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EXOSAT OBSERVATIONS OF THE HOT GAS IN THE A1060 CLUSTER OF GALAXIES

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ABSTRACT

We have used the *EXOSAT* Observatory to map and to obtain the X-ray spectrum of the hot gas in the A1060 cluster of galaxies. The density and temperature profiles of the intracluster gas have been determined by spherical deprojection of the X-ray surface brightness distribution obtained. We assume hydrostatic equilibrium and a cluster gravitational potential as described analytically by a King law, with a total binding mass of $10^{14}\ M_\odot$. The electron density and the temperature of the hot gas within a radius of 16 kpc from the cluster center are found to lie in the range $(1.1–1.2) \times 10^{-2}\ \mathrm{cm}^{-3}$ and $(1.0–1.5) \times 10^{7}$ K, respectively, when the effects of an extra "galaxy-like" potential are also included. We confirm the presence of cooling inflow in the central regions (<70 kpc) of the cluster with mass accretion rate falling from 7–14 $M_\odot\ \mathrm{yr}^{-1}$ at the periphery of the start of the cooling flow to 2–4 $M_\odot\ \mathrm{yr}^{-1}$ in the innermost bin. The observed X-ray gas when extrapolated out to a radius of ~500 kpc has ~5% of the total binding mass.

Subject headings: galaxies: clustering — galaxies: intergalactic medium — X-rays: sources

I. INTRODUCTION

A1060, also known as Hydra I, has the lowest redshift ($z = 0.011$) of any cluster in the Abell's (1958) catalog. There are two elliptical galaxies, NGC 3309 and NGC 3311, in the central region of this cluster (Smith and Weedman 1976; van den Bergh 1977; Disney and Wall 1977). Lindblad, Jörsäter, and Sandqvist (1985) have made 6 cm radio continuum observations of the cluster and found a two-sided radio jet in the elliptical galaxy NGC 3309, whereas a weak radio source has barely been detected in the other central galaxy, NGC 3311. X-ray observations of the cluster have been carried out with the *OSO 8* (Mushotzky *et al.* 1978). *Ariel 5* (Mitchell *et al.* 1979), *HEAO 1* (Mitchell and Mushotzky 1980), and the *Einstein Observatory* (Jones and Forman 1984). According to *HEAO 1* spectral measurements the energy spectrum of A1060 is best explained by a fit to a two-temperature ($kT_1 = 2$ keV and $kT_2 = 12–14$ keV) thermal model with line emission due to highly ionized Fe. The X-ray surface brightness distribution of the gas in cluster was measured by Jones and Forman (1984) with the *Einstein* Imaging Proportional Counter (IPC), and they found evidence for a central excess X-ray emission. Stewart *et al.* (1984*b*) determined the density and the temperature distribution of the hot intracluster gas by deprojecting the IPC X-ray surface brightness distribution. They detected the presence of a cooling inflow at the rate of 6 $M_\odot\ \mathrm{yr}^{-1}$ in its center. We present here the density and temperature distribution of this gas as deprojected from the surface brightness measurements made with the low-energy imaging detector on *EXOSAT*. Our analysis confirms the existence of the cooling flow in this cluster and suggests that the accretion rate drops with decreasing distance from the center of the cluster.

II. OBSERVATIONS

A 5.9 hr exposure centered on A1060 was obtained on 1984 January 4–5 with the low-energy (LE) experiment on *EXOSAT*. The LE experiment consisted of a channel multiplier array (CMA) and the 3000 Å Lexan filter at the focus of the low-energy telescope (for details see de Korte *et al.* 1981). Preliminary results from this observation were presented by Nørgaard-Nielsen, Westergaard, and Hansen (1985). A 0.05–2.0 keV X-ray map of the region which is free of detector spatial variations was obtained after subtracting the background obtained from a deep exposure on the blank sky. The image, smoothed by a Gaussian with standard deviation of 60″, is shown superposed on an optical photograph of the region in Figure 1 (Plate 15). The two central galaxies appear as the blobs inside the third contour level in Figure 1. Assuming azimuthal symmetry we have obtained the radial brightness distribution of the cluster in 0.05–2.0 keV X-rays. The maximum extent at which the source was visible in X-rays is 258 kpc (for a Hubble constant of 50 km s^{-1} Mpc^{-1}) which is smaller than the 320 kpc extent observed by Stewart *et al.* (1984*b*) with the IPC.

The X-ray source was also observed for ~7.6 hr with the medium-energy (ME) experiment (see Turner, Smith, and Zimmerman 1981 for a description) onboard *EXOSAT*. The ME experiment consists of eight proportional counters with a geometric area of 1500 cm^2 and a square field of view with 45′ FWHM. The observations were made in the offset mode where four detectors are pointed at the source, and the other four detectors are offset by 2° to monitor the background. The background during this observation was ~3–4 times higher than normal, and, since the offset and aligned set of detectors were not interchanged during the observation, the statistical precision of the spectral data is not very good. Analysis of the background subtracted pulse height data from the argon-filled proportional counters which are sensitive in the energy range 1–20 keV determined $T = (3.7 \pm 0.5) \times 10^7$ K from a thermal bremsstrahlung fit to the energy spectrum. In Figure 2 we show the incident photon spectrum based on this fit. The estimated limit of the intervening column density, $N_\mathrm{H} < 2 \times 10^{21}\ \mathrm{cm}^{-2}$, of absorbing interstellar material is compatible with that observed with the 21 cm observations (Heiles 1975).

III. ANALYSIS AND RESULTS

We have applied the deprojection scheme described by Fabian *et al.* (1981) (also see Stewart *et al.* 1984*b*) to the radial

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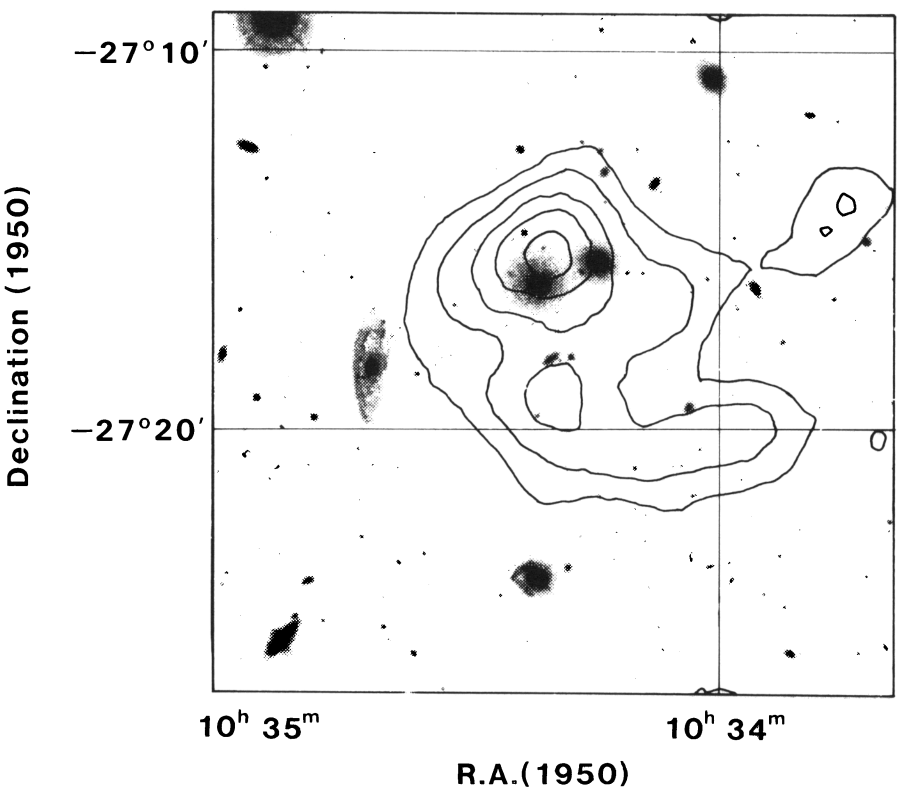

FIG. 1.—A 0.05–2.0 keV contour map of the X-ray surface brightness of A1060 superposed on an optical photograph of the cluster. The optical photograph is a reproduction of Fig. 1 from Smith and Weedman (1976). The X-ray contour levels are 0.4, 0.6, 0.8, 1.0, 1.2 CMA counts per pixel (pixel size = 16″ × 16″). The two elliptical galaxies, NGC 3309 and NGC 3311, can be seen close to the X-ray emission maximum, NGC 3311 being closer.

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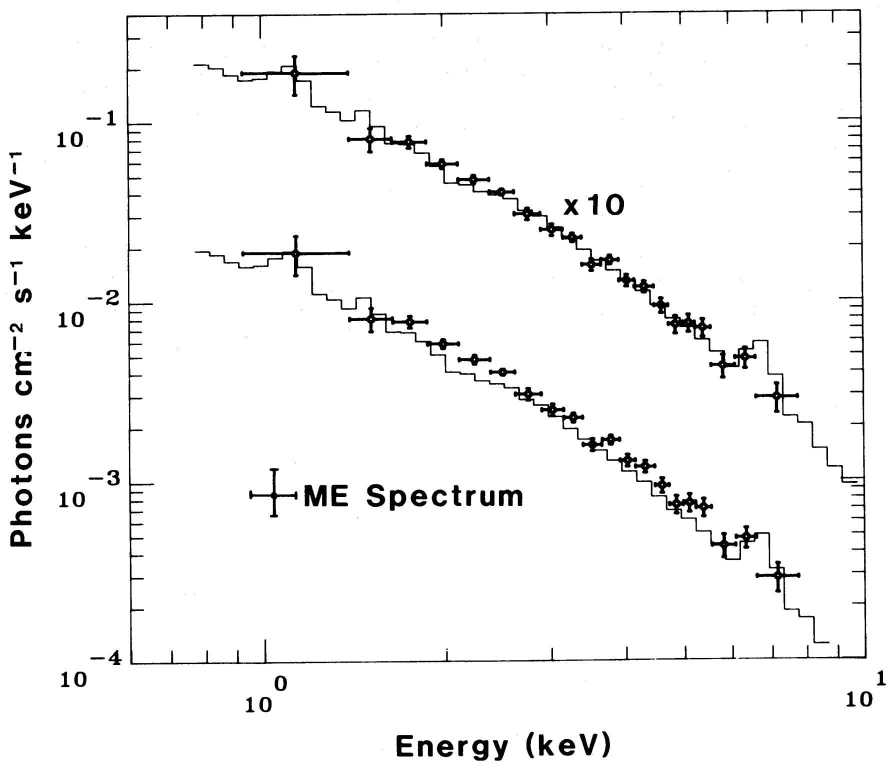

FIG. 2.—X-ray spectrum of A1060 from the medium-energy experiment *EXOSAT*. Also shown are the summed spectra histograms from our analysis of the CMA image and using the plasma emission models of Mewe, Gronenschild, and van den Oord (1985). The two models plotted are shown separately for clarity, where the upper model histogram and the ME spectrum have been scaled by a factor of 10. Upper model is the best fit obtained to the total ME flux by adding an extra outer shell to the CMA data. Lower model is the best fit obtained to the ME temperature but predicts a total flux which is lower by 15% with respect to the flux measured with the ME experiment.

brightness distribution obtained above to deduce the radial density and the temperature profile (Fig. 3) of the cluster. We began by binning the data into large radial bins (50″) to enable us to ignore the point spread function of the detector. The analysis then proceeded with the choice of a spherically symmetrical gravitational potential and the value of the gas pressure, P_0, in the outermost usable radial shell at $\sim$258 kpc. Assuming hydrostatic equilibrium we compute the temperature and density which yield the observed emissivity of successive shells. We used a gravitational potential described by a King model having a core radius of 250 kpc and the line-of-sight velocity dispersion of 777 km s^{-1} (Danese, de Zotti, and di Tullio 1980) for the cluster. The total binding mass of such a cluster is $\sim 10^{14}$ $M_\odot$ (see Sarazin 1986). We also studied the effect of including a central "galaxy-like" potential (see Canizares, Stewart, and Fabian 1983; Stewart *et al.* 1984*b*) described by a King law with an assumed core radius of 1 kpc and a velocity dispersion of 300 km s^{-1}. The velocity distributions are assumed to be isotropic. The plasma emissivity functions are from Mewe, Gronenschild, and van den Oord (1985) and assume half-solar abundances of the heavy elements as suggested by the iron line measurement (Mitchell and Mushotzky 1980; Rothenflug and Arnaud 1985). The count rates were calculated assuming absorption by a column density $N_H = 6 \times 10^{20}$ cm^{-2} (Heiles 1975) and absorption cross sections given by Morrison and McCammon (1983). The outer pressure was varied and various density and temperature distributions were obtained. These distributions were then used to predict the photon spectrum for comparison with the ME photon spectrum. The closest match to the ME temperature resulted for $P_0 = 1.3 \times 10^{-11}$ dynes cm^{-2} and mean temperature, $T_m = 4.0 \times 10^7$ K in Figure 2 (*lower set*). The density and temperature profiles derived from this fit, assuming a cluster potential alone, are shown in Figure 3. The predicted total photon flux from this fit falls 15% below the observed ME flux. We tried to add an extra shell beyond the outermost observed shell in the LE with both the shells having the same temperature. The outer radius of the extra shell and pressure P_0 were then varied to match as closely as possible the measured ME flux keeping the mean temperature within the error limits of the ME observation. Thus for an outer radius of 320 kpc for the extra shell we obtained the best fit to the ME photon flux. This best fit shown in Figure 2 (*upper set*) is, however, at a slightly higher mean temperature of 4.2×10^7 K but the same pressure in the outermost bin of LE as before. The derived density for the extra shell is 6.5×10^{-4} cm^{-3}.

In Table 1 we give the principal results from our analysis. The effect of assumed outer pressure, P_0, on the mean temperature for the cluster can be seen clearly. The central densities and the central temperatures are not effected strongly by the assumed P_0. The effect of including a central "galaxy-like" potential in the cluster is to increase the central density and the temperature, without appreciably affecting their values at the outer radii and thus has a negligible effect on the deduced mean temperature of the cluster. The electron density and the temperature of the gas within a central radius of 16 kpc are in the range $(1.1–1.2) \times 10^{-2}$ cm^{-3} and $(1.0–1.5) \times 10^7$ K.

The derived densities inside the radius of 65 kpc indicate that the radiative cooling time (Fig. 4) in this region is smaller than the Hubble time $t_H = 2 \times 10^{10}$ yr, thereby suggesting the

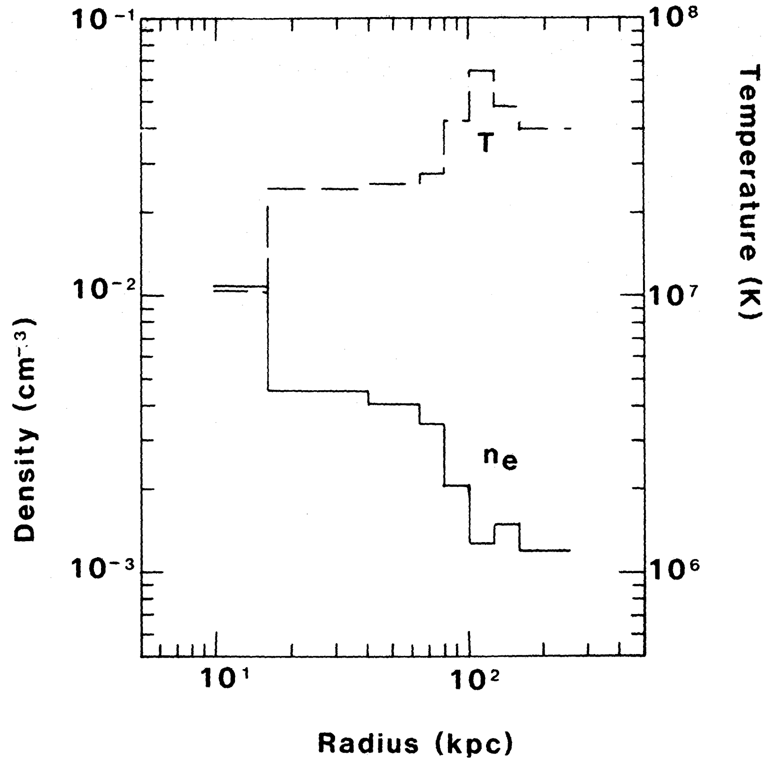

FIG. 3.—Electron density and the temperature profiles of the intracluster gas in A1060, derived assuming a single-component King model for the cluster gravitational potential.

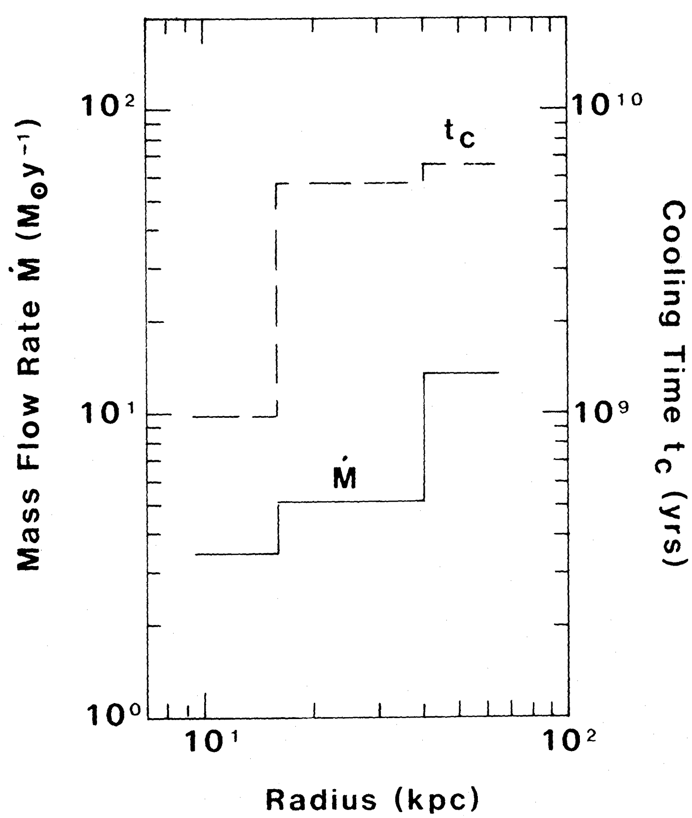

FIG. 4.—Mass flow rates and the cooling times of the intracluster gas in the center of the A1060 cluster, and corresponding to the profiles shown in Fig. 3

TABLE 1

RESULTS OF ANALYSIS

ASSUMED PARAMETER	DERIVED PARAMETERS				
Pressure P_0 (10^{-11} dynes cm^{-2})	Central Density (10^{-2} cm^{-3})	Central Temperature (10^7 K)	Mean Temperature (10^7 K)	Cooling Time[a] (10^9 yr)	Mass Flow Rate[a] ($M_\odot$ yr^{-1})
A. Without Inclusion of Central "Galaxy-like" Potential					
0.9	1.06	0.95	3.0	0.89–6.0	3.7–15
1.1	1.07	1.00	3.5	0.94–6.3	3.5–14
1.3	1.09	1.04	3.9	0.98–6.6	3.4–14
1.5	1.11	1.09	4.3	1.0–6.9	3.4–13
1.7	1.12	1.14	4.8	1.1–7.2	3.3–13
B. Including Central "Galaxy-like" Potential					
0.9	1.17	1.45	3.1	1.4–6.4	2.6–7.6
1.1	1.18	1.50	3.5	1.4–6.7	2.5–7.5
1.3	1.18	1.54	4.0	1.5–6.0	2.5–7.4
1.5	1.18	1.59	4.4	1.5–7.2	2.4–7.3
1.7	1.19	1.64	4.9	1.6–7.5	2.4–7.2

[a] Quoted for the inermost shell and an outer shell (radius = 65 kpc) where the cooling flow starts.

presence of a cooling inflow (Fabian, Nulsen, and Canizares 1984). The mass flow rate at each radius is calculated using the expression of Stewart *et al.* (1984*b*) and is shown in Figure 4. The accretion rate decreases with decreasing distance from the center of the cluster which is probably due to the matter dropping out of the flow because of thermal instabilities (Fabian *et al.* 1985). As a rough check we use the expression (4) given by Stewart *et al.* (1984*b*) and the estimated luminosity of 7.6×10^{42} ergs s^{-1} inside the cooling region to calculate the overall mass-flow rate of 12 $M_\odot$ yr^{-1}. This corresponds to a flat gravitational potential within this cooling region. The total mass of the intracluster gas observed up to the outermost radius of 258 kpc is 1.4×10^{12} $M_\odot$.

IV. DISCUSSION

The X-ray image of the core of A1060 presented here shows an irregular structure. Most of the X-ray emission is from the region containing the two central galaxies with the centroid lying closer to the optically dominant galaxy NGC 3311 than to the radio galaxy NGC 3309. The spatial resolution of the CMA image is, however, not sufficient to detect any spatially resolved clumping of X-ray gas around individual galaxies.

Our analysis of the accreting X-ray gas in the core assuming azimuthal symmetry and using spherical deprojection gives average plasma density (5.5×10^{-3} cm^{-3}) and temperature ($\sim 2.2 \times 10^7$ K) in a radius of 30 kpc from the cluster center in rough agreement with the results obtained previously from application of the same technique on the IPC image by Stewart *et al.* (1984*b*) who obtained an electron density of 4.5×10^{-3} cm^{-3} and temperature of 2.1×10^7 K for their central bin of 30 kpc radius. The accretion rate is found to drop from $\sim$7.5–15 $M_\odot$ yr^{-1} at a distance of 65 kpc to $\sim$2.5–3.5 $M_\odot$ yr^{-1} at a distance of 16 kpc from the cluster core. That $\dot{M}$ decreases with decreasing distance from the cluster core is also seen from the high-resolution observations of M87 and Perseus (Fabian, Nulsen, and Canizares 1984; Stewart *et al.* 1984*a*).

The analysis presented here automatically provides the plausible values for the pressure of the gas at different distances from the cluster core. The thermal pressure of the gas in the second nearest radial shell with an outer radius of 40 kpc from the core, which includes the radio galaxy, is $\gtrsim 2.9 \times 10^{-11}$ dynes cm^{-2}. This is larger than the minimum relativistic particle plus magnetic field pressure reported by Lindblad, Jörsäter, and Sandqvist (1985) for the radio "lobe" and "spur" structures and, therefore, could confine them under the various assumptions used by Lindblad *et al.* (1985).

The X-ray spectrum of A1060 as measured by Mitchell and Mushotzky (1980) has two thermal components one with $kT = 2.0$ keV and the other with $kT = 12$ keV. Because of the poorer statistical precision the present ME observations measure only a mean temperature of $\sim$3.2 keV agreeing with those obtained from a single-temperature fit of the *HEAO 1* MED data (Mitchell and Mushotzky 1980), and the *OSO 8* data (Mushotzky *et al.* 1978). The total emission measure, EM, for A1060 as measured with the *HEAO 1* experiment (field of view = $1\overset{\circ}{.}5 \times 3\overset{\circ}{.}0$ and $3° \times 3°$) is 7.5×10^{66} cm^{-3} with the low kT component contributing $\sim$70% (Mitchell and Mushotzky 1980). From our analysis of the X-ray image of hot intracluster gas we find that an emission integral of only 4.2×10^{66} cm^{-3} has been seen with the *EXOSAT* CMA. Extrapolating from the derived density gradient of the intracluster gas, we find that an extent of $\sim$330 kpc, slightly larger than the extent seen with the IPC, could provide nearly all the EM of the low kT gas component. To account for the total emission measure, however, we would have to extrapolate the density law out to at least 500 pc. The total mass of the X-ray gas up to a radial distance of 500 kpc would then be 4.7×10^{12} $M_\odot$. The intracluster gas would then account for nearly 5% of the total binding mass as estimated from the virial theorem. The total binding mass of the cluster may have been overestimated (see Cowie, Henriksen, and Mushotzky 1987), however, and the X-ray gas may in fact account for a larger fraction of the cluster binding mass, particularly if the gas extent is much larger than what has been detected so far. Future X-ray observations with high throughput telescopes with large field of view, and good sensitivity near 10 keV would be very important.

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