

A *ROSAT* PSPC investigation of the Centaurus cluster of galaxies

S. W. Allen and A. C. Fabian

Institute of Astronomy, Madingley Road, Cambridge CB3 0HA

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ABSTRACT

We present the results of a detailed spatially resolved, spectroscopic X-ray study of the Centaurus cluster of galaxies carried out using the Position Sensitive Proportional Counter (PSPC) on *ROSAT*. The PSPC data tightly constrain the radial temperature profile of the intracluster gas and provide an accurate measurement of the gas mass and total gravitating mass within a radius of 0.5 Mpc. The PSPC spectra show that the cluster either has a strong radial metallicity gradient or, like several more massive cooling-flow clusters, contains a significant central concentration of X-ray-absorbing gas. The PSPC data reveal no patchy or filamentary spatial structure in the cluster. However, some variation in the position angles and centroids of the X-ray isophotes is observed at small ($r \lesssim 30$ kpc) radii, indicating that the gas here may not have fully relaxed, perhaps following a recent subcluster merger event. The structure of the X-ray emission, outside the innermost region, and the optical emission from the central cluster galaxy, NGC 4696, are strongly correlated, demonstrating an intimate link between the central galaxy and the gravitational potential of the cluster as a whole.

Key words: galaxies: clustering – galaxies: clusters: individual: Centaurus – cooling flows – galaxies: individual: NGC 4696 – intergalactic medium – X-rays: galaxies.

1 INTRODUCTION

The development of X-ray astronomy has significantly advanced our understanding of the structure and dynamics of clusters of galaxies. The bulk of the X-ray emission from clusters comes from the large masses ($\geq 10^{14} M_{\odot}$ in a rich cluster) of hot (10^7 – 10^8 K), quasi-virialized gas, trapped within their deep gravitational potentials. (The total gravitating masses of the richest clusters exceed $10^{15} M_{\odot}$.) Spectroscopic studies of the intracluster medium (ICM) have demonstrated that it can be well modelled as an optically thin, metal-enriched thermal plasma. Although the outer regions of clusters appear to be remarkably isothermal (e.g. Allen et al. 1992), imaging studies in soft X-rays have shown that in the centres of most clusters the gas is cooling rapidly, which results in the formation of cooling flows. Spectroscopic studies have confirmed the presence of cooler X-ray-emitting material in the cores of clusters at a level in excellent agreement with the imaging results [see Canizares, Markert & Donahue (1987) and Mushotzky & Szymkowiak (1987). For a discussion of the general X-ray properties of clusters of galaxies, see Sarazin (1988). Theoretical and observational aspects of cooling flows are reviewed by Fabian, Nulsen & Canizares (1991).] One of the most important questions that X-ray observations can address is the distribution of mass within clusters. As well as measuring the mass in gas, the

X-ray observations also measure the total gravitating mass within a cluster. The distribution of total mass, $M(r)$, is determined if both the temperature, $T(r)$, and (electron) density, $n_e(r)$, distributions of the intracluster gas are known. Although X-ray imaging studies provide accurate measures of $n_e(r)$, the determination of $T(r)$ requires combined spectrally and spatially resolved X-ray observations which have not, until now, been available.

The Position Sensitive Proportional Counter (PSPC) on *ROSAT* (Trümper 1983) observes in the energy range 0.1–2.4 keV and combines good spatial (~ 25 -arcsec FWHM) and moderate spectral [$\Delta E/E = 0.43(E/0.93 \text{ keV})^{-0.5}$, FWHM] resolution. Of instruments on previous X-ray satellites, only the Imaging Proportional Counter (IPC) on the *Einstein Observatory* also combined these two elements, but with poorer spectral and spatial resolution and a significantly higher background count rate. With its improved performance, the PSPC now enables the first detailed, combined spectral and imaging analyses of clusters of galaxies to be made. In this paper we present the analysis of a PSPC observation of the Centaurus cluster of galaxies (Abell 3526). At a redshift of $z = 0.0104$ (Lucey, Currie & Dickens 1986), Centaurus is the second-nearest X-ray bright cluster and, having a lower mean gas temperature (3.6 ± 0.4 keV; Edge & Stewart 1991) than most other X-ray bright clusters, is particularly well suited for study with the PSPC. In

contrast to larger, hotter clusters where the 0.1–2.4 keV bandpass makes accurate temperature determinations difficult, with Centaurus the PSPC provides a precise measurement of the variation of temperature with radius. Previous X-ray studies of the Centaurus cluster, using instruments on the *Einstein Observatory*, have shown that the cluster contains a cooling flow of 20–50 $M_{\odot} \text{ yr}^{-1}$ (Matlsky, Jones & Forman 1985; Canizares et al. 1987; White 1992). The PSPC enables us to carry out spatially resolved spectroscopy on a scale of ~ 25 kpc and investigate, in detail, the properties of the cooling gas.

The structure of this paper is as follows: Section 2 describes the X-ray observations and data reduction procedures. In Section 3 we discuss the spectral analysis and the results on the temperature, metallicity and absorption variation within the cluster. Section 4 describes the image deprojection analysis and the results on the form of the gravitational potential in the cluster. In Section 5 we investigate the properties of the cooling flow, and in Section 6 we examine structure in the X-ray image. Section 7 summarizes the results and their implications. In Section 8 we list our conclusions. Throughout the paper, a value for the Hubble constant of $H_0 = 50 \text{ km s}^{-1} \text{ Mpc}^{-1}$ and a cosmological deceleration parameter $q_0 = 0$ are assumed.

2 OBSERVATIONS

The *ROSAT* PSPC observation of the Centaurus cluster was made on 1992 February 2 with a total on-target exposure of 7985 s. The pointing of the observation, $12^{\text{h}} 48^{\text{m}} 48^{\text{s}}$, $-41^{\circ} 18' 36''$ (2000.), places the cluster very nearly at the centre of the circular $\sim 1^{\circ}$ -radius PSPC field of view [the peak of the X-ray emission is found to lie at $12^{\text{h}} 48^{\text{m}} 50^{\text{s}}.3$, $-41^{\circ} 18' 45''$ (2000.)]. We note that the peak of the X-ray emission closely matches the position of the central dominant galaxy, NGC 4696 [$12^{\text{h}} 48^{\text{m}} 49^{\text{s}}.2$, $-41^{\circ} 18' 46''$ (2000.; Dickens, Currie & Lucey 1986)]. A grey-scale image of the Centaurus field, covering the full (0.1–2.4 keV) energy range, is presented in Fig. 1(a). The pixel size is 15 arcsec and the image has been smoothed using a Gaussian of FWHM 60 arcsec to illustrate the extent of the cluster and to highlight point sources (which do not significantly contaminate the cluster emission). Emission from the cluster is detected out to the edge of the PSPC field of view. The point source ~ 17 arcmin to the west of the cluster at $12^{\text{h}} 47^{\text{m}} 27^{\text{s}}$, $-41^{\circ} 13' 43''$ (2000; source A) is probably the S0 galaxy NGC 4696B (Dickens et al. 1986). The sources ~ 34 arcmin to the north-east [$12^{\text{h}} 50^{\text{m}} 06^{\text{s}}$, $-40^{\circ} 47' 22''$ (2000; source B)] and ~ 28 arcmin to the south-west [$12^{\text{h}} 47^{\text{m}} 54^{\text{s}}$, $-41^{\circ} 27' 42''$ (2000; source C)] have no catalogued optical counterparts. (We note that the second optically dominant galaxy in the cluster, NGC 4709, is not significantly detected above the cluster X-ray emission; see Section 6.) The X-ray spectrum of the south-western object shows evidence for absorption at soft energies by a column density consistent with the Galactic value. The signal-to-noise ratios in the spectra of the other serendipitous sources do not permit further discrimination on source type to be made. A contour map of the central regions of the cluster is shown in Fig. 1(b). Reduction of the PSPC data was performed using the Starlink ASTERIX data reduction package, with the exception

of the structure analysis in Section 6, for which the isophote-fitting routines in IRAF were used.

Unfortunately, the PSPC observation of the Centaurus cluster was severely contaminated by scattered solar X-rays. This contamination produces a characteristic increase in soft < 0.3 -keV counts (due to Thomson scattering of solar X-rays by electrons in the Earth's outer atmosphere) and a strong fluorescently scattered oxygen K α line at 0.54 keV. [A full description of the scattered solar X-ray background in the PSPC is given by Snowden & Freyberg (1993).] More than half of the data gathered in the observation were too severely contaminated (with scattered solar X-rays contributing $\geq$ half of the total observed counts) for use in our analysis. After the selective removal of periods of high scattered-solar contamination and high particle background, and accounting for detector dead-time, we were left with a 'clean' observation of 3311 s. This reduced, clean data set is used exclusively in the analysis reported in this paper.

3 ANNULAR SPECTRAL ANALYSIS

3.1 Method

The cluster image was divided into annular regions, about the X-ray centroid, of radial widths selected on the basis of several criteria: the annular regions should each contain sufficient counts to permit reasonable spectral analyses. They should be small enough to maximize the information on the radial dependence of fit parameters, but also not be so small as to be significantly affected by smearing due to the energy dependence of the joint XRT and PSPC point spread function (Hasinger et al. 1992). A compromise between these competing effects was achieved with our final selection of annuli, described in Table 1.

Due to its proximity (other than Virgo, Centaurus is the nearest X-ray-bright cluster), the angular diameter of the cluster is large and the X-ray emission from it fills the whole of the $\sim 1^{\circ}$ -radius PSPC field of view. There is no region of the image from which a background spectrum can be directly extracted. In order to perform a detailed spectral analysis, we are required to separate the foreground (cluster) and background emissions. This was carried out using the procedure described below.

A spectrum was extracted from an annular region, $0^{\circ}6$ – $0^{\circ}8$ from the centre of the PSPC field, where the cluster emission is relatively weak (having approximately half the background flux level in the 0.1–2.0 keV band) and where sufficient signal is obtained in the background to permit detailed spectral modelling. (This spectrum will hereafter be referred to as the background spectrum.) The particle background was subtracted using the parametrization in terms of the PSPC Master Veto Rate described by Snowden et al. (1992). Those regions of the annulus obscured by the PSPC rib support structure, or with obvious contaminating sources, were masked out and ignored in the analyses. The spectrum was corrected for dead time and vignetting, and was fitted with a composite background-plus-cluster emission model. The background was modelled using the prescription of Hasinger (1992; determined from deep pointed observations of ~ 20 high Galactic latitude fields with the PSPC). Residual oxygen K α contamination from scattered solar X-rays was accounted for by an additional Gaussian component of zero

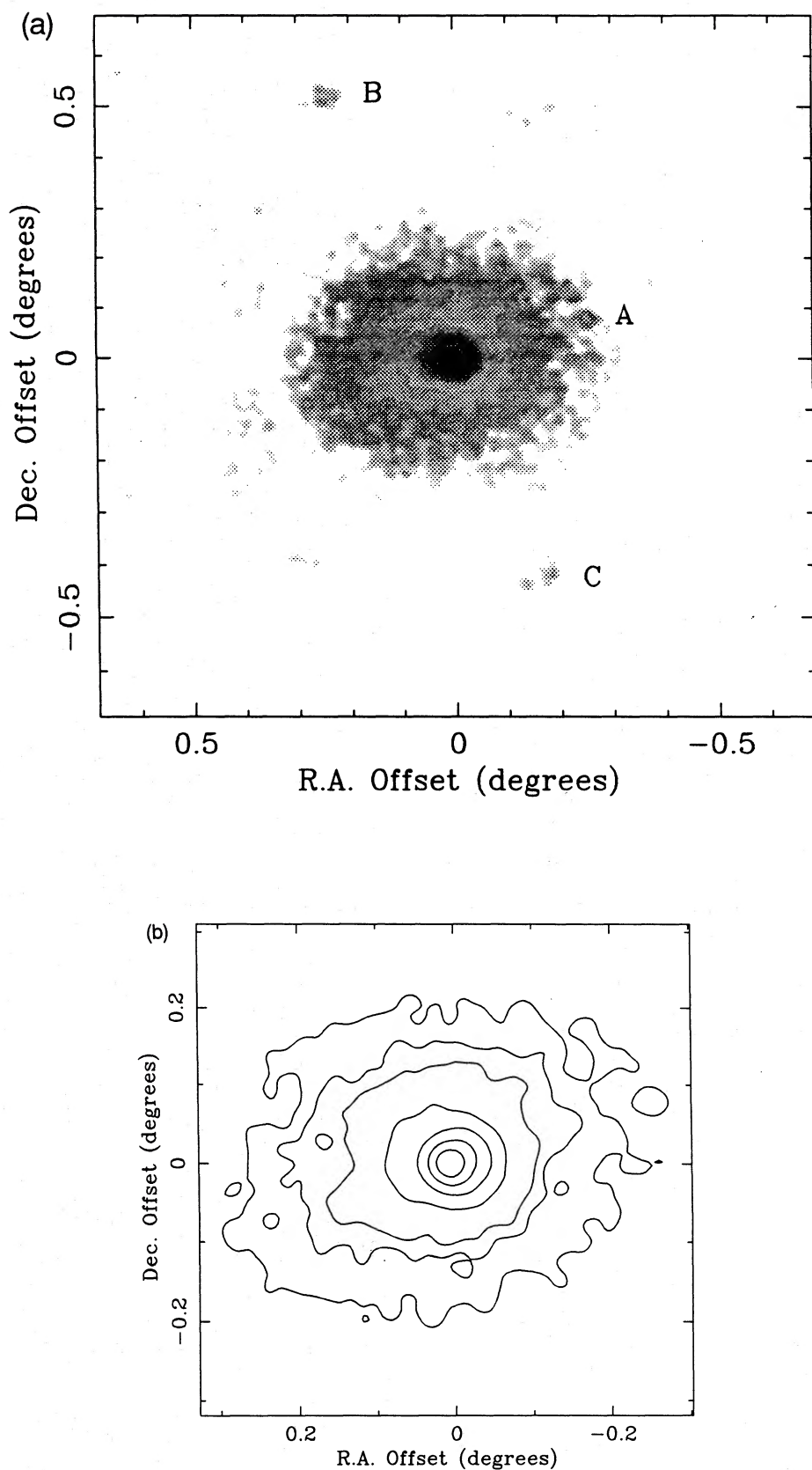


Figure 1. (a) A grey-scale representation of the PSPC image of the Centaurus cluster of galaxies, generated from the 3311 s of clean data. The pixel size is ~ 15 arcsec and the image has been vignetting-corrected and smoothed using a Gaussian of FWHM 60 arcsec. North is up and east is to the left. (b) A contour map of the X-ray emission from the central regions of the cluster. The pixel size and orientation are the same as in (a). The image has been smoothed twice using a Gaussian of FWHM 60 arcsec. Contours are drawn at 1, 1.5, 2, 4, 8, 16 and 32 count pixel $^{-1}$.

Table 1. Description of annuli used in the spectral analysis.

Annulus name	Inner radius, r_1 arcmin/kpc	Outer radius, r_2 arcmin/kpc	$(r_2 - r_1)$ arcmin/kpc
CORE	0/0	1.5/26.6	1.5/26.6
ANN1	1.5/26.6	3.0/53.1	1.5/26.6
ANN2	3.0/53.1	6.0/106	3.0/53.1
ANN3	6.0/106	9.0/159	3.0/53.1
ANN4	9.0/159	12.0/212	3.0/53.1
ANN5	12.0/212	15.0/265	3.0/53.1
ANN6	15.0/265	20.0/354	5.0/88.7
ANN7	22.5/398	30.0/531	7.5/133

width and energy 0.54 keV. The foreground cluster emission was assumed to have the spectrum determined from observations made with the Medium Energy (ME) detector on *EXOSAT* (Edge & Stewart 1991), i.e. a 3.6-keV thermal plasma of 0.6-solar metallicity (we note that the 40×40 arcmin² field of view of the ME observed a similar region of the cluster to that examined here). No statistical improvement to the fit was obtained by allowing the cluster parameters to vary from these values. The column densities acting on all extragalactic components were fixed at the equivalent Galactic neutral hydrogen column density of $N_H = 8.8 \times 10^{20}$ atom cm⁻², determined from 21-cm H I observations (Stark et al. 1992).

The resulting best-fitting model provides a simple parametrization of the vignetted component of the X-ray background. Each annular spectrum was then examined in turn and the appropriate particle background component removed. In modelling the annular spectra, a component corresponding to the contribution from the best-fitting background model, scaled by source area and corrected for telescope vignetting, was included. We note that the detailed values of the best-fitting model parameters (and, indeed, the strict physical validity of the background model itself) are not themselves important to the analysis. We require only a suitable parametrization of the vignetted background counts in the individual annular spectra. The uniformity of the background spectrum across the field was examined by splitting the background annulus into four quadrants and fitting each individually. No evidence for strong variation of fit parameters across the field was observed.

The Snowden et al. (1992) parametrization of the particle background is strictly valid only for PSPC observations made before 1991 May. For observations after 1991 September, it is known to be inaccurate. The particles account for ≤ 2 per cent of the total counts in the background spectrum, however, and uncertainty in their removal affects only Pulse Height Analyser (PHA) channels at the highest energies, ≥ 2.4 keV. For the modelling of the background spectrum, only data from those PHA channels in the energy range 0.1–2.0 keV have been used.

The annular spectra have been analysed using the *xSPEC* spectral fitting package (Shafer et al. 1991). PHA channels corresponding to energies below 0.1 keV (which are not

correctly calibrated by the PSPC response matrix) and above 2.4 keV (where the particle background becomes significant) were ignored. (We note that for the outer two annuli, where the background is most significant, channels corresponding to energies > 2 keV have been ignored.) The spectra were rebinned to have a minimum of 20 counts per PHA channel (to enable a reliable χ^2 analysis to be carried out) and then binned again, by an integral factor, to give ~ 30 final PHA channels which were used for fitting. The most recent version of the *ROSAT* PSPC response matrix, available in 1993 January (version 36), has been used in this analysis. A systematic error of 1 per cent of the measured count rate in each of the ~ 30 fitted PHA channels has been quadratically summed with the photon noise in those channels to allow for uncertainties in the calibration of the PSPC response matrix.

3.2 Results using the Raymond & Smith code

The individual annular spectra were fitted with a model consisting of emission from a hot, diffuse, thermal plasma [a recent update of the models of Raymond & Smith (1977) has been used; this will hereafter be referred to as the RS component] and a photoelectric absorption component (Morrison & McCammon 1983) normalized to the equivalent Galactic neutral hydrogen column density ($N_H = 8.8 \times 10^{20}$ atom cm⁻²) determined from 21-cm observations (Stark et al. 1992). Heavy-element abundances were fixed at 0.6 solar in accordance with the results from *EXOSAT* (a solar Fe/H ratio of 3.16×10^{-5} was assumed), and the redshift was fixed at the value determined optically for the cluster of $z = 0.0104$ (Lucey et al. 1986). The only free parameters in the spectral model at this point were the temperature and normalization of the RS component (we shall refer to this spectral model as model 1). The best-fitting χ^2 values obtained from the fits to the individual annuli are summarized in column 2 of Table 2. Although the fits obtained with the model in the outer regions of the cluster are good, model 1 clearly cannot adequately describe the data for the innermost annulus.

Our analysis of the PSPC observation of Abell 478 (Allen et al. 1993) demonstrated the presence of large amounts of intrinsic X-ray-absorbing material within the cluster core. Since the most simple spectral model (model 1) cannot adequately describe the data from the core of the Centaurus cluster, we investigated the improvement that could be obtained by allowing the column density to vary as a free parameter (this model shall be referred to as model 2). The best-fitting temperatures, column densities and χ^2 values obtained in the annular fits with model 2 are summarized in columns 3, 4 and 5 of Table 2. This model was found to provide statistically acceptable fits to the data for all of the annuli.

We tested whether similarly good fits to the annular spectra could be obtained by introducing free parameters other than column density into the fits. The inclusion of a power-law component (either intrinsically absorbed or unabsorbed) did not improve the fits to the inner annuli. [We note that analysis of an observation of NGC 4696 obtained with the High Resolution Imager on the *Einstein Observatory* (Matilsky et al. 1985) found no evidence for X-ray emission from a central point source.] Excellent fits to the central annuli could be obtained, however, by allowing the metal-

Table 2. Annular spectral analysis: Raymond & Smith code.

	Model 1	Model 2			Model 3			Model 4			
	χ^2/DOF	χ^2/DOF	kT	N_H	χ^2/DOF	kT	Z	χ^2/DOF	kT	N_H	Z
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
CORE	65.5/26	26.9/25	$1.14^{+0.02}_{-0.01}$	$14.4^{+1.6}_{-1.2}$	20.0/25	$1.26^{+0.04}_{-0.04}$	$1.9^{+0.5}_{-0.3}$	20.0/24	$1.25^{+0.05}_{-0.06}$	$9.3^{+3.9}_{-2.5}$	$1.7^{+0.9}_{-0.6}$
ANN1	22.8/25	17.6/24	$1.8^{+0.2}_{-0.1}$	$10.9^{+1.1}_{-1.0}$	13.1/24	$2.2^{+0.4}_{-0.3}$	$1.4^{+0.5}_{-0.4}$	12.3/23	$2.4^{+0.8}_{-0.4}$	$7.6^{+1.4}_{-1.1}$	$2.1^{+2.1}_{-0.9}$
ANN2	25.6/27	25.5/26	$3.8^{+0.9}_{-0.8}$	$8.5^{+0.7}_{-0.6}$	23.4/26	$3.7^{+0.8}_{-0.6}$	$1.1^{+0.4}_{-0.6}$	18.3/25	$5.0^{+0.9}_{-1.1}$	$7.1^{+0.7}_{-0.5}$	$3.7^{+1.3}_{-1.9}$
ANN3	31.1/25	31.1/24	$5.2^{+2.0}_{-1.2}$	$8.7^{+0.8}_{-0.7}$	31.1/24	$5.1^{+1.6}_{-1.1}$	$0.7^{+0.9}_{-0.6}$	31.0/23	$5.4^{+2.0}_{-1.4}$	$8.5^{+1.2}_{-0.9}$	$0.9^{+2.7}_{-0.9}$
ANN4	16.2/25	16.0/24	$3.3^{+0.9}_{-0.6}$	$9.2^{+0.9}_{-0.8}$	16.1/24	$3.5^{+0.9}_{-0.7}$	$0.7^{+0.5}_{-0.3}$	16.0/23	$3.2^{+1.1}_{-0.8}$	$9.3^{+1.1}_{-1.2}$	$0.55^{+0.71}_{-0.37}$
ANN5	18.8/24	17.6/23	$4.1^{+1.5}_{-1.0}$	$7.8^{+0.9}_{-0.7}$	18.7/23	$3.5^{+1.0}_{-0.7}$	$0.5^{+0.5}_{-0.4}$	16.8/22	$4.8^{+2.3}_{-1.4}$	$7.1^{+1.2}_{-0.9}$	$1.7^{+3.3}_{-1.1}$
ANN6	23.7/24	23.6/23	$3.6^{+1.5}_{-1.0}$	$9.0^{+1.3}_{-1.1}$	23.7/23	$3.6^{+1.5}_{-0.9}$	$0.6^{+0.8}_{-0.5}$	23.6/22	$3.4^{+1.9}_{-1.3}$	$9.3^{+2.2}_{-1.7}$	$0.5^{+1.4}_{-0.5}$
ANN7	23.6/24	23.5/23	$3.7^{+1.6}_{-1.40}$	$9.1^{+1.2}_{-1.1}$	22.8/23	$3.6^{+1.4}_{-1.0}$	$0.2^{+0.5}_{-0.2}$	20.4/22	$2.1^{+1.7}_{-0.7}$	$12.4^{+3.2}_{-2.5}$	$0.0^{+0.2}_{-0.0}$

Notes. Summary of best-fitting parameters from the annular spectral analysis using the Raymond & Smith code. Results are given for all four spectral models. Errors on the best-fitting values indicate regions of 68 per cent confidence on a single interesting parameter. Temperatures (kT) are expressed in keV, column densities (N_H) in 10^{20} cm^{-2} and metallicities (Z) as a function of the solar value. We note that the confidence contours for spectral model 4 show evidence of mild non-linearity, which may cause the quoted confidence limits to underestimate slightly the true 68 per cent confidence region.

licity to be a free parameter, whilst maintaining the column density at the Galactic value. (Such a model was not able adequately to describe the PSPC data for Abell 478.) The temperatures, metallicities and χ^2 values obtained with this model (model 3) are given in columns 6, 7 and 8 of Table 2. Finally, we re-fitted the data with both column density *and* metallicity included as free parameters. The best-fitting parameters obtained with this model (model 4) are given in columns 9–12 of Table 2.

In Fig. 2 we present the spectrum of the innermost annulus of the cluster, with the best fit using model 2 overlaid as a solid line. Fig. 3(a) shows the variation of column density with radius, $N_H(r)$, obtained with model 2. Fig. 3(b) illustrates the metallicity gradient, $Z(r)$, obtained in the fits using model 3. In Fig. 3(c) the temperature profiles, $kT(r)$, obtained using models 2 and 3 are shown. The confidence regions on the parameters, particularly in models with metallicity included as a free parameter, are slightly asymmetric. To illustrate that the trends shown in Figs 3(a)–(c) are not severely influenced by non-linearities in the fitting, we also plot the two-dimensional χ^2 contours of kT versus N_H (spectral model 2; Fig. 3d) and kT versus Z (model 3; Fig. 3e) for the three innermost annuli. The confidence contours illustrate that the radial profiles are a reasonable representation of the properties of the data.

Several important conclusions can immediately be drawn from the plots in Fig. 3. First, we see that the temperature profile of the cluster gas in Centaurus is tightly constrained by the PSPC data. From radii of ~ 50 kpc, out to the edge of the field, the gas is remarkably isothermal, with a temperature in excellent agreement with the mean value of 3.6 ± 0.4 keV determined by *EXOSAT*. Within the central ~ 50 kpc, however, the temperature drops rapidly, to an average value in the inner ~ 25 kpc of ~ 1.2 keV. Secondly, the results in Table 2 and Figs 3(a) and (b) show that, to explain the PSPC

data for Centaurus, our spectral model must include *either* a significant amount of excess X-ray absorption by material centrally concentrated within the cluster, *or* a strong metallicity gradient. Both the increase in column density and the departure of metallicity from the average value for the cluster (0.6 ± 0.3 solar; determined by *EXOSAT*) are required in the same central few annuli. We note that, although *both* model 2 and model 3 provide statistically acceptable fits to the annular spectra, model 3 (free metallicity) is statistically preferred, as can be seen by comparison of the χ^2 values for the models given in Table 2. A simple *F*-test for the significance of introducing metallicity as a further free parameter into the fits to the cluster core using model 2 shows it to be required at > 99 per cent significance. The introduction of column density as a free parameter in model 3 does not similarly improve the fits. It remains possible, however, that *both* a metallicity gradient *and* intrinsic absorbing material are present in the cluster. Finally, we note that the measured equivalent hydrogen column densities are dependent on the elemental abundances assumed to be present in the absorbing material. The models of Morrison & McCammon (1983) used in this analysis have oxygen (the principal absorber in the *ROSAT* band) at the solar value. Any intrinsic absorbing material need not necessarily have this abundance.

3.3 Verification using the Mewe & Gronenschild code

In order to examine to what extent the detailed results of the spectral fitting depend on the specific atomic physics of the RS plasma code, we have re-fitted the spectra using the code of Mewe & Gronenschild [hereafter MG; Mewe, Lemen & Van den Oord (1986) and references therein]. The best-fitting parameters for the fits to the three inner annuli using the MG code are summarized in Table 3. The conclusions

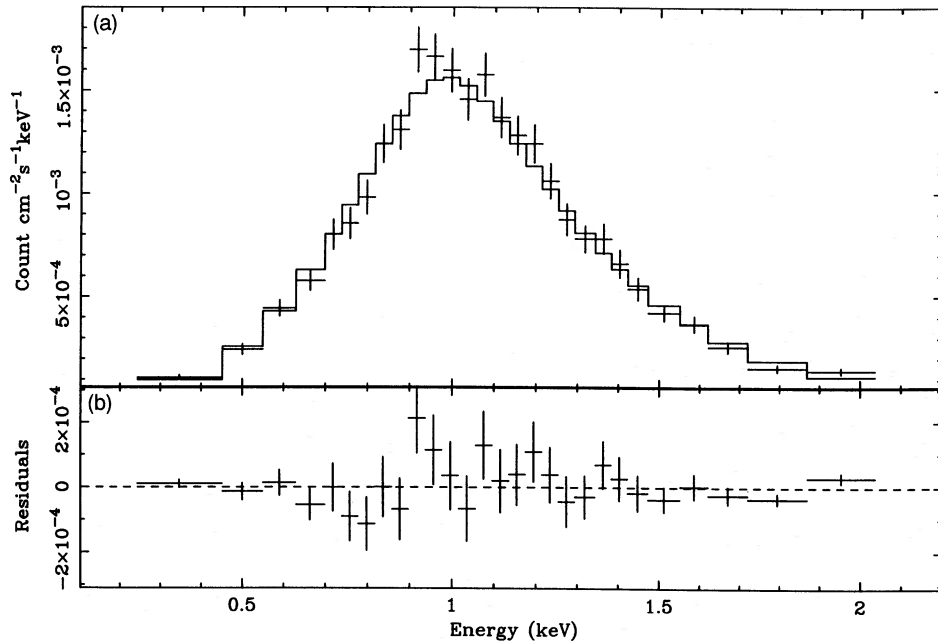


Figure 2. (a) The *ROSAT* PSPC spectrum for the central (~ 25 kpc) annulus, and the best-fitting isothermal model (using spectral model 2), folded through the detector response (solid line). (b) Residuals from the best-fitting model.

from the spectral analysis with the MG code are similar to those obtained with the RS code. Although both model 2 and model 3 again provide good descriptions of the data, model 2 (column density free, metallicity fixed at 0.6 solar) is now the statistically preferred model for the innermost annulus. A simple F -test of the significance of introducing the column density as a further free parameter into the fits to this region using model 3 shows it to be required at > 99 per cent significance. The introduction of metallicity as an additional free parameter into model 2 does not improve the fits. By combining these results with those of Section 3.2, we conclude that model 2 and model 3 both adequately describe the X-ray emission from the Centaurus cluster, and that the statistical preference for one model over the other is entirely dependent on the atomic physics in the plasma code used.

The major differences between the MG and RS codes, with respect to *ROSAT* studies, are the emissivities of the emission lines in the complex at ~ 1 keV. The RS code predicts much greater ~ 1 -keV line emissivities (see also Raymond 1988). Finally, we have re-fitted the data using the recent update of the MG code by Kaastra & Mewe (1993). The results are similar to those obtained with the MG code and re-affirm our conclusion on the statistical preference of the spectral models discussed above.

3.4 The effects of projection

One of the potential problems of a simple annular spectral analysis like the one carried out here is that of projection. X-rays, which in projection come from the inner 25 kpc of the cluster, in reality come from a cylinder of gas of radius 25 kpc with the radial axis along the line of sight. If the cluster

contains a cooling core surrounded by a hotter, roughly isothermal halo, we would expect the temperature profile obtained with our annular method to overestimate the temperature in the cluster core.

We have examined the possible effects of projection on the measured $kT(r)$ profile using the results of the deprojection analysis, described in Section 4. Amongst the parameters derived with the deprojection analysis is the bolometric luminosity of the cluster as a function of radius. If the bulk of the X-ray emission from the cluster is observed in the PSPC field [the good agreement between the results of our analysis and the luminosity measured using the Large Area Counter on *Ginga*, which has a $1^\circ \times 2^\circ$ field of view, suggests that this is the case (Butcher, private communication)] then, from simple geometric arguments, we can calculate the fraction of the flux in projection for a particular source region. In Fig. 4 we plot this fraction, as a function of the projected radius, for a circular source region centred on the X-ray centroid. For the innermost (CORE) annulus the flux in projection is ~ 20 per cent of the total.

We have carried out a simple test in which a projected component, with a temperature fixed at the ambient cluster temperature of ~ 3.8 keV and contributing one-quarter of the flux of the unprojected RS emission (the metallicities and column densities acting on the projected and unprojected components were forced to be equal), is also included in the fits. With this model the temperature of the CORE region (using spectral model 2) is measured to be $1.11^{+0.02}_{-0.03}$ keV. This result is close to that listed in Table 2. (Similar results are found for the other spectral models.) We conclude that projection effects do not cause a serious overestimation of the gas temperature in the cluster centre.

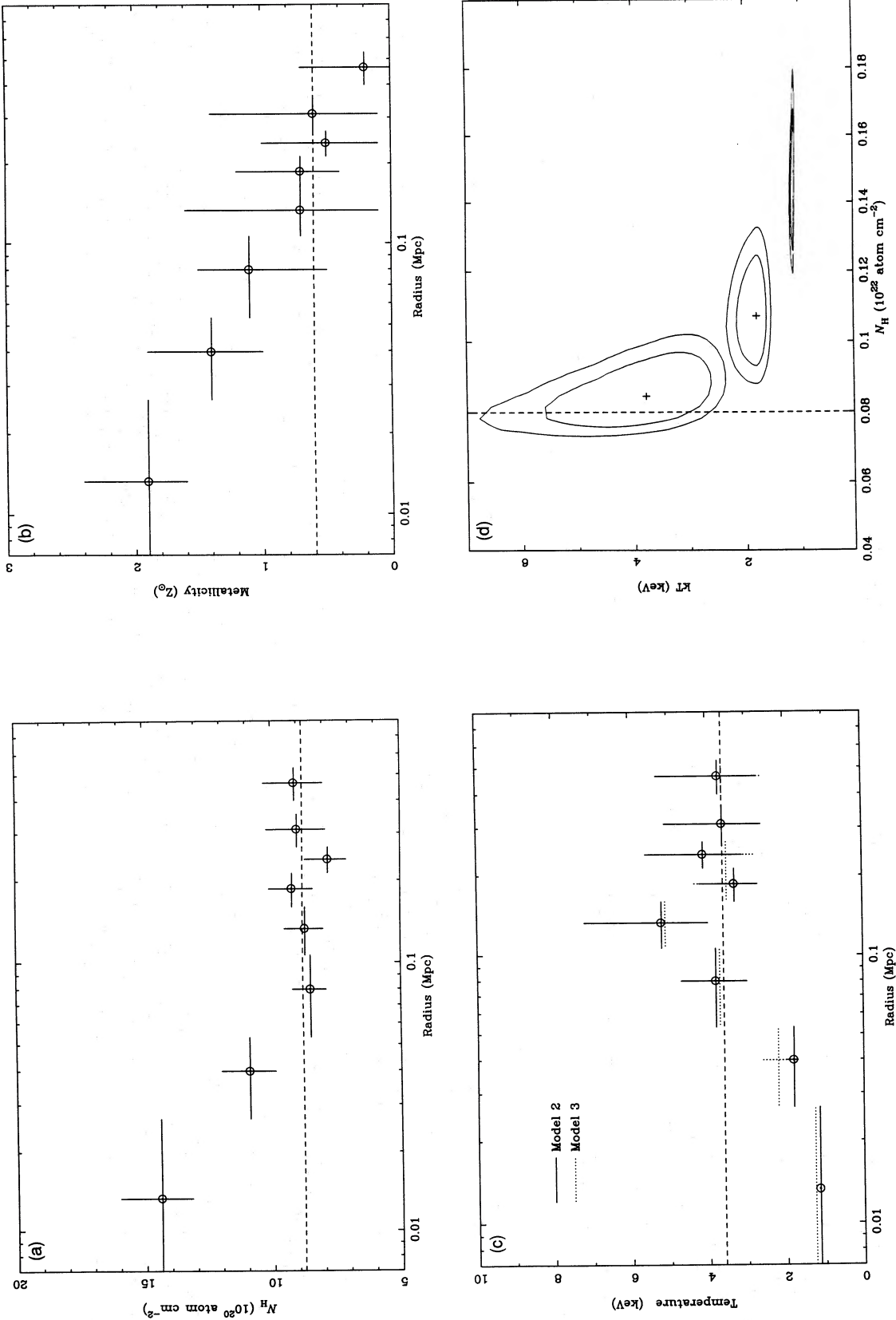


Figure 3. (a) The variation of column density with radius, determined from the annular spectral analysis using spectral model 2. Vertical error bars indicate regions of 68 per cent confidence on a single interesting parameter. Horizontal error bars show the extent of the annuli. The dashed line marks the equivalent Galactic neutral hydrogen column density, $N_H = 8.8 \times 10^{20} \text{ atom cm}^{-2}$, determined from H I observations. (b) The variation of metallicity with radius determined using spectral model 3. The dashed line marks the average metallicity for the cluster of $Z = 0.6 Z_\odot$, measured with EXOSAT. (c) The variation of temperature with radius in the cluster. The solid bars show the temperature profile determined using spectral model 2. The dotted bars show the values obtained using spectral model 3. (d) Contours of constant χ^2 in kT versus N_H parameter space for spectral model 2 corresponding to regions of 68 and 90 per cent confidence. Contours for the three innermost annuli are shown. The dashed line marks the Galactic neutral hydrogen column density. (e) Contours of constant χ^2 in kT versus Z parameter space for the three innermost annuli, using spectral model 3. The dashed line marks the average metallicity for the cluster of $Z = 0.6 Z_\odot$, measured with EXOSAT.

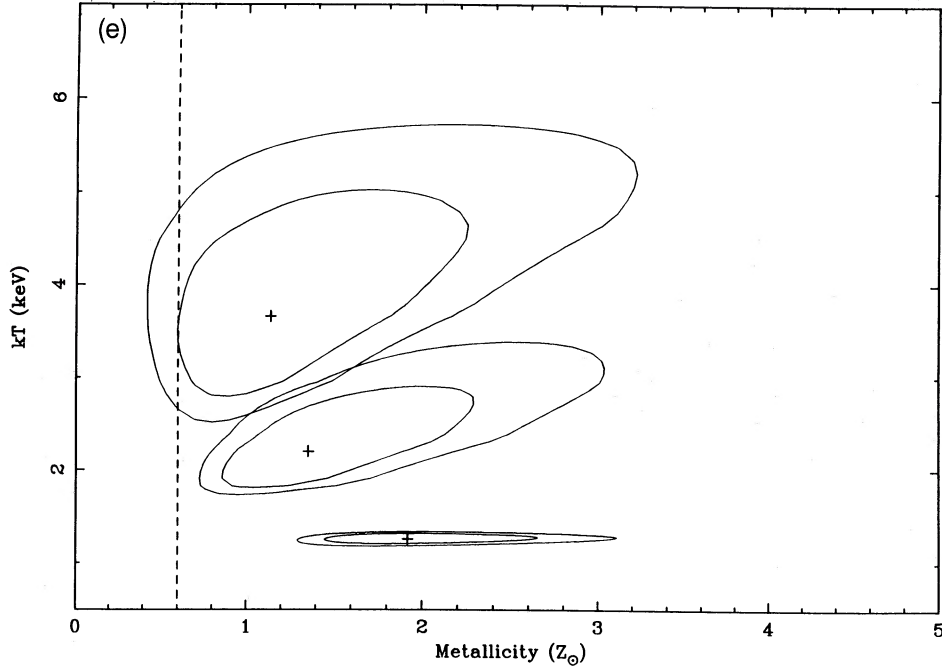


Figure 3 - continued

Table 3. Annular spectral analysis: Mewe & Gronenschild code.

Annulus	Model 1	Model 2	Model 3				Model 4				
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
	χ^2/DOF	χ^2/DOF	kT	N_H	χ^2/DOF	kT	Z	χ^2/DOF	kT	N_H	Z
CORE	53.8/26	22.4/25	$1.01^{+0.03}_{-0.03}$	$13.8^{+1.3}_{-1.2}$	31.1/25	$1.07^{+0.03}_{-0.03}$	$1.14^{+0.19}_{-0.15}$	22.3/24	$1.00^{+0.04}_{-0.04}$	$14.6^{+2.8}_{-2.3}$	$0.54^{+0.18}_{-0.15}$
ANN1	18.8/25	15.3/24	$1.8^{+0.2}_{-0.2}$	$10.5^{+1.0}_{-1.0}$	12.7/24	$2.1^{+0.4}_{-0.3}$	$1.1^{+0.4}_{-0.3}$	12.3/23	$2.3^{+0.7}_{-0.4}$	$7.9^{+1.5}_{-1.1}$	$1.5^{+1.2}_{-0.6}$
ANN2	24.5/27	23.9/26	$3.5^{+0.9}_{-0.6}$	$8.4^{+0.6}_{-0.5}$	23.4/26	$3.5^{+0.8}_{-0.5}$	$0.9^{+0.4}_{-0.3}$	18.7/25	$5.0^{+1.5}_{-1.2}$	$7.1^{+0.7}_{-0.6}$	$2.7^{+2.3}_{-1.4}$

Notes. Summary of best-fitting parameters from the annular spectral analysis using the Mewe et al. (1986) code. Results are given for all four spectral models. Errors on the best-fitting values indicate regions of 68 per cent confidence on a single interesting parameter. Temperatures (kT) are expressed in keV, column densities (N_H) in 10^{20} atom cm^{-2} and metallicities (Z) as a fraction of the solar value.

4 DEPROJECTION OF THE CLUSTER IMAGE

4.1 Analysis

We have analysed the PSPC image of the Centaurus cluster using the ‘deprojection’ technique of Fabian et al. (1981). This method, used extensively in the analyses of a large sample of clusters observed with the *Einstein Observatory* by Arnaud (1985) and White (1992), assumes that the observed X-ray emission originates from a spherically symmetrically distributed ideal gas in hydrostatic equilibrium with the cluster gravitational potential. The free parameters in the deprojection analysis are the form of the cluster potential and the pressure of the X-ray-emitting gas at a selected outer radius. As an estimate for the gravitational potential, we have

used the combination of a King approximation to an isothermal sphere (equation 1) to describe the bulk cluster potential (various core radii, r_c , have been examined; see discussion in Section 4.2), and a de Vaucouleurs potential with an effective radius of 9.1 kpc (Schombert 1987) and a velocity dispersion of 274 km s^{-1} (Dressler, Faber & Burnstein 1991) to model the additional contribution to the potential from the central dominant galaxy, NGC 4696:

$$\rho(r) = \rho(0) \left[\frac{1}{1 + (r/r_c)^2} \right]^{3/2}. \quad (1)$$

Here, $\rho(0)$ (which is equal to $9\sigma^2/4\pi Gr_c^2$) is the central ($r=0$) density in the cluster, r_c is the core radius and σ is the line-of-

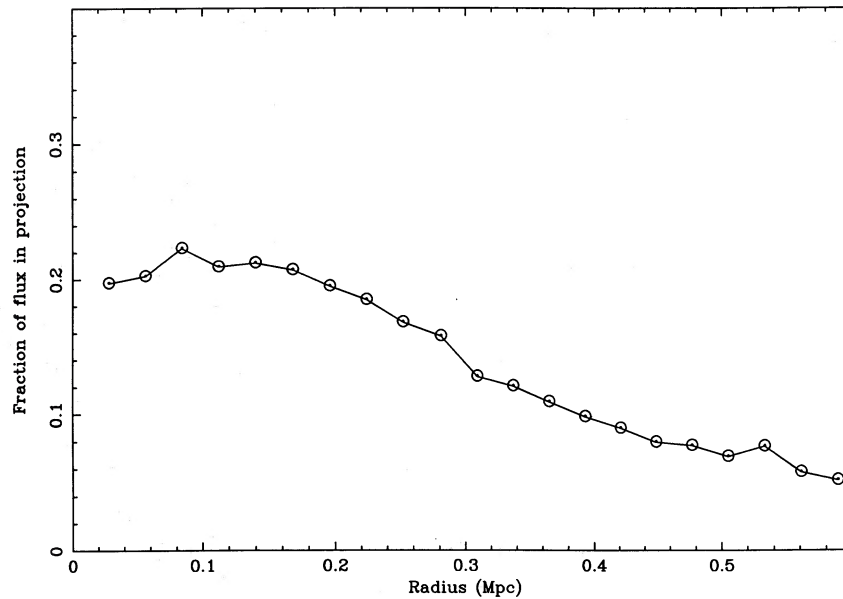


Figure 4. The fraction of flux in projection, as a function of the projected radius, for a circular source region centred on the X-ray centroid of the Centaurus cluster.

sight velocity dispersion of the cluster. The velocity dispersion of the cluster has been fixed at the optically determined value of 577 km s^{-1} (Lucey et al. 1986). The outer pressure of the cluster gas is varied iteratively until consistent solutions to the equilibrium equations are found. A strong constraint on possible solutions is obtained by ensuring that the temperature profile of the cluster predicted by the deprojection analysis is in agreement with the spectral results.

The deprojection analysis was performed on a vignetting-corrected image of the cluster constructed on a 28-arcsec pixel scale (approximately the FWHM spatial resolution of the PSPC) from counts in the energy range 0.1–2.4 keV (i.e. PHA channels 11–240). Those parts of the image covered by the PSPC rib support structure or with obvious contaminating sources were masked out. A radial surface brightness profile centred on the cluster X-ray centroid and extending out to $0^{\circ}8$ (the maximum radius at which the vignetting function of the *ROSAT* X-ray Telescope is accurately determined) was calculated. Between $0^{\circ}3$ and $0^{\circ}4$ (the region masked by the rib support structure), the form of the surface brightness profile was estimated by fitting a fourth-order polynomial to the data from radii $0^{\circ}15$ to $0^{\circ}8$ and interpolating across the missing region. The outermost bin of the profile was used to estimate the background emission.

4.2 Results

The results of the deprojection analysis are summarized in Figs 5(a)–(h). These show, as a function of radius, the azimuthally averaged surface brightness profile (background-subtracted and corrected for telescope vignetting) and the derived pressure, bolometric luminosity, temperature, electron density, cooling time, gas mass and total mass, and mass deposition rate (these values are calculated using a

King potential of core radius 110 kpc; see Section 4.3). A uniformly covering absorbing column density of $N_{\text{H}} = 8.8 \times 10^{20} \text{ atom cm}^{-2}$ (as determined by H I observations, and in agreement with the value measured over the bulk of the cluster in our annular spectral analysis) was assumed to cover the cluster. The deprojection results confirm that Centaurus contains a moderate cooling flow. Using the 110-kpc core radius potential, the cooling time calculated in the central 28-arcsec (radius) bin (i.e. the central 8 kpc) is $1.8^{+0.1}_{-0.1} \times 10^8 \text{ yr}$, significantly less than the age of the cluster. We derive a value for the cooling radius, i.e. the radius at which the mean emission-weighted cooling time of the gas equals the Hubble time ($H_0^{-1} = 2 \times 10^{10} \text{ yr}$), of $130^{+80}_{-30} \text{ kpc}$ and an integrated mass deposition rate within this radius of $35^{+40}_{-20} \text{ M}_{\odot} \text{ yr}^{-1}$. Confidence regions for the derived parameters have been estimated using a Monte Carlo technique. The errors on the central cooling time describe the 10- and 90-percentile values from 100 simulations. The upper and lower confidence limits on the cooling radius mark the radii where the 10 and 90 percentiles exceed, and become less than, the Hubble time, respectively. Errors on the mass deposition rate are the 90- and 10-percentile values at the upper and lower limits for the cooling radius.

We have examined the systematic effect that the elliptical (see Section 6) rather than spherical geometry of the cluster may have on the deprojection results. This has been carried out by splitting the cluster into four quadrants, and deprojecting each one individually. The mass deposition rates, central cooling times and cooling radii estimated from the quadrants vary from 33 to $69 \text{ M}_{\odot} \text{ yr}^{-1}$, 1.3×10^8 to $3.3 \times 10^8 \text{ yr}$, and 120 to 210 kpc, respectively. We conclude that the results of the deprojection analysis are not severely affected by the approximation of spherical symmetry.

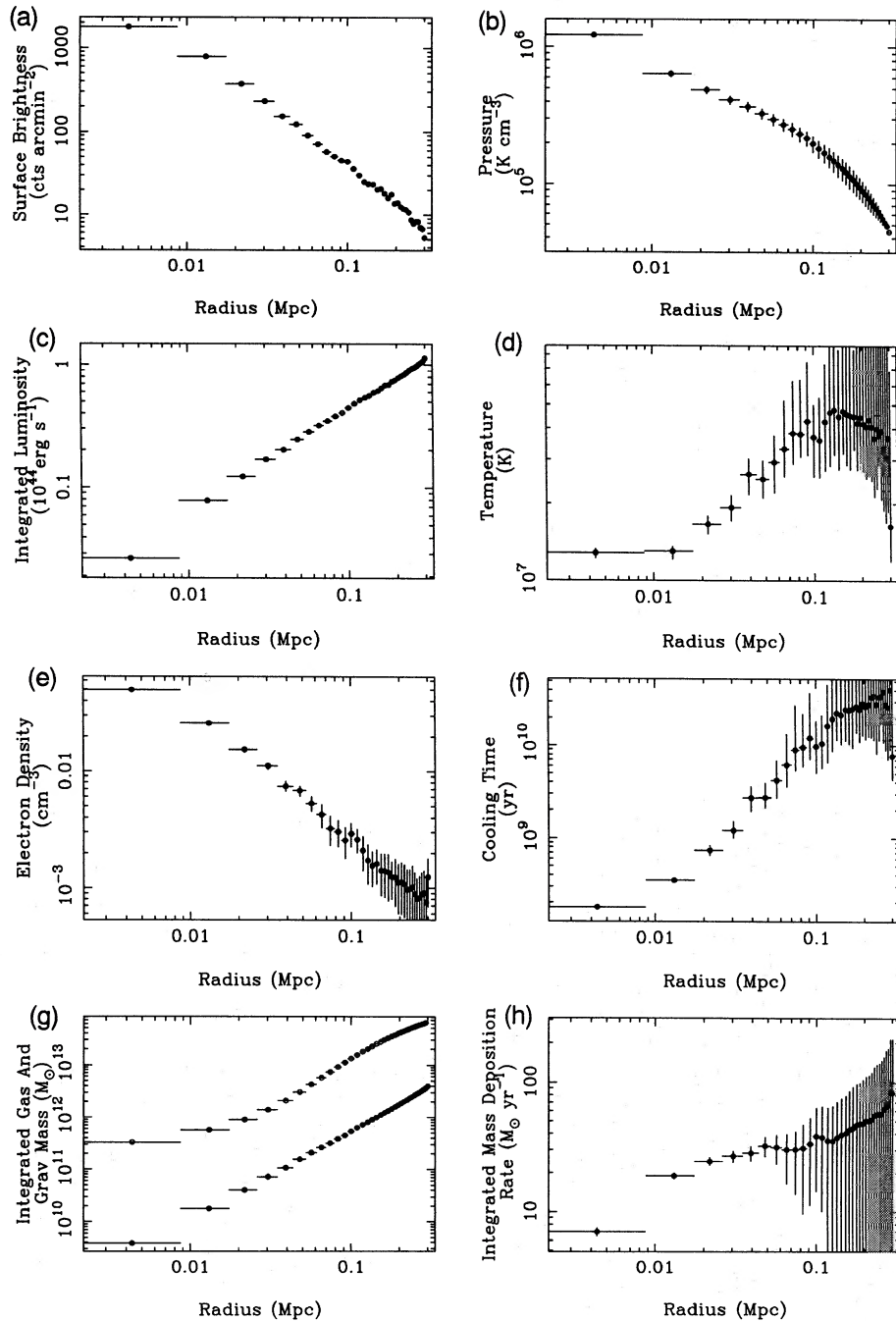


Figure 5. Summary of results from the deprojection analysis of the cluster image using a 110-kpc core radius King potential. Results obtained using the finest (28 arcsec pixel⁻¹) image binning are shown. From left to right, top to bottom, we plot (a) surface brightness, (b) pressure, (c) integrated luminosity, (d) temperature, (e) electron density, (f) cooling time, (g) integrated gas and gravitational mass and (h) integrated mass deposition rate. In panels (a), (b), (c), (e) and (g) the plotted points show the mean values and 1 σ errors (in each radial bin) from 100 Monte Carlo simulations. In panels (d), (f) and (h) the points and errors mark the median and 10- and 90-percentile values from 100 Monte Carlo simulations.

4.3 Constraints on the gravitational potential

The gravitational potential of the cluster, modelled using a King approximation to an isothermal sphere, has two free parameters: the velocity dispersion and the core radius. If we are to place constraints on the core radius, we require that the velocity dispersion of the system be accurately measured.

The galaxy velocities in the Centaurus cluster have been extensively studied by Lucey et al. (1986), who present strong evidence for a bimodal galaxy velocity structure in the cluster. The larger component of galaxies has its dynamical centre on NGC 4696 (the optically dominant galaxy at the X-ray centroid; see Section 2). The second, smaller component (which has ~ 2.5 times fewer galaxies) is centred on

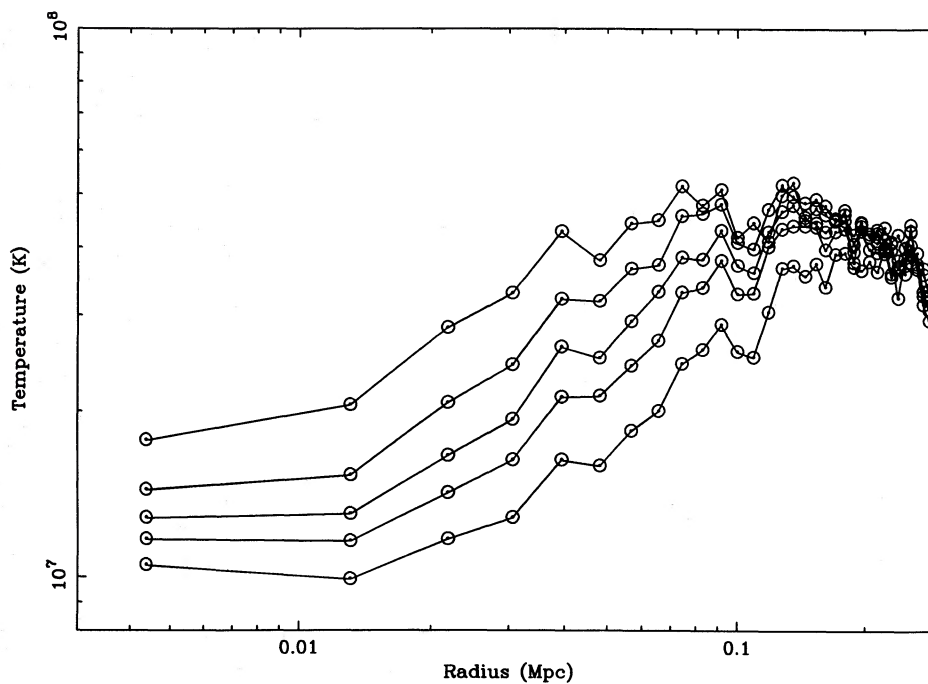


Figure 6. Deprojected temperature profiles illustrating the effect of varying the core radius of the gravitational potential. Profiles obtained for King law potentials with core radii of 50 (upper curve), 80, 110, 140 and 200 kpc (lower curve) are shown.

the other large elliptical galaxy in the cluster, NGC 4709. From the 180 galaxies within 3° of the cluster centre, Lucey et al. derive velocity dispersions for the large and small components of 577 and 262 km s $^{-1}$, respectively.

The X-ray emission from the bulk of the cluster shows no evidence for significant deviation from a smooth elliptical distribution, approximately centred on NGC 4696 (see discussion in Section 7), implying that the gravitational potential of the cluster is also smooth and elliptical. The larger concentration of galaxies, centred on NGC 4696, seems to be responding to the gravitational potential of the cluster, whereas the second concentration of galaxies does not. From a detailed examination of the optical properties of the member galaxies in the two components, Lucey et al. (1986) conclude that the smaller component represents a subsystem of galaxies within the main cluster. We note that the relaxation time-scale for the galaxies in a cluster merger event is significantly longer than that of the gas or dark matter. The gas will relax during a few sound crossing times ($t_{\text{cross}} \sim 10^9$ yr across the inner 1 Mpc), whereas the time-scale for the general galaxy population to relax (through two-body relaxation and dynamical friction) will be an order of magnitude longer. The smaller velocity component may represent the 'fossil record' of galaxies from a subcluster which earlier merged with Centaurus, and from which the dark matter and gas have since relaxed, leading to the smooth observed X-ray emission.

However, the form of the gravitational potential remains the most uncertain element of the deprojection analysis, since so few observational constraints exist. We have examined the effect on the deprojection results of varying the cluster core radius. Core radii of between 50 and 200 kpc were examined, with the velocity dispersion of the cluster kept fixed at the optically determined value (the galaxy

potential was also unchanged). The mass deposition rate obtained with the steepest (50 kpc) potential is 31^{+130}_{-17} $M_\odot$ yr $^{-1}$, the cooling radius is 130^{+110}_{-60} kpc and the central cooling time $2.2^{+0.2}_{-0.1} \times 10^8$ yr. With the flattest (200 kpc) potential these values become 45^{+65}_{-23} $M_\odot$ yr $^{-1}$, 150^{+90}_{-50} kpc and $1.7^{+0.1}_{-0.1} \times 10^8$ yr, respectively. Clearly, these values are little changed by altering the core radius by a factor of 4 in size. The most sensitive parameter to the change of potentials is the temperature. This is illustrated in Fig. 6, where we overlay the temperature profiles obtained with five different core radii (50, 80, 110, 140 and 200 kpc). Qualitatively, the effect of steepening the potential is to decrease the radius at which the temperature profile starts to drop, and increase the temperature in the central bin. With a shallower potential, the gas temperature starts to fall at larger radii and the central temperature is lower.

The spectral results of Section 3 show that the temperature profile measured in the cluster is mildly dependent on the spectral model used (compare columns 4, 7 and 10 of Table 2). In Fig. 7 we compare the spectrally determined results using (a) model 2 and (b) model 3 with the temperature profiles obtained from the deprojection analysis with the different core radii. The surface brightness profile used in the deprojection was rebinned to the same 1.5-arcmin spatial scale as in the spectral analysis. In each figure the deprojected profile that provides the best visual match to the spectral results is shown. We see that the temperature profile measured spectrally using model 2 (N_H free, Z fixed) is well described by the deprojection results using an isothermal potential with a 110 ± 30 kpc core. Similarly, the temperature profile measured using spectral model 3 (N_H fixed, Z free) is well fitted by the deprojected profile for a 90 ± 30 kpc core. If we assume that the differences between the spectral results obtained using models 2 and 3 provide a

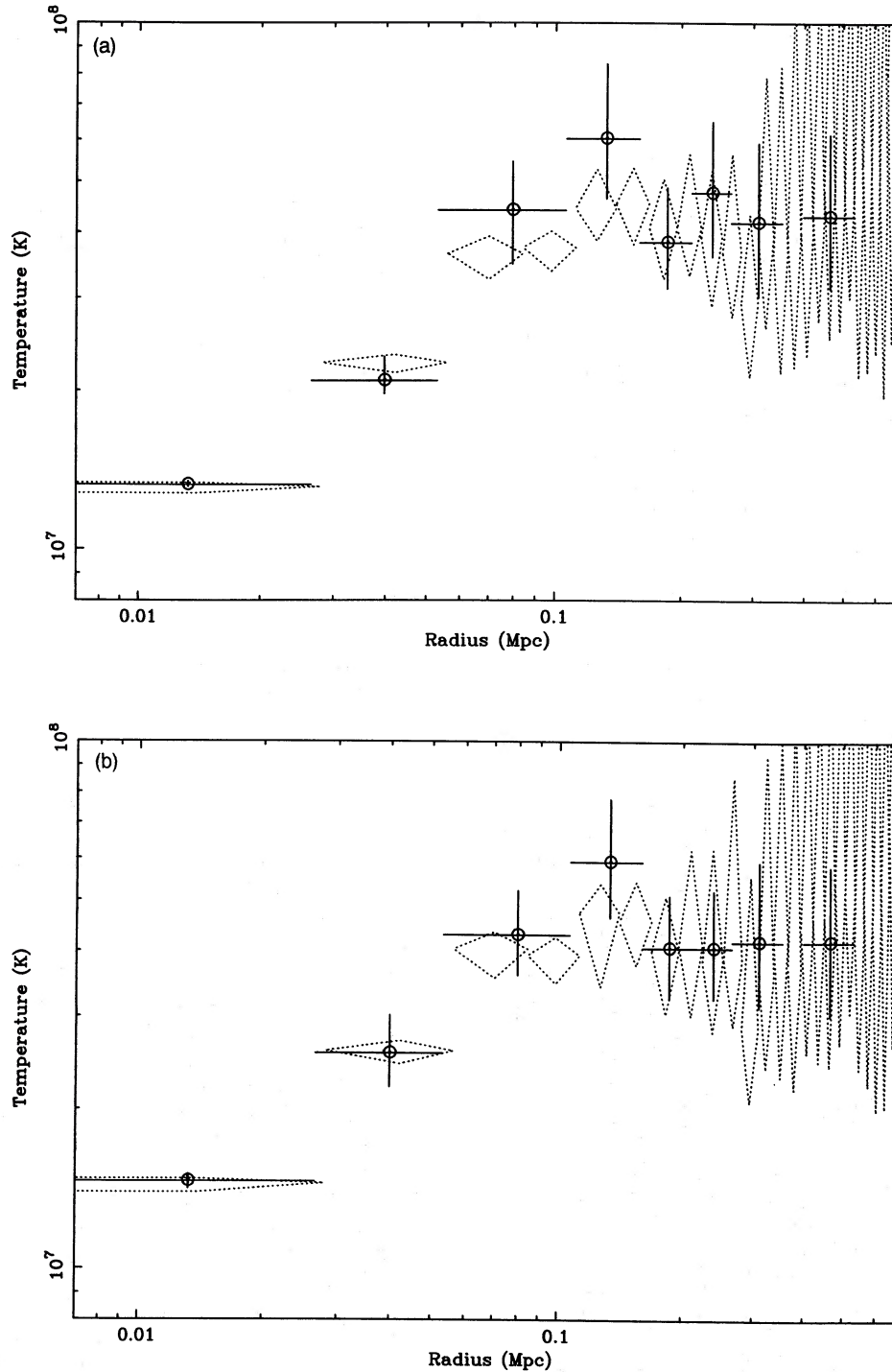


Figure 7. Comparisons of the spectrally determined temperature profile for the Centaurus cluster with results from the deprojection analysis. These are used to estimate the core radius of the gravitating matter in the Centaurus cluster. (a) The spectral profile determined using spectral model 2 (solid bars) and the deprojection results for a 110-kpc core radius cluster overlaid (diamonds). (b) The spectral profile determined using spectral model 3 (solid bars) with the deprojection results for a 90-kpc core radius cluster overlaid (diamonds).

reasonable estimate of the systematic uncertainty in the measurement of the temperature profile (particularly given the limits on projection effects discussed in Section 3.3), our results constrain the core radius of the cluster (modelled with a King approximation to an isothermal sphere) to be in the range 60–140 kpc. A direct comparison of Figs 7(a) and (b)

with Fig. 6 shows that core radii greater or less than these values predict temperature profiles inconsistent with the spectral results. However, the limitations of the simple, single-phase models used in this analysis, and further uncertainties due to the emission-weighting of the spectrally determined temperatures (although for Centaurus this is less

of a problem than for similar studies of hotter clusters, where the limited 0.1–2.4 keV band-pass of the PSPC makes measurements of cluster temperatures substantially more difficult), should be noted in interpreting the core radius result.

4.4 Calculation of the cluster mass profile

For a spherically symmetric, ideal gas in hydrostatic equilibrium with the cluster gravitational potential, the radial distribution of total mass, M , of the system can be written as a simple function of the electron density, n_e , and temperature, T , of the gas:

$$M = -\frac{rkT}{G\mu m_p} \left(\frac{\partial \ln n_e}{\partial \ln r} + \frac{\partial \ln T}{\partial \ln r} \right). \quad (2)$$

The temperatures measured with spectral model 2 (Table 2, column 3), and the density profile obtained by deprojection with a King potential of 110-kpc core radius (which was shown in Section 4.3 to provide an excellent match to the spectral results), have been used in the above relationship to calculate $M(r)$. The electron density profile of the gas is well determined by the PSPC data (Fig. 5e), and is not a sensitive function of the gravitational potential used in the analysis. The measured temperature profile shows no evidence for variation at $r > 50$ kpc, and we have assumed the gas in this region to be isothermal (with a best-fitting temperature of 3.8 keV) and hence $\partial \ln T / \partial \ln r = 0$ there. The mass profile calculated with equation (2) is plotted in Fig. 8, together with the mass profile from the deprojection analysis, and the mass in X-ray-emitting gas. The agreement between the results is

good and demonstrates the self-consistency of our combined spatial and spectral determinations of the cluster mass profile.

5 THE SPECTRUM OF THE COOLING FLOW

The results of the deprojection analysis described in Section 4 show that the Centaurus cluster contains a cooling flow of 30–40 $M_\odot \text{ yr}^{-1}$. We have extracted a spectrum from the inner 7.5 arcmin of the image (i.e. the inner 130 kpc of the cluster; the cooling radius determined from the deprojection analysis being ~ 130 kpc) to investigate the spectral properties of the cooling flow. The emission from material in projection was estimated from Fig. 4 (the projected component accounts for ~ 20 per cent of the total flux in the spectrum). We have modelled the projected component as 3.8-keV RS emission ($Z = 0.6 Z_\odot$, $N_H = \text{Galactic}$) with a normalization fixed at the calculated value.

We first examined how well the emission from the cooling flow could be modelled by a single isothermal RS component (the temperature of which was a free parameter in the fits). The results, summarized in Table 4 (model A), demonstrate that a single RS component with Galactic absorption and the *EXOSAT* average metallicity of 0.6 solar cannot adequately describe the emission from the cooling flow. With the inclusion of either an excess absorbing column density ($\Delta N_H \sim 2 \times 10^{20} \text{ atom cm}^{-2}$) or increased metallicity ($Z = 1.2^{+0.1}_{-0.2}$ solar), however, the fits are significantly improved, and are both statistically acceptable.

A second model (model B), in which the emission from the cooling gas was approximated by two RS components, was examined. The temperature of the first component was fixed

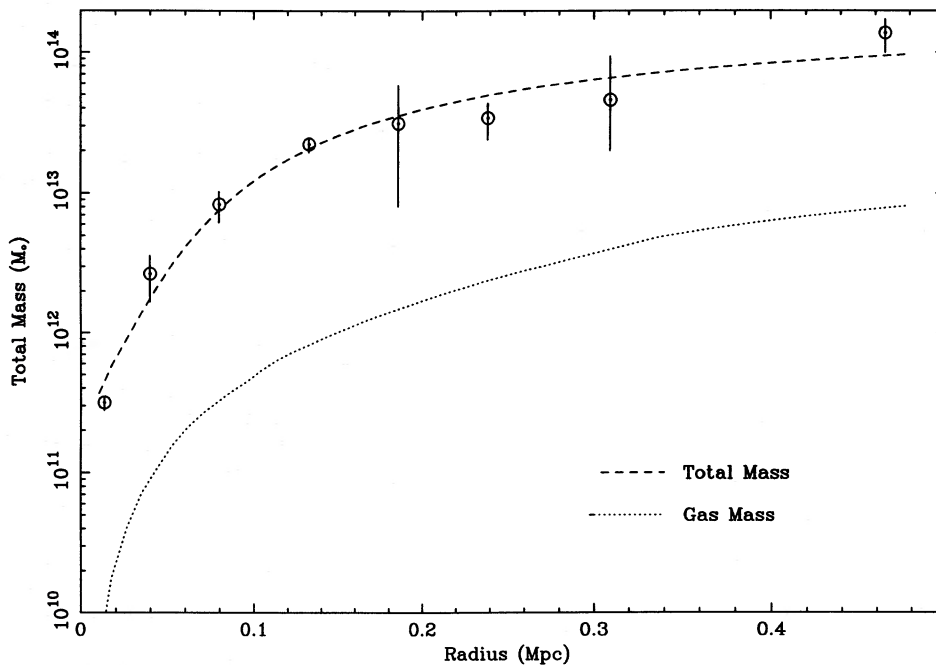


Figure 8. A comparison of the total gravitating mass as a function of radius for the best-fitting (to spectral model 2) 110-kpc core radius King law potential (dashed curve) with the total mass calculated in Section 4.4 (points with 1σ errors plotted as solid bars). The X-ray-emitting gas mass profile determined from the deprojection analysis is plotted as the dotted curve.

at 3.8 keV and the temperature of the second RS component left as a free parameter in the fits. The metallicities and column densities of the two components were forced to be equal. The results (summarized in Table 4; model B) demonstrate that a two-temperature RS model, with Galactic column density and 0.6-solar metallicity, again cannot adequately describe the data. As with model A, the introduction of either an excess column density or an increase in the metallicity of the emitting gas improves the fits to an acceptable level. The ratio of the fluxes in the hot (3.8 keV) and cool (kT freely fitted) RS components (measured in the 0.1–2.4 keV *ROSAT* band) is $F_{\text{cool}}/F_{\text{hot}} \sim 4:1$ for the model with N_{H} free and $F_{\text{cool}}/F_{\text{hot}} \sim 4:5$ for models with metallicity free. The total flux in the cooling region, $5.6 \times 10^{-11} \text{ erg cm}^{-2} \text{ s}^{-1}$ (over the 0.1–2.4 keV band), corresponds to a luminosity in this band of $2.9 \times 10^{43} \text{ erg s}^{-1}$.

Finally, we examined the effect of including a third emission component (together with the two RS components) to model emission from gas cooling from the virial temperature of the cluster to zero at constant pressure (i.e. a constant-pressure cooling flow; Johnstone et al. 1992). For a steady-state cooling flow, the size of this component should approximately equal the mass deposition rate obtained from the deprojection analysis. Although such a spectrum is not found to be statistically required in addition to the two RS components (which is not surprising, given the limited spectral resolution of the PSPC, which makes the detector insensitive to the characteristic changes in the emissivities of individual spectral lines as the gas cools), a component consistent with the deprojection results is statistically permitted by the data if the average metallicity in the cooling region exceeds the solar value.

Table 4. The spectrum of the cooling flow.

MODEL A (1 RS)

Free Parameters	χ^2/DOF	kT	N_{H}	Z
kT	63.4/38	$1.59^{+0.07}_{-0.08}$	8.80	0.6
kT, N_{H}	32.7/37	$1.59^{+0.07}_{-0.08}$	$11.1^{+0.5}_{-0.6}$	0.6
kT, Z	33.0/37	$1.74^{+0.07}_{-0.07}$	8.80	$1.2^{+0.1}_{-0.2}$
kT, N_{H}, Z	29.6/36	$1.69^{+0.07}_{-0.08}$	$9.9^{+0.8}_{-0.7}$	$0.9^{+0.2}_{-0.2}$

MODEL B (2 RS)

Free Parameters	χ^2/DOF	kT	N_{H}	Z
kT_2	57.8/37	$1.41^{+0.07}_{-0.09}$	8.80	0.6
kT_2, N_{H}	31.7/36	$1.44^{+0.14}_{-0.06}$	$10.8^{+0.5}_{-0.5}$	0.6
kT_2, Z	26.4/36	$1.25^{+0.16}_{-0.13}$	8.80	$1.7^{+0.5}_{-0.5}$
kT_2, N_{H}, Z	26.0/35	$1.34^{+0.10}_{-0.22}$	$9.1^{+0.8}_{-0.7}$	$1.3^{+1.1}_{-0.4}$

Notes. Summary of best-fitting parameters from fits to the cooling-flow spectrum (covering the central 130 kpc of the cluster). Errors on the best-fitting value indicate regions of 68 per cent confidence on a single interesting parameter. Temperatures (kT) are expressed in keV, column densities (N_{H}) in $10^{20} \text{ atom cm}^{-2}$ and metallicities (Z) as a fraction of the solar value.

6 STRUCTURE IN THE X-RAY EMISSION

The contour map in Fig. 1(b) illustrates the elliptical nature of the X-ray emission from the Centaurus cluster. We have measured the variation of ellipticity with radius, and searched for statistical deviations from a smooth elliptical structure [such as may be caused by filamentary emission (e.g. Sarazin, O'Connell & McNamara 1992a,b), subclustering, point sources or patchy variations in column density across the image]. The structural analysis was carried out using an unsmoothed version of the image in Fig. 1(a), covering the energy range 0.1–2.4 keV, with 28-arcsec pixels (corresponding to a linear scale at the cluster of $\sim 8 \text{ kpc}$). A smooth model of the emission was generated from least-squares fits of elliptical isophotes to the X-ray image (Jedrzejewski 1987), with the ellipticities and centroids being free parameters in the fits. The results are summarized in Figs 9(a)–(c). Fig. 9(a) shows the variation in the ellipticity of the X-ray isophotes with radius (i.e. semimajor axis). The ellipticity is approximately constant with a value ~ 0.1 . However, variation is observed in the position angle (PA) of the isophotes (Fig. 9b). The PA rotates from a value of $\sim 50^\circ$ at small radii to a value of $\sim 100^\circ$ at a radius of $\sim 100 \text{ arcsec}$. At larger radii the PA remains approximately constant at 80° – 120° . In Fig. 9(c) we plot the variation of X-ray centroid with radius. A clear variation of the centroid, with the displacement approximately along the major axis of the cluster, is observed across the inner 3 arcmin of the cluster. The variation of PA at small radii (and corresponding variation in the centroid location) may indicate that the gas here has not yet fully relaxed in the cluster potential. A recent cluster merger event could lead to a significant mixing up of the inner regions of the cluster, but could leave the outer regions relatively undisturbed (e.g. see Fabian & Daines 1991). The post-merger gas will then relax over a few sound crossing times. This interpretation is consistent with the observed galaxy velocity substructure discussed in Section 4.3.

The comparison between the results of the X-ray isophotal analysis described above and those from a similar analysis of optical observations of the dominant galaxy NGC 4696 (Sparks, Macchetto & Golombek 1989) is striking. Sparks et al. show that, for semimajor axes of 3–90 arcsec, the ellipticity of the central galaxy varies between 0.1 and 0.2, with position angles in the range 90° – 100° . These values are in excellent agreement with the ellipticity and position angle of the X-ray emission at large ($r \geq 100 \text{ arcsec}$) radii, although they do not trace the emission close to the galaxy ($r < 100 \text{ arcsec}$) where the rapid variation in X-ray PA is observed. Together, the X-ray and optical observations show that the central dominant galaxy NGC 4696 is intimately linked to the gravitational potential of the cluster.

Within the inner $\sim 4 \text{ arcmin}$ of the image (the region covered by the two inner annuli used in the spectral analysis), sufficient counts per pixel are present for a χ^2 test to be used to search for substructure in the image, which will take the form of statistically significant variations between the cluster image and the elliptical model. The total χ^2 of 275 for the 284 pixels in this region (giving a reduced $\chi^2 = 0.97$) demonstrates that the smooth elliptical model is an adequate description of the X-ray emission from the cluster. No evidence for non-elliptical substructure is observed.

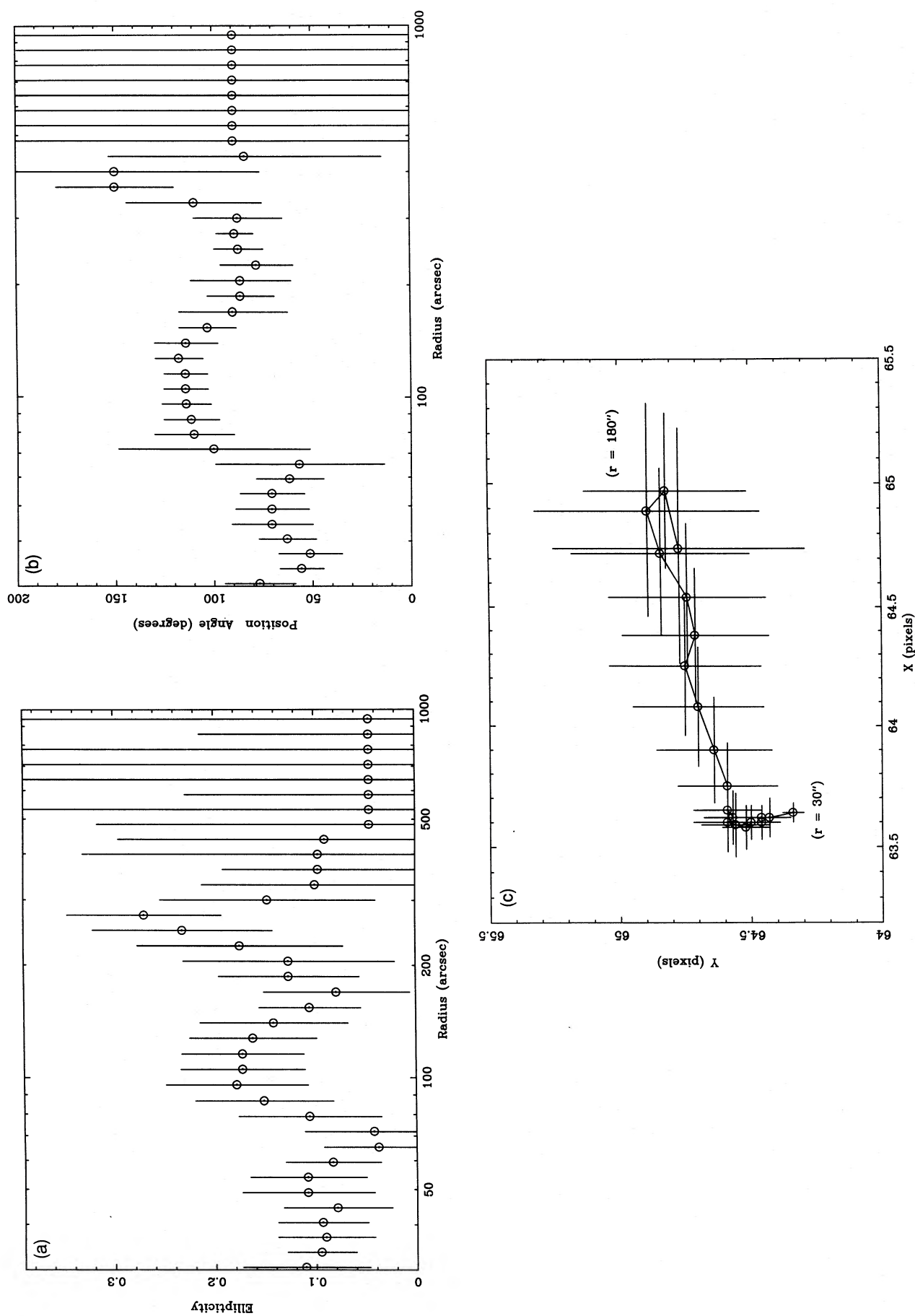


Figure 9. The variation of (a) ellipticity with radius of the X-ray isophotes, (b) position angle with radius and (c) X-ray centroid location for the inner 3 arcmin of the cluster. The pixel size is 28 arcsec.

A search for substructure on larger scales, in the region of the second optically dominant cluster galaxy NGC 4709, was also performed. With the image binned to a 1-arcmin pixel scale, no significant deviation from elliptical symmetry was observed at the position of NGC 4709. We note, however, that the test is complicated, since the coordinates of the galaxy [$12^{\text{h}} 50^{\text{m}} 04^{\text{s}}.0$, $-41^{\circ} 23' 1''$ (2000.)] place it along the semimajor axis of the cluster. Using a 3-arcmin source box centred on the optical coordinates, and a background extracted from regions either side of the source box along the isophotes, we place a limit on the intrinsic 0.1–2.4 keV luminosity of NGC 4709 (assuming it to be at the same distance as the rest of the cluster) of $L_X \lesssim 2 \times 10^{41} \text{ erg s}^{-1}$.

7 DISCUSSION

The combined spectral and imaging analyses described in Sections 3 and 4 provide a comprehensive picture of the X-ray properties of the ICM of the Centaurus cluster. At radii $50 < r < 500$ kpc the ICM is remarkably isothermal, with a temperature of 3.8 ± 0.5 keV. This is in good agreement with the best-fitting average cluster temperature of 3.6 ± 0.4 keV determined with *EXOSAT* (Edge & Stewart 1991), and with the 3.9 ± 0.1 keV measured with the Monitor Proportional Counter on the *Einstein Observatory* (David et al. 1993). The column density measured in this region is also in excellent agreement with the Galactic value, determined from 21-cm observations, and the metallicity is well matched to the $Z = 0.6 Z_{\odot}$ measured with *EXOSAT* (Edge & Stewart 1991). Within the inner 50 kpc of the cluster, the temperature drops rapidly, to an average (emission-weighted) value for the inner 25 kpc of ~ 1.2 keV (the precise value depending on the spectral model used). The PSPC spectra for the inner 50 kpc require either a sharp increase in metallicity (to values $\geq$ solar) or the presence of a significant amount of intrinsic X-ray-absorbing material in the cluster core.

The inability of the PSPC spectra to discriminate between the excess-absorption and excess-metallicity models is due to the inadequate spectral resolution (~ 0.5 keV in the range 0.5–1 keV) of the detector. We are unable to discriminate statistically between the presence of an absorption edge at 0.53 keV (the K edge of neutral oxygen, the strongest absorption feature in the PSPC band) and an increase in line emission from the iron complex at ~ 1 keV (the strongest emission-line feature). It is interesting, however, to compare the results of this analysis with those obtained from the study of the PSPC data for Abell 478 (Allen et al. 1993). The Abell 478 data require the presence of excess absorbing material in the core of the cluster, and cannot be explained by a metallicity effect. The Abell 478 data can be used to make this distinction primarily because the temperature in the core of the cluster is significantly higher (~ 3 keV across the inner 150 kpc) than in Centaurus. The emissivity of the iron complex is a strong function of temperature, peaking at $kT \sim 0.5$ keV and decreasing rapidly with increasing temperature. A metallicity gradient therefore has a much weaker effect on the 0.1–2.4 keV X-ray spectrum of a hot cluster like Abell 478 than on that of a cool one like Centaurus. Much better discrimination between metallicity and absorption models will be possible in the near future with the improved spectral capabilities of *ASCA*.

We note that, using spectral model 2, the excess column density measured in the cluster core ($\Delta N_{\text{H}} = 5.6 \times 10^{20} \text{ atom cm}^{-2}$ across the inner 1.5-arcmin region) implies a mass of X-ray absorbing material in this region of $\sim 10^{10} M_{\odot}$. A similar mass is derived in the 1.5–3 arcmin annulus. The deprojection analysis of Section 4 shows that a cooling flow of $30\text{--}40 M_{\odot} \text{ yr}^{-1}$ is present in the cluster, with the bulk of the material cooling out within the central 3 arcmin. It is interesting to note that, as in the analysis of the PSPC data for Abell 478, the region of excess column density is very well matched to the region of mass deposition from the flow (compare Figs 3a and 5h). Previous authors (White et al. 1991; Allen et al. 1993) have suggested that the X-ray-absorbing material could be the end-point for the bulk of the material cooling out of the flow. The $\sim 2 \times 10^{10} M_{\odot}$ of absorbing material in the central 3 arcmin of the Centaurus cluster would take the cooling flow $\sim 10^9$ yr to accumulate (a time-scale similar to the mean cooling time in this region; Fig. 5f). The assumption that the X-ray-absorbing material is the major sink of the cooling flow then implies that the observed flow of $30\text{--}40 M_{\odot} \text{ yr}^{-1}$ cannot have existed for significantly longer than 10^9 yr, otherwise a substantial amount of (predominantly low-mass) star formation must have occurred in the flow.

As discussed by Daines et al. (1994), when a cluster undergoes a significant subcluster merger event, the kinetic energy of the infalling material will disturb the cooling region and disrupt the accumulated cold gas. The bulk of the gas is then likely to be heated back to the cluster virial temperature. Some of the thermal and kinetic energy of the merger event will also be channelled into generating the luminous optical emission-line nebulae which frequently surround the central cluster galaxy (Crawford & Fabian 1992). Based on the observed mass of absorbing material in Centaurus, and the present mass cooling rate, we expect the cluster to have undergone a significant merger event in the last few $\times 10^9$ yr. This is consistent with the observed optical galaxy velocity structure and smooth X-ray surface brightness contours discussed in Section 4.3.

We have re-examined the *Einstein* Solid State Spectrometer (SSS) observations of the Centaurus cluster. In reporting the discovery of large amounts of cold, X-ray-absorbing matter in clusters of galaxies, White et al. (1991) noted that Centaurus was the only cooling-flow cluster not to show evidence for excess X-ray absorption. A comparison of the pointing of the SSS observation [$12^{\text{h}} 48^{\text{m}} 47^{\text{s}}$, $-41^{\circ} 22' 30''$ (2000.)] with the X-ray centroid determined here [$12^{\text{h}} 48^{\text{m}} 50^{\text{s}}.3$, $-41^{\circ} 18' 45''$ (2000.)], however, shows that the SSS observation did not observe the centre of the cluster (the SSS had a 6-arcmin diameter circular field of view), which may account for this anomaly. The SSS data do not allow us to discriminate further between the excess-absorption and excess-metallicity hypotheses for explaining the spectral properties of the cluster core.

The central regions of the Centaurus cluster exhibit several unusual optical properties. The dominant galaxy, NGC 4696, is surrounded by a large, horse-shoe-shaped dust lane, and is rich in filamentary optical line emission (Jørgensen et al. 1983; Sadler 1987; Sparks et al. 1989). Sparks et al. (1989) measure a mean reddening in the inner 50 kpc² of $E(B - V) = 0.046$. The column density in neutral hydrogen associated with this reddening can be estimated

using the standard relation for our Galaxy [$N_{\text{H}}/E(B-V) = 5.8 \times 10^{21} \text{ atom cm}^{-2} \text{ mag}^{-1}$ (Bohlin, Savage & Drake 1978)]; we obtain a value of $2.7 \times 10^{20} \text{ atom cm}^{-2}$. This is less than the intrinsic column density measured from the X-ray data using spectral model 2 (Fig. 3a) although similar to that obtained from our more detailed fits to the cooling region (Table 4). We note, however, that there is no a priori reason why the standard Galactic gas/dust ratio should apply to a large elliptical galaxy in the middle of a cooling flow.

One of the most important results of this analysis is the tightly constrained density and temperature profiles for the cluster gas, and the constraints that these place on the gravitational potential of the cluster. Our results (Figs 8a and b) tightly constrain the radial mass distribution in the cluster out to $\sim 0.5 \text{ Mpc}$. The total mass within this radius is $1.0 \times 10^{14} M_{\odot}$ and the mass in gas is $8.9 \times 10^{12} M_{\odot}$ (in agreement with the value obtained by Edge & Stewart 1991). The gas mass therefore makes up ~ 9 per cent of the total gravitating mass within this radius. This is a significantly lower fraction than is observed for larger, more massive clusters – e.g. Abell 478 (Allen et al. 1993), for which the total mass within 0.5 Mpc is $\sim 2.7 \times 10^{14} M_{\odot}$ and the gas mass/total mass ratio is ~ 17 per cent. Clearly, the X-ray-emitting gas in the Centaurus cluster has not undergone the same degree of concentration as has the gas in the more massive clusters.

The PSPC on *ROSAT* heralds the advent of spatially resolved X-ray spectroscopy of clusters of galaxies. The next few years should bring rapid advances in our understanding of the natures of these objects as a new generation of X-ray instrumentation comes into use. Observations with X-ray CCDs, providing much higher spectral resolution in energy bands better suited to the study of clusters (e.g. *ASCA* provides $\Delta E = 50\text{--}100 \text{ eV}$ in a $0.3\text{--}12 \text{ keV}$ observing band) will permit accurate determination of gas temperature profiles (and therefore mass profiles) for the most massive clusters, out to large ($2\text{--}3 \text{ Mpc}$) radii. Firm constraints will be placed on the total mass of clusters and the distributions of the dark and observed mass components, and therefore on the formation histories of the clusters and the nature of the dark matter itself. The high spectral resolution offered by *ASCA* (and future emissions such as *XMM* and *AXAF*) will enable us to discriminate unambiguously between the excess-absorption and metallicity-gradient hypotheses for explaining the spectral profiles of clusters like Centaurus, and will enable us to probe, in detail, the multiphase nature of cooling flows.

8 CONCLUSIONS

We have used spatially resolved X-ray spectroscopic observations of the Centaurus cluster of galaxies, made with the *ROSAT* PSPC, to determine the distributions of gas mass and total gravitating mass out to a radius of $\sim 0.5 \text{ Mpc}$. The gravitational potential of the cluster can be well modelled using a King approximation to an isothermal sphere, with the observed galaxy velocity dispersion and a core radius of $60\text{--}140 \text{ kpc}$. The X-ray spectra tightly constrain the radial temperature profile of the cluster (leading to the tight mass constraints), and show that the cluster either possesses a strong metallicity gradient or contains a significant central concentration ($\sim 2 \times 10^{10} M_{\odot}$ in the inner $\sim 50 \text{ kpc}$) of intrinsic, X-ray-absorbing material (or some combination of

these characteristics). A strong correlation is observed between the X-ray structure of the cluster and the optical structure of the central cluster galaxy, NGC 4696, indicating that the central galaxy is intimately linked to the gravitational potential of the cluster.

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