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X-RAY SPECTRUM OF THE 2A 0335+096 CLUSTER OF GALAXIES

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ABSTRACT

We present the X-ray spectrum of a poor cluster of galaxies 2A 0335+096 obtained with the medium energy and the gas scintillation proportional counter experiments on board *EXOSAT*. The observed spectrum is best explained by a thermal bremsstrahlung emission process from a hot intracluster gas with a temperature of $\sim 3.4 \times 10^7$ K, and a line at 6.5 keV arising from transitions in highly ionized iron, i.e., Fe XXIV, Fe XXV, and Fe XXVI, which is redshifted to the observed peak energy. An iron abundance value of 0.4 times the solar value is derived for the hot gas in the cluster. The 99% confidence range derived for the iron abundance is 0.2–0.55 times the solar value, making it one of the most precise measurements of an iron line in X-ray clusters of galaxies. The iron abundance is remarkably similar to the values found for rich clusters and, therefore, is indicative of a universal value of iron abundance in all the X-ray clusters irrespective of their evolutionary and dynamical states.

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

I. INTRODUCTION

The X-ray source 2A 0335+096 was indentified by Schwartz, Schwarz, and Tucker (1980) and is associated with a compact group or "poor cluster" of galaxies which is centered on a dominant galaxy at a redshift of 0.035. Their observations with the scanning modulation collimator experiment on *HEAO 1* indicated that the X-ray source is extended with a FWHM of 1′.4 ± 0′.6.

We report here new, high-sensitivity, X-ray spectral observations carried out with *EXOSAT* over the photon energy range 1–10 keV. The X-ray spectrum is found to be isothermal and an emission line associated with a $K\alpha$ iron-line blend of emission from Fe XXIV, Fe XXV, and Fe XXVI states is detected very clearly in both the medium-energy and the gas scintillation proportional counter experiments. Analysis of the low-energy X-ray image of this cluster obtained with the *EXOSAT*, and a detailed study of its X-ray structure will be presented elsewhere.

II. OBSERVATIONS AND RESULTS

The X-ray spectral observations were performed on day 264 of 1984 using the medium-energy detectors (ME: see Turner, Smith, and Zimmermann 1981 for a description) and the gas scintillation proportional counters (GSPC: for a description, see Peacock *et al.* 1981). The ME experiment consists of eight proportional counters with a total geometric area of 1500 cm^2 and a square field of view with 45′ FWHM. The data from the argon-filled counters, sensitive in the energy range 1–20 keV, were used. The X-ray source 2A 0335+096 was observed for a total of ~ 15 hr with the ME detectors in the offset mode, where four detectors are pointed on the source and the other four detectors are offset by ~ 2° to monitor the background. The offset and aligned sets of detectors were interchanged after $8\frac{1}{2}$ hr. The data taken during times when a detector showed transient abnormal counting rates were excluded giving a useful exposure of 44,910 s on source. The detector background was removed using the data taken by the same detector while offset. The quality of the background subtraction was judged by monitoring the pulse-height channels 45–68, which are completely background dominated. The background-subtracted ME counts spectrum from the combined eight argon filled detectors is shown in Figure 1 (*top*). The error bars due to counting statistics are 1 σ. The total counting rate from the source is 8.8 ± 0.1 counts s^{-1}. No X-ray emission was detected in the xenon-filled proportional counters located behind argon-filled counters.

The GSPC also observed 2A 0335+096 at the same time as did the ME. The background subtraction for the GSPC was performed using a standard background which has been accumulated in-flight over a very long time while observing blank fields. The GSPC gain was established from two lines in the background spectrum arising from fluorescence of the lead collimator (see Peacock *et al.* 1985 for the in-flight performance of GSPC). The background-subtracted counts spectrum of 2A 0335+096 from the GSPC (useful exposure $= 5 \times 10^4$ s) is shown in Figure 1 (*top*). A line feature at ~ 6.5 keV appears in this raw spectrum.

The analysis of the spectral data 2A 0335+096 is summarized in Table 1. A thermal bremsstrahlung plus temperature-weighted Gaunt factor (model 1) was considered first. The free parameters of the model were the normalizations, temperature, and interstellar absorption. As determined from the $\chi^2_{\min}$ criterion, this model was found to give an unsatisfac-

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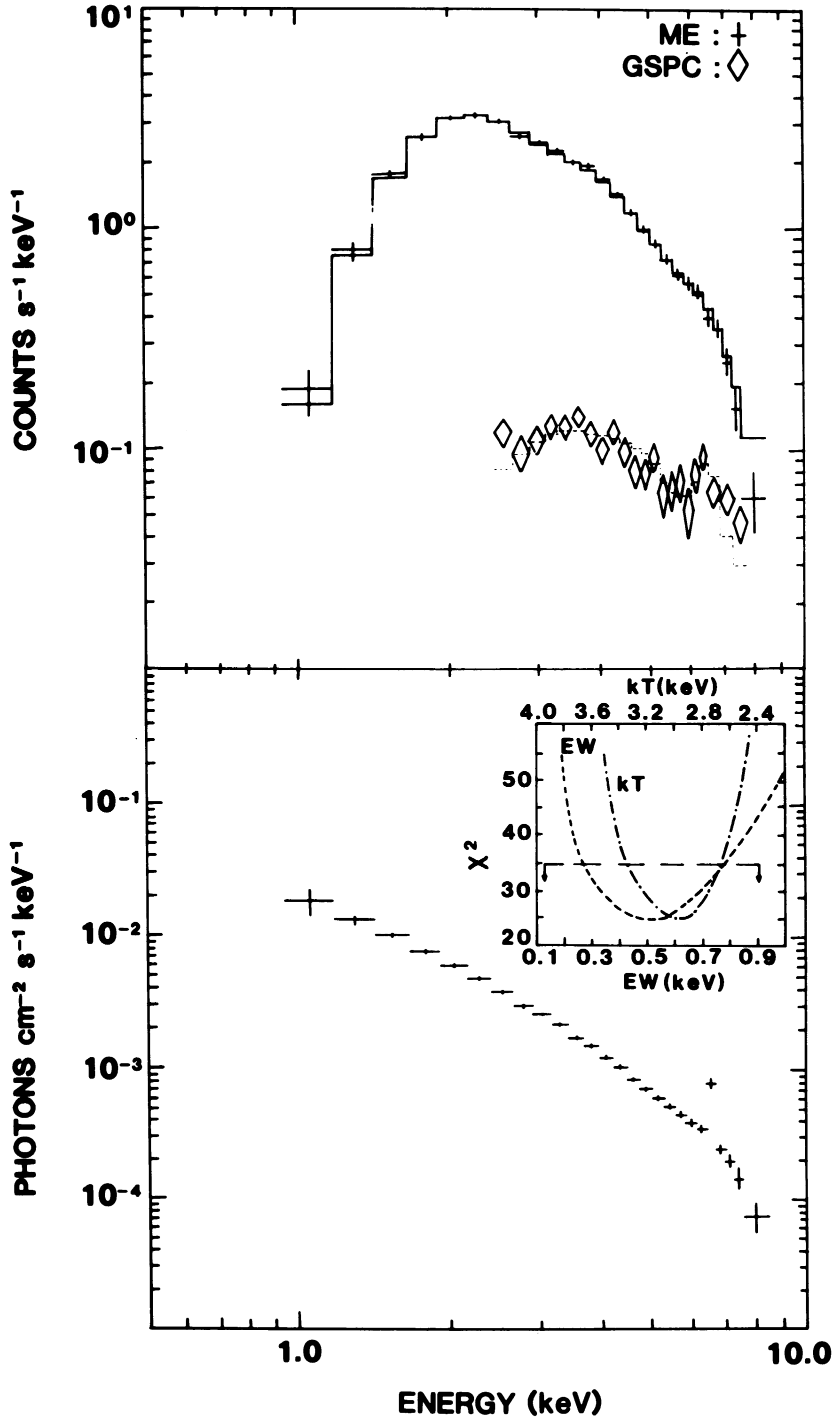

FIG. 1.—(*top*) The background-subtracted pulse-height spectra from the ME and the GSPC instruments. The histograms show the best-fit thermal bremsstrahlung plus a 6.5 keV line feature due to iron. (*bottom*) The incident photon spectrum deconvolved through the ME detector resolution and response functions. The inset shows the variation of χ^2 with the temperature of the thermal continuum and with the equivalent width of the line. The dashed line indicates the 99% confidence limit on these parameters based on the $\chi^2_{\min}$ + 9.2 criterion for two interesting parameters.

TABLE 1

PARAMETERS OF SPECTRAL MODELS FOR 2A 0335+096

Parameter[a]	ME	GSPC
Model 1: Bremsstrahlung with Gaunt Factor		
$A^b(10^{-2}$ photons cm^{-2} s^{-1} keV^{-1})	1.48	1.46
kT (keV)	3.30	4.47
N_H (10^{21} cm^{-2})	0.14	0.05
χ^2	50.4	40.8
DOF	23	22
Model 2: Power Law		
A^b(photons cm^{-2} s^{-1} keV^{-1})	0.12	0.054
Photon index (Γ)	2.74	2.41
N_H (10^{21} cm^{-2})	8.9	0.05
χ^2	37.2	31
DOF	22	22
Model 3: Model 1 + Emission Line		
$A^b(10^{-2}$ photons cm^{-2} s^{-1} keV^{-1})	$1.75^{+0.30}_{-0.17}$	$1.90^{+1.6}_{-0.5}$
kT (keV)	2.9 ± 0.3	$3.6^{+1.4}_{-1.0}$
N_H (10^{21} cm^{-2})	$1.1^{+1.2}_{-0.9}$	< 6.5
Line intensity (10^{-4} photons cm^{-2} s^{-1})	1.6	3.25
Peak energy (keV)	6.47	6.56
EW (keV)	0.54 ± 0.16	0.71 ± 0.38
χ^2	25.4	26.6
DOF	20	19

[a] Quoted errors and upper limit are with 90% confidence, using χ^2_{min} + 4.6 criterion for two interesting parameters (Lampton, Margon, and Bowyer 1976).

[b] A is the normalization constant for the continuum model.

tory fit to both the ME and the GSPC pulse height data. Next, we tried a simple power law (model 2) which gave an unacceptable fit to the ME data but an acceptable one to the GSPC data. We then considered a third (model 3) in which we added an emission line to Model 1, with line strength, peak energy, and line width as the additional free parameters. Acceptable fits to both the ME and the GSPC pulse-height data were obtained with this model indicating the presence of a line at 6.5 keV in both the data sets. For the GSPC data the improvement in χ^2_{min} with this model over that of a simple power law model is significant at a level of 99%, using the F-statistic (Bevington 1969). The best-fit parameters derived from this analysis are shown in Table 1. Although the parameters of model 3 which are derived independently from the ME and from the GSPC data are consistent with each other, the greater statistical precision of the ME data gives better constraints on the parameters. The best-fit incident spectrum derived from the ME data is shown in Figure 1 (*bottom*). The X-ray flux in the 1–8 keV band derived from this spectrum is 7.1×10^{-11} ergs cm^{-2} s^{-1} which, for a distance of 210 Mpc (using Hubble constant $H_0 = 50$ km s^{-1} Mpc^{-1}), gives an X-ray luminosity of 4×10^{44} ergs s^{-1} for 2A 0335+096. The emission integral for the whole cluster is $n_e^2 V \approx 8 \times 10^{67}$ cm^3 based on the emissivity of 5×10^{-24} ergs cm^{-3} s^{-1} in the 1.5–8 keV band for a cluster gas temperature of 3.4×10^7 K (Raymond, Cox, and Smith 1976). The inset in Figure 1 (*bottom*) shows the variations, based on the ME data alone, of χ^2 with the temperature of the continuum and with the equivalent width of the line at 6.5 keV. The line feature at 6.5 keV is seen even more clearly in Figure 2 where we plot the

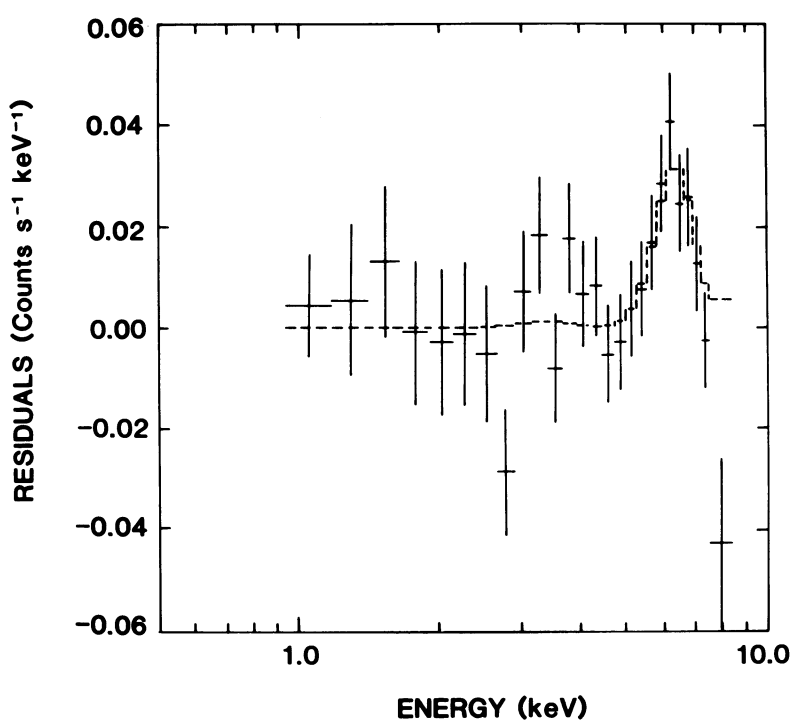

FIG. 2.—The residual counts spectrum obtained from the ME data after subtracting the continuum from Model 3 in Table 1. The dashed line shows the fit to the line feature at 6.5 keV.

residuals obtained after subtracting the thermal continuum of model 3 from the ME counts spectrum.

The observed line feature is the redshifted 6.7 keV $K\alpha$ iron-line blend representing primarily the K transitions in Fe XXIV, Fe XXV, and Fe XXVI. We use the recent detailed computations of Rothenflug and Arnaud (1985) to interpret the strength of the observed Fe line blend in terms of the iron abundance in the cluster gas. For the best-fit isothermal model with $kT = 2.9$ keV, the measured equivalent width of 0.54 keV gives an iron abundance Fe/H of 1.28×10^{-5} which is 0.4 times the solar value. The 99% confidence range for the iron abundance derived by us is 0.2–0.55 times the solar value.

The 90% confidence range of values for temperature of the continuum and the abundance of the Fe derived here are consistent with the values of these parameters obtained from the analysis of the *Einstein* Solid State Spectrometer data (R. F. Mushotzky, private communication). An earlier, preliminary analysis (Nørgaard-Nielsen *et al.* 1985), where an Fe line seemed to be absent, was based on an automatic reduction of the ME data alone which did not exclude data contaminated with transient background events and which used an approximate detector response function.

The column density of neutral hydrogen N_H estimated from the ME data is consistent with absorption in the Galaxy derived from the 21 cm radio observations (1.3×10^{21} cm^{-2}; Heiles 1975).

III. DISCUSSION

The temperature and X-ray luminosity observed from the hot gas in 2A 0335+096 are similar to previous observations of X-ray–bright, poor clusters of galaxies (Schwartz *et al.* 1980; Kriss, Cioffi, and Canizares 1983). The equivalent width of the Fe feature is nearly identical to that observed from another poor cluster of galaxies, viz., AWM 7 (Schwartz *et al.* 1980). Although the temperatures for the poor clusters are generally lower than those of rich cD clusters, the iron abundance value measured for the poor cluster 2A 0335+096 is in remarkable agreement with the iron abundance values measured for rich clusters (Schwartz *et al.* 1980; Mushotzky 1984; Rothenflug and Arnaud 1985). This measurement could indicate a universal value of iron abundance in all the X-ray clusters, rich and poor, irrespective of their evolutionary and dynamical states. The importance of Fe abundance in clusters of galaxies has been discussed by Vigroux (1977), De Young (1978), and Rothenflug *et al.* (1984). In brief, the presence of iron in the hot cluster gas implies that the intracluster medium has been enriched with iron from the galaxies where it is produced in the course of normal galactic evolution as a result of star formation. Iron is ejected into the interstellar medium during supernovae explosions. The enrichment of the intergalactic medium then could take place as the interstellar material is stripped from galaxies by either the ram pressure of the intergalactic medium (Gunn and Gott 1972) or during close encounters of galaxies (De Young 1978). The heavy elements could also be expelled into the intergalactic medium by an extremely high supernova rate sustaining a hot wind—a process that is possible only in the beginning of galactic evolution (Larson 1974). The constancy of the Fe abundance observed in all cluster types suggests that the enrichment of intergalactic gas results from normal galactic evolution rather than cluster evolution, and that the bulk of stripping probably occurs at the earliest epochs in the dynamical evolution of the X-ray clusters, as has been suggested previously by Rothenflug *et al.* (1984).

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