3C 295: A CLUSTER AND ITS COOLING FLOW AT \( z = 0.46 \)

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ABSTRACT

We present ROSAT HRI data of the distant and X-ray–luminous \([L_X(\text{bol}) = 2.6^{+0.4}_{-0.2} \times 10^{45} \text{ergs s}^{-1}]\) cluster of galaxies 3C 295. We fit both a one-dimensional and a two-dimensional isothermal \(\beta\)-model to the data, the latter taking into account the effects of the point spread function (PSF). For the error analysis of the parameters of the two-dimensional model, we introduce a Monte Carlo technique. Applying a substructure analysis by subtracting a cluster model from the data, we find no evidence for a merger, but we see a decrement in emission southeast of the center of the cluster, which might be due to absorption. We confirm previous results by Henry & Henriksen that 3C 295 hosts a cooling flow. The increase of \(10\%\) can be explained by a shallower gravitational potential inferred by the broader overall profile caused by the PSF, which diminishes the efficiency of mass accretion. We also determine the total mass of the cluster using the hydrostatic approach. At a radius of 2.1 Mpc, we estimate the total mass of the cluster \(M_{\text{tot}}\) to be \(9.2 \pm 2.7 \times 10^{14} M_\odot\). For the gas-to-total mass ratio, we get \(M_{\text{gas}}/M_{\text{tot}} = 0.17–0.31\), in very good agreement with the results for other clusters of galaxies, giving strong evidence for a low-density universe.

Subject headings: cooling flows — dark matter — galaxies: clusters: individual (3C 295) — galaxies: fundamental parameters — X-rays: galaxies

1. INTRODUCTION

In recent years, the investigation of distant clusters of galaxies has become a key issue for the study of cosmological parameters as well as structure formation. In addition, the comparison of the physical properties of distant and nearby galaxy clusters can give useful insights into their evolution.

The distant cluster 3C 295, also known as Cl 1409 + 526, has been extensively studied in optical wavelength bands: Dressler & Gunn (1992) determined its velocity dispersion to be \(\sigma = 1300 \text{ km s}^{-1}\) in a study of seven distant clusters of galaxies. Thimm et al. (1994), in the search for line emission in galaxies, observed the cluster with an Imaging Fabry-Perot interferometer and found the percentage of emission line galaxies in 3C 295 to be \(40\% \pm 11\%\). Smail et al. (1997) presented the results of a weak-lensing analysis of 12 distant clusters, among them 3C 295. The analysis they present is based on data from the Hubble Space Telescope.

Henry & Henriksen (1986) presented an analysis of Einstein data of the cluster. The authors conclude that there is strong evidence for 3C 295 hosting a cooling flow in the center.

Cooling flows generally occur in clusters in which the cooling time of the hot gas, the intracluster medium (ICM), is less than the age of the cluster, so that the energy loss due to radiation cannot be neglected and mechanisms for the compensation must occur. This was first found by Cowie & Binney (1977), Fabian & Nulsen (1977), and Mathews & Bregman (1978), based on the findings of observations by Uhuru (Lea et al. 1973); for reviews see Fabian, Nulsen, & Canizares (1984, 1991) and Sarazin (1986, 1988).

In recent years, a handful of other high-redshift clusters have also shown indications of hosting cooling flows in their centers. Most recently, Schindler et al. (1997) reported RX J1347 – 1145 \((z = 0.45)\) to have an extremely massive cooling flow, with a mass accretion rate exceeding \(3000 M_\odot \text{ yr}^{-1}\). Fabian & Crawford (1995) reported on the detection of a cooling flow in IRAS P09104 + 4109 \((z = 0.442)\) with a mass accretion rate of about \(1000 M_\odot \text{ yr}^{-1}\), and Edge et al. (1994) found a cooling flow with similar strength in Zw 3146 at \(z = 0.29\).

In this paper we aim to give more insight into the cooling flow and its dependence on the temperature structure of the ICM, the gas and dark matter distribution, and the overall dynamical state of 3C 295. The outline is therefore as follows: § 2 gives a brief description of the observation and data handling. In § 3 we describe our spatial analysis based on the isothermal \(\beta\)-model, followed by a section describing our method for calculating the X-ray luminosity of the cluster. The cooling flow analysis is presented in § 5, and § 6 describes the details of our mass analysis. A discussion and conclusions follow.

Throughout the paper we assume \(H_0 = 50 \text{ km s}^{-1} \text{Mpc}^{-1}, q_0 = 0.5,\) and \(\Lambda = 0\).

2. X-RAY OBSERVATIONS

3C 295 was observed with the ROSAT HRI for 29.6 ks. Figure 1 shows the resulting image of the cluster. We only get in very good agreement with the results for other clusters of galaxies, giving strong evidence for a low-density universe.
photon within a radius of 8.3, we obtain a count rate of 0.028 ± 0.001 s⁻¹ for the cluster.

3. SPATIAL ANALYSIS

3.1. Overall Morphology

The cluster is elongated in the north-south direction, with an axial ratio of 0.78 (see below and Table 2). The emission is centrally peaked, which is a strong indication of the existence of a cooling flow (see below). There is some isophote twist visible in the contours in Figure 1. The lines are more compressed in the southeast and more stretched in the northwest. We will discuss this feature and its significance later on in more detail.

There are no other clearly extended sources visible in the vicinity of the cluster, since all other emission peaks in Figure 1 that have at least two contour lines are consistent with point sources; we checked whether these sources were possibly extended by determining their individual surface brightness profiles and comparing them to the on-axis point-spread function (PSF) of the ROSAT HRI.

3.2. Surface Brightness and Isothermal β-Model

The radial surface brightness profile of the cluster can be seen in Figure 2. To explore the physical quantities of 3C 295, we make use of the isothermal β-model (Cavaliere & Fusco-Femiano 1976, 1981; Sarazin 1986). This model enables us to convert the brightness profile of a cluster analytically into a density profile of the gas. The one-dimensional surface brightness profile of this model has the following form:

\[
S(r) = S_0 \left( 1 + \frac{r^2}{a^2} \right)^{-3\beta + 1/2} + B, \quad (1)
\]

which translates into a density profile

\[
n(r) = n_0 \left( 1 + \frac{r^2}{a^2} \right)^{-3\beta/2}, \quad (2)
\]

where \( a \) (the so-called core radius), \( S_0 \) (the central surface brightness), \( B \) (the background), and \( \beta \) are all fit parameters.

There is also a two-dimensional form of the isothermal \( \beta \)-model, which takes into account a possible elongation of the cluster. This model has the representation

\[
S(x, y) = S_0(1 + F_1 + F_2)^{-3\beta + 1/2} + B, \quad (3)
\]

with

\[
F_1 = \frac{[\cos \alpha(x - x_0) + \sin \alpha(y - y_0)]^2}{a_1^2},
\]

\[
F_2 = \frac{[-\sin \alpha(x - x_0) + \cos \alpha(y - y_0)]^2}{a_2^2}.
\]

In the following discussion, we apply the one-dimensional and two-dimensional isothermal \( \beta \)-models to the data. The first model has four fit parameters \((S_0, a, \beta, B)\), the second eight fit parameters \((S_0, a_1, a_2, \beta, B, x_0, y_0, \alpha)\) [two core radii, one for the major axis, one for the minor axis], \(-\beta, B, x_0,\) and \(y_0\) [the position of the center of the cluster in \(x\) and \(y\)], and the position angle, \(\alpha\). In the one-dimensional fit we predefine the center of the cluster by sorting the photons into concentric annuli centered on the peak of the X-ray cluster emission. In the two-dimensional case, in which we look at pixels instead of annuli, this predetermination is not necessary, and the center of the cluster emission is simultaneously fitted together with the other parameters.

The two-dimensional fit we apply here takes into account the effects of the PSF of the ROSAT HRI by convolving each tested model with the PSF before fitting. For the fitting we exclude serendipitous sources, which are clearly not connected to the X-ray emission of the cluster. The positions of these excluded sources can be seen in Table 1.

3.2.1. The One-dimensional Fit

For the one-dimensional fit, we bin the data in concentric annuli with a width of 10”. The results for this fit give a core
Poisson distribution. To overcome the problem here, we show Gaussian behavior, but instead show a classical counts per pixel, especially in outer regions, are too low to of the same size, this compensation does not occur. Here the decrease in cluster emission outward in this case is compensated for by the increase in area of the annuli. However, in the two-dimensional case, in which we use image pixels all of the same size, this compensation does not occur. Here the counts per pixel, especially in outer regions, are too low to show Gaussian behavior, but instead show a classical Poisson distribution. To overcome the problem here, we apply a small Gaussian filter ($\sigma = 3'$) to the image before fitting. This Gaussian filter changes the Poisson statistics into a Gaussian shape. For the error determination in each pixel we can fully account for the Gaussian filtering by taking into account the corresponding errors all contributing pixels quadratically (the exact formalism of the error determination can be found in Neumann & Böhringer 1997). In this way, we can change the errors in the count rate per pixel without reducing the number of degrees of freedom. We do not lower the number of degrees of freedom here, as we would if we increased the pixel size of the image used, since we keep all the available spatial information.

To account for the Gaussian filtering, which causes the inferred profile of the cluster to become shallower, we also apply the same Gaussian filter to the PSF image with which we convolve the fitted cluster model. To prove that with this procedure we indeed are able to determine the precise shape of the cluster, we constructed a simulated cluster image with known properties, similar to 3C 295, and with an exposure time equal to our analyzed ROSAT HRI pointing. We apply Poisson noise on this image and convolve it with the on-axis PSF of the ROSAT HRI. Subsequently we apply the Gaussian filter and fit the two-dimensional $\beta$-model to the simulated cluster image, taking into account the (Gaussian-filtered) PSF. The results can be seen in Table 3. The intrinsic cluster model properties and the obtained fit parameters agree very well within the errors, giving clear evidence that our method indeed gives correct results.

Since $\chi^2$ statistics does not allow an error of 0, we define the error of a pixel with value 0 to have an error of 1 (before filtering). Because of this necessary modification, we are, unfortunately, not able to give a confidence level or a reduced $\chi^2$ value of the fitted elliptical cluster model, and therefore we base our error determination on a Monte Carlo technique (see below). Our fit results are as follows: for the core radii we get $a_1 = 4.2 \pm 2.3 = 29 \pm 16$ kpc and $a_2 = 3.3 \pm 1.8 = 23 \pm 12$ kpc; for the slope parameter we get $\beta = 0.52 \pm 0.07$ (2 $\sigma$ results). The results for the other six fit parameters can be seen in Table 2, and the profile can be seen in Figure 2. One can see that while $\beta$ is relatively unaffected by the PSF of the ROSAT HRI, the same is not true for the core radius. The core radius changes when the PSF is taken into account, dropping from 7.2 to 4.2 or 3.3, respectively. However, one should note that the errors of this parameter (which are all 2 $\sigma$ errors) show a large overlap.

### Table 1

| Source | R.A. | Decl. | Total Counts |
|--------|------|-------|--------------|
| 1. Galaxy ($z = 0.2737$) | 14 11 21.5 | +52 12 53 | 10 |
| 2. Galaxy ($z = 0.4733$) | 14 11 23.1 | +52 13 32 | 60 |
| 3. QSO ($z = 1.29$) | 14 11 19.2 | +52 14 05 | 20 |

Note.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds. The sources agree within 6' with the X-ray position.

### Table 2

| Case | $S_0$ ($s^{-1}$ arcsec$^{-2}$) | $a_1$ (arcsec) | $a_2$ (arcsec) | $\beta$ | $x_0$ (2000.0) | $y_0$ (2000.0) | $\alpha$ (deg) | $B$ ($s^{-1}$ arcsec$^{-2}$) |
|------|----------------|----------------|----------------|------|---------------|---------------|--------------|----------------|
| One-dimensional | $3.8 \times 10^{-5}$ | $7.2_{-3.3}^{+3.4}$ | ... | $0.56_{-0.07}^{+0.10}$ | 14 11 20.3 | 52 12 12 | ... | $9.6 \times 10^{-7}$ |
| Two-dimensional | $(9.2 \pm 7.0) \times 10^{-5}$ | $4.2 \pm 2.3$ | $3.3 \pm 1.8$ | $0.52 \pm 0.07$ | 14 11 20.2 | 52 12 12 | $14 \pm 27$ | $9.1_{-0.18}^{+0.09} \times 10^{-7}$ |

Note.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

### Table 3

| Parameter | $S_0$ ($s^{-1}$ arcsec$^{-2}$) | $a_1$ (arcsec) | $a_2$ (arcsec) | $\beta$ | $x_0$ (arcsec) | $y_0$ (arcsec) | $\alpha$ (deg) | $B$ ($s^{-1}$ arcsec$^{-2}$) |
|----------|----------------|----------------|----------------|------|---------------|---------------|--------------|----------------|
| Input | $9.2 \times 10^{-5}$ | 4.2 | 3.3 | 0.52 | 0.0 | 0.0 | 14 | $9.0 \times 10^{-7}$ |
| Fit | $(10.5 \pm 5.8) \times 10^{-5}$ | $4.0 \pm 2.0$ | $3.2 \pm 1.5$ | $0.52 \pm 0.05$ | 0.0 | $0.0 \pm 0.8$ | $14 \pm 28$ | $(9.1 \pm 0.7) \times 10^{-7}$ |
The approach of fitting after the application of a Gaussian filter in the two-dimensional case has already been successfully applied to other clusters, such as Cl 0016 (Neumann & Böhringer 1997) and A2218 (Neumann & Böhringer 1999).

### 3.2.3. Error Estimates for the Two-dimensional Fit

For the error determination of the two-dimensional fit parameters, we apply a Monte Carlo method for which we construct 100 artificial images by adding random Poisson noise to the real cluster image and fitting each individual Poisson image in the same way as the original image. For the errors we use 2 times the standard deviation of each fit parameter from the 100 different fit results.

### 3.2.4. Comparison of the Fits

The comparison of the two fits to the original data, one taking into account the effects of the PSF the other not, can be seen in Figure 2. In fact, apart from the central region, which has a more peaked emission when the PSF is taken into account, the differences in the surface brightness profile are rather small. Therefore, we conclude that the PSF might affect the cooling flow analysis (see below), but not the overall cluster properties at large radii. In order to see whether the differences in the fit results are partly due to ellipticity, we perform a one-dimensional fit, which takes into account the effects of the PSF. The results are identical to our fit result for the two-dimensional fit, showing that the differences are only due to PSF effects.

### 3.2.5. Effects of Blurring

In the above analysis we neglected possible errors in the aspect resolution of the instrument. In order to see whether the PSF is degraded because of wobbling in the telescope or the effects of reacquisition of guide stars, we compared the theoretical PSF of the telescope and HRI with point sources in the field of view. The comparison of theoretical and actual PSFs gives somewhat different results depending on the binning of the actual observed point sources. (This effect is most likely due to Poisson noise, since all point sources have a count rate well below 0.003 counts s⁻¹, very faint.) The brightest source has about 60 source counts (see Table 1). However, all surface brightness profiles of serendipitous sources are quite consistent with the theoretical PSF (see above). If the aspect resolution is slightly degraded, it is not possible to assess the error it introduces and it is also not possible to correct for it, owing to the lack of bright sources in the pointing (for corrections for blurring, see, for example, Morse 1994 and Harris et al. 1998). This blurring can in principle affect our β-model fits and the resulting analysis. However, we do not expect the effects to play an important role.

### 3.3. Search for Substructure

In order to search for possible substructure in the cluster, we construct a cluster model image from the best-fit parameters of our two-dimensional fit, which includes the background (the model can be seen in Fig. 3). We then convolve the model with the PSF of the ROSAT HRI and subtract the model from the original data. The image of the residuals thus obtained is shown in Figure 4.

In this image we find positive residuals only below a significance level of 3σ above background and cluster emission, so there is no strong evidence for a perturbation in the cluster potential, such as a subgroup falling onto the cluster. There is a decrement in the residual map in the southeast of the cluster, which could in principle be an indication of some disturbance. However, it could also be just an indication of a region with higher intrinsic Galactic absorption. Unfortunately, surveys of the 21 cm line do not (yet) provide the necessary spatial resolution to confirm or rule out a strong gradient in Galactic absorption along the line of sight of the cluster.

The fact that this is the only evidence that the cluster deviates from the applied cluster model weakens the case
for a perturbation in the potential. To see whether this decrement might be due to an offset between the true cluster center and the cluster model (which is very unlikely, since the peak of emission in Fig. 1 and the cluster center in Fig. 3 coincide very well), we shift the center of the subtracted cluster model several arcseconds northwest of the center. The decrement still remains after the shift, indicating that this deficit in emission might indeed be real.

Finally, we conclude that, apart from this decrement, there is no further evidence for the cluster being dynamically young. It does not seem that the cluster is suffering or has recently suffered from a major merger phase, which is in agreement with the cluster hosting a cooling flow—normally a strong indication for a relaxed cluster. This fact is strengthened by the high confidence level of the one-dimensional fit, which is not expected in case of a non-relaxed cluster. However, we want to stress that our 3C 295 exposure has a limited signal-to-noise ratio, and that future X-ray telescopes, such as the Advanced X-Ray Astrophysics Facility (AXAF) or X-Ray Maximum Mission (XMM) will give further information as a result of their higher sensitivity and lower background.

3.4. Central Electron Density

To calculate the central electron density of the cluster we employ the results of the isothermal $\beta$-model. Using the one-dimensional model as input, we calculate a central electron density of $n_0 = 0.040 \pm 0.007 \times 10^{20}$ cm$^{-3}$. For the two-dimensional $\beta$-model, we use as a mean core radius the geometrical mean of $a_0$ and $a_2$, giving $\bar{a} = 3.7'$. The derived $n_0$ in this case is $n_0 = 0.084^{+0.074}_{-0.065} \times 10^{20}$ cm$^{-3}$. The errors are hardly dependent on the temperature due to the ROSAT energy band (see for example Jones & Forman 1992; Böhringer 1994), but they are dependent on the intrinsic shape parameters of the isothermal $\beta$-model. The errors are larger for the two-dimensional case, since we take into account the errors of the two core radii, $\beta$, and $S_0$, while for the one-dimensional case we only take into account the error of one core radius and $\beta$.

4. X-RAY LUMINOSITY

The ROSAT/HRI source count rate of 3C 295 is $0.028 \pm 0.001$ s$^{-1}$. To determine this count rate we subtract from the original data the background rate determined from the so-called cooling time, $t_{\text{cool}}$, which is defined as the enthalpy of the ICM divided by the energy loss due to radiation in X-rays, i.e.,

$$t_{\text{cool}} = \frac{(5/2)n_k T}{n_e n_h \Lambda(T)}.$$  

(4)

Here, $\Lambda$ is defined as the cooling rate and is only dependent on metallicity and temperature. Typical values for $\Lambda$ are in the range of $1 \times 10^{-23}$ ergs s$^{-1}$ cm$^6$. Inserting our results from the isothermal $\beta$-model together with some estimates of $\Lambda$ from Böhringer & Hensler (1989) (see also Table 4), we can calculate the cooling time as a function of radius. The cooling flow radius is then defined as the radius at which the cooling time is equal to the cluster formation time, which depends on cosmological parameters. Assuming the cooling time to be $t_{\text{cool}} = 7.4 \times 10^9$ yr, which corresponds to the age of the cluster at a redshift of $z = 0.46$, we get cooling flow radii corresponding to 60–100 kpc, depending on the $\beta$-model and on the temperature we apply. For a comparison with nearby clusters, if we neglect the fact that we see the cluster in a younger stage than nearby ones, and assume a cooling time of $t_{\text{cool}} = 10^{10}$ yr, we get cooling flow radii in the range of 70–120 kpc.

5. COOLING FLOW ANALYSIS

5.1. Cooling Time and Cooling Flow Radius

In the central parts of clusters of galaxies, the time in which the ICM cools from several $10^7$–$10^8$ K to temperatures several orders of magnitude less can be lower than the age of the cluster. In these regions the energy loss due to radiation is therefore not negligible, and mechanisms for the compensation must occur (for details, see, e.g., Fabian et al. 1991). To give an estimate of the radius out to which the energy loss is not negligible, it is common to make use of the so-called cooling time, $t_{\text{cool}}$, which is defined as the enthalpy of the ICM divided by the energy loss due to radiation in X-rays, i.e.,

$$n_e n_h \Lambda(T) \frac{dM}{dt} = \frac{dE}{dt}.$$  

(5)

where $\Phi$ is the gravitational potential. The left-hand side of this equation is the energy loss due to radiation as a func-

| $\Lambda(T)$ | $b_0 T$ |
|------------|----------|
| (10$^{-23}$ ergs s$^{-1}$ cm$^6$) | (keV) |
| 1.4 | 2.0 |
| 2.1 | 5.8 |
| 2.3 | 7.8 |
| 2.6 | 9.2 |
tion of radius; the right-hand side shows the mechanisms of compensation, cooling and accretion.

Now we can insert our results for the isothermal $\beta$-model into equation (5) and calculate the mass accretion. To determine the gravitational potential, we can use the hydrostatic equation,

$$\frac{dP}{dr} = -\rho_g \frac{d\Phi}{dr}.$$  \hspace{1cm} (6)

Assuming that the ICM has the same properties as an ideal gas, in combination with the isothermal $\beta$-model we can calculate the gravitational potential of the cluster, and with it the total mass as function of radius, i.e.,

$$\Phi(r) = \frac{GM(r)}{r} = -\frac{r k_b T}{\mu m_p} \left( \frac{1}{n} \frac{dn}{dr} + \frac{1}{T} \frac{dT}{dr} \right),$$  \hspace{1cm} (7)

where $M(r)$ is the total mass within radius $r$. We employ the isothermal $\beta$-model for the gas density distribution even though the cluster might not be isothermal, since the emission in the ROSAT energy band (0.1–2.4 keV) depends only weakly on the temperature of the ICM (see above). We would like to stress here that we use the isothermal $\beta$-model only as a fit function to deproject the surface brightness profile into a density profile of the ICM, and that possible temperature gradients or the presence of multiphase gas can be neglected, since the measured count rate in the ROSAT band hardly depends on cluster temperature. The use of any other analytical function instead of the $\beta$-model for deprojecting would not increase the reliability of the calculated density profile, since we do not have any information on the temperature distribution. Deprojecting numerically by subtracting shell by shell, as is done for nearby clusters, cannot be undertaken here, since the statistics for our data are too poor.

We also note that the analysis presented here describes and assumes idealized circumstances, for example that the cooling flow region either is isothermal or has a constant temperature gradient.

5.2.1. The Isothermal Case

Assuming for now the strongly idealized case in which the cluster is isothermal, and inserting equations (2), (6), and (7) into equation (5), we can directly calculate the mass accretion rate from

$$M = \frac{4 \pi \mu m_p a^2}{3 k_b} n_{e0} n_{h0} \Lambda(T) \left( 1 + \frac{r^2}{a^2} \right)^{-3 \beta + 1}.$$  \hspace{1cm} (8)

With this equation, one can see the dependence of $M$ on $r$, $a$, and $\beta$. In the case in which the cooling flow radius is smaller than the core radius $a$, or in case in which the $\beta$-value is very small ($\beta < 0.33$), the mass accretion rate is proportional to $r$, since then the term $\left[ 1 + (r^2/a^2)^{-3 \beta + 1} \right]$ stays almost constant. This is in agreement with the findings of other authors, e.g., Thomas, Fabian, & Nulsen (1987), Fabian et al. (1991), and Neumann & Böhringer (1995). However, as in the case of 3C 295, the core radius is between 25 and 50 kpc and is therefore smaller than the cooling flow radius, and since $\beta \geq 0.33$, the term $\left[ 1 + (r^2/a^2)^{-3 \beta + 1} \right]$ changes significantly and therefore influences the shape of the mass accretion rate as a function of radius. The results can be seen in Figure 5 (for the isothermal $\beta$-model taking into account the PSF) and Figure 6 (for the isothermal $\beta$-model neglecting the effects of the PSF). The maximal mass accretion rate is in the range 550–900 $M_\odot$ yr$^{-1}$, depending on the assumed temperature. In the isothermal case the mass accretion rates rise with radius up to 50 kpc and then stay more or less constant.

5.2.2. The Case of Constant Temperature Gradient

It is generally found that the temperatures in cooling flow regions are lower than the overall cluster temperature. Often a temperature gradient in the cooling flow region can be observed. If we assume that there exists a constant temperature gradient in the cooling flow region of 3C 295, we can rewrite equation (5) as

$$M = \frac{4 \pi r^2 \mu m_p n_{e0} n_{h0}}{3 k_b} \times \left[ 1 + (r^2/a^2)^{-3 \beta + 1} \right] \Lambda(T) \frac{\Lambda(T)}{\left[ \Lambda(T) a^2 + \left( r^2 + r^2 \right)^2 \right]} + \nabla T / 2,$$  \hspace{1cm} (9)

where $\nabla T$ is the temperature gradient one infers and $T_{center}$ is the central temperature. In equation (9) we take into account that a temperature gradient changes the shape.
of the gravitational potential (see eq. [7]). We assume that the gas is still in hydrostatic equilibrium and that the hydrostatic equation (7) is still applicable, assuming a single-phase ICM. One way to see this is that while the gas is cooling down, its density distribution changes accordingly to fulfill equation (7). For our calculation of mass accretion rates, we assume the temperature at the center to be 2 keV and at a radius of 120 kpc to be either 5.8, 7.1, or 9.2 keV—the range of temperatures representing the error in the determination of the overall temperature of 3C 295 by Mushotzky & Scharf (1997). For simplicity, we assume that $\Lambda(T)$ is linear in temperature between 2 and 10 keV. The adopted values for $\Lambda$ can be seen in Table 4. For intermediate temperatures, we interpolate linearly. The results of our calculations are shown in Figures 5 and 6, respectively.

Applying a temperature gradient lowers the mass accretion rates and changes the shape of the mass accretion rate as a function of radius. The maximum mass accretion rate occurs close to the core radius of either model, being in the range of 400–600 $M_\odot$ yr$^{-1}$. After its maximum, the mass accretion rate drops at larger radii; the mass accretion rate at 120 kpc varies between 300 and 500 $M_\odot$ yr$^{-1}$.

5.3. Comparison with Previous Work

Henry & Henriksen (1986), analyzing Einstein IPC and HRI data, have already suggested that 3C 295 hosts a cooling flow in the center. The authors calculated a mass accretion rate ($\dot{M}$) of about 145 $M_\odot$ yr$^{-1}$. The determination of $\dot{M}$ was based on pointlike excess emission over the best-fit isothermal $\beta$-model in the center. As one can see in Figure 2, we do not see excess emission in the center. The isothermal $\beta$-model coincides very well with the cluster emission in the center. This suggests two possibilities. The first is that there was an active point source in the center of the cluster while it was exposed with the Einstein HRI, and that this source was no longer active when exposed with the ROSAT HRI. The second possibility is that because Henry & Henriksen (1986) simultaneously fitted a point source and an isothermal $\beta$-model to the data, this led to an overestimate of the central point source resulting from an underestimate of the emission from the cluster itself. A weak indication for this is the fact that Henry & Henriksen obtain a core radius of $a = 9.2_{-4.1}^{+1.0}$ and $\beta = 0.58_{-0.08}^{+0.25}$—both higher values than our best-fit results. However, the overall agreement between Einstein and ROSAT data is very encouraging. The higher fit values for the core radius and $\beta$ obtained by Henry & Henriksen (1986) cause the estimated cluster profile to be flatter in the center than in our fitted models.

5.4. Contamination by Radio or Point Sources Emitting in X-Rays

The cluster of galaxies 3C 295 is known to host a luminous radio source in the center (Akujor et al. 1994 and references therein). The source consists of two radio lobes with a separation of about 5″. The extent of the lobes is each about 2″. In principle, the spatial resolution of the HRI is sufficient to resolve these lobes, if they emit in X-rays. However, the Poisson statistics, which is the factor that really limits the spatial resolution here, makes a detection of their separation difficult. It is also not clear whether these lobes lead to an enhancement in X-rays or diminish the X-ray brightness in this area. An example of radio lobes dimming the X-ray luminosity in the center of a cluster can be found in Böhringer et al. (1993) for the Perseus cluster or Schindler & Prieto (1997) for A2634.

Strong evidence that these sources are not very prominent and do not obscure the X-ray surface brightness profile is the fact that we yield a very high confidence level for the isothermal $\beta$-fit with a reduced $\chi^2 = 1.03$. The good agreement between the fit and real data is difficult to explain in the presence of additional sources in the center, whether they enhance or diminish the X-ray brightness, since they affect the overall fit.

A single point source in the center can also be ruled out by the same argument. It seems very unlikely that a central point source would have exactly the “right” emission to fit the model. In addition, in this unlikely scenario, a central source would affect the profile only out to about 3″–5″—the size of the PSF. Since our calculated cooling flow radius is larger than this (12″–17″), a single central point source cannot explain the X-ray peak in the center. Another test to see whether a central point source can influence the surface brightness profile in the center of the cluster is to perform an isothermal $\beta$-model fit (one-dimensional), neglecting the innermost bin of the radial profile (see Fig. 2). This central bin should contain almost all the emission from a central point source, if present. The result of this fit leads to an even more centrally peaked cluster model, with a best-fit result for the core radius of about 1.5″, $\beta = 0.54$, and a very high central surface brightness of $S_\beta = 8.3 \times 10^{-4}$ s$^{-1}$ arcsec$^{-2}$. However, this fitted model has much larger error bars than the original one-dimensional fit, and the uncertainties in the core radius and $\beta$ of the original fit are very well encompassed in the error estimates of the modified fit.

Putting this all together, we conclude that if there are other individual X-ray sources present in the center of the cluster, then their effect on the cooling flow analysis is negligible, and they are unlikely to lead to a dramatic overestimate of the mass accretion rates.

6. MASS ANALYSIS

To determine the total and mass of the cluster we utilize the results of the isothermal $\beta$-model fitting for the gas-density profile. We assume that the temperature throughout the whole cluster lies between 5.8 and 9.2 keV, which are the results obtained by Mushotzky & Scharf (1997) analyzing ASCA data. For the mass determination, we assume spherical symmetry and hydrostatic equilibrium; under these assumptions we can use equation (7). These assumptions are justified and lead to reliable estimates for the mass determination of clusters of galaxies, as shown by Schindler (1996) and Evrard, Metzler, & Navarro (1996), who analyzed hydrodynamic simulations under these assumptions and compared the results with the intrinsic properties. For the determination of the total mass, we perform a Monte Carlo analysis (Neumann & Böhringer 1995), which calculates possible random temperature variations within the above given limits. For the step width of these temperature variations we use 300 kpc. Since the uncertainties in temperature by far exceed the uncertainties in the density profile, we here neglect the errors of the isothermal $\beta$-model, which introduce errors in the density distribution of the gas.

As a smoothing parameter, to avoid strong and unphysical oscillations of the temperature profiles, we use $\Delta T = 0.3$ keV, which means that each temperature at a certain radius must lie within 0.3 keV of the adjacent step.
radius. The results can be seen in Figure 7 and Table 5. Calculating the total mass of the cluster, we get $M_{\text{tot}} = 9.2 \pm 2.7 \times 10^{14} M_\odot$ at a radius of 2.1 Mpc. The result is slightly dependent on the employed $\beta$-model. For the gas-to-total mass ratio, we get $M_{\text{gas}}/M_{\text{tot}} = 0.18^{+0.08}_{-0.04}$ for $\beta = 0.56$ and $M_{\text{gas}}/M_{\text{tot}} = 0.22^{+0.09}_{-0.05}$ for $\beta = 0.52$. A summary of the results is given in Table 5.

7. DISCUSSION

7.1. Cooling Flow and $\beta$-Model Fitting

Despite the fact that 3C 295 hosts a cooling flow, we do not see evidence for central excess emission above the fitted isothermal $\beta$-model, as seen in almost all other cooling flow clusters. Normally, fitting an isothermal $\beta$-model to the X-ray data of these kinds of clusters leads to results that underestimate the central emission. However, most of these studies are based on nearby clusters, which can be traced out to larger radii than 3C 295. We can trace the X-ray emission of 3C 295 only out to a radius of 2.0–2.5 (see Fig. 2), which corresponds to 900–1100 kpc. Therefore, we are unable to see the outer parts of the cluster, and our fit is only based on the central parts. Fits of this kind, which only take into account the center of a cooling flow cluster, generally lead to smaller core radii and $\beta$ values. Our values for the core radius and $\beta$ are also relatively small when compared to other clusters, which generally have core radii of several 100 kpc and $\beta$ values between 0.6 and 0.9 for rich and X-ray–luminous clusters of galaxies. Therefore, we conclude that the reason we do not see a central excess lies solely in the fact that we see and fit only the central part of 3C 295. In other words, we more or less see only the tip of the iceberg.

Future X-ray instruments such as those aboard AXAF or XMM, which have higher sensitivity and lower background than the ROSAT/HRI, will enable us to trace distant clusters out to much larger radii.

7.2. The Effects of the PSF on the Cooling Flow Analysis

We determine two different isothermal $\beta$-models in our spatial analysis: one takes into account the effects of the PSF and ellipticity, and gives $\beta = 0.52$ and a small core radius ($a = 3.7''$), while the other neglects PSF effects and gives $\beta = 0.56$, with a larger value for the core radius ($a = 7.2''$).

Comparing the results of the subsequent cooling flow analyses of the two models, one can see that in the $\beta = 0.56$ case, we overestimate the cooling flow radius and the mass accretion rates (see Figs. 5 and 6). The reason why we determine a larger cooling flow radius when using the $\beta = 0.56$ model instead of the $\beta = 0.52$ model lies in the fact that the inferred gas density profile shows a less steep drop in the first case. This is a result of the fact that the PSF makes the appearance of the profiles more shallow.

Even though the calculated central electron density is lower in the $\beta = 0.56$ case, the densities of the gas are equal in both models at a radius of 60 kpc, and at larger radii the $\beta = 0.56$ model gives higher values for the gas density than the $\beta = 0.52$ case. The consequence is that the cooling times in the $\beta = 0.56$ case at radii larger than 60 kpc are smaller than those of the other model, because $\tau_{\text{cool}} \propto n^{-2}$. Since the cooling flow region is determined by its cooling time being less than a certain time interval, the cooling flow radius is, of course, larger in the $\beta = 0.56$ case.

The overestimate of the cooling flow radius is of the order of 20%, but does not have a large influence on the resulting maximal mass accretion rate, since at the outer regions the mass accretion rate stays almost constant. The overestimate of the mass accretion rates in the $\beta = 0.56$ case again results from a shallower profile, in this case from the gravitational potential. A shallower potential stands for a smaller potential gradient; this means that more gas must flow into the center to compensate for the energy loss due to radiation (see eq. [5]). The overestimate of the mass accretion rate due to PSF effects is of the order of 10%–25%, which is not very high given all the other uncertainties of the physical properties that enter into the determination of the mass accretion rates.

7.3. Mass Accretion Rates and Temperature Gradient

Introducing a temperature gradient in the center of the cluster reduces the resulting mass accretion rates (see Figs. 5 and 6). This shows how sensitive the determination of mass accretion rates is to the temperature structure of the ICM. With a temperature gradient, the gas has another mechanism to compensate for the energy loss due to radiation (we assume here the case of a homogenous cooling flow): while the gas is falling into the center it loses not only potential energy but also kinetic energy due to cooling. However, assuming that the hydrostatic equation is valid in this region, and assuming that multiphases in the gas are negligible, a temperature gradient also causes the gravitational potential to be more shallow (see eq. [7]). Because of this shallower potential, the energy supported by the loss of...
potential energy of the gas falling inward is not as efficient as in the isothermal case. However, as the overall mass accretion rates drop, the effect of cooling easily compensates for the effect of a shallower gravitational potential.

We only want to stress here that our assumed models for the cooling flow are simple, since we, for example, neglect the presence of a multiphase gas in the cooling flow region. However, since 3C 295 is a very distant cluster, a fact that makes a more detailed analysis of the cooling flow almost impossible at the moment, we only want to give an idea of what mechanisms occur in the cooling flow region of this cluster, and how sensitive the analysis is to the observational uncertainties.

7.4. Correlation of the Mass Accretion Rate and Cooling Flow Radius

Comparing the determined mass accretion rate and the calculated cooling flow radius with other clusters, for example in the sample of White, Jones, & Forman (1997), one can see that 3C 295 is relatively outstanding. It shows a very high mass accretion rate for its size of cooling flow radius. Following the fit results of White et al. (1997), the cluster should have a mass accretion rate of about \(60 M_{\odot} \, \text{yr}^{-1}\), with a cooling flow radius of roughly 100 kpc; alternatively, with its mass accretion rate it should have a cooling flow radius of about 200 kpc. However, the difference between the calculation of White et al. and ours is that we neglect inhomogeneities in the cooling flow, in which material can cool out completely and provide additional energy resources for radiation. But it is very unlikely that this effect causes the mass accretion rate to drop by a factor of 10. The discrepancy more likely arises from the fact that the e†ect causes the mass accretion rate to drop by a factor of less than 2. Both estimates have relatively large error bars, which, however, do not overlap.

Where can this discrepancy come from? Partly it may be due to the fact that the mass inferred from X-rays is biased downward because of the cooling flow. The cooling flow in the central parts of the cluster could lower the overall temperature measured by \(\text{ASCA}\) due to cooled gas. In addition, the small values for \(\beta\) and the core radius, typical for a cluster with a central cooling flow, might bias the value for the inferred mass downward—the mass calculated from the hydrostatic approach is proportional to \(\beta\). Finally, the fact that we do not see the outer regions of the cluster in X-rays could systematically lower the result of our mass determination. On the other hand, the mass determined with the weak-lensing approach is dependent on the mean redshift of the lensed galaxies. While this is not a strong effect for nearby clusters, it plays an important role for distant clusters such as 3C 295. Smail et al. (1997) used an approach with a mean redshift of the background galaxies of \(z = 0.83\). Increasing the value to, for example, \(z = 1\) lowers the inferred mass considerably. One indication that the mass from the weak lensing might be estimated too high is the fact that the \(M/L\) for this cluster found by Smail et al. (1997) is relatively high compared to other clusters in their sample. Therefore, it might be that the different results of the mass can be entirely explained by systematic errors in the two approaches. However, we cannot rule out the possibility that there might be some physical reason for this apparent discrepancy of the mass results, and that, for example, 3C 295 either has prolate symmetry or suffers from projection effect from another massive structure.

7.5. The Baryon Fraction in 3C 295

The determined gas-to-total mass ratio in 3C 295 is \(M_{\text{gas}}/M_{\text{tot}} \sim 0.22\)—similar to the findings in other clusters. Since the gas-to-total mass ratio is a limit on the baryon fraction in clusters, which is thought to be representative for the universe in total (based on numerical simulations; see, e.g., Evrard 1990; Cen & Ostriker 1993), this approach can be used to measure the fraction of baryon to dark matter density in the entire universe (the mass in galaxies in clusters is only a small fraction of the mass of the ICM). Since studies of primordial nucleosynthesis give precise values of \(\Omega_b\) (the ratio of baryon to critical density of the universe), with \(\Omega_b h_0^2 = 0.05 \pm 0.01\) (see, for example, Walker et al. 1991) this can be directly used to determine \(\Omega_{\text{tot}}\), the total density of the universe, as shown by Briel, Henry, & Böhringer (1992) and White et al. (1993) in calculating \(M_{\text{gas}}/M_{\text{tot}} = \Omega_b/\Omega_{\text{tot}} = (0.05 \pm 0.01)/\Omega_{\text{tot}}\). The determined values of \(\Omega_{\text{tot}}\) range between 0.2 and 0.4, and give strong evidence for a low-density universe. Our values for the gas-to-total mass ratio of 3C 295 suggest \(\Omega_{\text{tot}} = 0.1–0.4\). The errors in the determination of \(\Omega\) come almost exclusively from the uncertainties in \(M_{\text{tot}}\).

7.6. Mass Estimates Compared to Weak-Lensing Results

Figure 7 shows the total mass profile of 3C 295. To be able to compare our results for the mass with the weak-lensing study by Smail et al. (1997) (the lensing approach determines the total mass along the line of sight within a certain radius), we also show the projected mass profile (along the line of sight). We project out to a radius of 3 Mpc.

There is some discrepancy between the mass results from the lensing analysis and from the hydrostatic equation used here. The lensing result gives a higher mass. The values differ by a factor of less than 2. Both estimates have relatively large error bars, which, however, do not overlap.

In this paper we analyze \(\text{ROSAT}\) HRI data of the distant cluster 3C 295. We fit one- and a two-dimensional isothermal \(\beta\)-models to the data, the two-dimensional fit taking into account the ellipticity of the cluster and effects of the PSF. The one-dimensional model, which does not take into account the PSF, gives higher values for \(\beta\) and the core radius \(a\); however, the results agree within the error bars. To determine the errors of the parameters of the two-dimensional fit, we use a Monte Carlo approach.

Calculating the cooling time of the central region, we confirm previous findings by Henry & Henriksen (1986) of a central cooling flow. We estimate the cooling flow radius to
lie between 60 and 120 kpc, depending on the model and adopted cooling time for the cluster. Generally, we find that the isothermal $\beta$-model, which does not take into account the effects of the PSF, gives higher values for the cooling flow radius and the mass accretion rates. For the determination of the mass accretion rates we present a simple model, based solely on the isothermal $\beta$-model, neglecting heat conduction, inhomogeneities, and heat sources. We show that the inferred mass accretion rates, with values of $M = 400$–$900 M_\odot$ yr$^{-1}$, are dependent on the temperature structure in the cooling flow region. A temperature gradient generally lowers the mass accretion rates.

The mass accretion rate in the central part of 3C 295 is somewhat too high for its cooling radius when compared to the sample of nearby clusters of White et al. (1997). Since 3C 295 is not the only distant cluster showing this behavior, this might be an indication that in general this relationship between mass accretion rate and cooling flow radius is evolving with time.

To search for substructure in the cluster, we subtract a two-dimensional cluster model, following the best-fit results of the isothermal $\beta$-model from the original data. Apart from a decrement in the southeast in the cluster, which might be caused by absorption, we do not find any strong indication that the cluster deviates from hydrostatic equilibrium. The fact that 3C 295 seems to be in complete hydrostatic equilibrium and has had enough time to form a cooling flow is an indication that the cluster must have had considerable time to relax, which suggests a low-density universe, with or without a cosmological constant.

Calculating the total mass of the cluster based on the hydrostatic equation using a temperature estimate of Mushotzky & Scharf (1997), we obtain results of $M_\text{tot} = (9.2 \pm 3) \times 10^{14} M_\odot$ at a radius of 2.1 Mpc. For the gas-to-total mass ratio, we obtain $M_\text{gas}/M_\text{tot} \approx 0.17$–$0.31$. This ratio is typical for other clusters, and is again a strong indication for a low-density universe.

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