abell G. O., Corwin H. G., Jr, Olowin R. P., 1989, *ApJS*, 70, 1
- Birkinshaw M., Hughes J. P., 1994, *ApJ*, 420, 33
- Boydton P. E., Radford S. J. E., Schommer R. A., Murray S. S., 1982, *ApJ*, 257, 473
- Cannon D. B., 1997, PhD thesis, Univ. Birmingham
- Cash W., 1979, *ApJ*, 228, 939
- Day C., Arnaud K., Ebisawa K., Gotthelf E., Ingham J., Mukai K., White N., 1995, *The ABC Guide*. Goddard Space Flight Centre, MD
- Dressler A., 1978, *ApJ*, 226, 55
- Ebbels T. M. D., Le Borgne J. F., Pello R., Ellis R. S., Kneib J. P., Smail I., Sanahuja B., 1996, *MNRAS*, 281, L75
- Eyles C. J., Watt M. P., Bertram D., Church M. J., Ponman T. J., Skinner G. K., Willmore A. P., 1991, *ApJ*, 376, 23
- Fabricant D., Rybicki G., Gorenstein P., 1984, *ApJ*, 286, 186
- Fort B., Mellier Y., 1994, *A&AR*, 2, 239
- Girardi M., Fadda D., Escalera E., Giuricin G., Mardirossian F., Mezzetti M., 1997, *ApJ*, 490, 56
- Harrison E. R., 1974, *ApJ*, 191, L51
- Hobbs I. S., Willmore A. P., 1997, *MNRAS*, 289, 685
- Jones M., 1995, *Astrophys. Lett.*, 32, 347
- Jones M. et al., 1993, *Nat*, 365, 320
- Kaiser N., Squires G., 1993, *ApJ*, 404, 441
- King I. R., 1962, *AJ*, 67, 471
- King I. R., 1972, *ApJ*, 174, L123
- Kneib J. P., Mellier Y., Pello R., Miralda-Escude J., Le Borgne J. F., Bohringer H., Picat J. P., 1995, *A&A*, 303, 27
- Kneib J. P., Ellis R. S., Smail I., Couch W. J., Sharples R. M., 1996, *ApJ*, 471, 643
- Kristian J., Sandage A., Westphal J. A., 1978, *ApJ*, 221, 383
- Le Borgne J. F., Pello R., Sanahuja B., 1992, *A&AS*, 95, 87
- Loeb A., Mao S., 1994, *ApJ*, 435, L109
- Makino N., 1996, *PASJ*, 48, 573
- McHardy I. M., Stewart G. C., Edge A. C., Cooke B., Yamashita K., Hatsukade I., 1990, *MNRAS*, 242, 215
- Markevitch M., 1997, *ApJ*, 483, L17
- Markevitch M., Vikhlinin A., 1997, *ApJ*, 474, 84
- Miralda-Escude J., Babul A., 1995, *ApJ*, 449, 18
- Mushotzky R. F., Loewenstein M., 1997, *ApJ*, 481, L63
- Natarajan P., Kneib J. P., 1996, *MNRAS*, 283, 1031
- Navarro J. F., Frenk C. S., White S. D. M., 1995, *MNRAS*, 275, 720
- Navarro J. F., Frenk C. S., White S. D. M., 1996, *ApJ*, 462, 563
- Pello-Descayre R., Soucail G., Sanahuja B., Mathez G., Ojereo E., 1988, *A&A*, 190, L11
- Pello R., Le Borgne J. F., Sanahuja B., Mathez G., Fort B., 1992, *A&A*, 266, 6

- Perrenod S. C., Henry J. P., 1981, *ApJ*, 247, L1
Raymond J. C., Smith B. W., 1977, *ApJS*, 35, 419 (RS)
Rood H. J., Page T. L., Kintner E. C., King I. R., 1972, *ApJ*, 175, 627
Saraniti D. W., Petrosian V., Lynds R., 1996, *ApJ*, 458, 57
Saunders R., 1996, preprint (astro-ph/9611213) Los Alamos National Laboratory, XXX1st Rencontre de Moriond, Microwave Background Anisotropies, in press
Schindler S., Bohringer H., 1993, *A&A*, 269, 83
Siddiqui H., 1995, PhD thesis, University of Leicester
Silk J. I., White S. D. M., 1978, *ApJ*, 226, L103
Squires G., Kaiser N., Babul A., Fahlman G., Woods D., Neumann D. M., Bohringer H., 1996, *ApJ*, 461, 572
Stark A. A., Gammie C. F., Wilson R. W., Bally J., Linke R., Heiles C., 1992, *ApJS*, 79, 77
Sunyaev R. A., Zel'dovich Y. B., 1972, *Comments Astrophys. Space Phys.*, 4, 173
Takahashi T. et al., 1994, *ASCA Internal Report*, Institute of Space and Astronautical Science, available at ftp.astro.isas.ac.jp/asca/report/xrt_us.ps
Tormen G., Bouchet F. R., White S. D. M., 1996, *MNRAS*, 286, 865
Watt M. P., Ponman T. J., Bertram D., Eyles C. J., Skinner G. K., Willmore A. P., 1992, *MNRAS*, 258, 738
White D. A., 1996, in Zimmermann H. U., Trümper J., Yorke H., eds, *Röntgenstrahlung from the Universe*. MPE Report 263, p. 691
Yahil A., Vidal N. V., 1977, *ApJ*, 214, 347
Yepes G., Dominguez-Tenreiro R., 1992, *ApJ*, 387, 27

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