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THE MASS AND DYNAMICS OF cD CLUSTERS WITH COOLING FLOWS.
I. ROSAT OBSERVATIONS OF A 496

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Abstract

As part of a program to determine the mass distribution of cD galaxy clusters with cooling flows, we obtained a ROSAT image of the cluster A 496. The image reveals sharply peaked emission centered on the cD galaxy. Both the peaked cooling flow emission and the more extended emission filling the cluster are centered on the cD galaxy to within 15″. The surface brightness profile is consistent with previous *Einstein* HRI observations. We measure spatially resolved spectra for the X-ray emission, and find a significant decline in temperature in the innermost 2′ to 4′. We also find a gradient in absorption due to cold neutral gas, with an excess above the neutral hydrogen column due to our own galaxy in the inner 4′. The excess absorption, however, is far below previously reported values. We caution that this is a progress report, and that our results are preliminary.

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1 Introduction

The cluster of galaxies A 496 (Abell 1958) is one of the brightest X-ray clusters. The surface brightness distribution is sharply peaked on the central cD galaxy, and low-energy X-ray spectra obtained with the Solid State Spectrometer (SSS) on the *Einstein Observatory* show cool gas with spectral lines indicative of a strong cooling flow (Nulsen et al. 1982). Subsequent re-analysis of these same data (White et al. 1992) show that in addition to the low central temperature, there appears to be excess absorption by cold gas, which they infer to be cold material condensing from the cooling flow.

2 Observations

We obtained a ROSAT position-sensitive proportional counter (PSPC) image of A 496 on 1991 March 6. The image was centered on the cD galaxy at $\alpha_{2000} = 4^{h}33^{m}38^{s}.4$, $\delta_{2000} = -13°15'36''.0$. Three separate observation intervals were summed to create the final image representing 8972 s of live observing time. The spacecraft wobble was normal, and there do not appear to be any extraordinary problems associated with the observation or the subsequent processing of the data.

3 Data Analysis

The data analysis of the image has been hampered by the lack of calibration material particularly relevant to large extended sources. The diffuse emission from the intergalactic medium in A 496 can be clearly traced to radii beyond the supporting rib structure of the central PSPC field. On such scales there is significant variation in the background structure of the PSPC. We do not currently have a background model which gives the energy-dependent surface brightness of the background. In the subsequent analysis the background is assumed to be spatially invariant. For computing our surface brightness profile, we use a background determined from regions free of supporting rib shadows at radii from $40'$ to $60\,'$. For our spectral analysis, we use the annulus from $15'$ to $20'$ to establish the background surface brightness and its spectrum.

3.1 Spatial Structure

The extended X-ray emission from A 496 and its centrally peaked surface brightness are apparent in the contour plot shown in Figure 1. Here we have smoothed the raw data with a Gaussian of dispersion $11''$, the approximate spatial resolution of the PSPC.

To test to see if the peaked emission centered on the cD galaxy might be physically distinct from the more diffuse cluster-filling emission, we fit the image with a composite model consisting of an ellipsoidal surface brightness distribution plus a Gaussian point source of dispersion 25″. This gives a good fit to the observed image. It is clearly ellipsoidal with ellipticity $1 - b/a = 0.14$ with the major axis at a position angle of 112°. Within the errors, however, the point source is centered at the same location as the more extended cluster emission.

Ignoring the slight ellipticity revealed by this analysis, we extract an azimuthally averaged surface brightness profile which is shown in Figure 2. Prior to our ROSAT observation, we had computed a surface brightness profile based on the *Einstein* High Resolution Imager (HRI) data (Nulsen et al. 1982) and the predicted properties of the PSPC. This prediction is shown as the solid line in the figure, and it agrees remarkably well with the observed profile.

3.2 Spectra

Again ignoring the ellipticity, we extracted spatially resolved spectra from the image in circular annuli centered on the peak of the surface brightness distribution. We fit the extracted spectra with single-temperature Raymond and Smith (1977) thermal models using the `xspectra` package in `PROS`. In our fits the temperature (T), the column density of neutral hydrogen absorption (N_H), the abundance of the emitting gas, and the overall normalization of the spectrum are permitted to vary freely. Our fits are restricted to the 27 energy channels spanning the energy range 0.10-2.00 keV. Data at higher and lower energies are excluded to avoid uncertainties in the PSPC response matrix. Our fits are based on the latest calibration files as distributed with the release of PROS 2.0 in 1992 April. All annuli produce satisfactory fits which are summarized in Table 1.

4 Discussion

The spatially resolved spectra we have obtained of A 496 show both a clear temperature gradient associated with the cooling flow, and evidence for excess absorption by cold gas in the same spatial region. The temperature of 1.79 keV in the innermost 2′ is consistent with the SSS observations which show a mixture of cold gas at ~ 1.4 keV and hotter gas at ~ 6 keV (Nulsen et al. 1982). The temperatures at larger radii all match the globally averaged higher temperature of $4.8^{+1.0}_{-0.8}$ keV as seen with the medium energy proportional counters on EXOSAT (Edge & Stewart 1991). The abundance of approximately half solar is typical of rich clusters, and also matches the Fe abundance as measured with EXOSAT.

Our spectra also show evidence for excess absorption by cold gas in the same spatial region as the cooling flow, bolstering arguments that this is material condensing out of the cooling flow (White et al. 1992). While we do see excess absorption of $\sim 1.2 \times 10^{20}\ cm^{-2}$ above the galactic value of $\sim 4.3 \times 10^{20}\ cm^{-2}$ (Stark et al. 1992), this is more than an order of magnitude lower than the value of $\sim 2.0 \times 10^{21}\ cm^{-2}$ reported by White et al. (1991). Absorption at $\sim 2.0 \times 10^{21}\ cm^{-2}$ can be excluded at high confidence. The reason for the discrepancy is not clear. While uncertainties in the background subtraction may have some effect on our fits at the larger radii, the background correction in the innermost $2'$ is almost negligible. Some portion of the difference is probably due to the way in which the spectra were modeled. We assumed a single temperature plasma. A cooling flow model would include more lower temperature gas, with more emission at lower energies. Using such a model to fit our data would probably lead to higher absorption columns in order to suppress the extra low energy emission and fit our data. We will test this possibility as we analyze our data further. Another possibility is that the model used by White et al. (1991) artificially produces excess low energy absorption. They determine their excess by using a single temperature spectrum fixed at the temperature determined by larger field of view instruments, allowing for excess low energy absorption, and also allowing for additional line emission as expected in simple cooling flow models. Forcing the presence of the hot gas at the temperature seen by EXOSAT may bias their fits to produce extraordinarily large excess absorption.

Our results are only preliminary, and they represent only the first stage in the full analysis. In the next step we will fit cooling flow models to the spatial and spectral data, and we will derive a mass profile for the cluster based on the X-ray data alone. When used in conjunction with the more than 140 redshifts we have previously measured in this cluster (Malumuth et al. 1992), we will then be able to place significant constraints on the distribution of galaxy orbits in A 496.

We are grateful to P. Mansour for his help with the data reduction.

Annulus (arc min)	kT (keV)	log N_H	Abundance	χ^{2a}
0 – 2	$1.79^{+0.28}_{-0.18}$	$20.740^{+0.021}_{-0.020}$	$0.50^{+0.50}_{-0.20}$	31.09
2 – 4	$3.31^{+1.70}_{-0.94}$	$20.722^{+0.036}_{-0.033}$	$0.50^{+0.75}_{-0.40}$	32.24
4 – 6	$3.86^{+3.20}_{-1.41}$	$20.669^{+0.049}_{-0.049}$	$0.50^{+1.00}_{-0.40}$	14.30
6 – 10	$3.06^{+2.38}_{-1.06}$	$20.580^{+0.058}_{-0.068}$	$0.50^{+1.00}_{-0.40}$	34.16
10 – 15	$3.27^{+\infty}_{-1.53}$	$20.319^{+0.126}_{-0.158}$	$0.10^{+1.50}_{-0.10}$	26.16

Table 1: Raymond & Smith thermal spectra fit to A 496.

[a]Each tabulated fit includes 27 data points and 4 free parameters for a total of 23 degrees of freedom.

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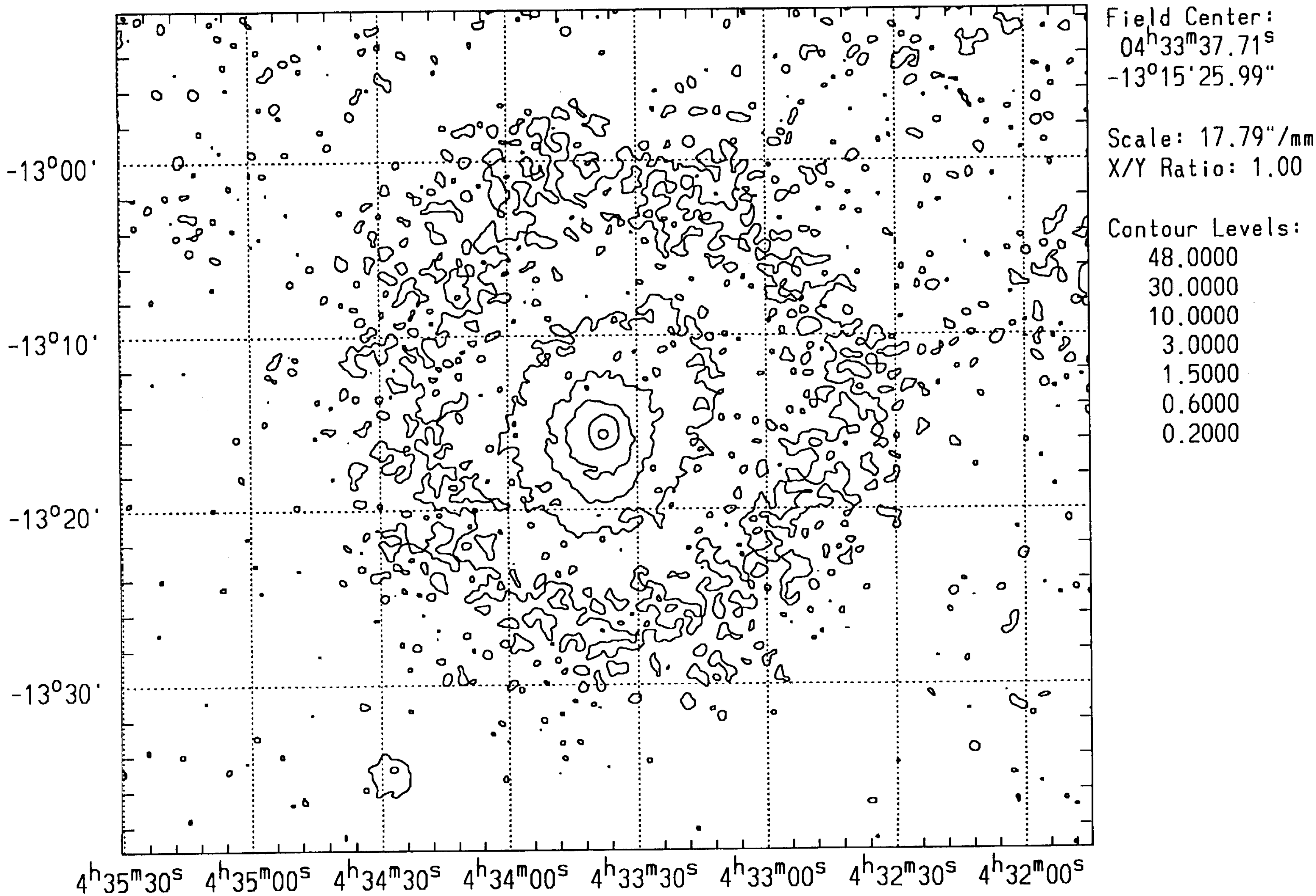
Figure 1: Contour plot of the total ROSAT image of A 496. The raw image has been blocked into pixels of 5.″5 and then smoothed with a Gaussian of dispersion 11″.

Figure 2: The X-ray surface brightness profile of A 496 as seen with the ROSAT PSPC. The scale on the sky is approximately 1″per kpc. The depression at $\sim 20'$ is the PSPC window support structure. Cluster emission can be traced well beyond the center of the field. The thin solid line is the predicted surface brightness profile based on the HRI data (Nulsen et al. 1982) and the PSPC parameters.

Figure 3: The temperature gradient indicative of a cooling flow is shown in this plot of the best-fit temperature *vs.* radius in A 496. The heavy solid line is the best-fit temperature from the medium energy EXOSAT observations of Edge & Stewart (1991). The lighter solid lines to either side are the 90% confidence limits on their temperature determination.

Figure 4: The spatial variation of the low energy absorption in A 496 is illustrated in this plot of log N_H *vs.* radius. The solid line illustrates the galactic column density along this sight line from Stark et al. (1992).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X/Y Ratio: 1.00
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10.0000
3.0000
1.5000
0.6000
0.2000
-13°00'
-13°10'
-13°20'
-13°30'
4h35m30s
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4h33m00s
4h32m30s
4h32m00s

Figure 1

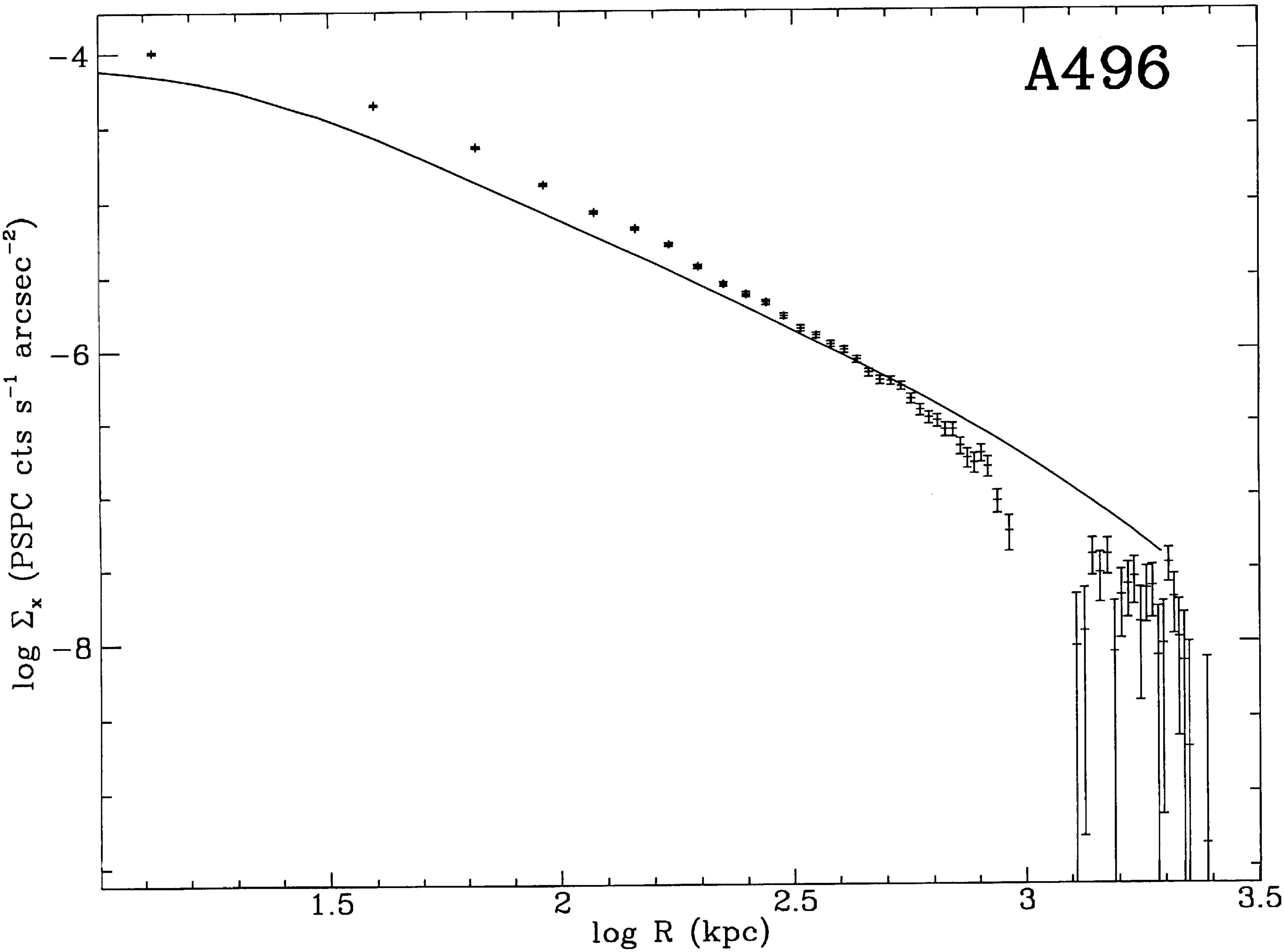

Figure 2

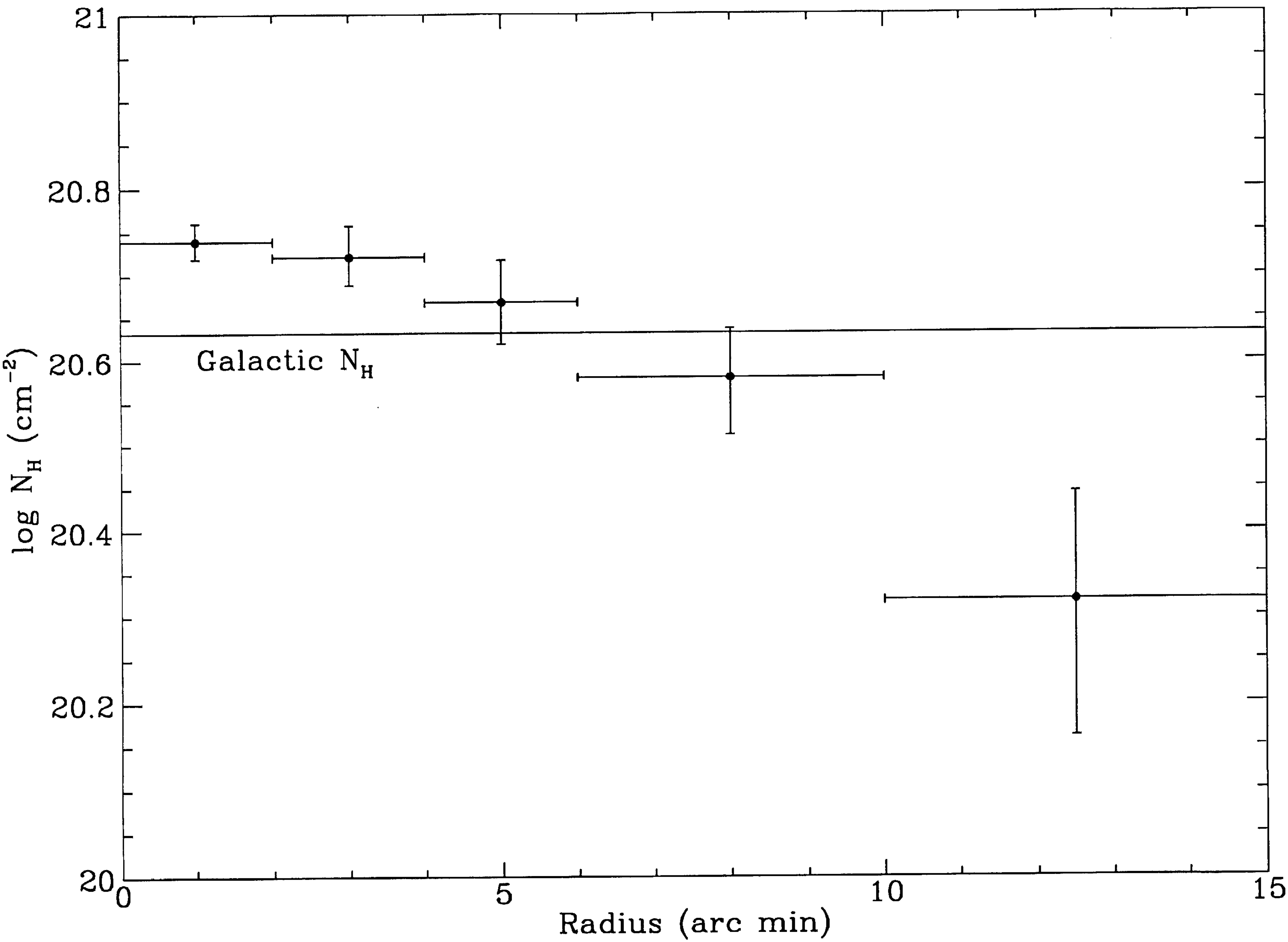
21
20.8
20.6
20.4
20.2
20
0
5
10
15
Galactic N_H
log N_H (cm^{-2})
Radius (arc min)

Figure 3

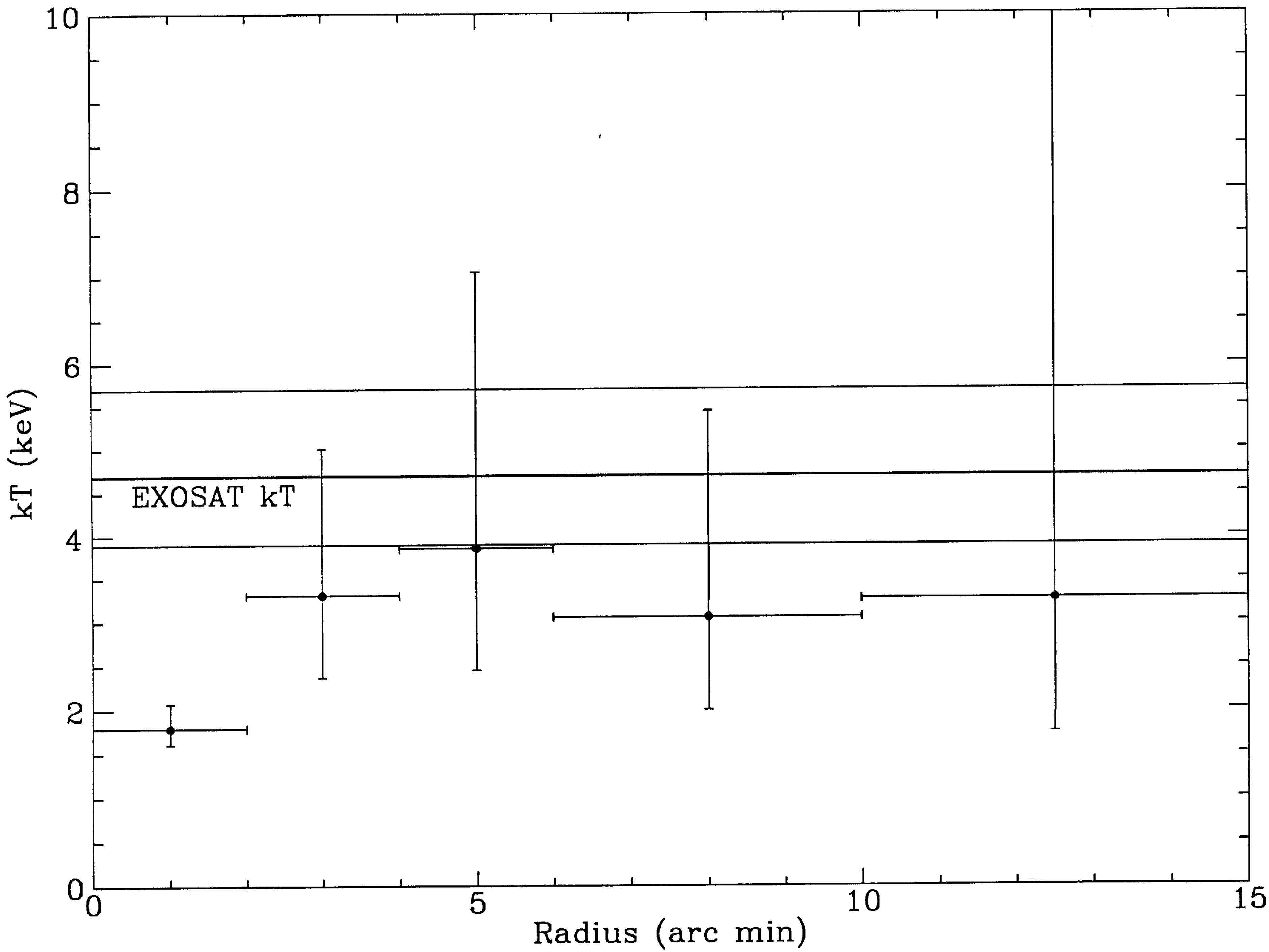

Figure 4